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Editors

Thoracic Aortic Diseases

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Hervé Rousseau · Jean-Philippe Verhoye · Jean-François Heautot (Eds.)

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Preface

Alain Cerene

When, more than 30 years ago, I started my residency in cardiovascular surgery, lesions of the descending thoracic aorta were considered a big surgical challenge.

We were dealing with acute De Bakey type III dissections, now called Shumway type B, and did not really know at that time whether we should treat them surgically or medically. Post-operative morbidity and mortality were so important that in the end we decided to treat them medically when these dissections were free of complications.

Certainly, some of the patients could die from a rupture of the aorta, but overall the mortality was much lower than with surgery. This attitude still prevails today.

There were also acute traumatic ruptures of the distal aortic arch, and in this case emergency surgical treatment was the rule. After cross-clamping the thoracic aorta, the lesion was repaired as fast as possible. Also in these cases mortality was high, and morbidity was significant, especially regarding paraplegia.

Then we started using the Gott shunt. This shunt allowed perfusion of the distal aorta during clamping without the need for severe anticoagulation and thus proved useful in multiple-trauma patients. Nevertheless, the Gott shunt was quite difficult to use, and was not really reliable. However, it represented some progress.

Later we got to use "active" shunts, such as partial extracorporeal circulation systems left-left, or right-left with centrifuge pumps and "heparin-like" circuits, which did allow very low anticoagulation in multiple-trauma patients, and the results improved both with regard to mortality and morbidity, as fewer patients were dying and less paraplegia was noted, but this neurologic complication was still a major factor.

In the end, surgery of thoracic aortic aneurysms was providing the best results at that time, but mortality was still substantial, as was morbidity. Five to 10% of patients were dying post-operatively.

Surgeons like De Bakey, Cooley, Crawford, Johnson, Kouchoukos, and others made major contributions in improving surgical technique.

Since then, much progress has been made regarding indications, extra-corporeal circulation with the use of deep hypothermia and circulatory arrest, anaesthesia, reanimation, and surgical techniques. We have also gained a better understanding of anatomy and physiology of spinal cord vascularisation. Presently, surgery of the descending thoracic aorta is not the "scary" event it used to be 30 years ago, but it still remains challenging.

We should not forget that some of the progress made in the surgical management of thoracic aortic aneurysms is due to improvements achieved in radiological imaging, which nowadays has become very reliable and is in practice devoid of risks.

In the early 1990s, an article by Parodi et al. entitled "Transfemoral intraluminal graft implantation for abdominal aortic aneurysms" heralded the development parallel to surgery of a new treatment strategy for aortic lesions, which could be repaired from "inside the lumen".

Most major surgeons did not really pay attention to this publication, until Dake, a radiologist from Stanford University, demonstrated that it was possible to treat most of the lesions of the descending thoracic aorta by the use of endovascular stent grafts, with little trauma, short hospital stay, little paraplegia, and a very low mortality rate.

Since then, close collaboration between industry and medicine has brought many improvements in the development of these stent grafts and has allowed the vast majority of lesions of the descending thoracic aorta to be treated by this technique. Furthermore, this technique can now be used in combination with a simple surgical procedure to repair even lesions of the aortic arch, and, in our view, this is not yet the end.

Traumatic ruptures and acute type B dissections can now be treated in the same way. Most aneurysms are also manageable by this strategy if certain anatomic prerequisites are fulfilled. And this is not to mention ulcers and their complications, which have become very easy to treat. Problems may arise often now only from certain aneurysms due to chronic dissections, but even in these cases is one not in his or her right to try first the endoluminal approach, and, if this fails, to entrust the patient to the surgeon?

In fact, endoluminal stent grafting really is a revolution in therapy and, like every revolution, it has been met with some distrust or even hostility by those in relevant positions, the surgeons.

For them, every endoleak was a failure. What was to become of the grafts? One cannot, however, treat all lesions by these means! They were leaning on the limitations of the method while forgetting that it killed a lot fewer patients than surgery and that the number of paraplegias was infinitesimal.

Furthermore, neither the technological progress of aortic stent grafts nor the skills of the people implanting them have reached their conclusion.

Hence, there are three major issues in this field:

1. There is the issue of the restrictions of the access to the aorta owing to the state of the femoro-iliac axis, an issue which will fade away (but not disappear completely) as technological progress is achieved.
2. There is the issue of the balance of the actions of surgeons and radiologists.
   (a) In our view, it is crucial that indications are established jointly.
   (b) Should the procedure be performed in a surgical operating room or in a radiology unit equipped for surgery? The procedure requires sophisticated radiological equipment which is usually unavailable in surgical operating rooms. If surgeons argue that it is impossible to operate on an aortic rupture in a radiology unit, they are right. But what are the figures for aortic ruptures? In Toulouse, in our institution, we have seen none in 150 consecutive cases, and the only problems we had arose from the femoro-iliac axis. Migration of the stent graft to another part of the aorta always leaves enough time to take the patient to the surgical operating room. In view of this, does the radiological equipment usually available in surgical operating rooms provide the necessary accuracy? We believe it does not. In fact, endoluminal stent grafting implies little surgery and there are nearly no complications which would require heavy-duty surgical equipment, while the interventional radiology technique is dependent upon the accuracy provided by sophisticated paraphernalia. So, in our view, the procedure should therefore be performed in a radiology unit equipped like an operating room, and it should be accomplished by an interdisciplinary medical and nursing staff including anaesthesiologists, surgeons, and radiologists.
3. There is the issue of who should operate? The radiologist, for the time being, needs the surgeon's help. The surgeon could do everything on his or her own! But we just proved that the procedure should be performed in a radiological unit! So why not a symbiosis between radiologists and surgeons, with a distribution of tasks and responsibilities, especially in terms of complications?

What needs to be avoided by every means is the recruitment of patients directly by radiologists, who would, once they did not need the surgeon's help anymore (and this is likely to happen soon for the femoral approach), establish the indication and perform the procedure on their own, calling the surgeon only if a complication arises. It would be equally hazardous for the surgeon to establish the indication alone and to perform the procedure by himself or herself in an operating room equipped only with austere mobile radiology gear. Neither of these two attitudes would benefit the patient and one must not forget that it is his or her interest that should always be at the heart of medical action.

Thus, our patients will be permitted to gain from the progress achieved in the field of cardiovascular surgery when necessary and from the accomplishments of interventional radiology the majority of the time.

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Radio-Anatomy of the Thoracic Aorta. 3D Imaging of the Aorta (CT, MRI and 3D Rotational Angiography)

Jos C. van den Berg

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Contents

1.1 Introduction

Traditionally radiological imaging of the human body has been limited to a two-dimensional depiction of a three-dimensional reality. The thoracic aorta modalities most commonly used were plain (chest) radiography, (digital subtraction) angiography and single-slice computerized tomography (CT). Over the last decade tremendous technical advancements have been made in various imaging modalities. The speed of data acquisition with CT scanning and MRI has increased, thus enabling fast, high-resolution axial imaging. The concurrent development of advanced 3D volume-rendering techniques, which require high computational speed, allowed for the development of CT angiography (CTA), magnetic resonance angiography (MRA) and 3D rotational angiography (3D-RA). In this chapter a brief overview on the technical aspects of the currently available modalities will be given and advantages and disadvantages of each technique will be discussed. The radiological anatomy of the thoracic aorta and its branches as depicted with these new imaging techniques will be described in detail.

1.2 Imaging Modalities

For successful evaluation of vascular pathology in general, an imaging study must enable accurate measurements, demonstrate intraluminal abnormalities and mural disease, and depict (patency of) side branches [1]. Evaluation of vascular disease is facilitated by 3D techniques, and improves appreciation of the geometry of vascular structures and lesions. The currently available imaging modalities that allow for 3D evaluation of the thoracic aorta are multidetector row CTA, contrast-enhanced MRA and 3D-RA.

1.2.1 Multidetector Row CTA

Compared with single-slice CT the scanning speed of multidetector row CT has increased 40-fold, which makes it possible to scan the entire thorax in a short breath-hold. The present generation of multidetector row or multislice CT scanners allows for a simultaneous acquisition of up to 16 slices, while in the near future systems with over 64 detectors will become available. With multidetector row CT a single acquisition yields a volume of data, instead of a number of slices (as when using helical CT). Thusfar resolution in the *z*-axis ("slice thickness") was a limiting factor in image quality for multiplanar reconstruction (MPR). With an increase of the number of detectors, the resolution increases as well, and thus (near) isotropic imaging becomes possible (i.e., imaging with a resolution that is equally high in all directions).

It has been demonstrated that in order to get optimal enhancement of the thoracic aorta preferably high-concentration contrast medium should be used (more than 300 mg I/ml), followed by flushing with a saline bolus [2–4]. The scan delay can be optimized, and the contrast medium dose can be reduced by using a test-bolus technique, or by using an automatic bolus recognition system (bolus triggering) [3]. Scanning protocols vary with different systems and manufacturers. With a four-row detector most examinations are performed with 2.5-mm collimation and a table speed of 15–20 mm per rotation, while using a 16-row detector collimation is reduced to 1.5 mm, and the table speed can be increased to 36 mm per rotation. Contrast medium is injected at a flow-rate of 3–5 ml/s, for a total volume of 120 ml.

The radiation dose for CTA is at least 2–3 times lower than the dose for angiography [5].

Anatomic coverage should include the thoracic inlet (in order to evaluate congenital anomalies of the supra-aortic arches) and the diaphragm (which can help to determine the side of the descending aorta) [5].

3D volume-rendering techniques permit real-time, interactive evaluation in any plane and projection. This enhances understanding of vessel dilatation, mural thrombus and branch vessel anatomy, and further allows visualization of both vascular structures and adjacent viscera and airways [1, 5]. After obtaining the volumetric data set, a number of postprocessing image reconstruction options are available [5]:

- MPR: 2D sections with a thickness of 1 voxel (fast, easily performed at the CT scanner).
- Variable-thickness displays consisting of an assimilation of various sections.
- Maximum-intensity projection (MIP) in which images are derived by projecting the highest attenuation voxel in a ray through the scan volume onto an image plane; vessels running in close proximity of osseous structures or calcifications can be easily obscured.
- Shaded surface display: this method uses a single threshold to choose relevant (high-density) voxels; because of the threshold this method is susceptible to artifacts, and may fail to demonstrate vascular calcifications.
- 3D volume-rendering techniques (require a separate workstation): each voxel is adjusted for opacity, color and brightness according to each CT value, according to preset color and opacity maps; the advantage of this technique is that no threshold levels are being selected, thus avoiding the possibility of altering apparent diameters of vessels [6].

Reversing the window-level transfer function, we can produce virtual angioscopic images [7, 8].

In summary the advantages of multidetector row CT include shorter imaging time, greater axial coverage, motion artifact suppression, improved *z*-axis resolution, higher axial spatial resolution, decreased total dose of iodinated contrast medium and real-time interactive 3D display facilities on workstations.

1.2.2 MR Angiography

Traditionally, MRI, using T1-weighted spin-echo (black blood) imaging and cine-MRI is well suited for evaluation of the gross anatomy of the thoracic aorta, as well as for evaluation of pericardial, pleural and mediastinal effusions [9]. Flow-based methods of imaging (using time-of-flight or phase-contrast properties) yield bright blood images using gradient-echo techniques [10]. The limitation of the latter techniques, however, is that they rely on the physical properties of flowing blood (velocity, direction, etc.), making the technique susceptible for artifacts, which may result in overestimation of stenoses or even a false diagnosis of occlusion of a vessel. Furthermore the spatial resolution and signal-to-noise ratio provided by these 2D techniques do not allow evaluation of small vessel lesions or small side branches [11].

The most-suited technique currently used in the evaluation of thoracic aortic anatomy and disease is dynamic subtraction MRA, using gadolinium (0.2 mmol/kg, flow rate of antecubital injection 2 ml/s) as the intravenous contrast agent [10, 12–16]. Gadolinium shortens the T1 of blood, and therefore allows shorter imaging times. Thus, fewer flow-related and motion-related artifacts occur, and therefore the technique can demonstrate subtle aortic lesions, such as penetrating ulcers, and small intercostal arteries. After a plain MRI, intravenous contrast agent is administered. Using bolus timing (either by using a test bolus or real-time fluoroscopic triggering) the arrival of the contrast agent can be timed, and the contrast-enhanced sequence is performed [10, 17]. This is followed by subtraction of the two series. The limitation of this test-bolus technique is the potential for diminished artery-to-vein contrast, associated additional cost of test-bolus contrast and the potential difficulty to observe the test bolus in distal vessels or in cases with slow flow [17]. To further reduce respiratory motion artifacts and artifacts related to cardiac motion and pulsatile flow, electrocardiographic triggering techniques can be used [9, 18]. The images thus obtained can either be viewed on a slice-to-slice basis, or can be reconstructed on a computer workstation into a MIP image. The appearance of MIP reconstructions resembles that of conventional angiography, and MIP reconstructions are therefore useful in planning of surgical procedures [13]. Using 3D reconstruction techniques it is also possible to obtain an internal view of the vessel and its walls (virtual intra-arterial endoscopy) [13]. It is of importance to evaluate

both source images and reconstructed images, in order to optimize diagnostic yield (e.g., a dissection can be easily overlooked by evaluating MIP images alone) [18].

Scanning parameters may vary depending on the type and the manufacturer of the MRI system, and will not be listed here.

1.2.3 3D Rotational Angiography

Conventional rotational angiography images are obtained by performing a motorized movement at constant speed of the C-arm around the patient during continuous contrast agent injection. To obtain 3D images from a conventional rotational angiographic run two methods exist. One consists of an examination in two phases, where at first the C-arm makes a sweep, acquiring images that act as a mask for the subsequent data acquisition. Subsequently a return sweep is performed while contrast agent is injected throughout the entire period of data acquisition [19, 20].

The other technique of obtaining 3D-RA images is directly based on conventional rotational angiographic images without the use of subtraction [21–23].

With both techniques images are transferred to a workstation, where they are converted into pseudo-CT slices (the image intensifier being considered a multiline detector). Using specific algorithms that correct for image intensifier and contrast distortion, the data set is reconstructed into a volume-rendered image. During this reconstruction process two different types of image correction are performed to limit visual distortion to a minimum: pincushion distortion correction, which is used for reducing the environmental influences caused by the earth's magnetic field, and isocenter correction, which corrects all the movement imperfections introduced by the rotating C-arm [24]. The 3D volume obtained in this way can be rotated and viewed in any direction, and optimal tube positioning (angulation, skew) can be chosen. Determination of vessel geometrical properties (length, diameter) can be done manually or using automated vessel analysis software. This software can also provide an endoscopic view (virtual angioscopy), used for evaluation of the vessel interior. Recent developments in software, using an unenhanced and a contrast-enhanced run, also allow visualization of calcifications. The same method can provide an improved depiction of stent location and its relation to the calcified plaque and vessel wall. Important information on flow characteristics can be gathered from the cinefluoroscopic angiographic images.

A disadvantage of the 3D-RA technique is nonvisualization of the thrombus. The same is true for conventional angiography. Calcification, however, can be demonstrated using 3D-RA using either the source images showing some indirect signs of the presence of a thrombus (discrepancy between angiographic lumen and location of calcification) or the calcified plaque software.

Table 1.1 Advantages and disadvantages of the various three-dimensional imaging techniques

Feature of technique	CTA	CE-MRA	3D-RA
Diameter measurements	+	+	+
Demonstration of thrombus	+	+	–
Demonstration of calcification	+	±	+
Demonstration of vessel wall	+	+	–
Intraluminal detail	+	+	–
Branch vessels	+	+	+
Dynamic flow information	–	–	+
Monitoring intervention	–	–	+

CTA computerized tomography angiography, *CE-MRA* contrast-enhanced magnetic resonance angiography, *3D-RA* 3D rotational angiography

The main use of 3D-RA is in a therapeutic setting in the interventional suite. Use as a diagnostic modality in cases with complex anatomy is another field of application of 3D-RA. The major advantage of 3D-RA is that owing to the short reconstruction times the physician can optimize projection and make adjustments during the interventional procedure, in order to ensure the optimal outcome, without additional procedure time.

Table 1.1 lists advantages and disadvantages of the various three-dimensional imaging techniques.

1.3 Gross Anatomy

The thoracic aorta starts at the level of the aortic valves in the right anterior mediastinum. The aortic root is formed by the three sinuses of Valsalva (Fig. 1.1).

The ascending thoracic aorta then follows an upward and subsequent left laterodorsal course through the thoracic cavity and is continuous with the aortic arch. The aortic arch has the shape of a semicircle, and slightly ventral to the vertex it gives off its three largest branches (innominate artery, left common carotid artery and left subclavian artery). Finally it makes a downward turn as the descending thoracic aorta. The transition of the aortic arch to the descending thoracic aorta lies at the level of the isthmus (insertion of the ligamentum arteriosum, the remainder of the ductus Botalli). At the level of the diaphragm the aorta starts its abdominal course. The diameter of the thoracic aorta normally measures 3.3 cm at the aortic root, 3.0 cm at the mid-ascending portion, 2.7 cm at the level of the aortic arch and 2.4 cm at the proximal descending aorta [25]. Along the course of the thoracic aorta several side branches originate, and these are described in the following.

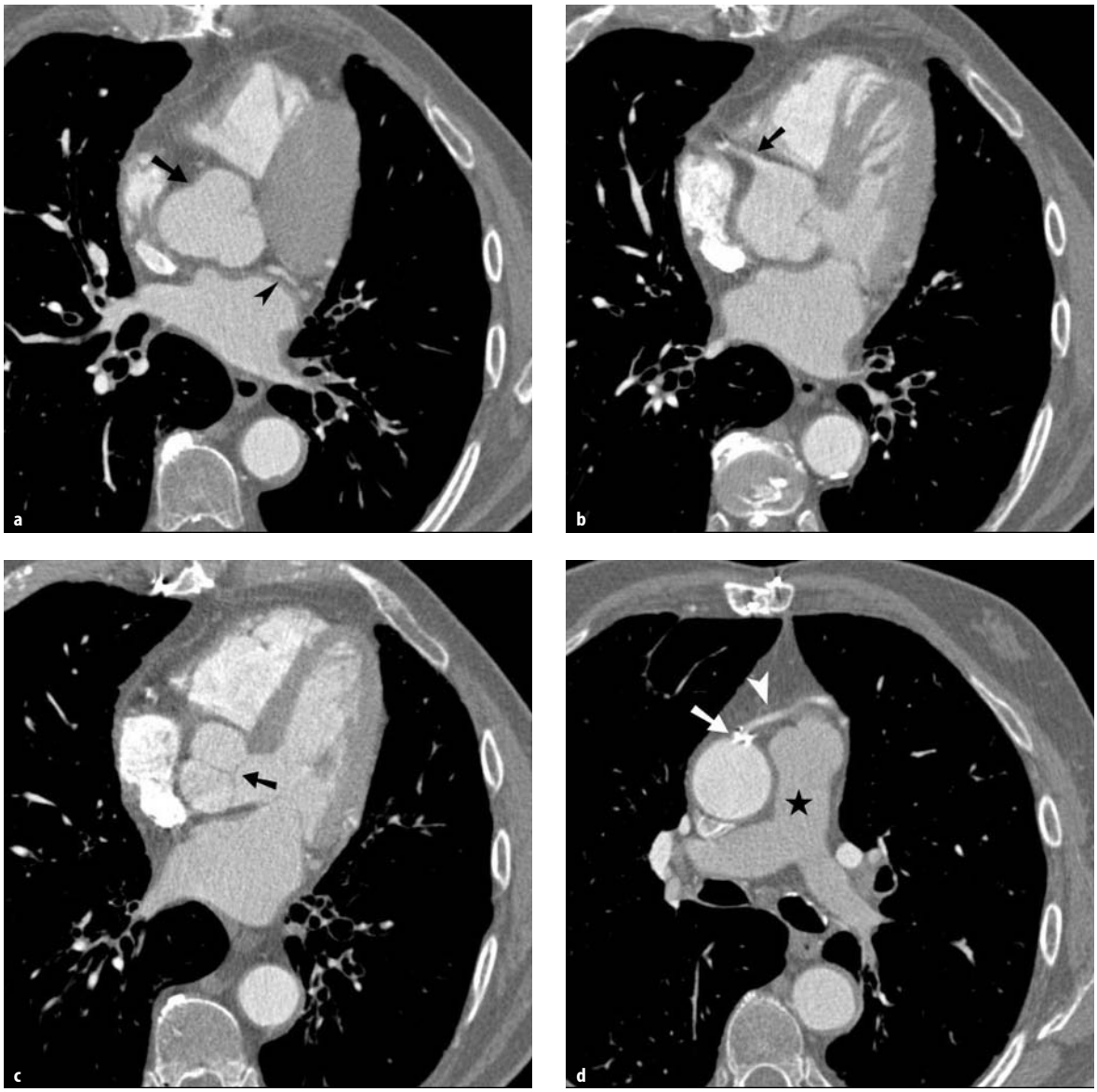
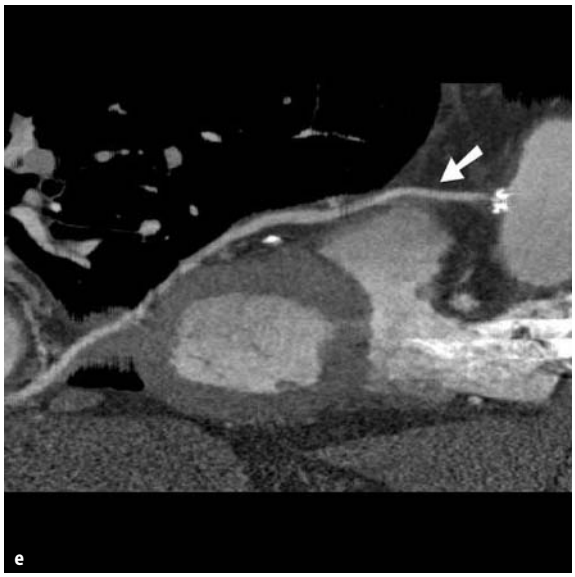


Fig. 1.1. **a** Axial computerized tomography (*CT*) at the level of the aortic sinus (*arrow*). The trilobar appearance is clearly appreciated; part of the main stem of the left coronary artery is clearly seen (*arrowhead*). **b** Axial CT at a slightly lower level than in **a** demonstrating the origin of the right coronary artery (*arrow*). **c** Axial CT at a level below that in **b** depicting cusps of aortic valves (*arrow*). **d** Axial CT at the level of the common trunk of the pulmonary artery (*asterisk*) demonstrating the site of anastomosis (*arrow*) of the aorto-coronary bypass graft (*arrowhead*). **e** Curved reformatted multiplanar reconstruction (*MPR*) demonstrating the full course of the bypass graft (*arrow*). **f** Volume-rendering technique (*VRT*) image depicting a aorto-coronary bypass graft to advantage (*arrow*)

1.3.1 Coronary arteries

The left main coronary artery arises from the left posterior Valsalva sinus and divides into the left anterior or descending artery (running to the left of the common trunk of the pulmonary artery and the left circumflex artery (following the left atrio-ventricular groove) (Fig. 1.2). The right coronary artery originates from the right anterior coronary sinus, caudally from the left coronary artery and prior to giving of its first branch (conus artery) it runs rightward posterior and inferiorly. With optimization of spatial resolution, decreasing scanning time and proper cardiac gating, these four main coronary arteries can be visualized using CT [26, 27] and MRI [28].



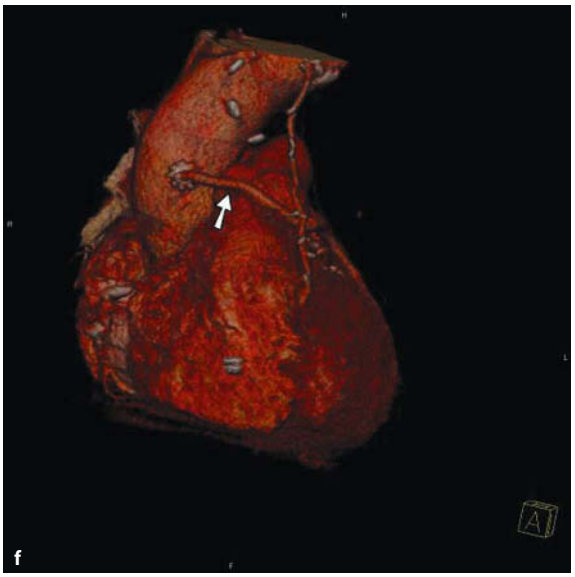
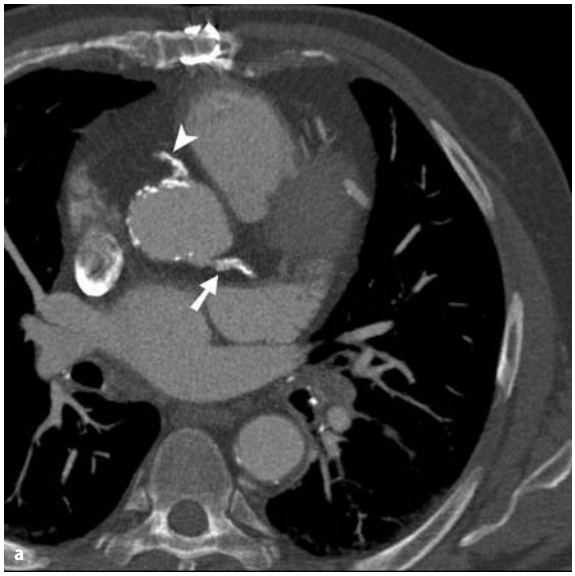


Fig. 1.1 e, f

1.3.2 Supra-aortic Vessels

The first and largest branch is the innominate or brachio-cephalic artery, which arises from the commencement of the aortic arch. It divides into the right subclavian and common carotid artery (Figs. 1.3, 1.4.). The innominate artery is bordered by the right innominate vein and pleura on the right side, and is crossed in front by the left brachiocephalic vein. Initially the course of the innominate artery is in front of the trachea, and then to the right of it. The second branch is the left common carotid artery that arises slightly to the left of the innominate artery. It extends upward, at first in front and then to the left of the trachea. Finally the left subclavian artery arises from the aortic arch, behind the left common carotid artery, and ascends lateral to the trachea.



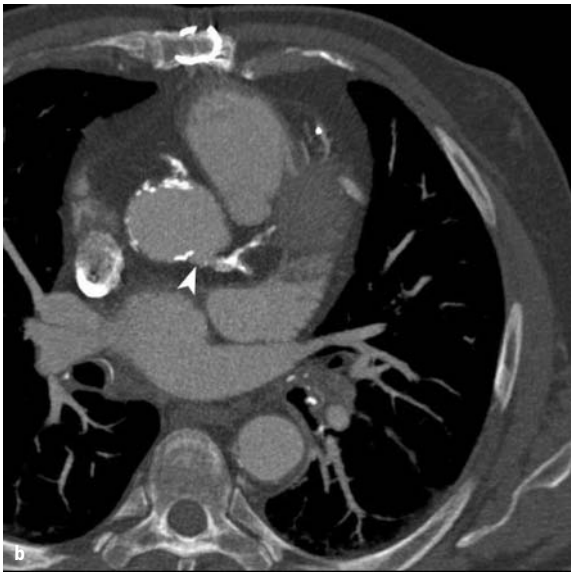


Fig. 1.2. a Axial CT; aortic root with heavily calcified right (*arrowhead*) and left (*arrow*) coronary arteries; the ostium of the right coronary artery is located in the anterior Valsalva sinus. **b** Axial CT; slightly higher plane, demonstrating the ostium of the left coronary artery (*arrowhead*), originating in the left posterior Valsalva sinus.

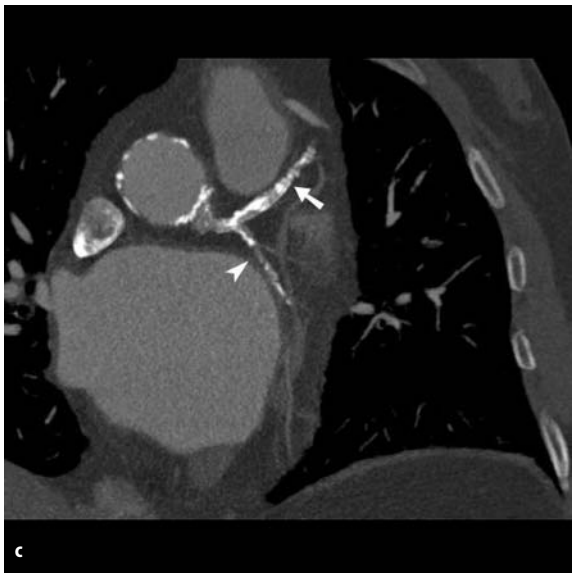


Fig. 1.2 c Curved reformatted MPR demonstrating the main stem of the left coronary artery, and its bifurcation into the left anterior or descending artery (*arrowhead*) and the left circumflex artery (*arrow*)

1.3.3 Intercostal Arteries

In most patients there are nine pairs of intercostal arteries that originate from the posterior aortic wall along the lower nine intercostals spaces [29]. In general, the orifices of the left and right intercostal arteries are located in close proximity to each other (Fig. 1.5).

1.3.4 Anterior Spinal Artery

The most important arterial feeding vessel of the thoracolumbar part of the spinal cord is the most dominant of the anterior radiculomedullary arteries (also known as the great anterior radiculomedullary artery or artery of Adamkiewicz). This artery arises from the radiculomedullary artery, which is a division of the posterior branches of intercostal and lumbar arteries. The distal portion of the great anterior radiculomedullary artery forms a characteristic "hairpin" turn. The artery originates in 68–73% of cases from left intercostal or lumbar arteries, with the level of origin ranging from the level of the ninth intercostals to the second lumbar artery (in 62–75% of cases at the ninth to twelfth intercostal artery) [30, 31]. With use of meticulous technique the artery of Adamkiewicz can be visualized in 66.7–69% of cases using MRA, and in 68–90% of cases using CTA [30–33].

1.3.5 Bronchial Arteries

Almost all bronchial arteries originate from the thoracic aorta between the level of Th4 and Th7 [29]. There are usually two bronchial arteries supplying the right side. The first commonly arises from the descending aorta as a common intercostobronchial trunk with the third right posterior intercostal artery, and has a posterolaterally lying orifice. The second important artery is the common right and left bronchial artery, which arises from the anterior surface and supplies both lungs. On the left side a separate left bronchial artery is usually present, and arises from the anterolateral surface of the aorta. Many variations occur, including origins from the internal thoracic artery, left subclavian artery and inferior thyroid artery (Figs. 1.6, 1.7).

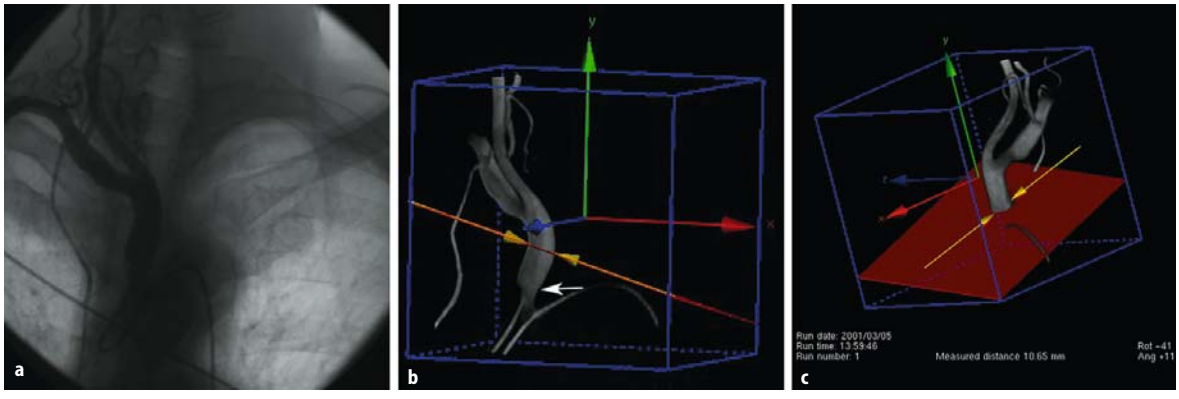


Fig. 1.3. a 3D rotational angiography (*3D-RA*); cinefluoroscopic image of selective injection into the innominate artery. **b** 3D-RA; reconstructive zoom with measurements (*yellow arrows*) of the innominate artery distally from stenosis at its origin (*white arrow*); *green*, *red*, and *blue arrows* indicate orientations of *x*-, *y*-, and *z*-axes. **c** 3D-RA; cut plane (*red*) indicating the plane of cross-section used for the measurements

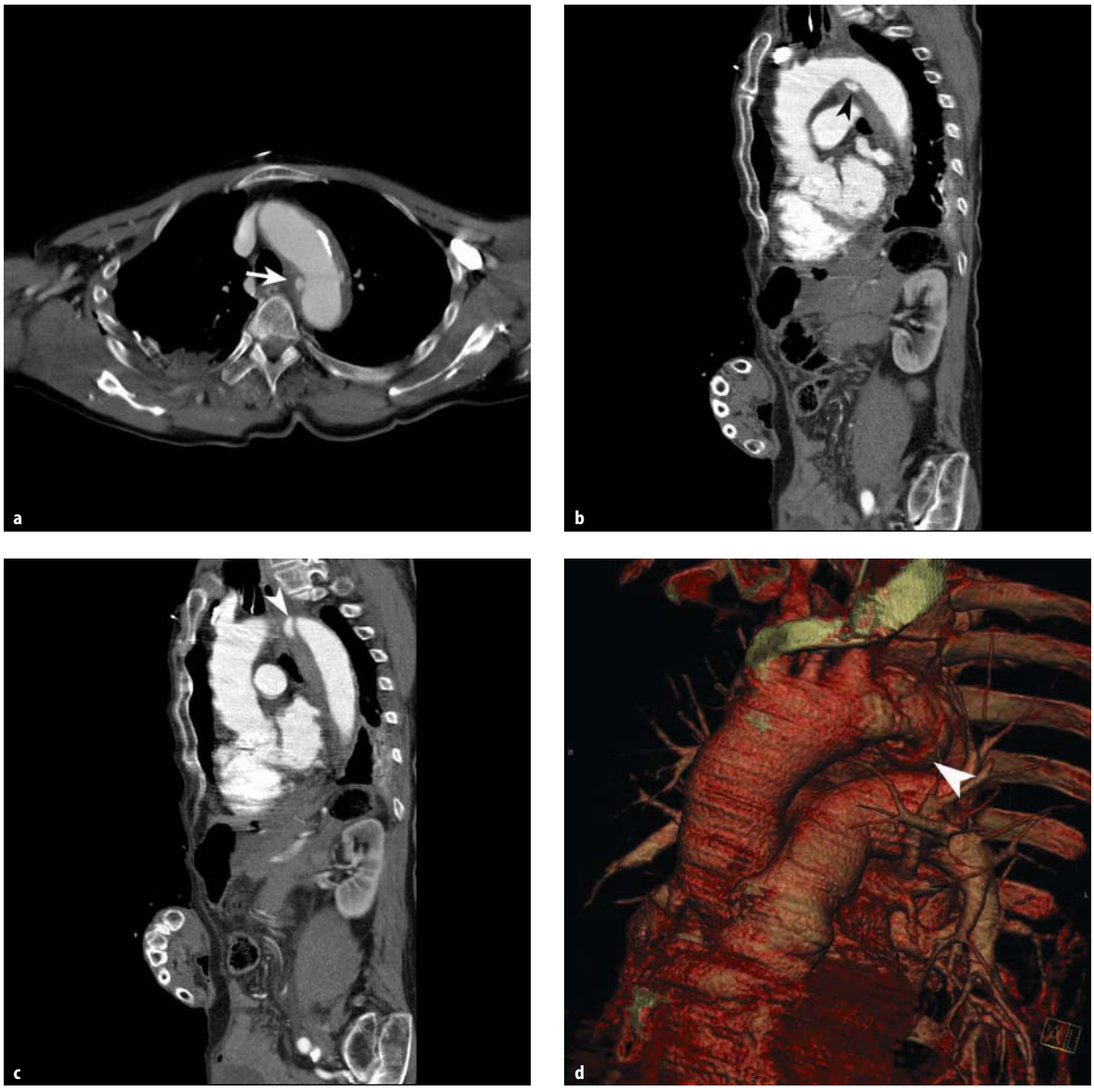
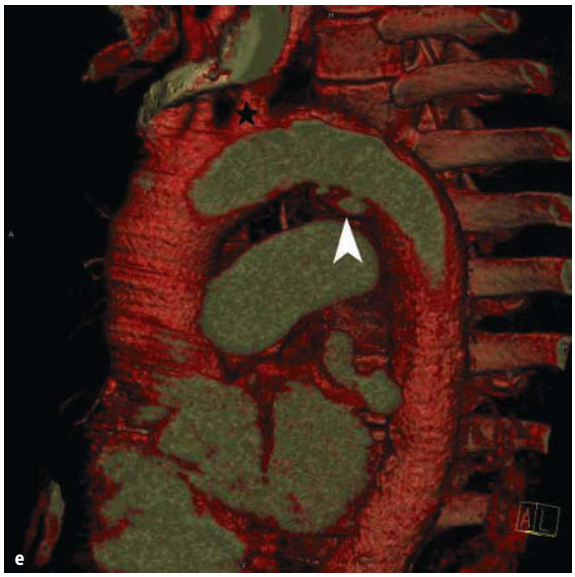


Fig. 1.4. **a** Axial CT of a patient after deceleration trauma demonstrating extravasation of the contrast medium at the level of the aortic arch (*arrow*). **b** Sagittal oblique MPR demonstrating aortic rupture at the inner curve of the aortic arch, at the level of the isthmus (*arrowhead*). **c** Sagittal oblique MPR slightly lateral from slice shown in **b** showing extension of the rupture (*arrowhead*). **d** VRT image demonstrating semicircular extension of the rupture to advantage (*arrowhead*).



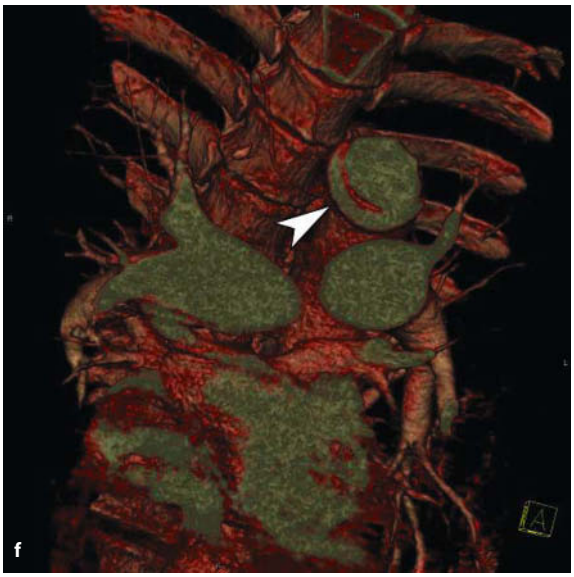


Fig. 1.4. **e** VRT image with the cut plane running through the aortic arch (same level as the MPR in Fig. 1.9b) demonstrating contrast extravasation (*arrowhead*); the relationship to supraaortic vessels can be clearly seen (*asterisk* left subclavian artery). **f** VRT image with the cut plane perpendicular to the aortic arch; semicircular extension of contrast extravasation (*arrowhead*)

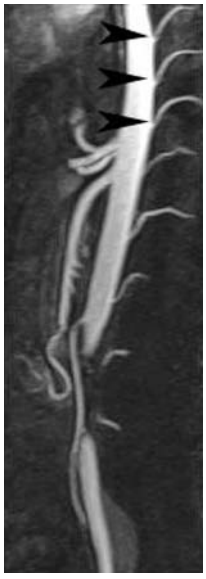


Fig. 1.5. Magnetic resonance angiography (*MRA*); maximum-intensity projection (*MIP*) reconstruction demonstrating lower intercostal arteries (*arrowheads*)

1.4 Congenital Variants and Abnormalities

1.4.1 Coronary Arteries

The commonest congenital anomalies are a left circumflex artery arising from the right coronary artery or right sinus and separate origins of the left circumflex and left anterior or descending artery from the left coronary sinus. Right coronary aneurysms (either congenital or acquired) can be clearly depicted using 3D techniques, thus aiding surgeons in preoperative planning [26, 34]. The aortic sinus itself can also demonstrate aneurysmal degeneration, which can be depicted using 3D imaging techniques [18]. Finally 3D techniques can be used to demonstrate aorto-coronary bypass grafts.

1.4.2 Supra-aortic Vessels and Aortic Arch

The normal aortic arch configuration with the innominate artery, the left common carotid artery and the left subclavian artery is seen in about 70% of patients (Fig. 1.8). The most frequent variant is a common origin of the brachiocephalic and the left common carotid arteries (a so-called bovine trunk).The second most frequent variation is a left vertebral artery, directly arising from the aorta; other but less common (less than 1%) variants are a common origin of both common carotid arteries, the presence of two brachiocephalic arteries

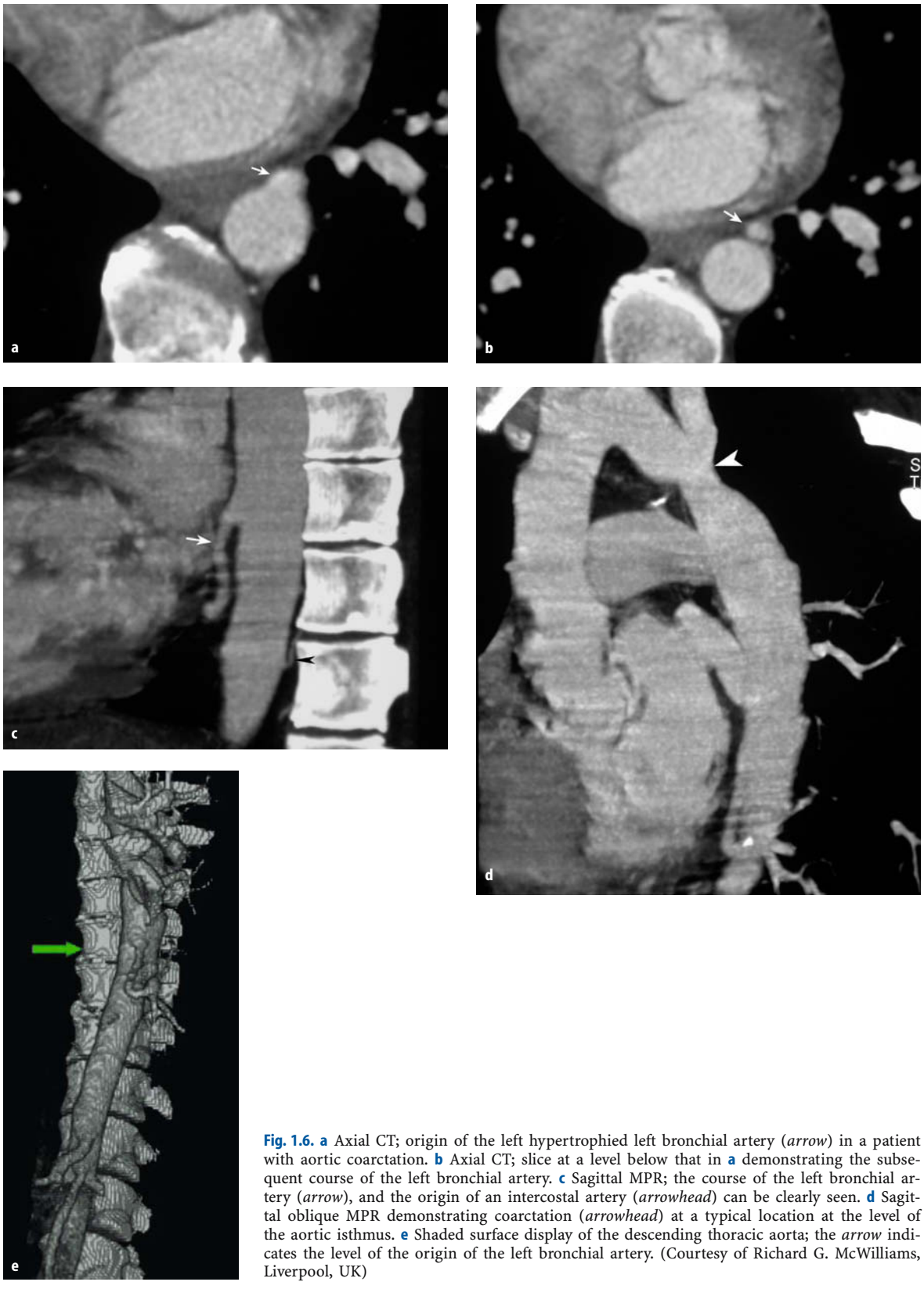
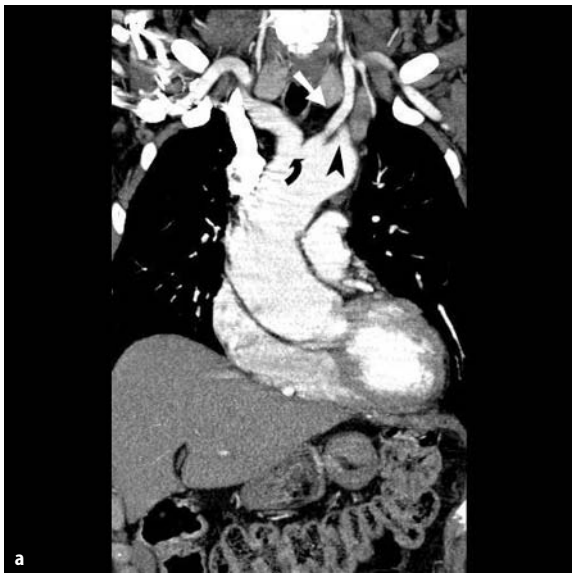
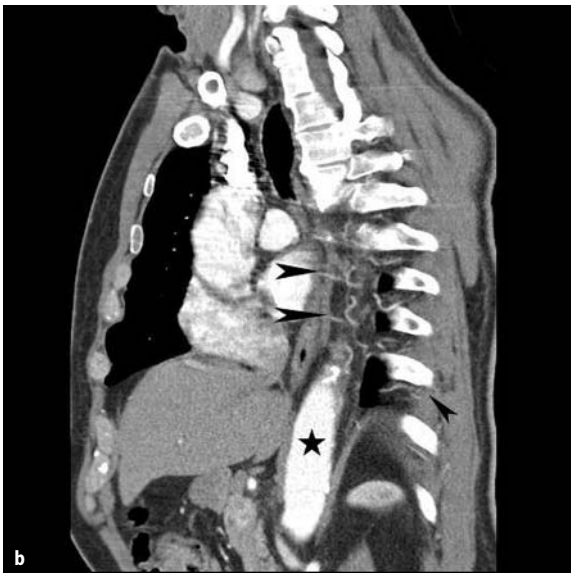


Fig. 1.6. **a** Axial CT; origin of the left hypertrophied left bronchial artery (*arrow*) in a patient with aortic coarctation. **b** Axial CT; slice at a level below that in **a** demonstrating the subsequent course of the left bronchial artery. **c** Sagittal MPR; the course of the left bronchial artery (*arrow*), and the origin of an intercostal artery (*arrowhead*) can be clearly seen. **d** Sagittal oblique MPR demonstrating coarctation (*arrowhead*) at a typical location at the level of the aortic isthmus. **e** Shaded surface display of the descending thoracic aorta; the *arrow* indicates the level of the origin of the left bronchial artery. (Courtesy of Richard G. McWilliams, Liverpool, UK)





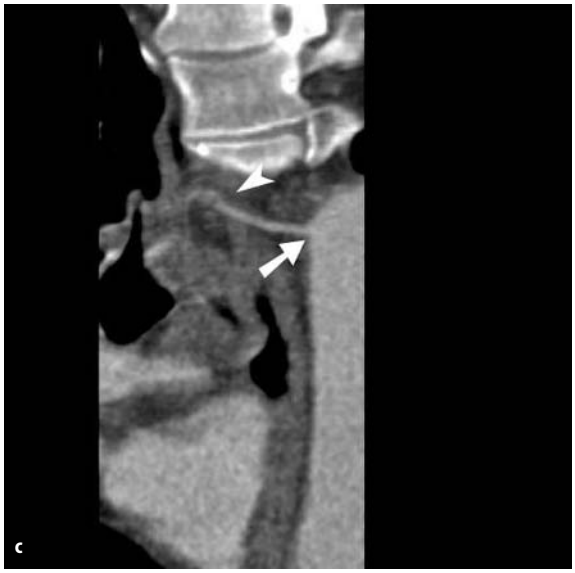


Fig. 1.7. a Coronal MPR; aortic arch with main supra-aortic arteries: innominate artery (*curved arrow*), left common carotid artery (*arrow*) and left subclavian artery (*arrowhead*). **b** Sagittal MPR; descending thoracic aorta (*asterisk*) with several intercostal arteries (*arrowheads*). **c** Curved reformatted MPR; origin of the common intercostobronchial trunk (*arrow*) and bifurcation into the right bronchial artery and the intercostal artery (*arrowhead*)

and finally a separate origin of all four great vessels [29].

The commonest malformation of the aortic arch is a left aortic arch with an aberrant origin of the right subclavian artery (arteria lusoria) (Fig. 1.9). In this type of malformation the right subclavian artery arises distally from the left subclavian artery and the right and left common carotid arteries. Another common anomaly is the presence of a right aortic arch, in which the ascending thoracic aorta arches posteriorly to the right side of trachea and esophagus (Fig. 1.10).

Vascular rings are characterized by encirclement of the trachea and esophagus by the aortic arch and associated structures. Vascular rings are the result of an abnormal embryologic development of the paired fourth aortic arches, in which primitive aortic arches fail to fuse or regress normally. Typically, each embryonic arch gives rise to their respective common carotid artery and subclavian artery. Normally the embryonic right arch regresses, while the left aortic arch persists, resulting in a left-sided aortic arch and great vessels. When the left embryonic arch regresses, the result is a right aortic arch, while failure of either arch to regress results in a double aortic arch. The commonest (symptomatic) vascular rings are associated with a complete double aortic arch, an incomplete double aortic arch with an atretic portion, a left aortic arch with an aberrant right subclavian artery (arteria lusoria, see before) and a right aortic arch with an aberrant left subclavian artery [11] (Fig. 1.11).

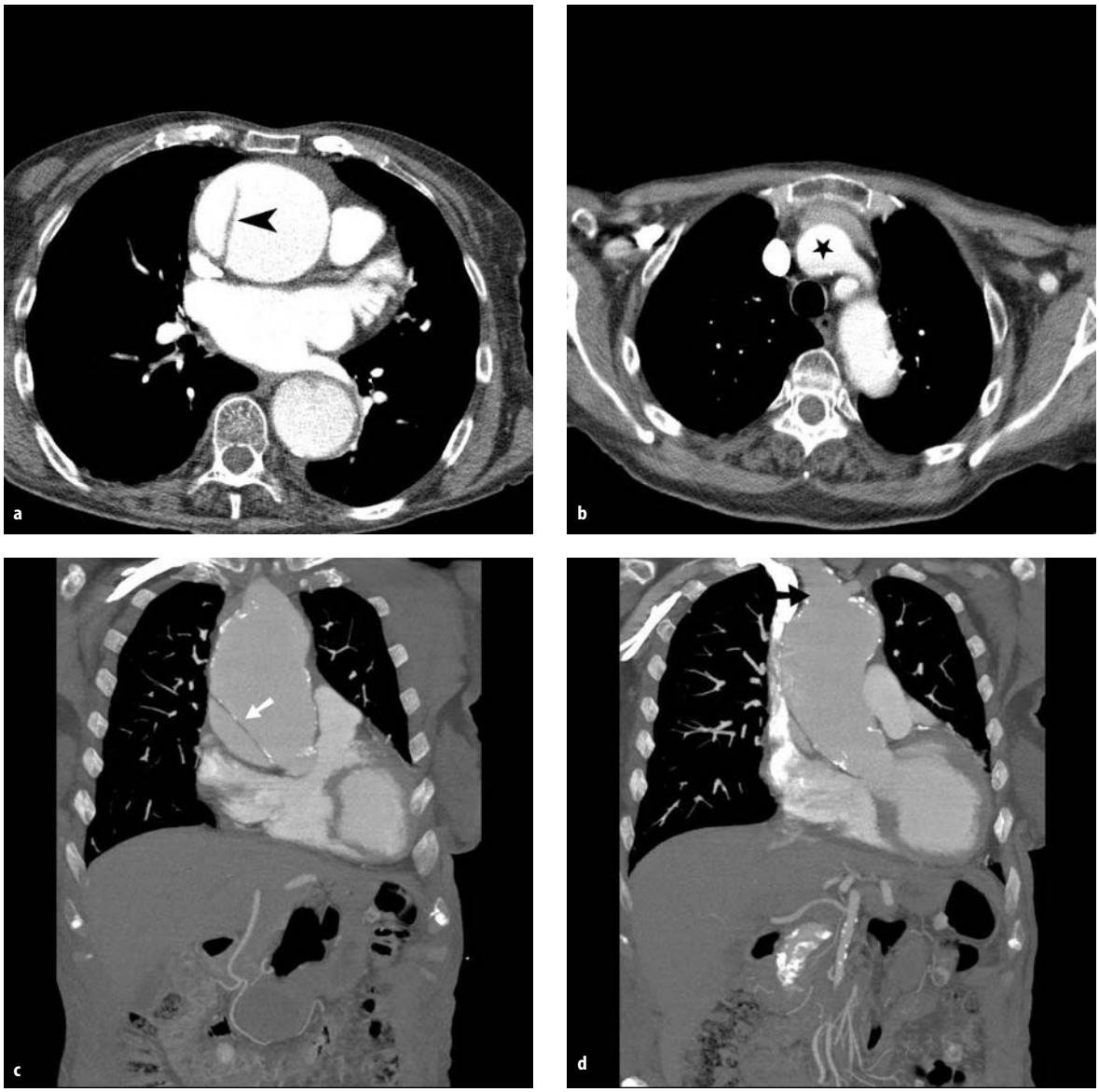
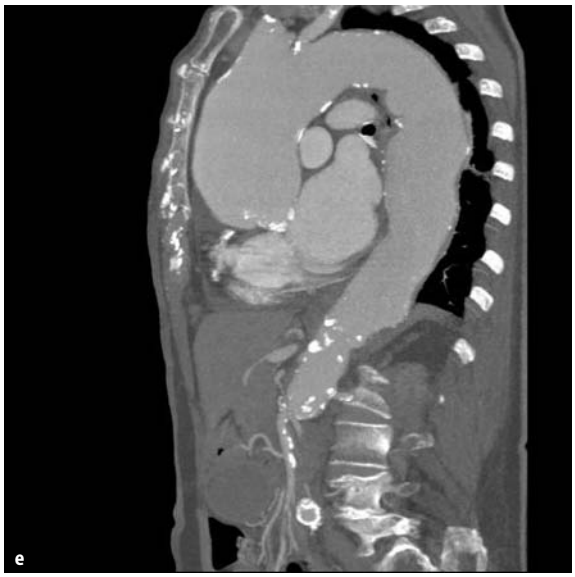


Fig. 1.8. a Axial CT in a patient with type A dissection; the intimal flap is clearly seen (*arrowhead*). **b** Axial CT of the same patient at the level of the origin of the supra-aortic vessels demonstrating the common origin of the innominate artery and the left common carotid artery (bovine trunk; *asterisk*). **c** Coronal MPR demonstrating the extent of the intimal flap (*arrow*) with calcification; the flap is limited to the ascending thoracic aorta. **d** Coronal MPR; bovine trunk clearly depicted (*asterisk*).

3D reconstructions of CT and MRI images can obviate the need for diagnostic angiography [13, 35]. Imaging studies should be evaluated for aortic position, coarctation, vascular compression of airways, collateral vessel formation and aortopulmonary shunts [6].

1.4.3 Aortic Coarctation

Aortic coarctation is one of the commonest congenital cardiovascular lesions, defined as a congenital narrowing of the aorta characterized by stenosis of the juxtaductal aorta (i.e., at the ductus arteriosus just distal to the origin of the left subclavian artery) [36]. 3D gadolinium-enhanced imaging is helpful in determining coarctation severity by demonstrating collateral vessels (e.g., intercostal and bronchial arteries), which are indi-



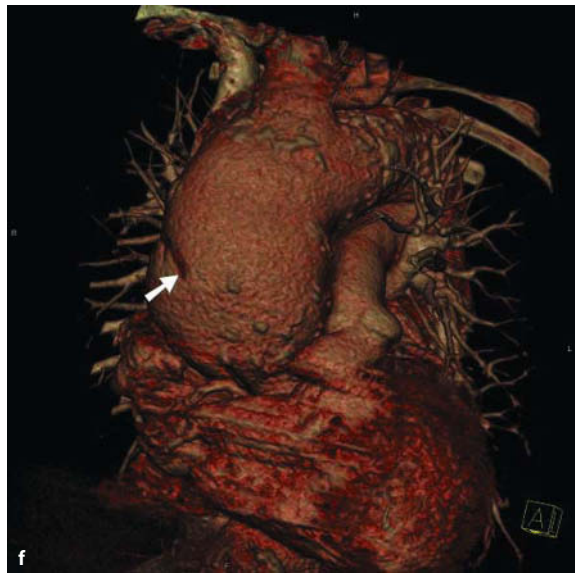
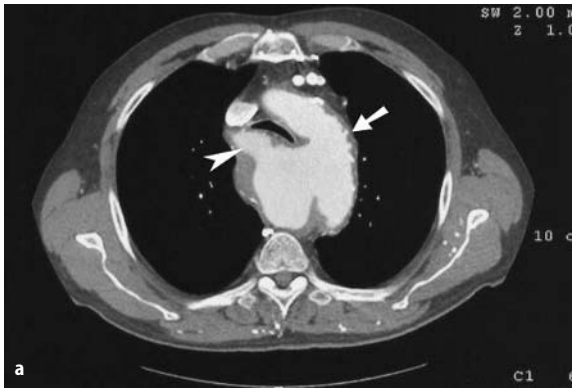


Fig. 1.8. e Sagittal oblique MPR demonstrating dilation of the ascending thoracic aorta, the origin of the supra-aortic vessels and aneurysmal changes in the descending thoracic aorta. **f** VRT image; depiction of the intimal flap (*arrow*) in the ascending thoracic aorta



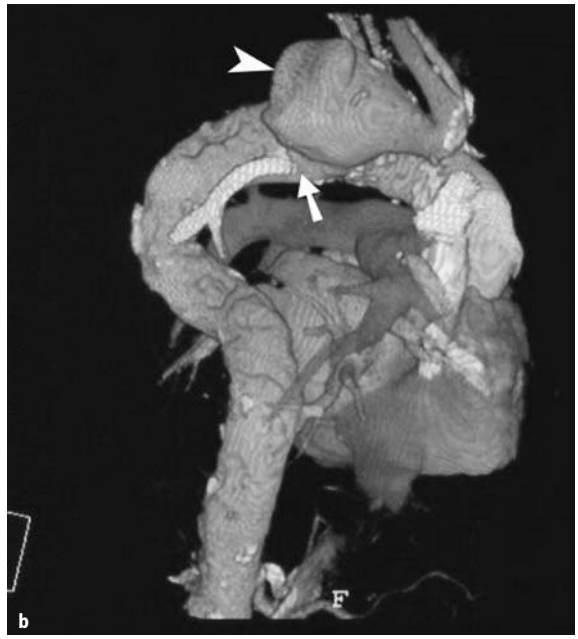


Fig. 1.9. a Axial CT at the level of the aortic arch (*arrow*); patient with aneurysm of an aberrant right subclavian artery (*asterisk*). **b** 3D reconstruction; posterior view demonstrating the extent of an aneurysm to advantage (*arrowhead*); origin of the right subclavian artery on the posterior aspect of the aortic arch (*arrow*). (Courtesy of Reinhard S. Pamler, Ulm, Germany)

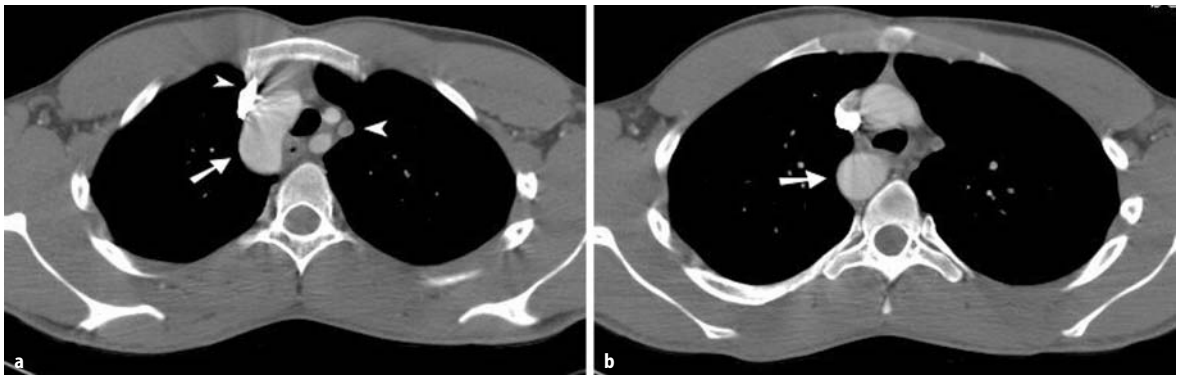


Fig. 1.10. a Axial CT; right-sided aortic arch (*arrow*); note the presence of the double superior caval vein (*arrowheads*). **b** Axial CT at a lower level demonstrating the course of the descending thoracic aorta to the right side of the vertebral column (*arrow*)

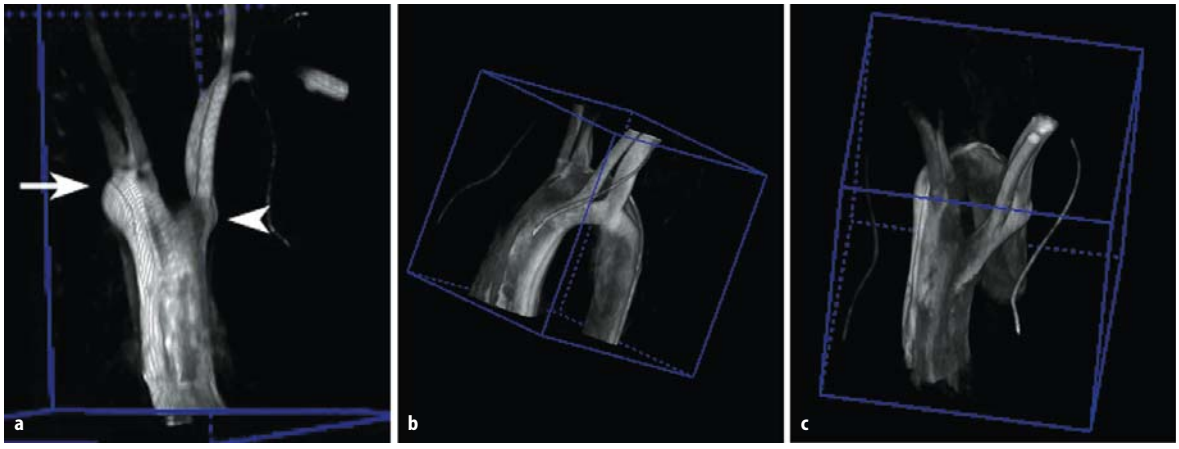


Fig. 1.11. a 3D-RA; default reconstruction in a patient with a double aortic arch; smaller ventral arch (*arrowhead*) and larger posterior arch (*arrow*). **b** 3D-RA; reconstructive zoom, more clearly depicting the separate origin of the left and right subclavian arteries and both common carotid arteries (absence of innominate artery). **c** 3D-RA; true cranio-caudad view depicting the double arch to advantage

cative of the hemodyamic significance of the lesion [11], while black blood images can demonstrate location and length of the aortic narrowing [10].

1.5 Acquired Aortic Disease

1.5.1 Dissection

MRI and CTA are established techniques in the assessment of aortic dissection, and are able to classify dissection according to the De Bakey or Stanford classification [9] (Figs. 1.13, 1.14). Detection of the intimal flap is best done using contrast-enhanced MRA or CTA [5].

High signal intensity/density within the false and true lumina is a finding consistent with patency, and allows for visualization of the intimal flap; in general, the true lumen has a higher density/signal intensity than the false lumen, owing to faster flow [11]. Delayed phase imaging can be used to depict the false lumen better [10]. The precise extent of an intimal flap and its relationship to the arch vessels can be clearly defined with customized reconstructions following the aortic course and angioscopic views [1].

1.5.2 Aneurysms

Thoracic aortic aneurysms occur in up to 10% of elderly patients, and are most commonly atherosclerotic in etiology (Figs. 1.15, 1.16). In the evaluation of aneurysms accurate depiction of aortic caliber, morphology, relationship to aortic arch vessels and the presence of thrombus or ulceration are of importance in deciding whether and how to intervene.

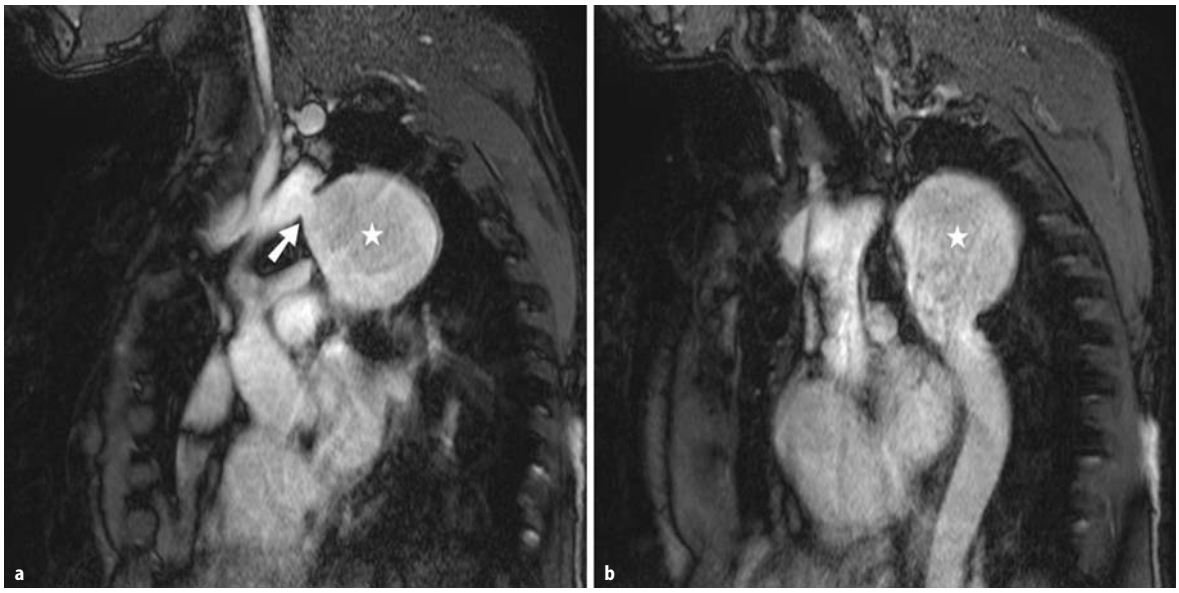
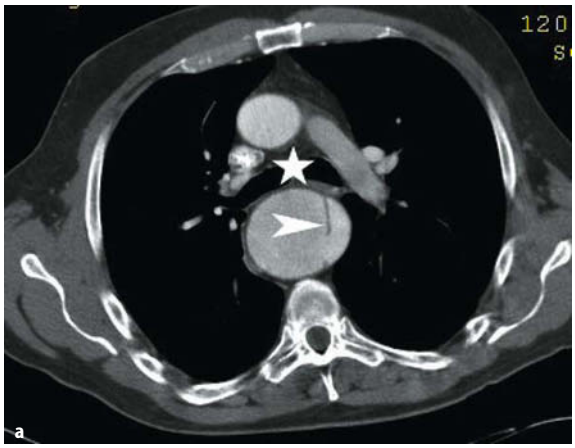


Fig. 1.12. a MRA; MIP reconstruction in a patient with a false aneurysm (*asterisk*) at the level of aortic coarctation (treated with percutaneous balloon angioplasty in the past (*arrow*)). **b** MRA; MPR showing the distal extent of a false aeurysm (*asterisk*)



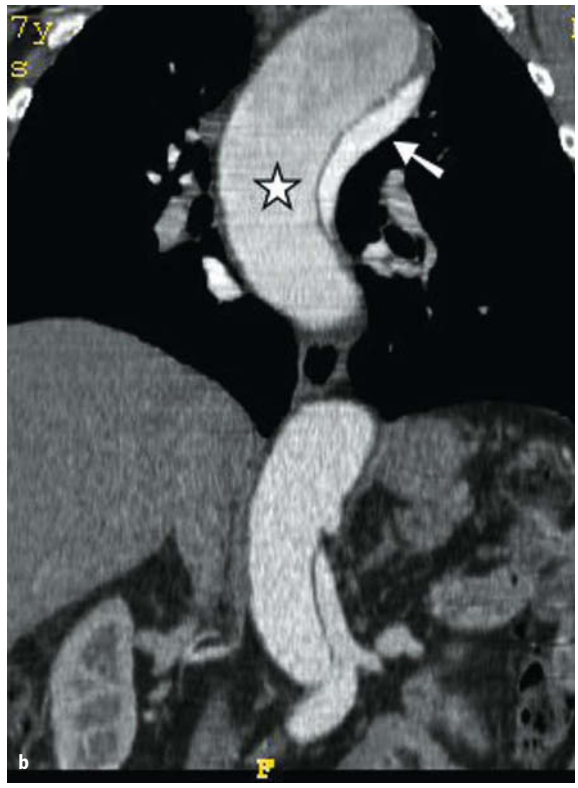


Fig. 1.13. a Axial CT at the level of the carina (*asterisk*) in a patient with widening of the descending thoracic aorta and an intimal flap (*arrowhead*); type B dissection. **b** Coronal MPR in the same patient depicting a larger-diameter false lumen (*asterisk*) and a small-diameter true lumen (*arrow*); note the difference in the enhancement with higher density in the, high-flow, true lumen

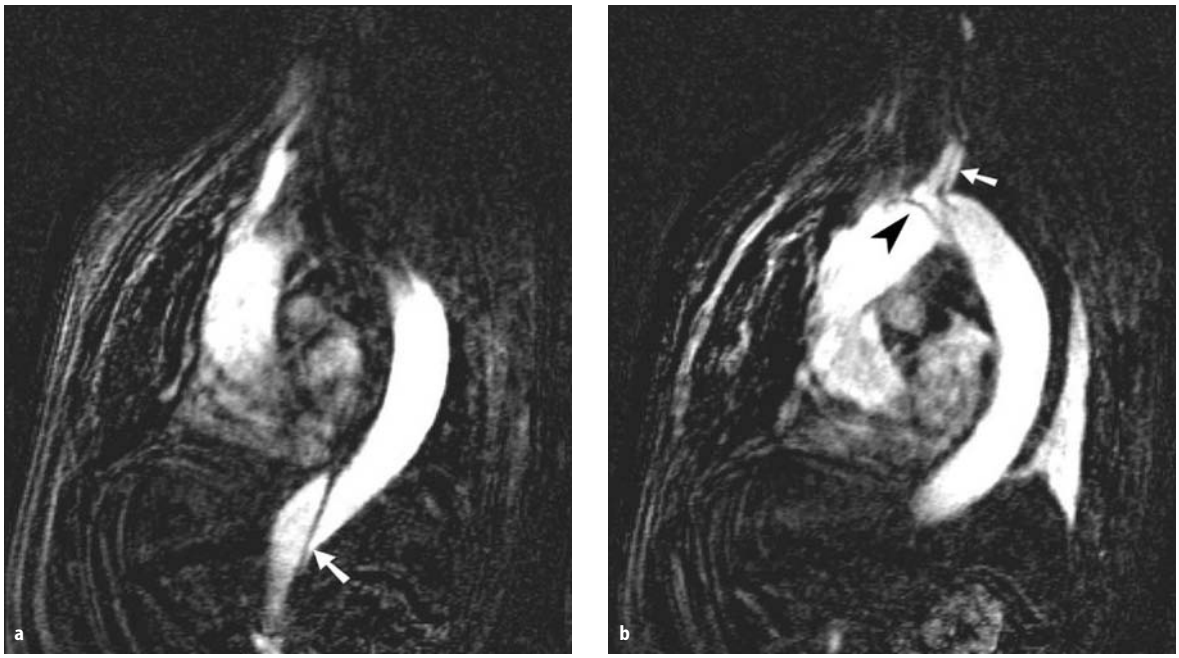
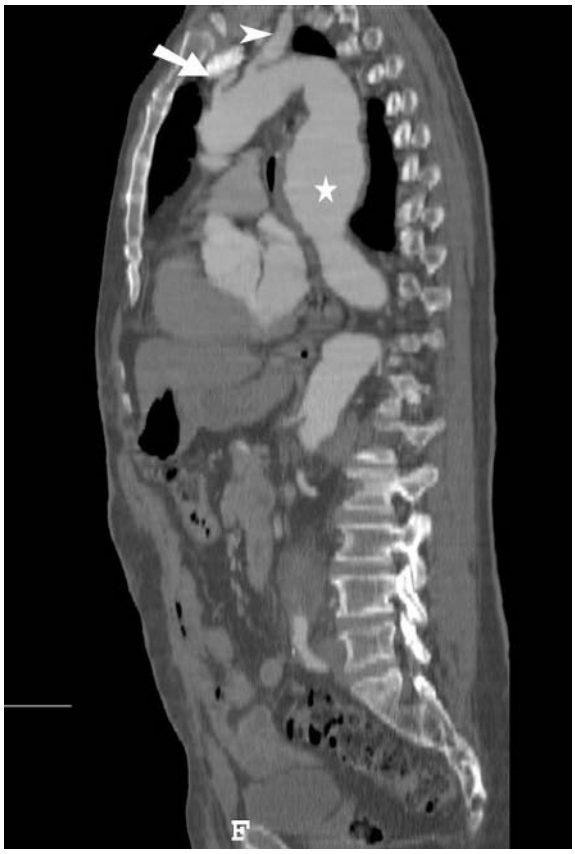


Fig. 1.14. a Sagittal oblique MIP from MRA; dissection flap (*arrow*) in the distal descending thoracic aorta. **b** Sagittal oblique MIP from MRA; extension of the intimal flap in the aortic arch (*arrowhead*) and the left subclavian artery (*arrow*); patient with type B dissection with secondary extension into type A



Volume-rendered imaging has become indispensable for the evaluation of endovascular stent placement, by demonstrating the spatial relationship between the aorta and major arch branches [1].

1.6 Conclusions

3D vascular imaging techniques offer a significant advantage over traditional imaging techniques. Using these techniques, we can perform anatomical dissection in vivo, thus helping in identifying disease, and helping in preoperative planning of surgical and endovascular procedures. Technical developments are rapidly evolving, and in the near future even more sophisticated imaging systems will emerge.

Fig. 1.15. Sagittal MPR of a patient with aneurysm of the descending thoracic aorta (*asterisk*); the absence of mural thrombus can be appreciated, as well as the relative position of the aneurysm with respect to the supra-aortic vessels: left common carotid artery (*arrow*) and left subclavian artery (*arrowhead*)

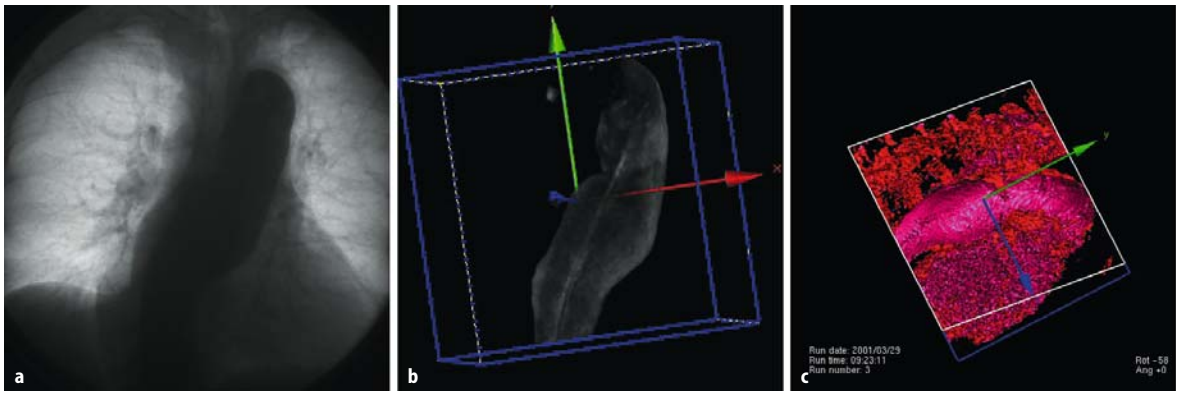


Fig. 1.16. **a** 3D-RA; cinefluoroscopic image (anterior–posterior projection) of aneurysm of the descending thoracic aorta. **b** 3D-RA; default reconstruction in same patient. **c** 3D-RA; volume-rendered image with the cut plane chosen through the longitudinal axis of the lumen, yielding an angioscopic view

References

1. Lawler LP, Fishman EK. Multi-detector row CT of thoracic disease with emphasis on 3D volume rendering and CT angiography. Radiographics 2001; 21(5):1257–1273.
2. Kopp AF, Kuttner A, Trabold T, Heuschmid M, Schroder S, Claussen CD. Contrast-enhanced MDCT of the thorax. Eur Radiol 2003; 13(Suppl 3):N44–49.
3. Catalano C, Fraioli F, Danti M, Napoli A, Votta V, Lanciotti K, et al. MDCT of the abdominal aorta: basics, technical improvements, and clinical applications. Eur Radiol 2003; 13(Suppl 3):N53–58.
4. Haage P, Schmitz-Rode T, Hubner D, Piroth W, Gunther RW. Reduction of contrast material dose and artifacts by a saline flush using a double power injector in helical CT of the thorax. AJR Am J Roentgenol 2000; 174(4):1049–1053.
5. Siegel MJ. Multiplanar and three-dimensional multi-detector row CT of thoracic vessels and airways in the pediatric population. Radiology 2003; 229(3):641–650.
6. Lee EY, Siegel MJ, Hildebolt CF, Gutierrez FR, Bhalla S, Fallah JH. MDCT evaluation of thoracic aortic anomalies in pediatric patients and young adults: comparison of axial, multiplanar, and 3D images. AJR Am J Roentgenol 2004; 182(3):777–784.
7. Smith PA, Heath DG, Fishman EK. Virtual angioscopy using spiral CT and real-time interactive volume-rendering techniques. J Comput Assist Tomogr 1998;22(2):212–214.
8. Bartolozzi C, Neri E, Caramella D. CT in vascular pathologies. Eur Radiol 1998; 8(5):679–684.
9. Kunz RP, Oberholzer K, Kuroczynski W, Horstick G, Krummenauer F, Thelen M, et al. Assessment of chronic aortic dissection: contribution of different ECG-gated breath-hold MRI techniques. AJR Am J Roentgenol 2004; 182(5):1319–1326.
10. Ho VB, Corse WR, Hood MN, Rowedder AM. MRA of the thoracic vessels. Semin Ultrasound CT MR 2003; 24(4):192–216.
11. Ho VB, Prince MR. Thoracic MR aortography: imaging techniques and strategies. Radiographics 1998; 18(2):287–309.
12. Merkle EM, Klein S, Wisianowsky C, Boll DT, Fleiter TR, Pamler R, et al. Magnetic resonance imaging versus multislice computed tomography of thoracic aortic endografts. J Endovasc Ther 2002; 9(Suppl 2):II2–13.
13. Leung DA, Debatin JF. Three-dimensional contrast-enhanced magnetic resonance angiography of the thoracic vasculature. Eur Radiol 1997; 7(7):981–989.
14. Holmqvist C, Larsson E-M, Stahlberg F, Laurin S. Contrast-enhanced thoracic 3D-MR angiography in infants and children. Acta Radiol 2001; 42(1):50–58.
15. Willinek WA, Gieseke J, Conrad R, Strunk H, Hoogeveen R, von Falkenhausen M, et al. Randomly segmented central k-space ordering in high-spatial-resolution contrast-enhanced MR angiography of the supraaortic arteries: initial experience. Radiology 2002; 225(2):583–588.
16. Wintersperger BJ, Huber A, Preissler G, Holzknecht N, Helmberger T, Petsch R, et al. [MR angiography of the supraaortic vessels]. Radiologe 2000; 40(9):785–791.
17. Riederer SJ, Bernstein MA, Breen JF, Busse RF, Ehman RL, Fain SB, et al. Three-dimensional contrast-enhanced MR angiography with real-time fluoroscopic triggering: design specifications and technical reliability in 330 patient studies. Radiology 2000; 215(2):584–593.
18. Arpasi PJ, Bis KG, Shetty AN, White RD, Simonetti OP. MR angiography of the thoracic aorta with an electrocardiographically triggered breath-hold contrast-enhanced sequence. Radiographics 2000; 20(1):107–120.
19. Klucznik RP. Current technology and clinical applications of three-dimensional angiography 56. Radiol Clin North Am 2002; 40(4):711–728.
20. Unno N, Mitsuoka H, Takei Y, Igarashi T, Uchiyama T, Yamamoto N, et al. Virtual angioscopy using 3-dimensional rotational digital subtraction angiography for endovascular assessment 52. J Endovasc Ther 2002; 9(4):529–534.
21. van den Berg JC. Three-dimensional rotational angiography. In: Wyatt MG, Watkinson AF, editors. Endovascular intervention-current controversies. Shrewsbury: tfm; 2004; p. 247–256.
22. van den Berg JC, Overtoom TT, de Valois JC, Moll FL. Using three-dimensional rotational angiography for sizing of covered stents 53. AJR Am J Roentgenol 2002; 178(1):149–152.
23. van den Berg JC, Moll FL. Three-dimensional rotational angiography in peripheral endovascular interventions 57. J Endovasc Ther 2003; 10(3):595–600.
24. Bridcut RR, Winder RJ, Workman A, Flynn P. Assessment of distortion in a three-dimensional rotational angiography system 17. Br J Radiol 2002; 75(891):266–270.
25. Kersting-Sommerhoff BA, Sechtem UP, Schiller NB, Lipton MJ, Higgins CB. MR imaging of the thoracic aorta in

Marfan patients. J Comput Assist Tomogr 1987; 11(4):633–639.
26. Pannu HK, Flohr TG, Corl FM, Fishman EK. Current concepts in multi-detector row CT evaluation of the coronary arteries: principles, techniques, and anatomy. Radiographics 2003; 23(Spec No):S111–125.
27. Cademartiri F, Marano R, Luccichenti G, Mollet N, Nieman K, De Feyter PJ, et al. [Normal anatomy of the vessels of the heart with 16-row multislice computed tomography]. Radiol Med 2004; 107(1–2):11–21.
28. Maintz D, Aepfelbacher FC, Kissinger KV, Botnar RM, Danias PG, Heindel W, et al. Coronary MR angiography: comparison of quantitative and qualitative data from four techniques. AJR Am J Roentgenol 2004; 182(2):515–521.
29. Kadir S. Regional angiography of the aorta-arteriography of the thoracic aorta. In: Kadir S, editor. Diagnostic angiography. Philadelphia: Saunders; 1986. p. 124–171.
30. Kudo K, Terae S, Asano T, Oka M, Kaneko K, Ushikoshi S, et al. Anterior spinal artery and artery of Adamkiewicz detected by using multi-detector row CT. AJNR Am J Neuroradiol 2003; 24(1):13–17.
31. Yoshioka K, Niinuma H, Ohira A, Nasu K, Kawakami T, Sasaki M, et al. MR angiography and CT angiography of the artery of Adamkiewicz: noninvasive preoperative assessment of thoracoabdominal aortic aneurysm. Radiographics 2003; 23(5):1215–1225.
32. Takase K, Sawamura Y, Igarashi K, Chiba Y, Haga K, Saito H, et al. Demonstration of the artery of Adamkiewicz at multi-detector row helical CT. Radiology 2002; 223(1):39–45.
33. Yamada N, Takamiya M, Kuribayashi S, Okita Y, Minatoya K, Tanaka R. MRA of the Adamkiewicz artery: a preoperative study for thoracic aortic aneurysm. J Comput Assist Tomogr 2000; 4(3):362–368.
34. Konen E, Feinberg MS, Morag B, Guetta V, Shinfeld A, Smolinsky A, et al. Giant right coronary aneurysm: CT angiographic and echocardiographic findings. AJR Am J Roentgenol 2001; 177(3):689–691.
35. Katz M, Konen E, Rozenman J, Szeinberg A, Itzchak Y. Spiral CT and 3D image reconstruction of vascular rings and associated tracheobronchial anomalies. J Comput Assist Tomogr 1995; 19(4):564–568.
36. Konen E, Merchant N, Provost Y, McLaughlin PR, Crossin J, Paul NS. Coarctation of the aorta before and after correction: the role of cardiovascular MRI. AJR Am J Roentgenol 2004; 182(5):1333–1339.

Embryology and Congenital Abnormalities of the Aorta

Jean Philippe Guibaud and Xavier Roques

2

Contents

2.1 Introduction

The complex evolution of the vascular system from the human embryo to the definitive pattern of the aortic arch has been provided by Congdon [1] and by Barry [2]. The ventral aortic root is in front of the oesophagus. It follows upon the conotroncus, last segment of the primitive cardiac tube, and is prolonged by two vessels, the first aortic arches, which cross the intestine laterally, to join in the dorsal part of the embryo, the two dorsal aortas. Six pairs of arches will develop, one for each branchial cleft, connecting the ventral aorta with the two dorsal aortas [3]. All are not present at any one time, the first regresses when the following appears; some disappear completely, others persist, but are notably modified [4]. The two dorsal aortas meet and merge in a single vessel, on the median line at the inferior part of the embryo. This fusion goes up until the seventh somite, at the level of the inferior part of the venous sinus (Fig. 2.1).

When the length of the embryo is 3 mm, the first and second pairs of primitive aortic arches are the first to be formed, and the first to disappear.

The third aortic arch is well developed when the length of the embryo is 4 mm, and the fourth and sixth arches are outlined. The fifth pair of arches makes only a brief appearance and then disappears. At this same stage, the dorsal aortic roots and dorsal aorta give off intersegmental arteries which supply blood to spinal cord and developing somites. The seventh intersegmental arteries enlarge to form the proximal portions of the subclavian arteries, they migrate cephalad and in the embryo of 5–6-mm length, they detach separately from right and left dorsal aortas, upstream from fusion of these two vessels.

In the embryo of 10-mm length, the third, fourth and sixth arches are well formed. The primitive aorta is now divided in trunks of aorta and pulmonary artery, so that the third and fourth arches are detached from the aorta, while the sixth one follows upon the trunk of the pulmonary artery.

At stage of 15-mm length, the embryo has lost its symmetrical aspect (Fig. 2.2). This transformation was the result of interruption and displacement of segments and the descent of the heart in the thorax. The proximal part of the third arch moved laterally, so that it rose at the union of the fourth arch and the ventral aorta. The third arch forms the common carotid artery. At this stage the dorsal aorta was interrupted between the third and the fourth arch. Circulation occurs in two directions: to the head by the third arch and to the rest of the body by the fourth arch. On the right side, the distal part of the sixth arch disappears, while the proximal one forms the right pulmonary artery. On the left, the proximal part of the sixth arch forms the left pulmonary artery, while its distal part persists until the birth and forms the ductus arteriosus. With the regression of the eighth segment of the right dorsal root and the right ductus arteriosus, the basic pattern of the normal left aortic arch is formed (Fig. 2.3).

2.2 Classification of Vascular Rings and Related Malformations

After different attempts of classification (Krauss, Rathke, Neuhauser, etc.), Stewart et al. [5] provided a pertinent system explaining malformations.

Most vascular rings and related malformations of the aortic arch result from either a lack of regression or an abnormal regression of segments. The formation of the normal aortic arch system is dependent primarily

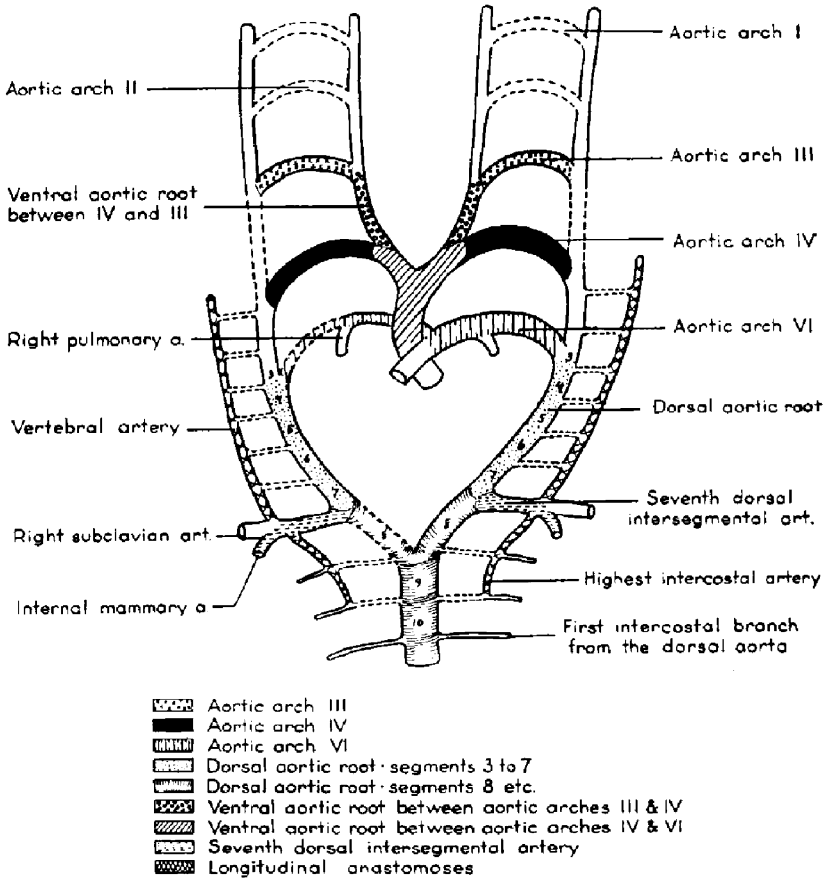


Fig. 2.1. Schematic diagram indicating the various components of the embryonic aortic arch complex in the human embryo. Those components which do not precisely persist in the adult are indicated by *broken outlines*. The *Arabic numbers* indicate the segments of each dorsal aorta. (From Barry [2] with permission)

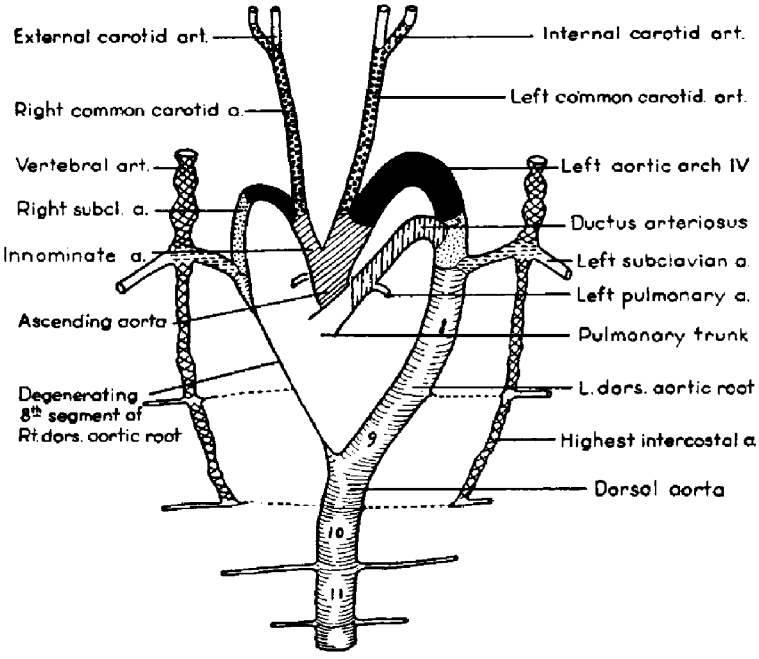


Fig. 2.2. Diagrammatic view of the aortic arch complex as it appears in the human embryo of 15-mm crown–rump length. The various components are indicated by the same shading as was used in Fig. 2.1. (From Barry [2] with permission)

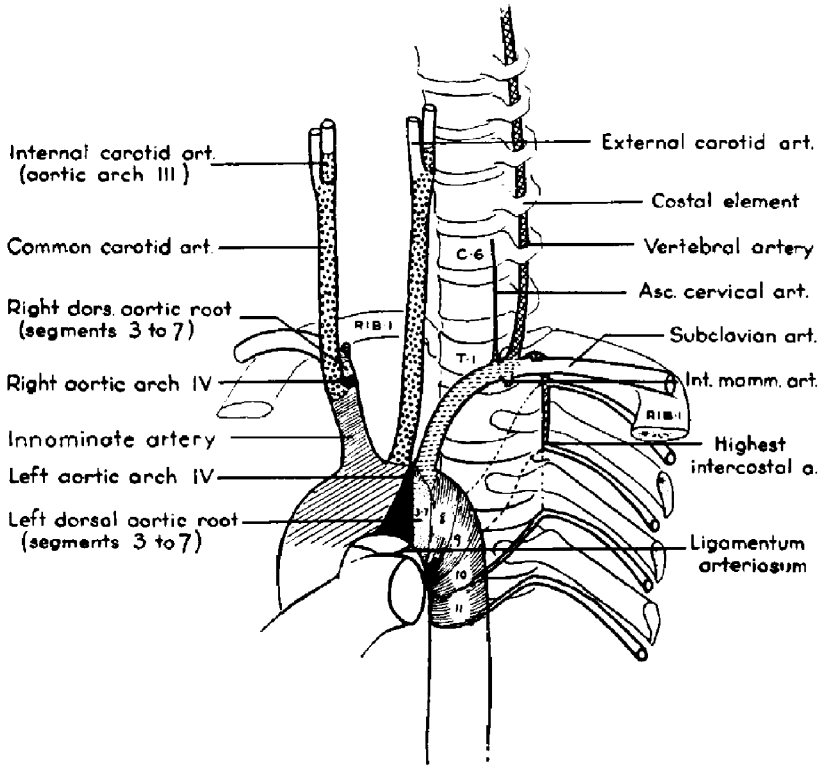


Fig. 2.3. Diagrammatic ventral view of the resultant normal aortic arch complex. Scheme of identification same as in Figs. 2.1 and 2.2. (From Barry [2] with permission)

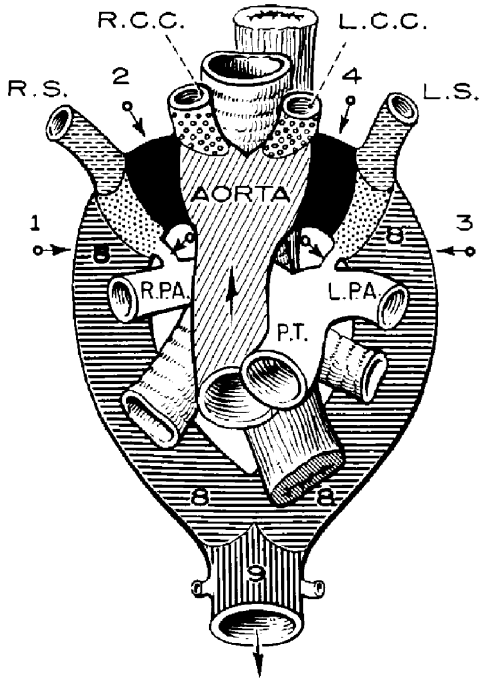


Fig. 2.4. Ventral view of Edwards' hypothetic double aortic arch and bilateral ductus arteriosi. The ascending and descending aorta are each depicted in midline positions. *Arrows* point to the four key locations where regression occurs and are numbered from *1* to *4*. *Arrow 1* indicates the eighth segment of the right dorsal aortic root, *arrow 2* the right fourth arch, and *arrows 3* and *4* the corresponding two positions on the left [5]

on regression of the eight segment of the right dorsal aortic root.

"The point of departure for this classification of malformation of the aortic arch is a hypothetic specimen in which there is no regression at any of these sites. This hypothetic form is a double aortic arch with bilateral ductus arteriosi" (Fig. 2.4). Some of the malformations were described before their discovery. The presence or the absence of one or both ductus arteriosi and the upper descending aorta is pertinent to the classification.

When the separation of the proximal outflow tract displaces the aorta and the pulmonary artery towards the left, the upper descending aorta and ductus arteriosus will be at the left. When the separation displaces these same vessels towards the right, the upper descending aorta and the ductus arteriosus will be at the right.

Regression or development of a segment can be explained by the intensity of blood flow in the vessels [6]. When blood flow decreases, the segment regresses or disappears.

Edwards described four main groups of malformations, and for each of them, there are subgroups:

- Group I is the group of the complete double aortic arch; there is no interruption at any point in the double aortic arch pattern. One or both arches may be patent or not (subgroup A or B), associated with the presence of left, right or bilateral ductus arteriosi

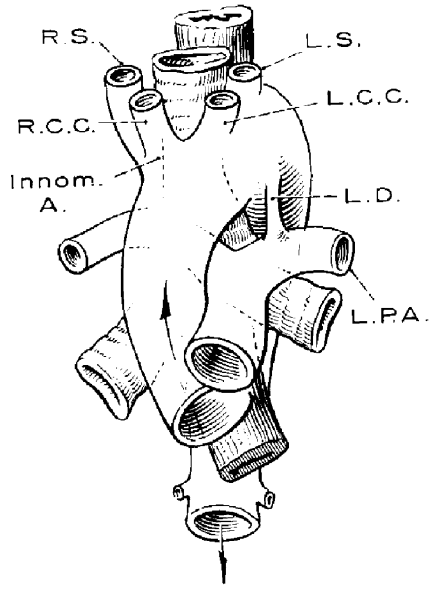


Fig. 2.5. Subgroup IIA1. The normal aortic arch [5]

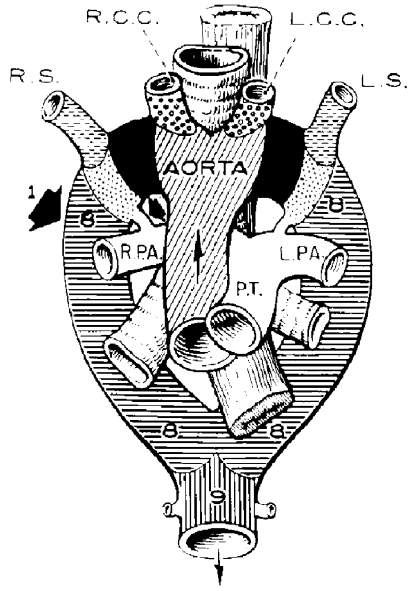


Fig. 2.6. Subgroup IIA1. The normal aortic arch system is formed when the right dorsal aortic root (region 1) and the right ductus arteriosus regress [5]

(subgroups 1, 2, 3). If one arch is not patent, the atretic segment may be region 1 (eighth segment of the right dorsal aortic root), region 2 (right fourth arch), region 3 (eighth segment of the left dorsal aortic root) or region 4 (left fourth arch).

- Group II is characterized by the presence of an intact left aortic arch. There are three main subgroups (A, B, C) according to the location of the interruption. The first subgroup (A) concerns normal

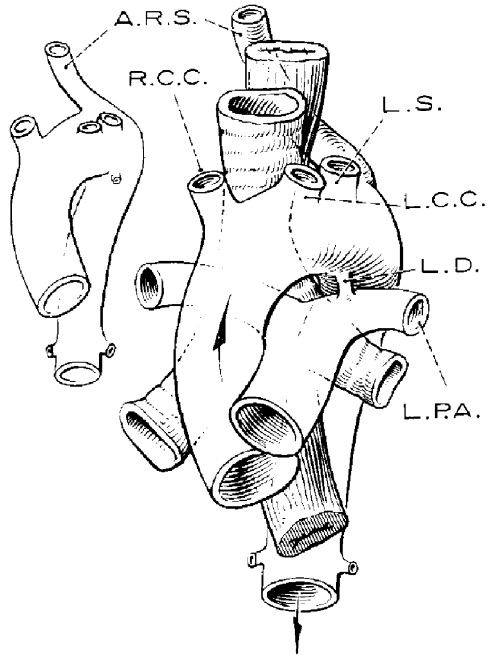


Fig. 2.7. The aberrant right subclavian artery arises from the posterior of the uppermost part of the descending aorta and ascends at an angle of about 70° from left to right behind the oesophagus [5]

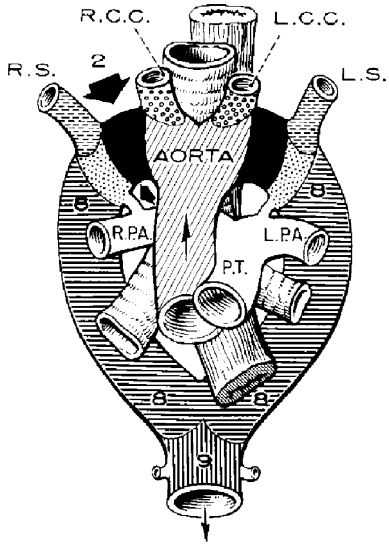


Fig. 2.8. Interruption at region 2 (right fourth arch) causes the right subclavian artery to arise from the right dorsal aortic root [5]

branching, the interruption occurs at region 1 (Figs. 2.5, 2.6). The second subgroup (B) concerns the aberrant right subclavian artery and the interruption is at region 2 (Figs 2.7, 2.8). The third subgroup (C) concerns the isolation of the right subcla-

vian artery from the aorta; the interruption occurs at both regions 1 and 2. Each of these subgroups may be associated with the presence of a left, right or bilateral ductus arteriosi (subgroups 1, 2, 3).

- Group III is characterized by the presence of a right aortic arch. The anomalies of this group are the mirror of the anomalies of group II: mirror-image branching, aberrant left subclavian artery and isolation of the left subclavian artery from the aorta (subgroups A, B, C).
- Group IV concerns unusual malformations explained by complex combinations of interruptions at the four sites.

2.3 Description of Main Aortic Arch Abnormalities

2.3.1 Coarctation of the Aorta

Coarctation of the aorta is a congenital narrowing of the upper descending thoracic aorta, adjacent to the site of attachment of the ductus arteriosus [7]. Preductal or postductal, this shelf is usually juxtaductal. Variability in coarctation morphology, associated lesions, differences between neonatal, infant and adult coarctations, and influence of the use of prostaglandin E1 in the preoperative management are many reasons underlying the complexity of this abnormality. Two embryologic factors will cause aortic obstruction at or near the isthmus. One is the underdevelopment or hypoplasia of the aortic arch or the isthmus. If this is present, tubular hypoplasia will be important. In this case the amount of flow across the distal aortic arch and the isthmus is an important factor of growth of this vascular structure [8]. Coarctation is usually most common when there are proximal lesions which decrease ascending aortic flow such as aortic stenosis or atresia, mitral stenosis or incompetence. The second factor is the presence of ectopic ductal tissue in the aorta at the aortic insertion of the ductus. This ectopic tissue tends to develop when ductal flow increases such as from an atrial or ventricular septal defect.

2.3.2 Interrupted Aortic Arch (Group IV)

This is the complete luminal and anatomic discontinuity between two segments of the aortic arch. Three types are described in the Celoria and Patton classification.

In type A interruption occurs at the level of the isthmus between the left subclavian artery and the ductus arteriosus or between the fourth and the sixth left aortic arch after migration of the left subclavian artery.

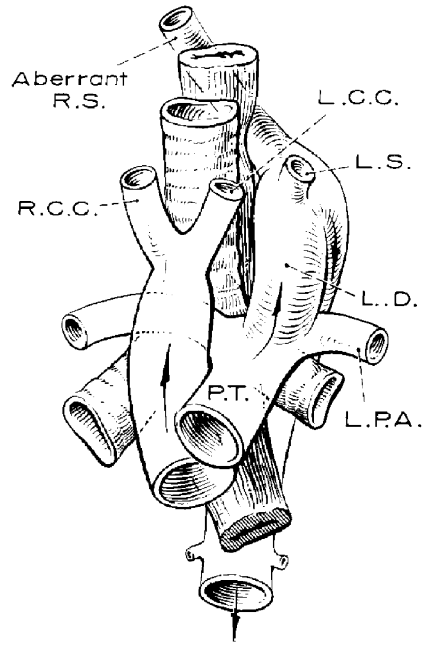


Fig. 2.9. Group IV. Interruption of aortic arch type B in the classification of Celeria and Patton. The ascending aorta terminates in the common carotid arteries. The descending aorta arises from the pulmonary system by way of a large patent ductus arteriosus. There is always an aberrant right subclavian artery [5]

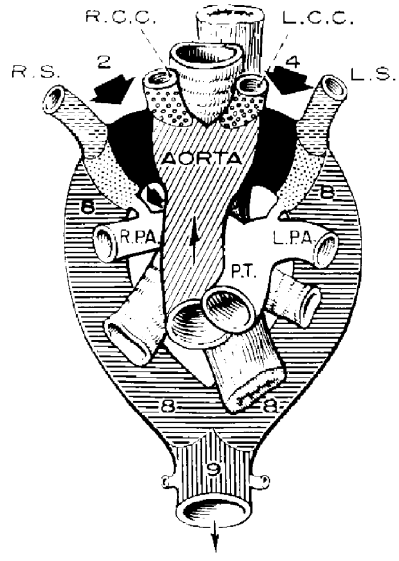


Fig. 2.10. Group IV. Interruption of the aortic arch type B. Regression at regions 2 and 4. The right ductus arteriosus disappears [5]

Type B (Figs. 2.9, 2.10) is the commonest type (55–69%). The interruption occurs between the left common artery and the left subclavian artery and concerns regression of the segment between the fourth and the

sixth left aortic arches but in this case before migration of the left subclavian artery. This type is often associated with an aberrant right subclavian artery.

Type C is extremely rare (less than 4%). The interruption occurs between the innominate artery and the left common carotid.

2.3.3 Aberrant Right Subclavian Artery or Arteria Lusoria (Subgroup IIB1)

The aberrant subclavian artery arises as the fourth branch of the left aortic arch and passes behind the oesophagus to reach the right arm. In the abnormality the interruption occurs at region 2 or the right fourth arch and the right ductus disappears (Figs. 2.7, 2.8).

References

1. Congdon ED. Transformation of the aortic-arch system during the development of the human embryo. Contrib Embryo 1922; 14:47–110.
2. Barry A. Aortic arch derivatives in the human adult. Anat Rec 1951; 111:221–238.
3. Bellot J. Embryologie des arcs aortiques. Nouv Presse Med 1972; 35:2321.
4. Mathey J, Binet JP, Denis B. Anomalies de développement des arcs aortiques. J Chir 1959; 77:505–527.
5. Stewart JR, Kincaid OW, Edwards JE. An atlas of vascular rings and related malformations of the aortic arch system. Springfield (IL): Thomas; 1964.
6. Rudolph AM, Heymann MA, Spitznas U. Hemodynamic considerations in the development of narrowing of the aorta. Am J Cardiol 1972; 30:514–525.
7. Goor D, Lillehei CW. Congenital malformations of the heart. Embryology, anatomy, and operative considerations. New York: Grune and Stratton; 1975.
8. Shinebourne EA, Elseed AM. Relation between fetal flow patterns, coarctation of the aorta, and pulmonary blood flow. Br Heart J 1974; 36:492–498.

Hemodynamics of Aortic Dissection

Chris Elkins and Michael D. Dake

3

Contents

3.1 Introduction and Background

Aortic dissection is the most frequent nontraumatic catastrophe that affects the aorta, with an annual incidence exceeding that of spontaneous rupture of aortic aneurysms [1]. Aortic dissection occurs with a frequency of 10–20 cases per million population per year. Approximately 30% (85 of 272 [2], 106 of 325 [3]) of patients with aortic dissection have one or more ischemic complications of the peripheral vasculature, including stroke, paraplegia, loss of peripheral pulses, and compromised renal or mesenteric perfusion. The surgical mortality rates for patients with acute aortic dissection complicated by compromise of a peripheral arterial branch exceed 50% [3]; visceral and renal ischemia are important independent predictors of death as a result of surgery [2].

In the past, the direct propagation of a dissection flap into an aortic branch with the resultant compromise or obstruction of the true lumen was considered to be the basic mechanism for ischemic complications in the peripheral vasculature. This understanding was based on observations of cross-clamped or decompressed aortas without flow and on findings at necropsy.

Recently, collapse or obliteration of the true lumen was proposed as another important mechanism for compromise of the aortic branch in aortic dissection [4, 5]. This is based on antemortem cross-sectional imaging studies, including those performed with intravascular ultrasonography, that facilitate an appreciation of the effects of flow on the anatomic relationships between the flap, aortic lumina, and branch vessels [4, 5]. In this setting, the plane of the dissection flap spares the branch vessel. Instead, the flap is positioned in a curtainlike fashion across the origin of the vessel, which causes dynamic obstruction of the branch artery [5]. According to the report by Williams et al. [6], dynamic obstruction due to true-lumen collapse was the cause of the infradiaphragmatic organ or limb ischemia in 20 of 24 patients. Among the 20 patients, 14 had ischemia in multiple organs that involved the mesenteric, renal, and lower-limb circulations. Recently, percutaneous endovascular treatment with balloon fenestration and stent placement was introduced to relieve true-lumen collapse and showed promising results [1, 5, 6]. However, there have been few clinical and experimental studies conducted to investigate the causes of true-lumen collapse in aortic dissection and the possible treatment methods to relieve true-lumen collapse or to determine the most effective methods.

Patients with chronic dissection often develop late complications mainly related to the patency of the false lumen [7]. In these cases, there is progressive dilatation of the false lumen that can lead to eventual rupture. An acute aortic diameter of greater than 4 cm in type B dissections has been found to be an indicator of possible future rupture [8, 9]. While some studies suggest medically treating dissections with maximum diameters less than 5 cm [10], others support surgery or placement of stent-grafts when the false lumen is greater than 4 cm [8], 5 cm [11], or 6 cm [12] in order to avoid certain rupture in the future. Obviously, there is considerable uncertainty about the critical diameter of the false lumen and how to treat false lumen aneurysms.

While formation and development of dissections are not well understood, it is generally accepted that hemodynamics plays a major role in the initiation, acute propagation, and chronic development of dissections. In all three of these stages, hemodynamic effects couple with mechanical and biological processes in the arterial walls. It may be some time before the initiation and propagation mechanics of dissection will be understood

as they involve hemodynamic forces interacting with the aortic wall in both its healthy and its diseased state. There are many studies of the hemodynamic effects in aneurysmal growth. In most cases, aortic dilatation evolves slowly over several years (1 mm per year [10]) and can be treated medically. Relatively less effort is being spent on understanding the problem of branch vessel ischemia and, in particular, the special case of true-lumen collapse. Yet, this problem is of critical importance in both acute and chronic dissection and is highly related to hemodynamics.

3.2 Experiments on the Hemodynamics of True-Lumen Collapse

An in vitro study at Stanford created two aortic dissection phantoms to investigate the causative factors for true-lumen collapse and to develop effective treatments [13, 14]. One phantom was compliant and opaque (Fig. 3.1), and the other was rigid and transparent (Fig. 3.2). The rigid, transparent phantom was created to allow visual observation of the true lumen along the length of the aorta. Each phantom had the following physical features to model a Stanford type B aortic dissection: an aortic arch, true and false lumens with abdominal branch vessels, and a distal bifurcation. These phantoms were placed in a pulsatile mock-flow loop, with water as the working fluid. The effects of anatomic factors (entry-tear size, branch-vessel flow distribution, fenestrations, distal reentry communication) and physiologic factors (peripheral resistance in the branch vessels, pump output and rate, vascular compliance) on true-lumen collapse were investigated. The morphology of the true lumen was observed. Branch pressures and flow rates were measured.

After true-lumen collapse had been induced, experiments were conducted to evaluate the effectiveness of clinically relevant variables in relieving the collapse. Variables included entry-tear size, branch-vessel flow distribution, distal reentry communication between the true and false limbs, aortic fenestrations, and pump output. To test the effect of closing the entry tear, a

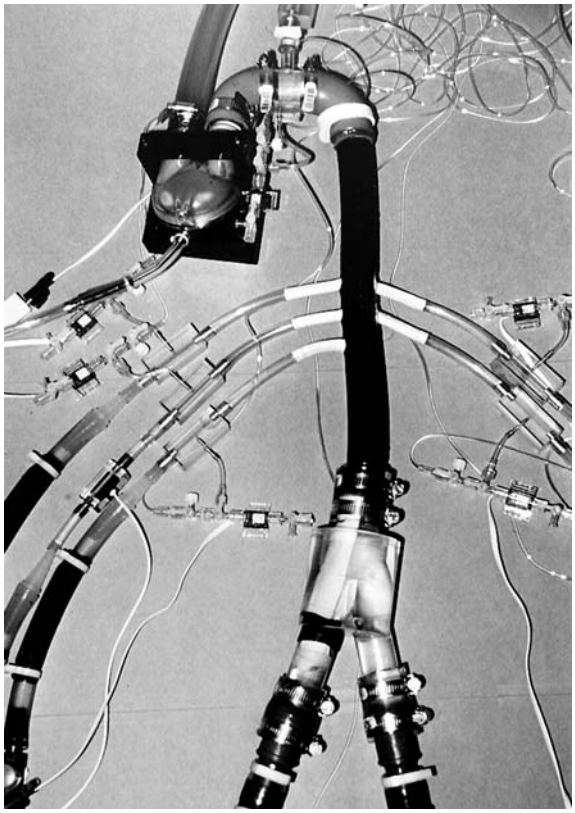


Fig. 3.1. Compliant model of aortic dissection. Compliant and opaque phantom model of type B aortic dissection with entry tear, true and false lumens, branch vessels, and distal bifurcation. This phantom was placed in a pulsatile mock-flow loop to observe and measure the effects of a variety of anatomical and physiological factors on branch-vessel flow rates

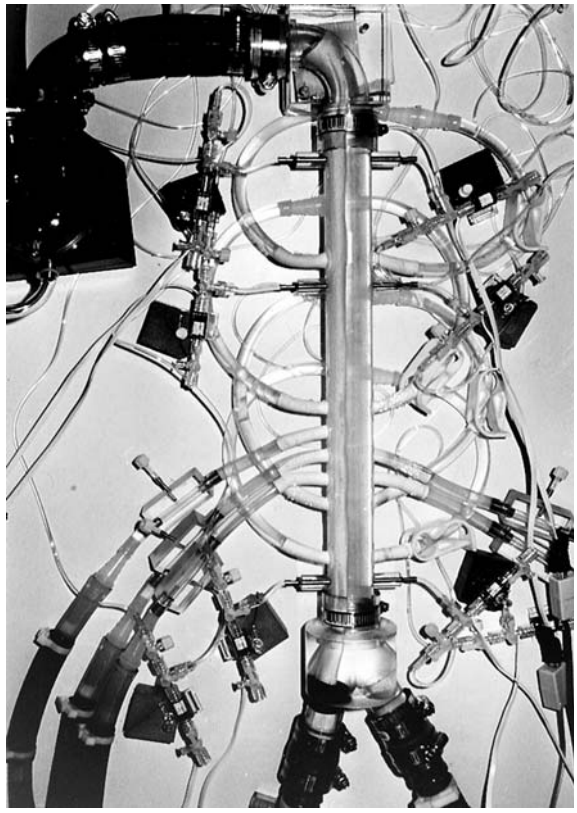


Fig. 3.2. Rigid model of aortic dissection. Rigid and transparent model of type B aortic dissection allowed visual observation of the true lumen along the length of the aorta. This allowed direct evaluation of the relative effectiveness of altering clinically relevant variables in relieving the complications of dissection with aortic true-lumen collapse

stent-graft was deployed over the entry tear under physiologic conditions. The difference in the effect of each variable on the prevention and relief of true-lumen collapse was also investigated.

Although not specifically aimed at true lumen collapse, another study used phase contrast MRI to look at the morphology of dissections in 14 patients and to quantify blood flow in the true and false lumens in the descending aorta at the level of the diaphragm [7]. True-lumen collapse was observed in one case: a case with a blind ending false lumen, a lumen with an entry tear but no outlet.

3.3 Causative Factors in True-Lumen Collapse

Findings from the Stanford in vitro experiment demonstrated that the true lumen collapsed with an increase in the size of the entry tear, a decrease in the false-lumen outflow caused by occluding the false-lumen branch vessels, and an increase in the true-lumen outflow created by lowering the peripheral resistance in true-lumen branch vessels.

On the basis of the observations, it is important to consider how easily blood flows into a lumen (inflow capacity) relative to how easily it flows out of a lumen (outflow capacity). A critical parameter is the ratio of inflow capacity to outflow resistance for a given lumen. In the study, it is hypothesized that the difference between these ratios for the true and false lumens generates a transmural pressure gradient across the dissection flap and that this pressure gradient moves the flap.

Not only was this demonstrated in the phantom experiments, but an example of this is found in the in vivo magnetic resonance data for a dissection with a blind-ending false lumen [7]. In this case, blood flows into both lumens. It stagnates in the false lumen and accelerates through the constricted true lumen. The false lumen has a high inflow capacity but a low outflow capacity (a high ratio), while the true lumen has similar values for its inflow and outflow capacity (a lower ratio). True-lumen collapse occurs in this case because the false lumen has a higher ratio. An alternative explanation based on similar principles employs the Bernoulli principle in which static pressure is traded for fluid velocity. To be strictly correct, some assumptions are required and the instantaneous flows should be compared since the flow is pulsatile, but it is obvious that the stagnated false-lumen flow will have a high pressure, while the accelerated true-lumen flow will have a low pressure. This pressure difference is large enough to move the dissection flap.

Low peripheral resistance in the true-lumen abdominal branches can contribute to true lumen collapse. Williams et al. [15] presented data from a patient in whom sudden restoration of true-lumen outflow resulted in a true-lumen collapse and in a profound systolic-pressure deficit. That clinical experience strongly supports the observations that an increase in the true-lumen outflow accelerates true-lumen collapse. Williams et al. [15] also suggest that if false-lumen pressure exceeds true-lumen pressure, an element of true-lumen compression may be added to the intrinsic true-lumen collapse. The Stanford experiment demonstrated the presence of true-lumen compression in cases with high pump output states and confirmed a higher false-lumen pressure in these situations.

In the phantom experiments, observations were compared for steady and pulsatile flow conditions. Pulsatile flow prevented true-lumen collapse in many conditions. It is believed that this may be related to wave propagation which is a function of phantom compliance and geometry. There are similar waves in the pulsatile flow within the human vascular system although they are not exactly the same. In light of this, the observations made in the experiment suggest that the regulation of heart rate and systemic pressure may provide a feasible treatment for the prevention of true-lumen collapse in patients with dissection.

An evaluation of the effects of the communication channels between the true and false lumens (i.e., fenestrations and reentry tears) showed that a distal communication was better at preventing true-lumen collapse. The beneficial effect of the fenestrations in the phantom aorta was unexpectedly limited or absent. In fact, fenestrations proximal to the abdominal branch vessels slightly aggravated the true-lumen collapse; this suggests that they may have acted as additional entry tears.

The distal reentry communication between the true and false limbs showed variable effectiveness in preventing true-lumen collapse, depending on its size. Although the distal reentry communication in our models simulated a distal reentry tear, strictly speaking, it was close to a femorofemoral bypass. Therefore, radiologic fenestrations just above the iliac bifurcation or femorofemoral bypass may mitigate the effects of true-lumen collapse.

In conclusion, true-lumen collapse in aortic dissection was demonstrated in phantoms with pulsatile flow; it strongly depended on the difference between the ratios of the inflow capacity to the outflow capacity for the true and false lumens. Low peripheral resistance in the true-lumen branches contributed to true lumen collapse. High-output compression of the true lumen developed in the conditions in which the false-lumen outflow was restricted compared with the inflow. Fenestrations in the dissection flap proximal to the aortic bifurcation had little effect on true-lumen collapse, whereas distal reentry communications showed a considerable effect in preventing true-lumen collapse.

Practical application: Both the rigid and the compliant phantoms simulated the gross morphology of the

human aorta. However, there were many differences from the human aorta in the compliance of the vascular wall, the hemodynamic characteristics of the pulsatile flow, the viscosity of the working fluid, and the detailed anatomy of the dissection. Therefore, one should be cautious when applying the results to human aortic dissection. The purpose of the study was to give insight into the pathophysiology and treatment of true-lumen collapse in aortic dissection and to motivate further experimental and clinical studies.

3.4 Effective Treatment for True-Lumen Collapse

The optimal therapeutic approach for patients with aortic dissection complicated by branch obstruction has not been established. The primary surgical treatment is resection of the primary entry tear in the thoracic aorta with redirection of the blood flow, preferentially into the true lumen. Repair of the thoracic aorta was reported to reverse peripheral pulse deficits (lower limb ischemia) in about 90% (44 of 48) of patients [2].

Uncomplicated acute type B dissections are usually medically managed because the surgical mortality rate for patients with acute type B dissection is historically high [16–18] and because the long-term outcome is similar in both medically treated patients and surgically treated patients [17, 19, 20]. Where ischemia persisted after repair of the thoracic aorta or where the patient was not considered a candidate for surgical repair of the entry tear in the thoracic aorta, revascularization procedures, including surgical fenestration of the aorta with or without graft placement [21] and a variety of direct or extraanatomic bypass operations, have been performed [3, 22].

Deficits in the peripheral pulses are usually successfully managed with surgical repair of the thoracic aorta, surgical fenestration of the aorta, or femorofemoral bypass, without a substantial increase in surgical mortality. In cases of mesenteric or renal ischemia, the surgical mortality rate is very high (50–80%) despite an aggressive surgical approach with repair of the thoracic aorta and direct revascularization of the obstructed vessels [2, 3]. Therefore, patients with mesenteric and renal ischemia are considered higher-risk candidates for surgery. Recently, endovascular treatment with balloon fenestration and stents was introduced. With this percutaneous management strategy, revascularization of the obstructed vessels is successful in more than 90% of patients; the procedure-related mortality rate is 25% or less [4, 6, 23].

The rational treatment for aortic-branch compromise in aortic dissection is predicated on an understanding of the mechanisms involved. Recently, two distinct mechanisms for branch ischemia were clarified. One is static obstruction due to direct propagation of the dissection into the branch vessel; the other is dynamic obstruction due to collapse of the aortic true lumen [5]. Static obstruction of the branch arteries can be best managed with direct revascularization of the obstructed vessel by means of an endovascular stent or a bypass graft. For dynamic obstruction, there are many available treatment options, including surgical repair of the primary entry tear, surgical fenestration of the aorta, placement of a bypass graft to reperfuse the threatened organ or limb, and placement of endovascular stents and balloon fenestration of the dissection flap. With experience from the in vitro experiments these treatments are now performed with verification of their effect in experimental studies and with a clear understanding of the hemodynamics in a double-barreled aorta.

In the experiments, with progressive augmentation of the causative factors for true-lumen collapse, compromise of aortic-branch flow initially occurred distally in the lower-limb vessels. This subsequently propagated to include the proximal abdominal vessels. According to the results, isolated lower-limb ischemia was the mildest form of true-lumen collapse. In the severest form of true-lumen collapse, all true-lumen branches were compromised, with negligible flow through them.

The severity of true-lumen collapse is an important determinative factor in the success of the treatment. In the marginal state of true-lumen collapse, minor natural fluctuations in contributing factors—including cardiac output, blood pressure, heart rate, and peripheral resistance in the branch vessels—can cause or relieve true-lumen collapse. In fact, deficits in peripheral pulses may wax and wane [24] and may be relieved spontaneously after the administration of antihypertensive medications or after retrograde arteriography [22, 25, 26]. The results of the experiment clearly showed that the creation of false-lumen outflow and distal reentry communication relieved true-lumen collapse in less-severe borderline cases. However, the extreme cases of true-lumen collapse were very difficult to treat and were resistant to these medical interventions.

Among the variables investigated, the most effective way to relieve true-lumen collapse was to obliterate the entry tear with the placement of a stent-graft. This result reinforced the rationale and the effectiveness of the current surgical approach in clinical practice to repair the thoracic aorta and suggested that procedures with stent-grafts can be effective alternatives to surgery for the treatment of true-lumen collapse in type B dissection.

The creation of a false-lumen outflow branch effectively relieved the high pressure in the false lumen compressing the true lumen. Currently, it is commonly thought that the compromised branch should be revascularized from the true lumen. However, according to the results, revascularization of the obstructed true-lumen branch increased the true-lumen outflow and exa-

cerbated true-lumen collapse. Williams et al. [15] presented data from a patient in whom sudden restoration of true-lumen outflow resulted in true-lumen collapse and a profound systolic-pressure deficit. Therefore, in the setting of true-lumen collapse, if an aortic branch is dissected and is supplied by both the true and the false lumina, revascularization of the branch from the false lumen is recommended to relieve true-lumen collapse.

Distal reentry communication between the true and false limbs also had a positive effect on true-lumen collapse. When the entry tear was closed with a stent-graft, the cases with distal reentry flow showed better results than those with fenestrations between the true and false lumens in the aorta. The distal reentry communication used in the experiment better resembled a femorofemoral bypass graft than an actual distal reentry communication created with endovascular techniques in a clinical situation. This result suggests a femorofemoral bypass can be used to treat isolated limb ischemia, with the possible beneficial effect of relieving true-lumen collapse.

As an endovascular technique, balloon fenestration has been a first-line treatment for true-lumen collapse. Surprisingly, the results of the experiment do not support the effectiveness of the procedure. One possible explanation is that the effect of aortic fenestrations was investigated in a noncompliant, rigid phantom that was different from the human aorta. There is also the possibility that the simulated fenestration-branch loops may not have accurately represented the fenestrations in the dissection flap. In the first part of the experiment, it was found that a larger reentry communication more readily relieved true-lumen collapse. Despite the limitations of the phantoms, the effect of creating an aortic fenestration is considered to be smaller than that of establishing a distal reentry communication, if they are the same size.

Clinical experience also shows that balloon fenestration alone is successful in relieving true-lumen collapse in less than 50% of the patients [4, 6]. At best, fenestration abolishes the pressure gradient between the true and false lumens. Because of the elastic recoil within the dissection flap, the true-lumen does not reexpand throughout its length, even after successful fenestration [6]. Consequently, it is often necessary to buttress the open true lumen with intravascular stents [4, 6, 23].

A question that requires further study is, what determines the ideal position for balloon fenestration? Fenestration at the supraceliac aorta has been frequently performed with some success [23, 27]. Williams et al. [6] recommend the creation of fenestrations at the level of the compromised vessel. In the experiments, it was difficult to compare the relative effectiveness of the different fenestration sites in relieving true-lumen collapse because the fenestration itself showed little salutary effect. However, when fenestrations were established proximal to the abdominal branch vessels after complete obliteration of the true lumen, the flow direction through the loops proceeded from the true lumen to the false lumen. This suggests that proximal fenestration loops may have acted as additional entry tears, effectively increasing the area of the primary entry tear.

Although true-lumen collapse was not relieved when the fenestrations were established distal to the abdominal branch vessels, the flow through the loops proceeded from the false lumen to the true lumen, which indicated that the distal fenestrations may have acted to decompress the false lumen. In addition, the distal fenestration was better at preventing true-lumen collapse. The results of the experiments also suggest that fenestration should be performed at or below the level of the compromised vessels, preferably just above the iliac bifurcation. Fenestration above the level of the celiac artery is not advisable.

In conclusion, findings from this study suggest that there are two complementary principles in the treatment of true-lumen collapse in aortic dissection: decrease the flow into the false lumen, and increase the flow from it. Surgical repair of the thoracic aorta and coverage of the entry tear with a endovascular stent-graft fulfill the former principle. The latter principle can be achieved with balloon fenestration of the obstructing dissection flap at the level of the orifices in the compromised vessels and with creation of an outflow channel from the false lumen by using balloon fenestrations or intravascular stents.

Practical applications: The successful translation of these in vitro observations to clinical application requires the definition of whether true-lumen collapse in a particular human aortic dissection belongs to the false lumen compressing the true lumen variety or to the high true lumen outflow collapsing the true lumen variety. Further investigations are necessary to clarify the roles of heart rate, blood pressure, and cardiac output in true-lumen collapse in aortic dissection and how manipulations of these physiologic parameters may prove to be clinically beneficial.

3.5 Conclusions

Typically in untreated aortic dissection, the blood flow through the true lumen is unidirectional and bidirectional in the false lumen, and the false lumen flow has higher irregularity (velocity fluctuations due to vortex-like structures) [7]. True-lumen collapse in type B dissection strongly depends on the ratios of inflow capacity and outflow capacity for both lumens. A higher ratio in the false lumen is characteristic of dissections with true-lumen collapse. Both anatomic and physiologic factors can affect true-lumen collapse.

On the basis of the results of experiments and on accumulated clinical experiences, it is possible to propose

a new protocol for the endovascular treatment of true-lumen collapse in type B aortic dissection. Placement of a stent-graft over the primary entry tear can stand alone as a definitive treatment. If stent-graft placement is not feasible or indicated, there are other options. Isolated unilateral lower-limb ischemia purely due to true-lumen collapse may be managed with balloon fenestration alone at the level of the iliac bifurcation. If there is a severe true-lumen compression associated with compromised flow to the lower limbs and abdominal branches, it can be treated with distal balloon fenestration of the dissection flap at the level of the aortic bifurcation. If the dissection extends directly into an aortic branch, any compromise in the flow to the branch associated with the true-lumen collapse is best managed with revascularization of the branch from the false lumen by using intravascular stents. If these maneuvers fail to relieve the true-lumen collapse, a stent may be placed in the true lumen of the aorta. Although not investigated here, the stent-grafting of the primary tear may have additional beneficial effects in chronic cases by preventing continued growth of the false lumen since false lumen patency seems to be linked strongly to late complications from aneurysmal growth.

References

1. Sarris GE, Miller DC. Aortic dissection: long-term results of surgical treatment. In: Yao JST, Pearce WH, editors. Long-term results in vascular surgery. Norwalk (CT): Appleton & Lange; 1992. p. 111–!34.
2. Fann JI, Sarris GE, Mitchell RS, et al. Treatment of patients with aortic dissection presenting with peripheral vascular complications. Ann Surg 1990; 212:705–713.
3. Cambria RP, Brewster DC, Gertler J, et al. Vascular complications associated with spontaneous aortic dissection. J Vasc Surg 1988; 7:199–209.
4. Slonim SM, Nyman UR, Semba CP, Miller DC, Mitchell RS, Dake MD. True lumen obliteration in complicated aortic dissection: endovascular treatment. Radiology 1996; 201:161–166.
5. Williams DM, Lee DY, Hamilton BH, et al. The dissected aorta. III. Anatomy and radiologic diagnosis of branch-vessel compromise. Radiology 1997; 203:37–44.
6. Williams DM, Lee DY, Hamilton BH, et al. The dissected aorta: percutaneous treatment of ischemic complications-principles and results. J Virol 1997; 8:605–625.
7. Strotzer M, Aebert H, Lenhart M, Nitz W, Wild T, Manke C, Volk M, Feuerbach S. Morphology and hemodynamics in dissection of the descending aorta—assessment with MR imaging. Acta Radiol 2000; 41:594–600.
8. Kato M, Bai H, Sato K, Kawamoto S, Kaneko M, Ueda T, Kishi D, Ohnishi K. Determining surgical indications for acute type B dissection based on enlargement of aortic diameter during the chronic phase. Circulation 1995 Nov 1; 92(9 Suppl):II107–112.
9. Marui A, Mochizuki T, Mitsui N, Koyama T, Kimura F, Horibe M. Toward the best treatment for uncomplicated patients with type B acute aortic dissection: A consideration for sound surgical indication. Circulation 1999 Nov 9; 100(19 Suppl):II275–280.
10. Iguchi A, Tabayashi K. Outcome of medically treated Stanford type B aortic dissection. Jpn Circ J 1998 Feb; 62(2):102–105.
11. Masuda Y, Yamada Z, Morooka N, Watanabe S, Inagaki Y. Prognosis of patients with medically treated aortic dissections. Circulation. 1991 Nov; 84(5 Suppl):III 7–13.
12. Neya K, Omoto R, Kyo S, Kimura S, Yokote Y, Takamoto S, Adachi H. Outcome of Stanford type B acute aortic dissection. Circulation. 1992 Nov; 86(5 Suppl):II 1–7.
13. Chung JW, Elkins C, Sakai T, Kato N, Vestring T, Semba CP, Slonim SM, Dake MD. True-lumen collapse in aortic dissection: part I. Evaluation of causative factors in phantoms with pulsatile flow. Radiology. 2000; 214:87–98.
14. Chung JW, Elkins C, Sakai T, Kato N, Vestring T, Semba CP, Slonim SM, Dake MD. True-lumen collapse in aortic dissection: part II. Evaluation of treatment methods in phantoms with pulsatile flow. Radiology 2000; 214:99–106.
15. Williams DM, LePage MA, Lee DY. The dissected aorta. I. Early anatomic changes in an in vitro model. Radiology 1997; 203:23–31.
16. De Bakey ME, McCollum CH, Crawford ES, et al. Dissection and dissecting aneurysms of the aorta: twenty-year follow-up of five hundred twenty-seven patients treated surgically. Surgery 1982; 92:1118–1134.
17. Glower DD, Fann JI, Speier RH, et al. Comparison of medical and surgical therapy for uncomplicated descending aortic dissection. Circulation 1990; 82(Suppl 4):39–46.
18. Miller DC, Mitchell RS, Oyer PE, et al. Independent determinants of operative mortality for patients with aortic dissections. Circulation 1984; 70(Suppl 1):153–164.
19. Crawford ES. The diagnosis and management of aortic dissection. JAMA 1990; 264:2537–2541.
20. DeSantis RW, Doroghazi RM, Austen WG, Buckley MJ. Aortic dissection. N Engl J Med 1987; 317:1060–1067.
21. Elefteriades JA, Hammond GL, Gusberg RJ, Kopf GS, Baldwin JC. Fenestration revisited: a safe and effective procedure for descending aortic dissection. Arch Surg 1990; 125:786–790.
22. Shah PM, Clauss RH. Dissecting hematoma presents as acute lower limb ischemia: diagnostic patient profile and management. J Cardiovasc Surg 1983; 24:649–653.
23. Slonim SM, Nyman U, Semba CP, Miller DC, Mitchell S, Dake MD. Aortic dissection: percutaneous management of ischemic complications with endovascular stents and balloon fenestration. J Vasc Surg 1996; 23:241–253.
24. Young JR, Dramer J, Humphries AW. The ischemic leg: a clue to dissecting aneurysm. Cardiovasc Clin 1975; 7:201–205.
25. Merkelbach JW, Van Rhede Vanderkloot JF. Intermittent peripheral arterial occlusion as a result of a dissecting aneurysm. Arch Chir Neerl 1970; 22:7–13.
26. Schoon IM, Holm J, Sudow G. Lower extremity ischemia in aortic dissection: report of three cases. Scand J Thorac Cardiovasc Surg 1985; 19:93–95.
27. Park JH, Chung JW, Cho YK, Kim SH, Ahn H, Oh BH. Percutaneous fenestration of aortic dissection: salvage of an ischemic solitary left kidney. Cardiovasc Intervent Radiol 1997; 20:146–154.

Transesophageal Echocardiography for Diagnosis and Treatment of Aortic Diseases

Pierre Massabuau

4

Contents

4.1 Introduction

Transesophageal echocardiography (TEE) provides optimal imaging of the whole aorta and sometimes visualizes the upper part of the abdominal aorta. Use of a multiplane probe reduces the classic blind zone, due to the trachea, at the junction of the ascending aorta and the proximal part of the arch. The origin of the left subclavian artery is easily observed. But, emergences of innominate and left carotid arteries remain inconsistently detected. In that case, the transthoracic echocardiographic (TTE) suprasternal view appears very useful. TEE is a semi-invasive procedure. Patient information, screening of contraindications and preparation (local anesthesia, intravenous access, material and structures for resuscitation) are especially important in cases of aortic pathologies. Patients with acute dissection or traumatic rupture of the isthmus need to be explored in an intensive care unit by a trained physician. TEE can be performed quickly, at the bedside and without nephrotoxic contrast agent.

The thoracic aorta is divided into three segments: ascending, horizontal (arch) and descending. TEE allows measurements of each segment, which is determinant for diagnosis, management and follow-up. The ascending aorta presents a particular aspect; four diameters need to be measured: annulus, sinus of Valsalva, sinotubular junction and ascending segment. Age, sex, height, weight and body surface area are independent determinant factors of these diameters. The aortic annulus and the sinus of Valsalva are correlated with body surface area; the sinotubular junction and the ascending segment are more related to age [19].

4.2 Transesophageal Echocardiography for Diagnosis of Aortic Diseases

4.2.1 Aortic Dissection

Aortic dissection occurs generally in patients with risk factors: age, hypertension, disease of fibroelastic tissue (Marfan syndrome), congenital disease (bicuspid valve, coarctation) or pregnancy. Iatrogenic or traumatic causes are less frequent. The dissecting process has generally an anterograde longitudinal extension, but retrograde dissection is possible. Circular extension involves partial or complete wall circumference. Two clas-

sifications may be used. De Bakey classification presents three types. In type I, the ascending segment is at least dissected with variable extension to horizontal and descending parts. In type II, dissection is only localized in the ascending aorta. Type III consists in an involvement of the descending thoracic aorta (IIIa) with possible extension to the abdominal aorta (IIIb). Stanford classification is now currently used. Type A defines dissections with, at least, the involvement of the ascending aorta, whatever the extension or the site of intimal tear. Type B dissection respects the ascending aorta. It concerns essentially the descending aorta with possible anterograde extension to the abdominal segment or retrograde to the horizontal aorta [5, 7].

4.2.1.1 Intimal Flap

Dissection consists in a cleavage of the medial layer of the aortic wall. It leads to formation of the intimal flap, which really corresponds to the association of the intimal layer and two thirds of media. The intimal flap represents the first echocardiographic sign of aortic dissection (Fig. 4.1) [7]. On TEE it appears as a linear intraluminal, thin and mobile echo that divides the aortic lumen in two parts: true and false lumens. There is a correlation between flap mobility and mortality.

4.2.1.2 Intimal Tear

The intimal tear corresponds to the beginning of the dissecting process. Its detection is determinant to choose the time and type of treatment. From this point, dissection has generally an anterograde progression but retrograde extension is possible. The tear appears as a discontinuity of the intimal flap. A multiplane TEE probe provides a direct image of the tear and allows its measurement (Fig. 4.2). Color Doppler imaging enhances detection of the tear and can reveal the presence of other multiple small communications between the two lumens, especially in the descending aorta. They appear as thin color flows without a direct image of the tear (Figs. 4.3, 4.4). Anatomical controls showed that these images might correspond to the origin of intercostal arteries [30]. Intravenous infusion of an echographic contrast agent can detect them with good accuracy (Fig. 4.5). There is a positive relation between flap mobility and the site of the tear. Increased mobility is observed around the tear and helps to localize it. Pulsed Doppler imaging flow velocities through the intimal tear reflect the pressure gradient between the two lumens (Fig. 4.6). During a cardiac cycle, the velocity profile may have a mono-, bi-, tri- or quadriphasic aspect [7].

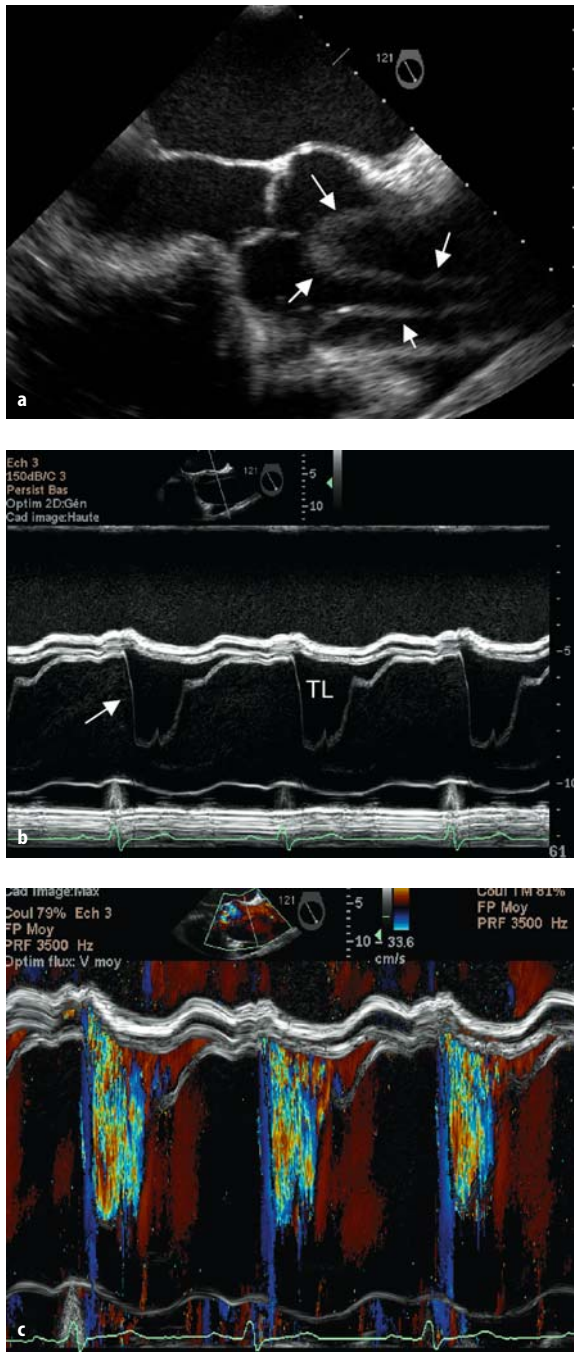
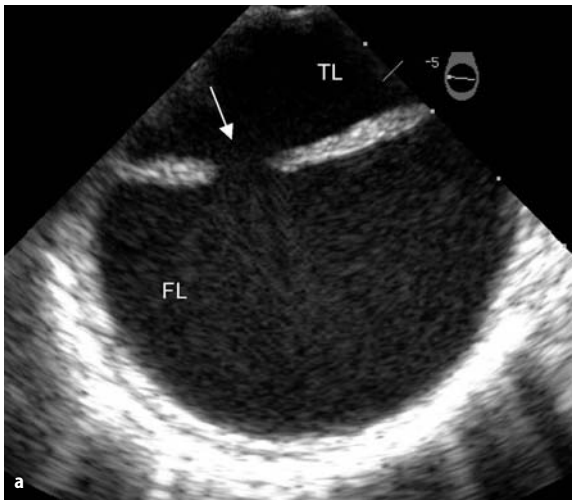


Fig. 4.1. Dissection of the ascending aorta. **a** Longitudinal view with sinuous intimal flap (*arrows*). **b** M mode showing amplitude of displacement of the intimal flap. **c** M mode color Doppler image showing systolic flow into the true lumen (*TL*)



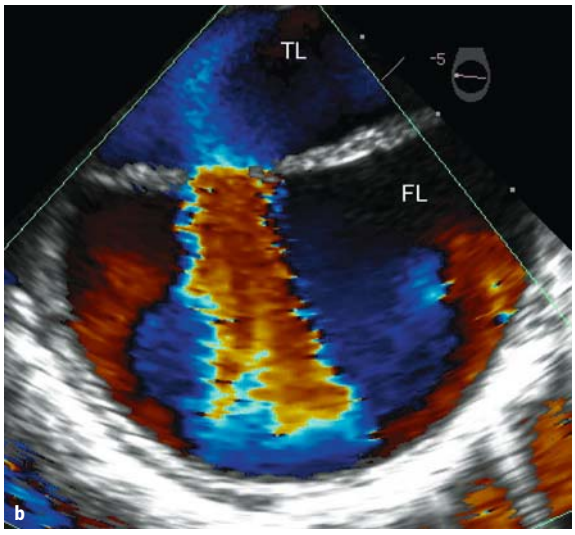
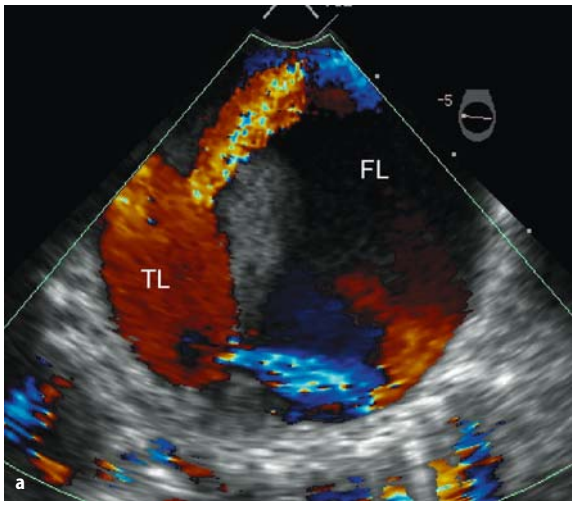


Fig. 4.2. Dissection of the descending aorta. **a** Intimal tear (*arrow*). **b** Color flow through the intimal tear, from the true lumen (*TL*) towards the false lumen (*FL*)



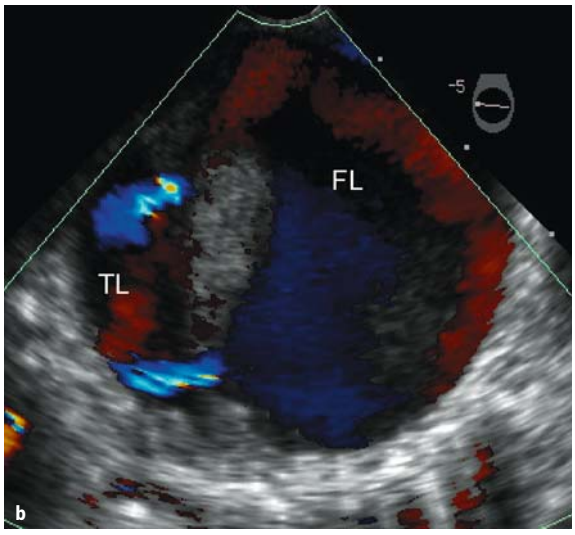


Fig. 4.3. Dissection of the descending aorta. Color Doppler flow through two intimal tears. **a** Towards the false lumen (*FL*) in the systole. **b** Towards the true lumen (*TL*) in the diastole

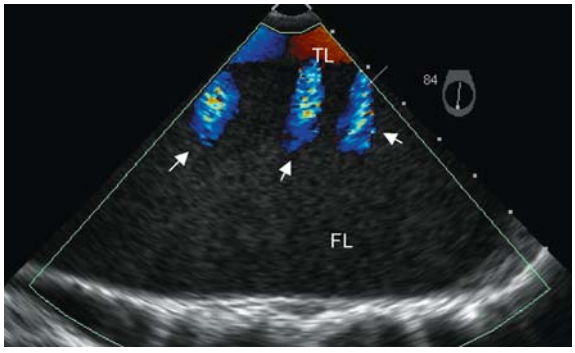


Fig. 4.4. Dissection of the descending aorta. Color Doppler flow of small communications (*arrows*) between the true lumen (*TL*) and the false iumen (*FL*) that might correspond to ostia of intercostal arteries

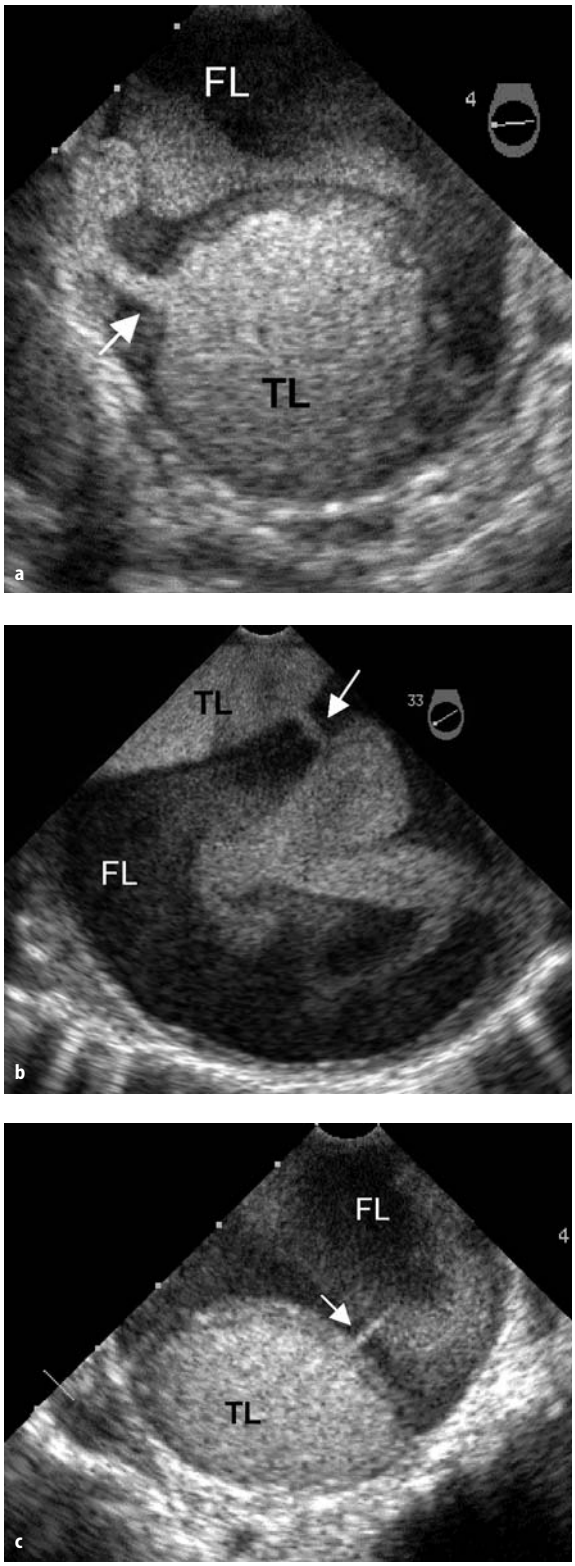


Fig. 4.5. Dissection of the descending aorta. Contrast echographic agent for detection of small intimal tears (*arrows*), true lumen (*TL*) and false lumen (*FL*)

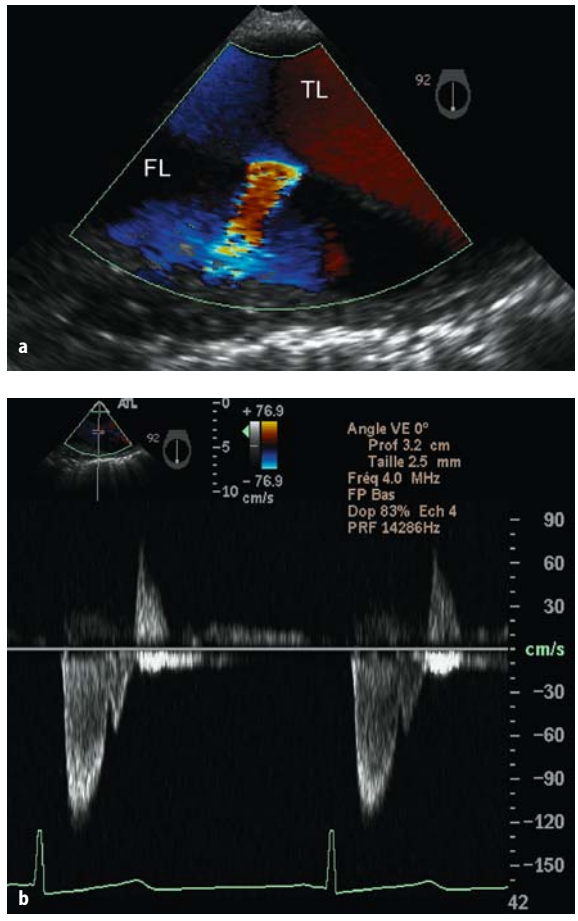


Fig. 4.6. Dissection of the descending aorta. **a** Color flow through the intimal tear, from the true lumen (*TL*) towards the false lumen (*FL*). **b** Pulsed Doppler image through the intimal tear

4.2.1.3 True and False Lumens

The true lumen is generally smaller than the false one but presents a systolic expansion [7]. Color Doppler imaging presents an aspect of aliasing owing to the high velocity of systolic anterograde flow (Fig. 4.7). The false lumen is larger and presents a systolic compression. Blood velocity is lower and, sometimes, results in a constitution of the spontaneous echo contrast effect. It appears as dynamic smokelike echos with slow swirling movements that are markers of blood stasis. So, a thrombus is frequently observed in the false lumen. The importance of thrombosis (partial or complete) seems to be negatively related with the site and the size of the tear. A thrombus must be distinguished from thin cobweblike echos joining the intimal flap to the outer wall of the false lumen. These residual strands of media, essentially observed in the descending aorta, may be helpful to identify the false lumen [29]. Dissection is frequently associated with and complicated by valvular regurgitation, involvement of collateral arteries, and blood extravasation to periaortic structures.

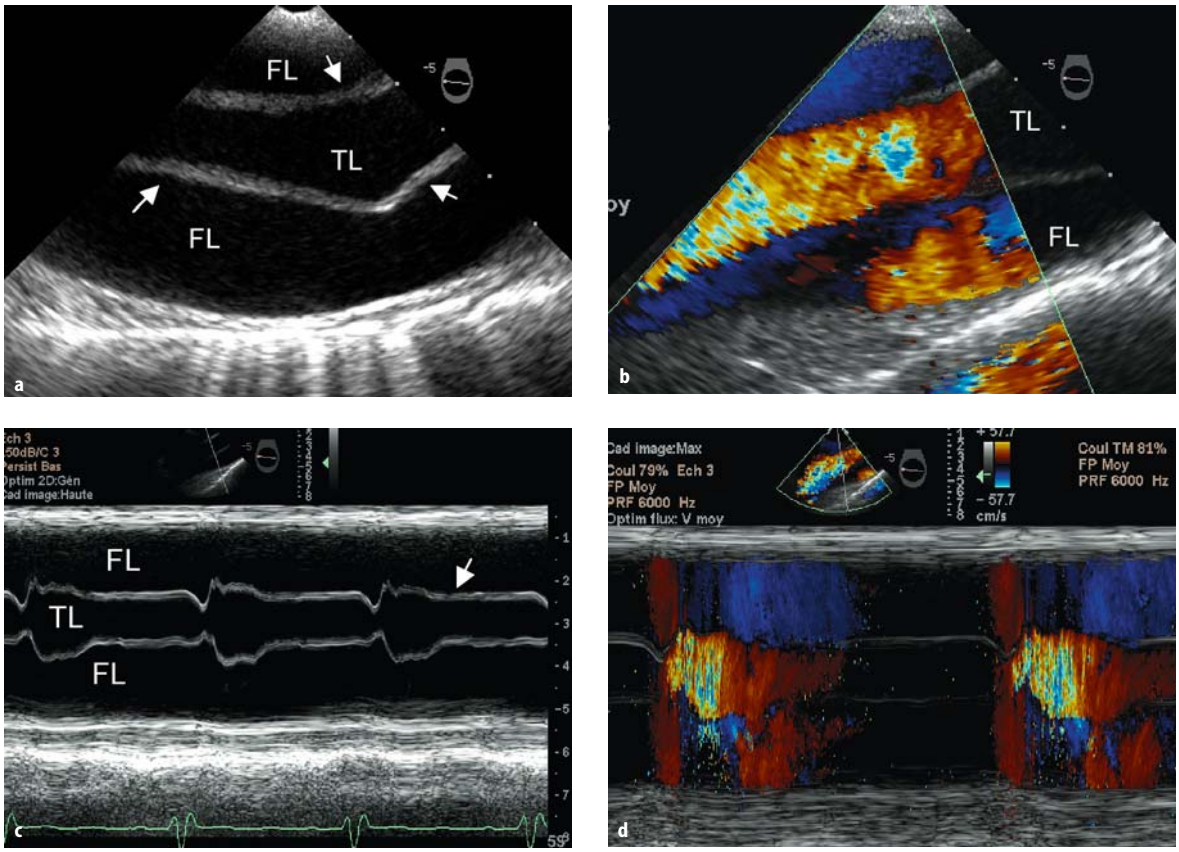


Fig. 4.7. Dissection of the aortic arch. **a** Two-dimensional view of the horizontal aorta showing the intimal flap (*arrows*) separating the true lumen (*TL*) and the false lumen (*FL*). **b** Color Doppler flow within the true lumen (*TL*). **c** M mode at the same level. **d** M mode color Doppler image into the true lumen

4.2.1.4 Aortic Regurgitation

This complication is frequent. It occurs in about 40–76% of patients [15]. Some cases require surgical treatment. TTE is used to evaluate the grade of regurgitation and its consequences on left ventricular size and function. TEE is determinant to analyze the mechanism of regurgitation and the possibility of valve repair. Five mechanisms are described: incomplete valve closure due to dilatation of the sinotubular junction, leaflet prolapse by extension of dissection to the valve attachment, intimal flap prolapse into aortic annulus [15] and bicuspid and degenerative valves. The first three mechanisms, characterized by a normal leaflet structure, may benefit from a conservative treatment by surgical valve repair. The last two mechanisms are independent of dissection and must be treated by valve replacement if needed.

4.2.1.5 Aortic Branches

Mechanisms of the involvement of aortic branches are multiple: dissection, disinsertion or obstruction of the artery ostium, compression by the false lumen. Except for the left subclavian artery, TEE fails to analyze these complications (Fig. 4.8). However, dissection of the initial part of the coronary artery has been detected by TEE. Computer tomography (CT) and MRI are more efficient in recognizing them [16]. Extension of dissection to the innominate and left carotid arteries can be detected by TTE in suprasternal incidence.

4.2.1.6 Periaortic Structures

Acute or subacute bleeding from the aorta can involve periaortic structures with constitution of pericardial, mediastinal or pleural effusions (Fig. 4.9). Mediastinal hematoma is characterized by an increased distance between the esophagus and the aorta or the left posterior atrial wall [12].

4.2.1.7 Pitfalls

TEE evaluation of aortic dissection includes some pitfalls that can impair its accuracy: intimal flap artefacts, localized or retrograde dissections, aneurysm or false aneurysm with a thrombus, complex plaque of athero-

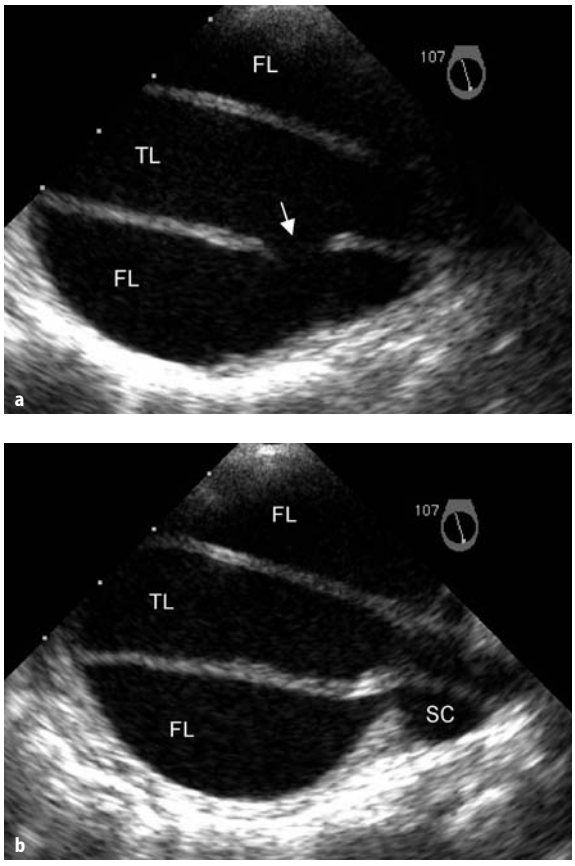


Fig. 4.8. Dissection of the aortic arch. **a** Intimal tear (*arrow*). **b** Extension of the intimal flap into the subclavian artery (*SC*). *TL* true lumen, *FL* false lumen

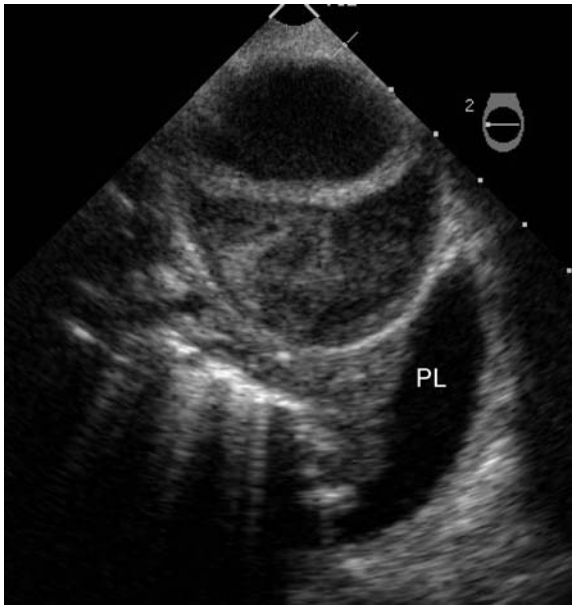
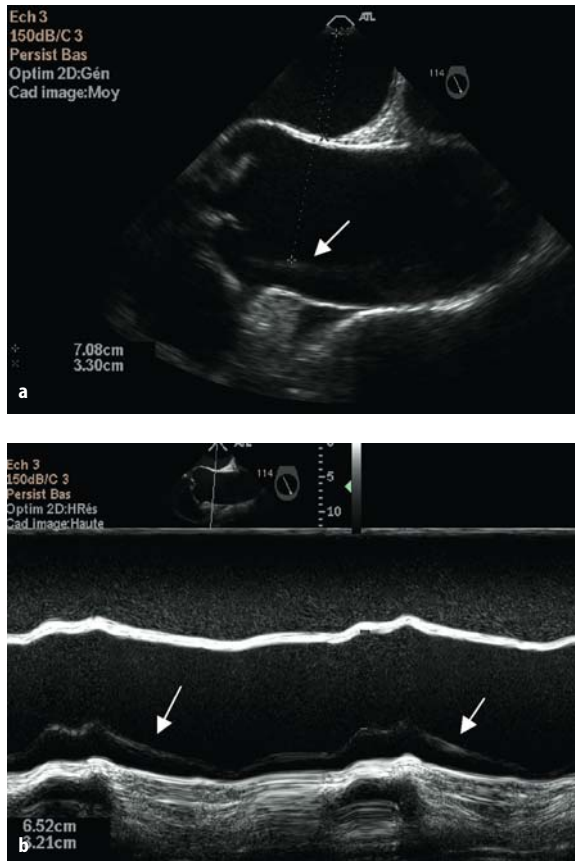


Fig. 4.9. Dissection of the descending aorta complicated by pleural effusion (*PL*)



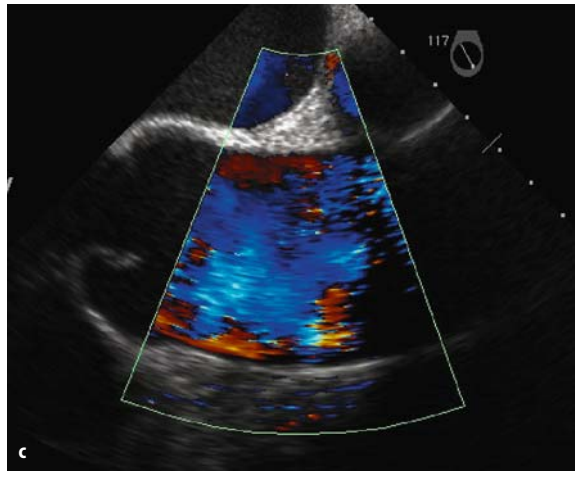


Fig. 4.10. Aortic dissection. Linear artefacts into ascending aorta. **a** Two-dimensional long-axis view. **b** M mode. **c** Color Doppler image showing homogeneous flow

ma with a mobile component, tumor, innominate or azygos veins, periaortic fat tissue or abscess. Linear artefacts mimicking the intimal flap are frequent in the ascending aorta and are infrequent in the horizontal arch (Fig 4.10). This is due to echographic reverberation of the left atrial or right pulmonary artery walls.

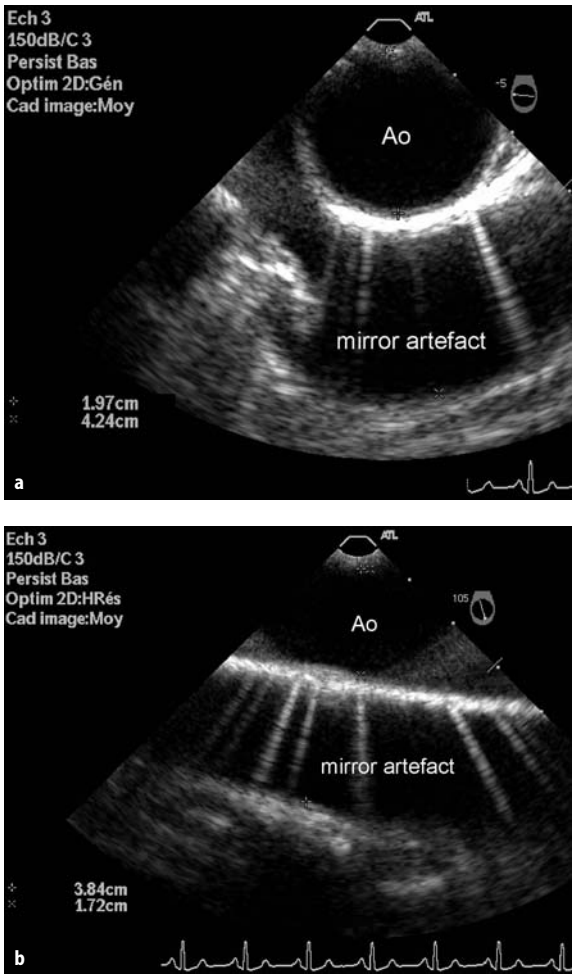


Fig. 4.11. Transesophageal artefacts of aortic dissection. Mirror artefact in descending aorta mimicking two channels. **a** Transverse view. **b** Longitudinal view. *Ao* aorta

In M mode, artefact echo is generally located at twice the distance from the transducer and structure that produces the artefact and presents a double-amplitude displacement. The color flow aspect is similar on both sides of the artefact [1, 6]. Pulsed Doppler imaging contributes by positioning the sample volume at the suspected image level. The intimal flap produces high-intensity signals with clicks that are absent in the case of an artefact [21]. A mirror artefact is frequent in the descending aorta. A typical aspect consists in an image of two parallel channels with the same diameter (Fig. 4.11) [1]. Despite these limits, TEE sensitivity, specificity, positive and negative predictive accuracies are greater than 90% and similar to those of CT. However, MRI offers the best accuracy (near 100%) [16].

New cardiovascular imaging tools and improvements of treatments and follow-up periods lead to a new concept of aortic diseases. A new classification recently proposed [27] includes five classes: class 1, classic aortic dissection; class 2, intramural hematoma or hemorrhage; class 3, small dissection with an eccentric bulge at the tear site; class 4, penetrating aortic ulcer; class 5, iatrogenic and traumatic dissections. Each class 2, 3 and 4 lesion could be a precursor of classic aortic dissection.

4.2.2 Intramural Hematoma

Intramural hematoma consists in bleeding into the medial layer of the aortic wall. A cystic medial degeneration is often present and leads to a rupture of the vasa vasorum. Intramural bleeding induces circular and longitudinal cleavage of the aortic wall. Hematoma can involve the whole aorta. It occurs typically in elderly patients (mean 65–70 years) with hypertension. Symptoms mimic aortic dissection. Complications are severe and frequent, especially if the ascending aorta is involved. Classification of hematoma is similar to that of dissection. Type A involves at least the ascending aorta; type B, the descending part. TEE findings are associated with the following: a circular or crescentic thickening (more than 5 mm) of the aortic wall (more than 7 mm in the initial description); an increased thrombuslike homogeneous echodensity; an absence of the intimal flap, intimal tear and flow; a longitudinal mean extension of 1–20 cm [13, 17]. The aortic diameter is generally increased. In the case of intimal calcification or atheroma, they are displaced towards the center of the aortic lumen. Hemomediastinum, pericardial or pleural effusions may be associated and represent signs of complications. Compared with this classic form, other echographic aspects could be observed. They are related to the importance and the onset of the intramural bleeding. The crescentic image can be heterogeneous with echo-free space or completely nonechogen. These forms correspond to recent bleeding or to liquefaction of hematoma (Fig. 4.12). In such cases, CT or MRI (by distinction between oxyhemoglobin and methemoglobin) are very helpful in evaluating the age of lesions [7, 17]. If important, intramural hematoma presents as a classic noncommunicating dissection with an intimal flap but no tear. However, increase of the bleeding and intramural pressure can induce an intimal tear. Several types of evolution have been described [13, 17]: normalization; decrease; stabilization or increase of wall thickness; circular and/or longitudinal extension; aortic dissection or rupture. TEE control within 3 months of acute syndrome helps to evaluate the trend of evolution. Aortic dilatation or aneurysm occur later. TEE signs of hematoma must be distinguished: aortic dissection and thrombosed false lumen; aneurysm with a thrombus; plaque of atheroma; penetrating aortic ulcer.

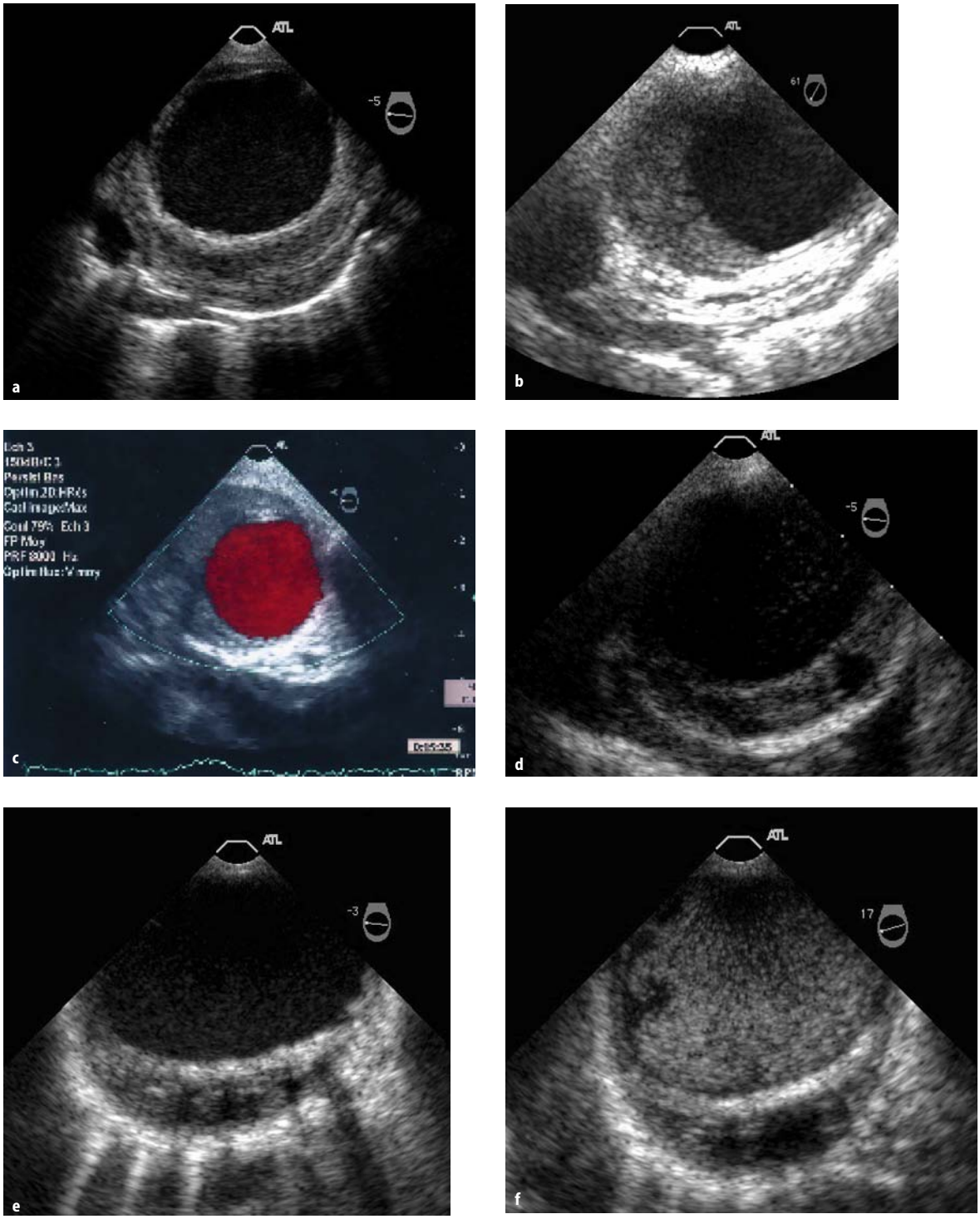


Fig. 4.12. Intramural hematoma of the descending aorta. Crescentic thickening of the aortic wall. **a**, **b** Typical aspect with thrombuslike homogeneous echodensity. **c** Crescentic aspect, color flow in the aortic lumen. **d** Inhomogeneous aspect with echo-free spaces. **e** Nonechogen aspect mimicking dissection. **f** After injection, echographic contrast agent is only present in the aortic lumen, confirming the absence of communication with the hematoma

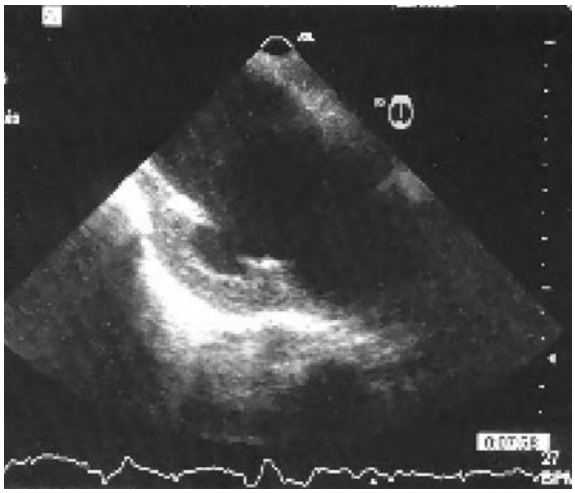


Fig. 4.13. Penetrating aortic ulcer of the descending aorta. Ulcerated plaque with crater and constitution of an adventitial false aneurysm

4.2.3 Penetrating Aortic Ulcer

A penetrating aortic ulcer is an entity described by Stanson et al. [26] as an ulceration of a plaque of atheroma that extends through intima into internal elastic lamina. It occurs generally in elderly patients (over 75 years) with hypertension, multiple-risk factors (smoking) and severe complex atheroma plaques. Symptoms are similar to those of aortic dissection. Penetrating ulcers involve a classic descending aorta. Circular and longitudinal extensions are less important than hematoma. The typical TEE aspect consists in a thick atherosclerotic plaque with a deep crater limited by irregular edges (Fig. 4.13). Color Doppler imaging enhances the detection of the ulcer and measurement of the crater dimensions. There is no intimal flap, nor false lumen. Angiography was the first method of diagnosis and showed a localized additional contrast image. CT and MRI are more efficient in the diagnosis of complications. It has been proved that a penetrating ulcer has a severe potential of evolution: aortic dissection, hematoma of the medial layer, adventitial false aneurysm or transmural rupture [14, 26].

4.2.4 Aortic Aneurysms

Aortic diameters are related to age, sex, height, weight, body surface area and site. Dimensions decrease regularly from the valve annulus to the iliac arteries. For one site, an aneurysm is defined as an increase (more than 50%) of the expected diameter and is associated with a loss of parallelism of the aortic wall. The two main etiologies are atherosclerosis (particular risk with hypertension and smoking) and dystrophy of conjunctive tissue [7].

4.2.4.1 Atherosclerotic Aneurysms

Atherosclerotic aneurysms involve generally horizontal and descending aorta. Two types are observed. The most frequent is the fusiform aneurysm characterized by an increased diameter of the lumen and nonparallelism of the wall. TEE determines the site, the diameters and the circular and longitudinal extensions, and detects associated abnormalities: wall thrombus, spontaneous echo contrast, complex atheroma plaques (Fig. 4.14).

The second type, less frequent and less extended, is the false (or pseudo) aneurysm. TEE signs are associated with a small neck and a large cavity (Fig. 4.15). These conditions promote a blood stasis, and a thrombus is frequent.

4.2.4.2 Dystrophic Aneurysms

Dystrophic aneurysms involve principally ascending aorta up to the innominate artery. The typical aspect is that of annulo-aortic ectasian disease. Etiologies include the Marfan syndrome (principally in patients younger than 40 years), characterized by mutation of genes localized on chromosome 15, and idiopathic forms. These forms present nearly similar histologic lesion of kystic medianecrosis. Dilatation involves the valve annulus, the sinus of Valsalva and sometimes the sinotubular junction. All these elements lead to raise valve commissures and to stretch the cusps. Valve movement is impaired and this results in an incomplete closure with diastolic regurgitation (Fig. 4.16). Bicuspid or valve prolapse with eccentric flow may be observed [7]. Quantification of regurgitation and consequences for the left ventricular size and function need to be evaluated by TTE. Tricuspid and mitral valve dystrophy may be associated. Aortic dissection is the main complication of dystrophic aneurysms.

4.2.4.3 Aneurysm of the Sinus of Valsalva

Aneurysm of the sinus of Valsalva is an infrequent disease, mainly observed in young men. A congenital origin is frequent and explains associations with other abnormalities: bicuspid aortic valve with regurgitation, coarctation, interventricular septal defect. Other etiologies are Marfan syndrome, endocarditis or inflammatory diseases of the aortic wall [11]. There are two TEE aspects: localized dilatation (generally right anterior part) of the sinus or fingerlike expansion of the sinus (Fig. 4.17). Color Doppler imaging is useful to detect the main complication that consists in a disruption into the right atrium, the right ventricle or more rarely the left atrium or pericardium. These images have to be distinguished from aortic annulus abscess.

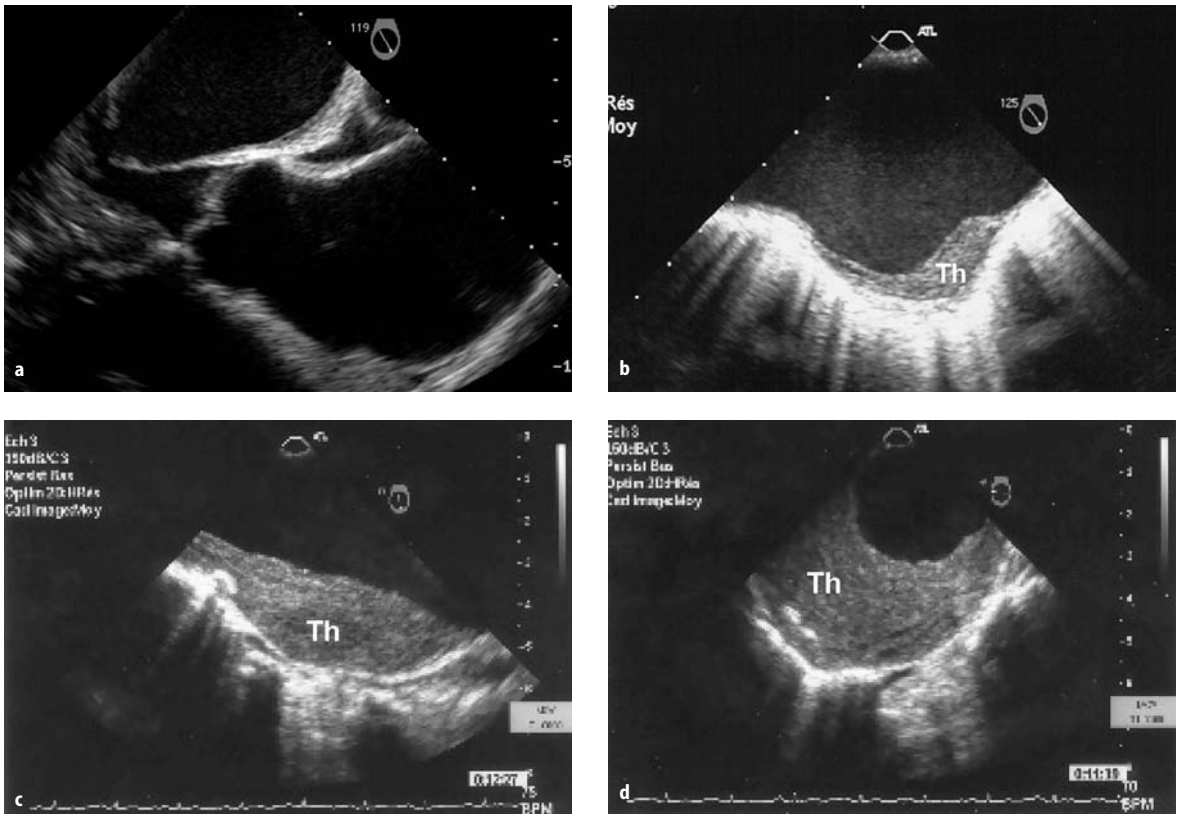


Fig. 4.14. a Aneurysm of the ascending aorta. **b** Fusiform aneurysm of the descending aorta with a mural thrombus (*Th*). **c,d** Longitudinal and transverse views of aneurysm with an important thrombus

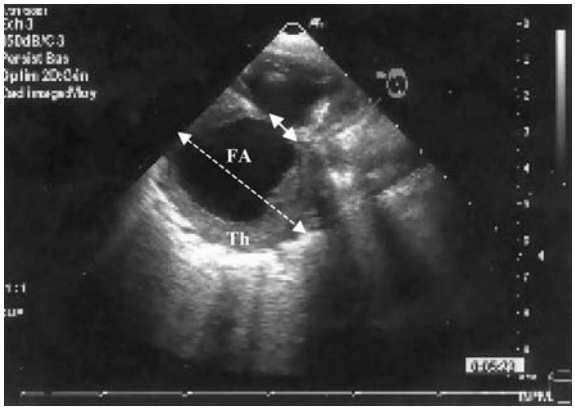


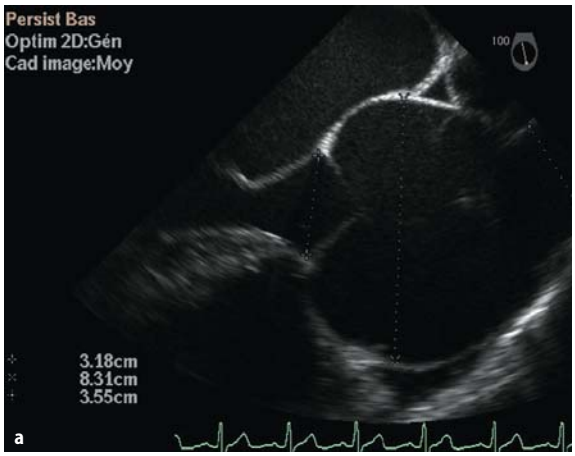
Fig. 4.15. False aneurysm (*FA*) of the descending aorta. The neck diameter (*full line*) is smaller than the aneurysm diameter (*dotted line*). *Th* mural thrombus

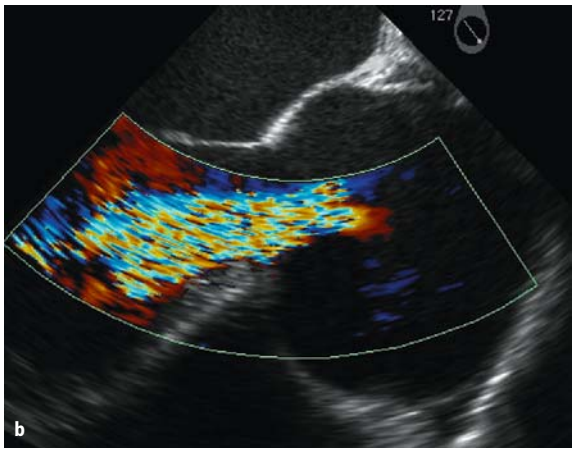
4.2.4.4 Aneurysms and Systemic or Inflammatory Diseases

Takayasu disease, observed in young women, involves the ascending aorta. It is associated with fusiform dilatations and stenosis. The aortic wall is thick. The main risk consists in rupture. Horton disease occurs in older patients (over 70 years). Aortic involvement is less frequent than temporal artery. In Behcet disease, pseudoaneurysms alternate with stenosis. Aneurysms can be observed in rheumatoid arthritis, Ormond and Cogan diseases and Reiter syndrome. Recently, cocaine and amphetamine have been suspected to induce dissection and aneurysm formation [7].

4.2.4.5 Aneurysms and Infectious Diseases

Syphilis involves generally the upper part of the ascending aorta. Lesions consist in pseudoaneurysm with a thrombus and calcification of the aortic wall. Actually, small mycotic aneurysms may be observed during bacterial or parasitical infections. In such situations, after aortic surgery, images of a false aneurysm may be observed at the anastomosis between the aortic tube graft and the native aorta.





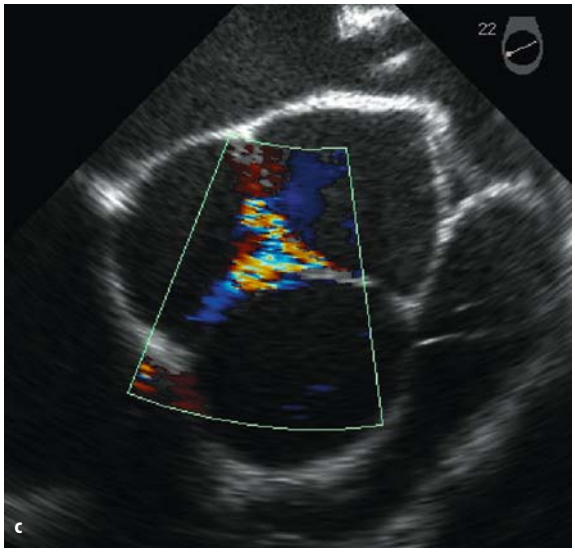
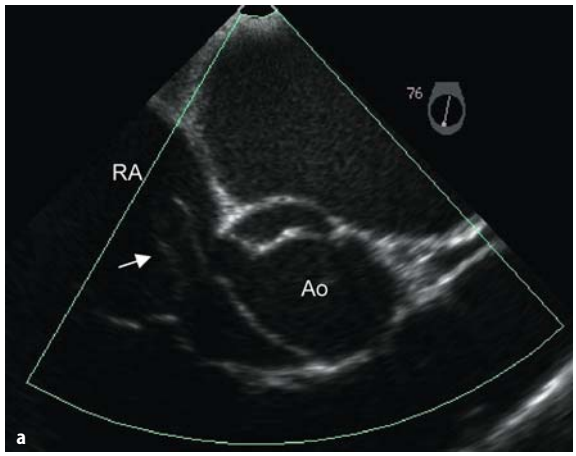


Fig. 4.16. Marfan syndrome: multiplane transesophageal views. **a** Enlargement of aortic annulus and sinus of Valsalva. **b** Color Doppler flow of aortic regurgitation. **c** Incomplete closure of aortic valves with central regurgitation



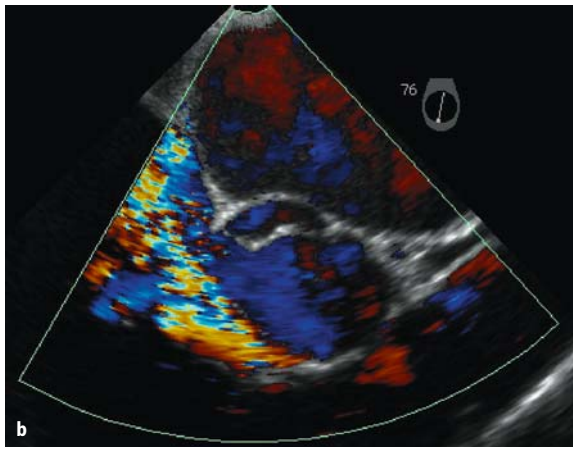
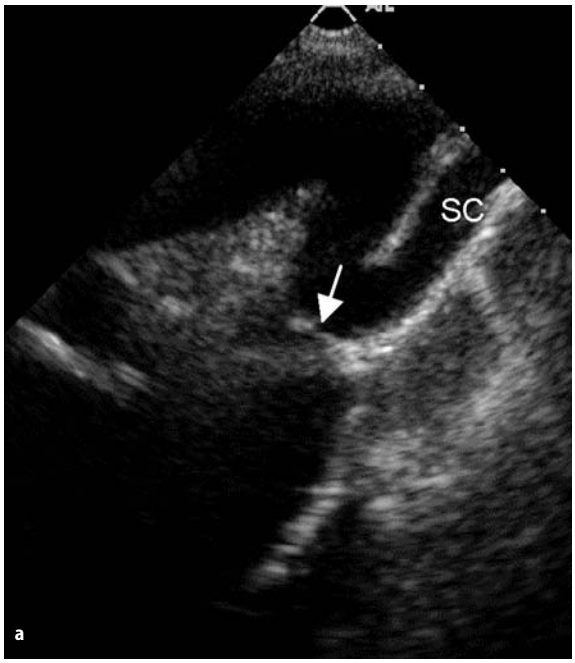
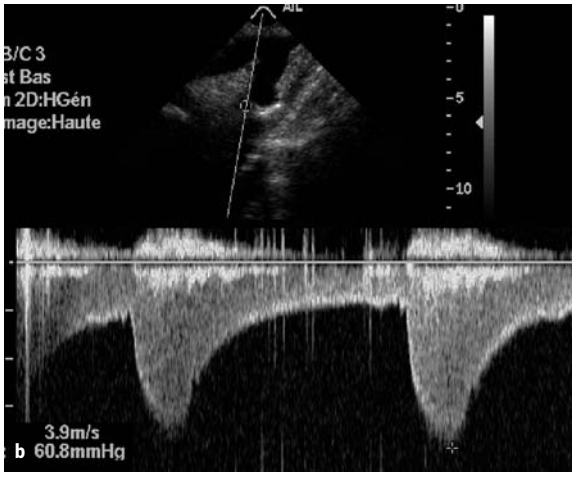


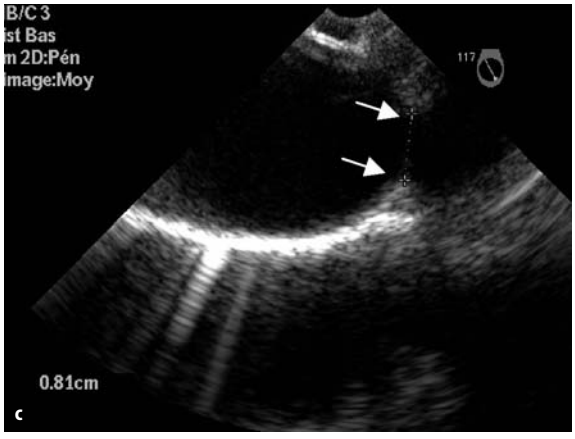
Fig. 4.17. Aneurysm of the sinus of Valsalva. **a** Fingerlike expansion of the anterior-lateral part of the sinus (*arrow*) with disruption into the right atrium (*RA*). **b** Color Doppler flow of the shunt between the aorta (*Ao*) and the right atrium through disruption of the sinus

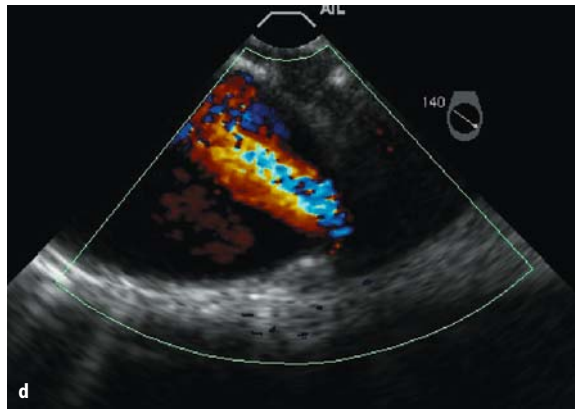
4.2.5 Coarctation of the Aorta

Aortic coarctation occurs more frequently in men than in women (sex ratio 2/1). It is often associated with Turner syndrome and aneurysm of the circle of Willis. There are three classic anatomic types: aortic membranous stenosis-like diaphragm (the most frequent), regular progressive stenosis, hypoplasia of the aortic isthmus. The stenosis induces the development of collateral circulation that involves internal mammary and intercostal arteries. Associated cardiac abnormalities are frequent: bicuspid aortic valve, ventricular septal defect, mitral stenosis or regurgitation. TEE examination requires a multiplane probe. Below the emergence of the subclavian artery, it shows a narrowed segment of aortic lumen with a poststenotic dilatation. All diameters can be measured. Color Doppler imaging velocity is increased at the stenotic level. However, the pressure gra-









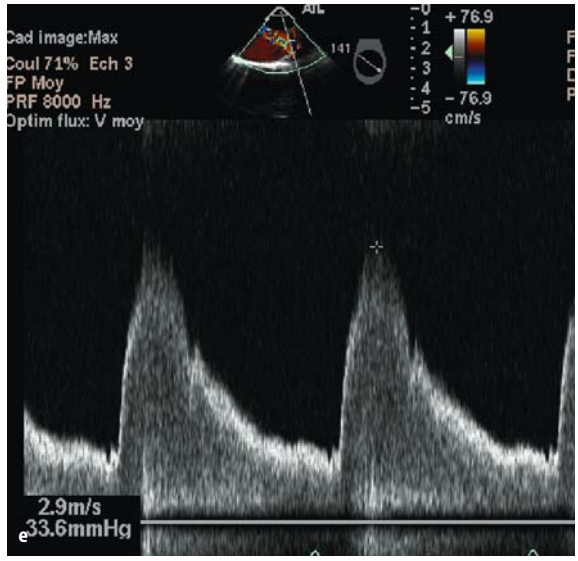


Fig. 4.18. Coarctation of the aorta. Transthoracic echocardiographic suprasternal view: **a** stenosis of the descending aorta (*arrow*) and subclavian artery (*SC*) emergence. **b** Measurement of the pressure gradient by continuous wave Doppler imaging. Transesophageal echocardiography (*TEE*) views: **c** stenosis of the aortic lumen (*arrows*); **d** color Doppler flow through the stenosis; **e** TEE assessment of flow velocity underestimates stenosis gradient

dient must be evaluated by TTE suprasternal incidence, using continuous wave Doppler imaging guided by color [23]. In severe form, high velocities can be observed throughout the diastole; they are due to persistent high pressure into the prestenotic segment (Fig. 4.18). Collateral circulation, which has an important role in treatment, can be observed by TEE but CT and MRI are more efficient.

4.2.6 Aortic Atheroma

Aortic atheroma plaques are common findings during TEE examination, especially in elderly patients and in patients with atheroma risk factors. The plaques appear as a thickening of the medial and intimal layers of the aortic wall. TEE allows a good evaluation of their site, number, characteristics and longitudinal and circular extensions. Four elements are associated with a high risk of embolism: thickness 4 mm or more, ulceration (width and depth 2 mm or more), presence of a mobile component, absence of calcification. These images can mimic an intramural hematoma or flap. Sometimes, an ulcerated plaque is the first stage of a penetrating process.

4.2.7 Traumatic Aortic Injuries

4.2.7.1 Traumatic Rupture of the Aortic Isthmus

Traumatic aortic injuries are becoming more frequent. They are related to the increase of blunt chest trauma owing to motor vehicle accidents. Falls from a elevated site represent the second cause. The mechanism consists in a sudden deceleration that submits the aortic wall to high shearing forces. The aortic isthmus, at the junction between the mobile arch and the fixed descending part, is especially exposed. Supraaortic arteries (8%) and ascending and descending (3%) aorta are less frequently involved [9]. In this particular emergent situation, TEE examination must be performed by a trained operator. Patients often have high injury severity score, unstable hemodynamic conditions and breathing assistance. If fractures of cervical vertebra are present, passage and manipulation of the TEE probe must be done very carefully. There are several TEE signs of traumatic aortic damage, each of them corresponds to variant degrees of injury: subadventitial disruption, free intimal flap, mural thrombus, wall hematoma, aortic dissection [10, 25, 28].

Subadventitial disruption is the most typical and frequent type of damage. It results in the involvement of intimal and medial layers. As a consequence, the aortic wall is limited to adventice. The first TEE sign is an intimomedial flap. It differs from the intimal flap observed in classic aortic dissection by three characteristics. It is thicker (two layers), generally less mobile with a shorter extension and it does not divide the aortic lumen into two independent channels. The same color Doppler aspect is observed on both sides of the flap. The second sign is a false aneurysm characterized by a saccular cavity communicating with the lumen by a neck (Fig. 4.19). With time, evolution to a fusiform aspect is possible. The circular extension of wall involvement leads to three types of subadventitial disruption being distinguished: complete, subtotal or partial. In the complete type, the flap describes a circular line within the lumen (Figs. 4.20, 4.21). An obstruction, with pseudocoarctation syndrome, may be observed. In the subtotal type, the flap crosses directly the lumen. Partial disruption appears as a localized rupture of intimal-medial layers.

Intimal disruption represents a minor type of injury. It appears as a thin flap. Its base is on the aortic wall, the free end is highly mobile. Several of these images may be observed in the same patient, and their detection may be difficult.

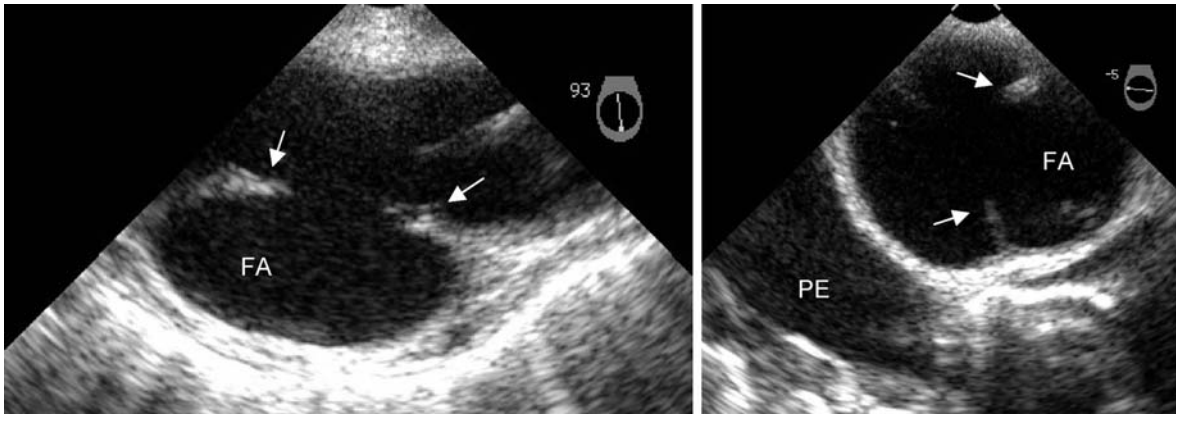


Fig. 4.19. Subadventitial partial disruption of the aortic isthmus, the intimomedial flap (*arrows*) and false aneurysm (*FA*). *PE* pleural effusion

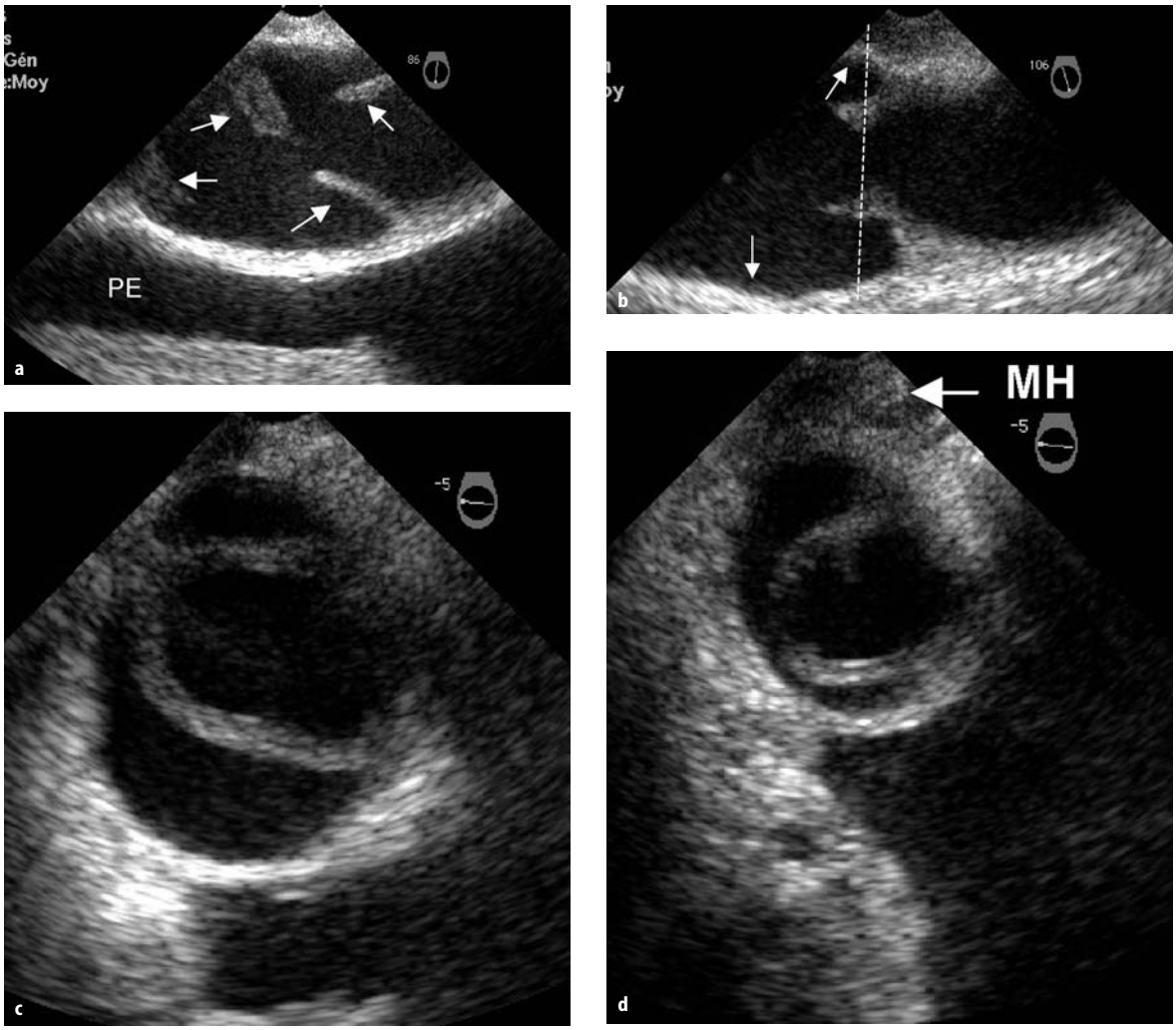


Fig. 4.20. Subadventitial subtotal disruption of the aortic isthmus. **a** Longitudinal view, intimomedial flap (*arrows*), pleural effusion (*PE*). **b** Enlargement of the aortic lumen at the site of disruption (*arrows*). **c** Transverse view from **b** (*dotted line*). **d** Mediastinal hematoma (*MH*)

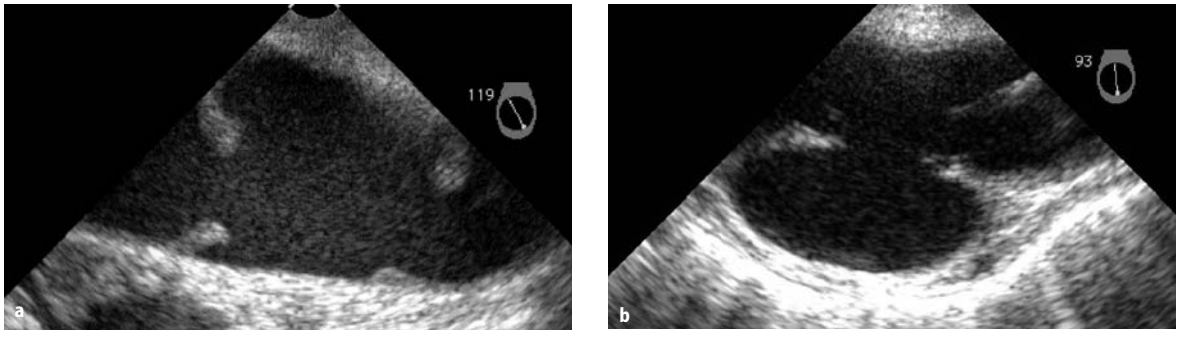


Fig. 4.21. Traumatic subadventitial rupture of aortic isthmus. **a** Subtotal rupture. **b** Partial rupture

A protruding mural thrombus may result from superficial lesion of intima. Mobile forms can induce systemic embolism. Such images have to be distinguished from complex atheroma plaques that are often observed in multiple sites and that are associated with calcifications.

Intramural hematoma is infrequent. It presents the same echographic signs as the typical form. However, it differs by a shorter longitudinal extension.

Traumatic aortic dissection is an uncommon form of subadventitial disruption. It is characterized by a flap that is less thick, parallel to the aortic wall with limited circular and longitudinal extension, and a false lumen with low flow on color Doppler imaging.

Blunt chest trauma can induces nonaortic severe injuries detected by TEE: mediastinal hematoma, myocardial contusion, valve damage.

Mediastinal hematoma [10, 12, 28] is frequently associated with traumatic aortic injury. It is considered as a marker of severity and as a sign of impending rupture. It can be due to fractures (vertebra or ribs) or bleeding of mediastinal vessels. At the isthmus level, the TEE sign of mediastinal hematoma consists in an increase of the distance between the TEE probe and the anteromedial wall of the aorta (more than 3 mm) or between the lateral posterior wall of the aorta and the left pleura (more than 7 mm). Hemothorax can be present.

Myocardial contusion induces segmental abnormal contraction. The right ventricular free wall is generally involved. Aortic, mitral and tricuspid valves may be affected. Lesions consist in a tear of the valve and a rupture of cordae or papillary muscle.

TEE pitfalls are due to nontypical localization of the rupture (horizontal aorta and its emergent arteries), a small lesion and linear or mirror artefacts. Sensivity (57–100%) and specificity (84–100%) are related to the type of probe and more especially to the experience of the physician.

4.2.7.2 Iatrogenic Aortic Injuries

Iatrogenic injuries correspond to class 5 of the new classification. They are rarely observed in current catheterization procedures. They occur principally during intraluminal manipulation: intra-aortic balloon pumping, stenting, balloon inflation for treatment of coarctation. Severe atheroma increases the risk. The main injuries are dissection (anterograde or retrograde) and systemic embolism. TEE is determinant to detect them during these high-risk catheterizations or after the event. During cardiac surgery with extracorporal circulation, TEE can prevent incidents by guiding the site of aortic clamping and cannulation [7].

4.3 Transesophageal Echocardiography for Treatment of Aortic Diseases

4.3.1 Aortic Dissection

Diagnosis accuracy of TEE allows an efficient classification of type (A and B) and risk stratification. The involved ascending aorta requires surgical treatment. Uncomplicated type B may be treated medically [2]. Angiography may have severe adverse effects in this disease. CT sensitivity (more than 90%) and specificity (more than 85%) are comparable to those of TEE for diagnosis [16]. CT provides determinant data about extension to arch emergent vessels. MRI global accuracy nearly reaches 100% [16]. It appears more efficient in detecting false-positive TEE findings, in evaluating the importance of mediastinal hematoma and hemothorax and in assessing follow-up.

4.3.2 Intramural Hematoma

Diagnosis, classification and choice of treatment (similar to dissection) can be assessed by TEE. Potential evolution of hematoma needs regular controls to detect aortic enlargement, signs of impending disruption and recurrence of bleeding [17]. In this last case, CT and MRI are very helpful to determine the age of the hematoma.

4.3.3 Penetrating Aortic Ulcer

Medical treatment is recommended. Angiography keeps a place in the detection and the diagnosis of complications. Actually TEE and CT provide similar images. MRI appears more accurate in detecting signs of impending disruption that lead to surgery.

4.3.4 Aneurysms

Symptoms, etiology, underlying pathology and TTE evaluation of left ventricular function or valvular dysfunction are necessary for treatment discussion. TEE provides determinant data about the site, involvement of collateral branches, mechanisms of complications, periaortic extension and diameters. The purpose of this chapter is not to define the dimension cutoff point for indication of surgery but to evaluate the ability of TEE for monitoring of aortic diameters. TEE allows measurement of diameters at each level of the thoracic aorta. As we have already seen, these measurements have to be related to age and sex, and indexed to height and

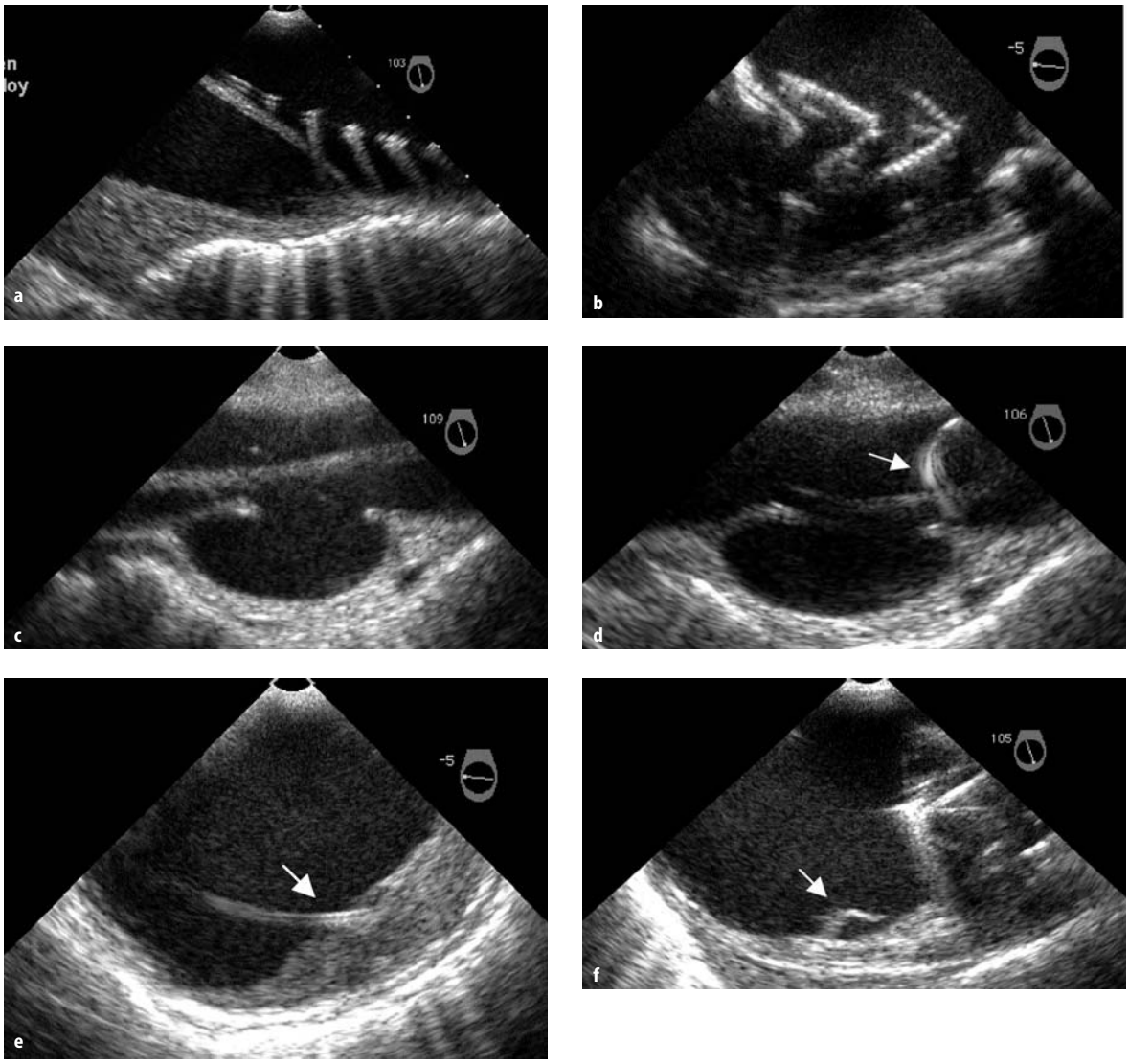


Fig. 4.22. Stenting procedure. **a** Guide with graduations. **b** Stent during deployment. **c** Guide into the aortic lumen. **d** Loop (*arrow*) of guide into the aortic lumen. **e** Impaction of guide (*arrow*) in a mural thrombus. **f** Aortic wall debris (*arrow*) after stenting

weight. Indication of surgical repair is based on the rate of diameter evolution, especially in Marfan syndrome. From TEE measurements, some equations to calculate the risk of rupture have been proposed [20, 24]. They confirm the ability of TEE for monitoring of these patients. Because of the need of frequent controls, MRI could be a convenient alternative to TEE.

Despite the accuracy of TEE in the diagnosis of aneurysm of the sinus of Valsalva, surgical indication could be preceded by an aortic and coronary angiogram.

In coarctation of the aorta, complete diagnosis can be assessed by TEE. An evaluation of collateral circulation by MRI is recommended before surgical treatment.

In aortic atheroma, TEE is sufficient to detect high-risk plaques and to establish and to evaluate medical treatment. If a mobile component is present and associated with embolism, surgery may be indicated from TEE data.

4.3.5 Traumatic Aortic Injuries

If performed by a trained physician, TEE is able to assume diagnosis of traumatic aortic injury and to indicate the precise type and emergency of treatment. Classically, subadventitial disruption requires surgical treat-

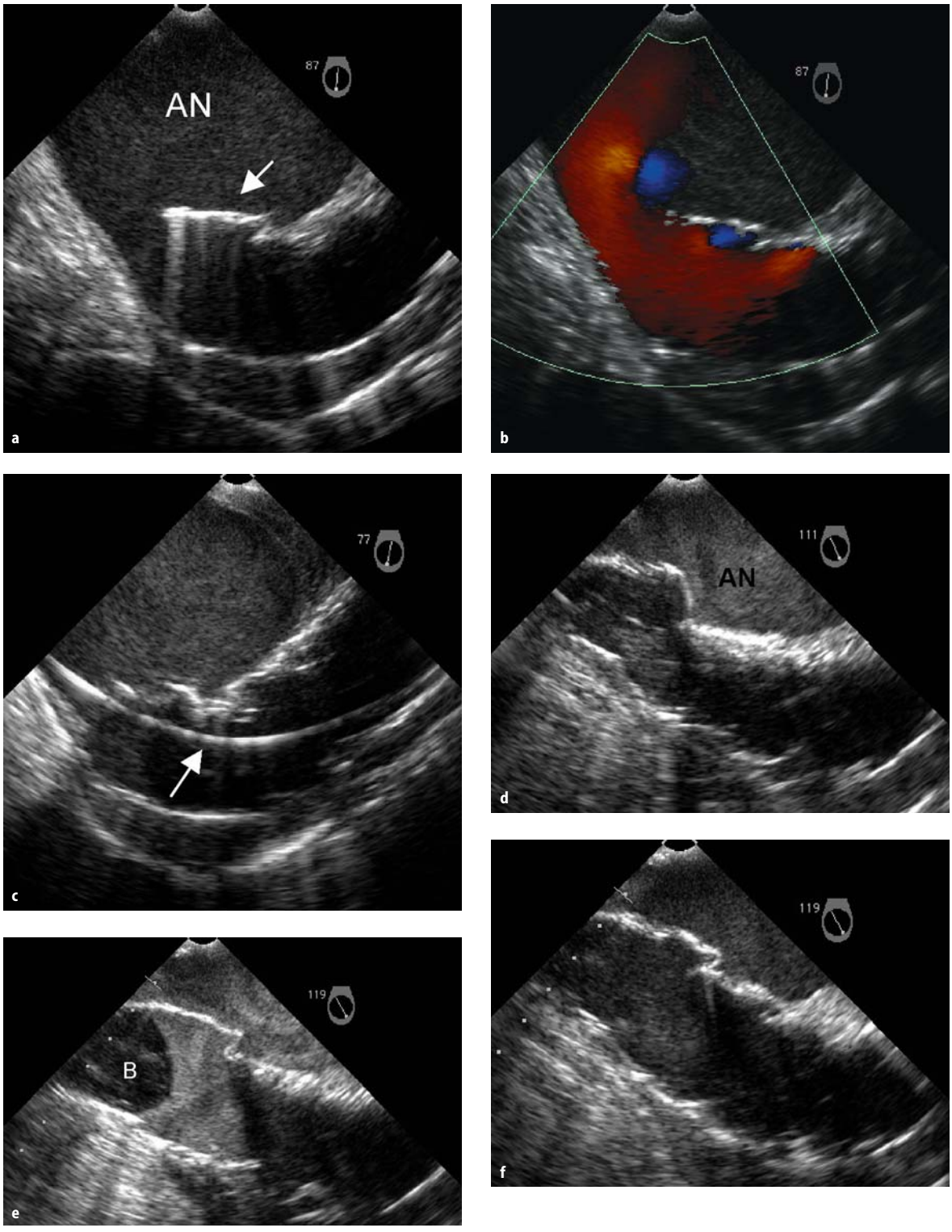


Fig. 4.23. Stenting procedure for aneurysm of the descending aorta (two stents). **a** After deployment of the first stent (*arrow*), uncovered aneurysm (*AN*). **b** Color Doppler image of aortic flow. **c** Guidewire (*arrow*). **d** After deployment of the second stent, aneurysm is excluded. **e** Baloon inflation (*B*) induces spontaneous contrast echo in the aneurysm and the aortic lumen upstream. **f** Spontaneous contrast echo into the aortic lumen

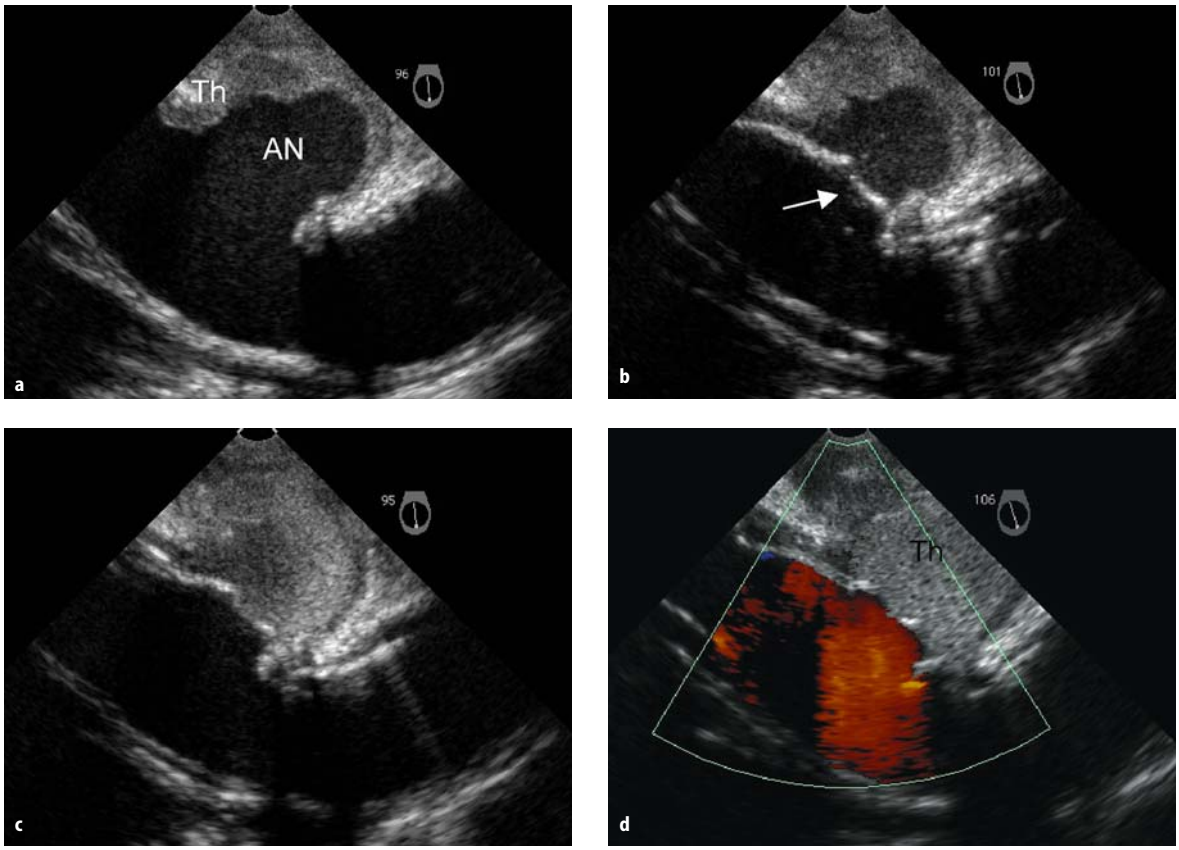


Fig. 4.24. Stenting procedure for aneurysm of the descending aorta. **a** Aneurysm (*AN*) with mural thrombus. **b** A few seconds after stent (*arrow*) deployment. **c** Increased thrombosis into aneurysm. **d** Complete thrombosis of aneurysm

ment. Nevertheless, multiple and severe associated lesions increase the risk of surgery and delayed treatment may be proposed. In such situations, MRI offers great advantages: noninvasive examination, evaluation of aortic lesions and complications (mediastinal hematoma, hemothorax), diagnosis of cerebral, visceral or vertebral injuries.

4.3.6 Stenting and Fenestration

For a few years, new therapies have been available: percutaneous stenting and fenestration [7]. They represent an alternative to surgical treatment; especially in some high-risk patients, in the case of an involved descending aorta: aneurysms, dissection and traumatic rupture of the isthmus, asacute as in chronicle phases.

Fenestration is particularly useful in aortic dissection. During the procedure, TEE can easily identify true and false lumen. An immediate evaluation of treatment can be assessed by color Doppler imaging.

Stenting may be indicated in type B aortic dissection (compression of true lumen, large intimal tear, enlargement of false lumen), aneurysm and traumatic rupture of the aortic isthmus [3, 4, 8, 22]. These classic indications are now extended to type A dissection (ascending part, arch), penetrating ulcer and complicated intramural hematoma. Stenting procedures are controlled by fluoroscopy and angiography. These techniques cannot provide any information concerning endovascular events. A stent-graft device is introduced by surgical access of femoral or iliac arteries. TEE can be used to guide the three different phases of the procedure: before, during and after deployment of the device. The first phase consists in an evaluation of the aortic wall: detection of the complex atheroma plaque, the thrombus and the site and size of aortic lesions. TEE controls progression of the guidewire, angiographic catheters and the sheath containing the stent. It can detect and avoid some complications: iatrogenic dissection; intimal tear, wrong passage in false lumen; contact with the thrombus, plaque of atheroma, aortic prosthetic valve; Fig. 4.22). A TEE probe could play the role of a landmark and help the interventional radiologist to optimize stent position and deployment. During the next phase, immediately after stent deployment, TEE allows visualization of both sides of the stent. Indeed, angiography cannot provide any information about the outer

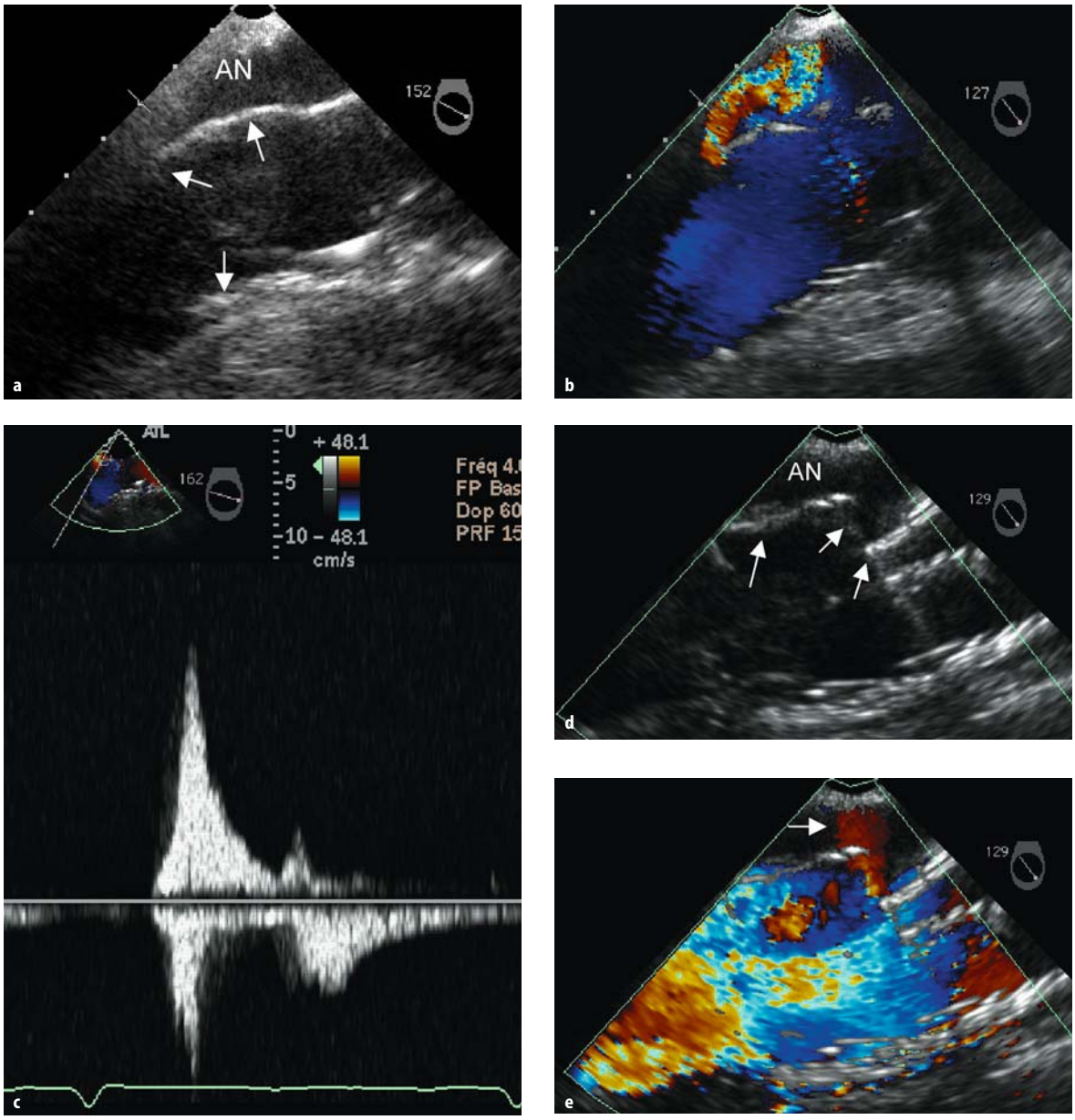


Fig. 4.25. Stent leak type I: **a** partial contact between the aortic wall and the stent (*arrows*); **b**, **c** color Doppler and pulsed Doppler images of the leak. Stent leak type IV: **d** stent protrusion (*arrows*) into the aneurysm (*AN*); **e** leak (*arrow*) through the stent

side of stent. The endoluminal side often presents some debris (Fig. 4.22), small clots or spontaneous echo contrast. These elements might be consequences of decreased aortic flow due to a medically induced fall in blood pressure before deployment. Failure of or incomplete stent deployment may be observed. Stent compression by persistency of a patent false lumen may occur a few days after. The degree of contact between the stent and the aortic wall can be evaluated and completed by inflation of a balloon guided by TEE (Fig. 4.23). In the case of aneurysm, the stent presents an out-pushing aspect at the neck level. After deployment, the extralumen side of the stent can only be visualized by TEE. A successful procedure is characterized by an important spontaneous contrast effect that is a marker of blood stasis and that precedes thrombus formation (Fig. 4.24). TEE also appears efficient for detection and quantification of leaks [8, 18]. They are classified in four types: type I, at the junction of the aorta and the stent; type II, intra-aneurysm bleeding from the collateral artery; type III, at the junction between two stents; type IV, leak through the stent-graft cover tissue (Fig. 4.25).

Stenting procedures are often performed in elderly patients with cardiac or multiorgan failures. Moreover, spontaneous or induced changes in blood pressure, bleeding or sudden arrhythmia may have important consequences in such high-risk patients. TEE can control valvular prosthesis, left ventricular function and volume.

4.4 Conclusion

TEE is a recognized and accurate method for diagnosis of all thoracic aortic diseases. This technique does not expose the patient to radiation or injection of toxic contrast agent. TEE can be performed at the bedside and in critical circumstances. In addition, it provides determinant data concerning left ventricular function, volumes and associated valve abnormalities. It requires a trained medical team. Nevertheless, aortic diseases need a regular follow-up. In that case, MRI offers the advantage of a noninvasive method. Management of stenting and other interventional procedures represents promising new perspectives for TEE.

References

1. Appelbe AF, Walker PG, Yeoh JK, et al. Clinical significance and origin of artefacts in transesophageal echocardiography. Utility of M-mode recognizing artefacts. J Am Coll Cardiol 1993; 21:754–760.
2. Crawford ES, Swenson LG, Coselli JS, Safi HJ, Hess KR. Surgical treatment of aneurysm and/or dissection of the ascending aorta, transverse aortic arch, and ascending and transverse aortic arch. J Thorac Cardiovasc Surg 1989; 98:659–674.
3. Dake MD, Miller DC, Semba CP, Mitchel RS, Walker PJ, Liddell RP. Transluminal placement of endovascular stentgrafts for the treatment of descending thoracic aneurysms. N Engl J Med 1994; 331:1729–1734.
4. Dake MD, Kato N, Mitchell RS, Semba CP, Razavi M, ShimonoT, Hirano T, Takeda K, Yada I, Miller DG. Endovascular stent-graft placement for treatment of acute aortic dissection. N Engl J Med 1999; 340:1546–1552.
5. De Bakey ME, McCollum CH, Crawford ES, et al. Dissection and dissecting aneurysms of the aorta: twenty-year follow- up of five hundred and twenty-seven patients treated surgically. Surgery 1982; 92:1118–1134.
6. Evangelista A, Garcia-del-Castillo H, Salas A, Permanyer-Miralda G, Soler-Soler J. Diagnosis of ascending aortic dissection by transesophageal echocardiography: utility of M-mode in recognizing artefacts. J Am Coll Cardiol 1996; 27:102–107.
7. Erbel R, Alfonso F, Boileau C, Dirsch O, Eber B, Haverich A, Rakowski H, Struyven J, Radegran K, Sechtem U, Taylor J, Zollikofer C. Diagnosis and management of aortic dissection. Eur Heart J 2001; 22:1642–1681.
8. Fattori R, Caldarera I, Rapezzi C, Rocchi G, Napoli G, Parlapino M, Favali M, Pierangeli A, Gavelli G. Primary endoleakage in endovascular treatment of the thoracic aorta: importance of intraoperative transesophageal echocardiography. J Thorac Cardiovasc Surg 2000; 120:490–495.
9. Fischer RG, Hadlock F, Ben-Menachem, et al. Laceration of the thoracic aorta and brachiocephalic arteries by blunt trauma. Radiol Clin North Am 1981; 19:91–110.
10. Goarin JP, Catoire P, JacquesY, Saada M, Riou B, Bonnet F, Coriat P. Use of transesophageal echocardiography for diagnosis of traumatic aortic injury. Chest 1997; 112:71–80
11. Katz ES, Cziner DG, Rosenzweig BP, Attubato M, Feit F, Kronzon I. Multifaceted echocardiographic approach to the diagnosis of ruptured sinus of Valsalva aneurysm. J Am Soc Echocardiogr 1991; 4:494–498.
12. Le Bret F, Ruel P, Rosier H, Goarin JP, Riou B, Viars P. Diagnosis of traumatic mediastinal hematoma with transesophageal echocardiography. Chest 1994; 105:373–376.
13. Mohr-Kahaly S, Erbel R, Kearny P, Puth M, Meyer J. Aortic intramural haemorrhage visualised by transesophageal echocardiography: findings and prognosis implications. J Am Coll Cardiol 1994; 23:658–664.
14. Movsowitz HD, Lampert C, Jacobs LE, Kotler MN. Penetrating aortic ulcers. Am Heart J 1994; 128:1210–1217.
15. Movsowitz HD, Levine RA, Hilgenberg AD, Isselbacher EM. Transesophageal echocardiographic description of the mechanisms of aortic regurgitation in acute type A aortic dissection: implication for aortic valve repair. J Am Coll Cardiol 2000; 36:884–890.
16. Nienaber CA, Spielmann RP, von Kodolitsch Y, Siglow V, Piepho A, Jamp T, Nicolas V, Weber P, Triebel HJ, Bleifeld W. Diagnosis of thoracic aortic dissection. Magnetic resonance imaging versus transesophageal echocardiography. Circulation 1992; 85:434–447.
17. Nienaber CA, von Kodolitsch Y, Petersen B, Loose R, Helmchen V, Haverich A, Spielman R. Intramural hemorrhage of the thoracic aorta. Diagnosis and therapeutic implications. Circulation 1995; 92:1465–1472.
18. Orihashi K, Matsuura Y, Sueda T, Watari M, Okada K, Sugawara Y, Ishii O. Echocardiography-assisted surgery in transthoracic endovascular stent grafting: role of transesophageal echocardiography. J Thorac Cardiovasc Surg 2000; 120:672–678.
19. Roman MJ, Devereux RB, Framer-Fox R, O'Louhlin J. Two-dimensionnal echographic aortic root dimensions in normal children and adults. Am J Cardiol 1989; 64:507–512.
20. Roman MJ, Rosen SE, Kramer-Fox R, Devereux RB. Prognosis significance of aortic root dilatation in the Marfan syndrome. J Am Coll Cardiol 1993; 22:1470–1476.
21. Roudaut R, Gosse P, Delarche N, Besse P, Dallochio M. Diagnostic échocardiographique des dissections aortiques: apport du Doppler pulse. Arch Mal Cur 1987; 13:1865–1872.
22. Rousseau H, Soula P, Perreault P, Bui B, Janne d'Othée B, Massabuau P, Meites G, Concina P, Mazerolles M, Joffre F, Otal P. Delayed treatment of traumatic rupture of the thoracic aorta with endoluminal covered stent. Circulation 1999; 99:498–504.
23. Ryan K, Sanyal RS, Pinheiro L, Nanda NC. Assessment of aortic coarctation and collateral circulation by biplane transesophageal echocardiography. Echocardiography 1992; 9:277–285.
24. Shimida I, Rooney SJ, Pagano D, Farneti PA, Davies P, Guest PJ, Bouser RS. Prediction of thoracic aortic aneurysm expansion: validation of formulae describing growth. Ann Thorac Surg 1999; 67:1968–1970.
25. Smith MD, Cassidy JM, Souther S, Morris EJ, Sapin PM, Johnson SB, Kearny PA. Transesophageal echocardiography in the diagnosis of traumatic rupture of aorta. N Engl J Med 1995; 332:356–362.
26. Stanson AV, Kazmier FJ, Hollier LH, et al. Penetrating atherosclerotic ulcers of the thoracic aorta: natural history and clinicopathologic correlations. Ann Vasc Surg 1986; 1:15–23.

27. Swenson LG, Labib SB, Eisenhauser AC, Butterfly JR. Intimal tear without hematoma. An important variant of aortic dissection that can elude current imaging techniques. Circulation 1999; 99:1331–1336.
28. Vignon P, Gueret P, Vedrinne JM, Lagrange Ph, Cornu E, Abrien O, Gastinne H, Bensaid J, Lang R. Role of transesophageal echocardiography in the diagnosis and management of traumatic aortic disruption. Circulation 1995; 92:2959–2968.
29. Vilacosta I, San Roman JA, Aragoncilla P, Peral V, Battle E, Perez MA, Rollan MJ, Sanchez-Harguindey L. Aortic cobwebs: an anatomic landmark of the false lumen in aortic dissection documented by transesophageal echocardiography [abstract]. Eur Heart J 1996; 17.
30. Vilacosta I, Aragoncillo P, San Roman JA, Peral V, Battle E, Perez MA, Rollan MJ, Sanchez-Harguindey L. New anatomical correlations in aortic dissection [abstract]. Eur Heart J 1996; 17.

Biomarkers in Acute Aortic Syndrome

Guglielmina Pepe, Betti Giusti, Maria Cristina Porciani and Magdi Yacoub

5

Contents

5.1 Introduction

The term acute aortic syndrome (AAS), coined 6 years ago [111], indicates a heterogeneous group of patients presenting one of the following acute aortic pathologies: aortic ulcer, intramural haematoma or classic aortic dissection (Fig. 5.1). More recently, aortitis [109] and intraluminal thrombus [106] were included in this syndrome (Fig. 5.1). Aortic ulcers penetrate the intima through the media; intramural haematoma presents a haemorrhage into the aortic media with the formation of a false lumen; the classic aortic dissection is characterized by the presence of an intimomedial entrance tear. The term aortitis indicates a thickening of the wall owing to different mechanisms such as infections and autoimmune disorders causing systemic vasculitis. Although these alterations appear mostly distinct, the fact that in some cases they coexist demonstrates a possible link between them (Fig. 5.1).

Aortic aneurysms and dissections can be classified on the basis of morphology, aetiology, and anatomic location. Although aneurysms may arise at any site along the aorta, they most frequently occur in the infrarenal abdominal aorta or the descending portion of the thoracic aorta. The ascending thoracic aorta is another common location for aortic aneurysm, which may develop in association with hypertension and spontaneous (type A) aortic dissection, congenital valvular abnormalities (e.g., bicuspid aortic valve, BAV) [98], and inherited connective tissue disorders, e.g., fibrillinopathies type 1 [30, 64] such as Marfan syndrome (MFS) [18, 19], classic, hypermobile and vascular Ehlers-Danlos syndromes (EDS) [78], osteogenesis imperfecta [40], X-fragile syndrome [41], and polycystic kidney disease (PKD) [103]. Aneurysms result primarily from degenerative changes in the aortic wall. Severe intimal atherosclerosis, chronic transmural inflammation, and destructive remodelling of the elastic media are associated with aneurysms dissections that affect primarily the descending thoracic aorta and abdominal aorta (thoracoabdominal aortic aneurysms, abdominal aortic aneurysms, AAAs, and type III dissections) [46, 105].

In contrast, aneurysms and dissections that affect the ascending aorta are primarily due to lesions that cause degeneration of the aortic media, a poorly understood pathological process called cystic medial necrosis (CMN) [26, 73, 75] (Fig. 5.2). CMN is characterized by degeneration and fragmentation of elastic fibres, loss of smooth muscle cells (SMCs), and interstitial collections of basophilic-staining ground substance. Although the pathogenesis of medial necrosis is not understood, it is almost certainly not a single disease entity. Medial necrosis occurs with normal aging of the aorta [88, 89] but it can be accelerated by conditions such as hypertension and it is also associated with genetic syndromes, such as MFS and aortic bicuspid valve (Fig. 5.2).

The specific factors causing aneurismal degeneration in the different locations remain unresolved.

Pathophysiological studies on human and experimental AAAs have focused on increased expression and tissue localization of elastin- and collagen-degrading enzymes, particularly matrix metalloproteinases (MMPs), cysteine proteases, and their respective inhibi-

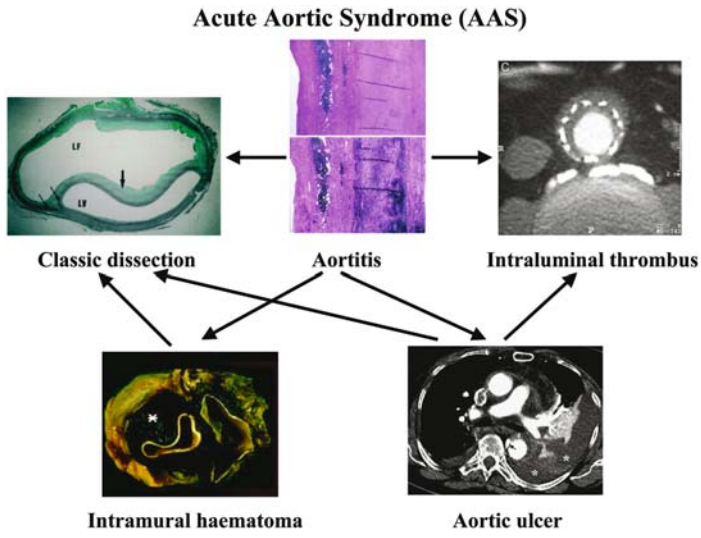


Fig. 5.1. Acute aortic syndrome. *Arrows* indicate the possible progression of each of these aortic lesions. (Adapted from van der Loo and Jenni [106]. Classic dissection and intramural haematoma adapted from Vilacosta [110]. Aortitis from Nuenninghoff et al. [76]. Aortic ulcer from Eggebrecht et al. [21]. Intraluminal thrombus from Wegener et al. [115])

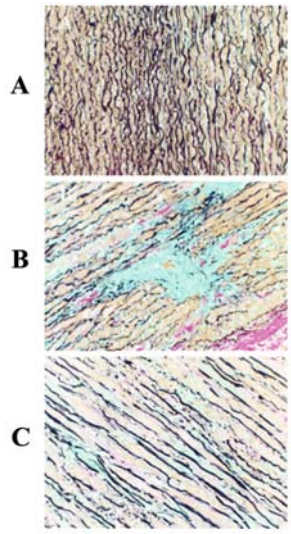


Fig. 5.2. Cross sections of ascending thoracic aorta of a control subject (**A**), of an aortic aneurysm associated with Marfan syndrome (**B**), and with bicuspid aortic valve (**C**) stained with Alcian blue and Verhoeff–van Gieson. Magnification×250. (From Nataatmadja et al. [73])

tors (TIMPs) [23, 93, 97]. Genes encoding a number of proinflammatory cytokines, leukotriene lipid mediators, chemotactic factors, and cell adhesion molecules have also been implicated in AAA [50, 77, 119), and depletion of vascular SMCs may influence the process of vascular remodelling that occurs during aneurismal degeneration [35, 58] (Fig. 5.3).

Studies focusing on thoracic aortic aneurysms (TAAs) have indicated that their hallmark, the cystic medial, is associated with elastin degradation and fragmentation [17, 62], SMC depletion and apoptosis [9], and increased expression of some MMPs [53, 56, 91]. However, the absence of a significant inflammatory response implies alternative mechanisms of aneurysm formation in TAAs with respect to AAAs, related to the different embryologic origin of cells populating the ascending and infrarenal aorta, to the different structural properties and propensities toward atherosclerotic degeneration, or to the distinct haemodynamic conditions in these two areas. Absi et al. [2] in 2003 by using microarray technology showed distinct patterns of gene expression for ascending aortic aneurysms and AAAs.

Clinical manifestation of AAS is aortic pain that affects neck, throat, and anterior chest when the ascending aorta is involved, while descending aorta alteration is associated with back pain and abdominal pain. The aortic pain (chest pain) is probably due to aortic root dilatation and is similar to that caused by ischemic syndromes (angina pectoris). Acute coronary syndromes may result from AAS or be associated with them [109]. Overall, AAS can remain asymptomatic until the initial dissection and also later since the symptoms are common to many pathologies.

The mortality rate of untreated dissection is about 1%/h for the first 48 h increasing up to 80% at 14 days [101]; the gold standard techniques for the diagnosis of AAS are represented by imaging analyses such as computerized tomography, transoesophageal echocardiography, and magnetic resonance. Each of these techniques has some advantages and some limitations; therefore, at least two are required for a diagnosis but the common limit is represented by the fact that the equipment and the personnel with the necessary expertise to perform the tests and interpret correctly the data are not available in all medical set-ups. For these reasons the identification of biochemical and genetic markers able to readily and rapidly diagnose and/or to recognize a predisposition to develop an AAS are highly required, also considering the importance of prophylactic surgery in all patients.

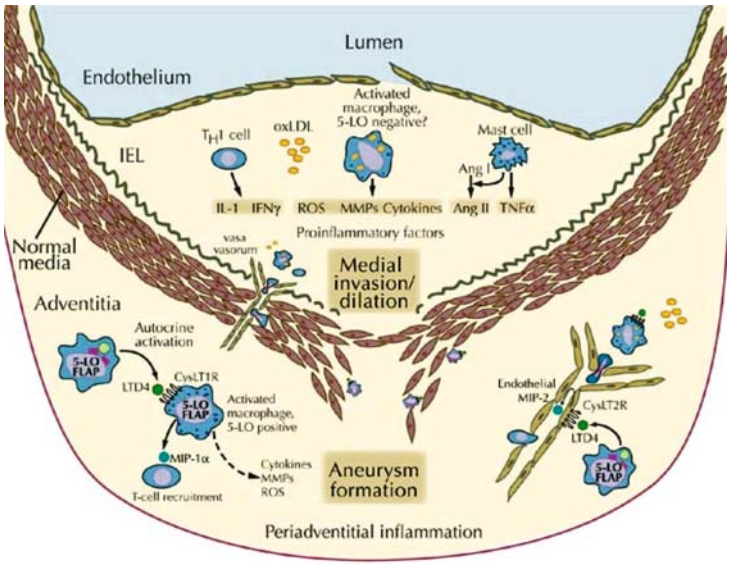


Fig. 5.3. Aortic remodelling and aneurysm formation. Zhao et al. [119] provide evidence that adventitial macrophages express 5-LO and its cofactor, FLAP, and generate leukotrienes, which set in motion a number of proinflammatory events. One of the leukotrienes, LTD_4, causes autocrine activation of macrophages through binding to $CysLT_1$ receptors. Increased leukotriene formation also promotes the recruitment of monocytes – the precursors of tissue macrophages – and T cells. Specifically, LTD_4 binds to $CysLT_2$ receptors on endothelial cells of the many microvessels present in the adventitia and media (vasa vasorum), resulting in increased endothelial release of MIP-2 and leukocyte extravasation. Activated macrophages also release MIP-1α, which may further promote T cell recruitment. Independent of the 5-LO pathway, activated macrophages generate other proinflammatory factors, including metalloproteinases (*MMPs*), which weaken the media. Atherosclerosis in the intima may act synergistically with adventitial inflammation. Intimal macrophages, T_H1 cells, and mast cells secrete many proinflammatory factors, including IFNγ, IL-1, MMPs, and TNFα. Mast cells may also contribute to the conversion of angiotensin I to angiotensin II, a powerful promoter of aneurysms in mice. Hypercholesterolemia is an essential cofactor of both adventitial and intimal inflammation. (From Palinski [77])

5.2 Biochemical Markers

Aortic dissection is an acute catastrophic aortic disease associated with high mortality and morbidity [4]. Rapid diagnosis and initiation of appropriate treatment is pivotal for patients with acute aortic dissection. Unfortunately, the disease is still not well recognized on clinical presentation owing to lack of specific signs and symptoms. Detection of acute aortic dissection is based on clinical presentation but mainly relies on imaging techniques [25]. However, up to 30–40% of patients remain undiagnosed until necropsy [112]. The investigation, characterization, and development of a biochemical diagnostic approach to the AASs are fundamental for improved survival. So far, there is no laboratory test – as opposed to acute coronary syndromes – to aid the diagnosis; nevertheless, several possible biochemical markers are showing promising results. In contrast to the expanding availability of cardiac biochemical markers (serum transaminase, creatine kinase (CK), lactate dehydrogenase, cardiac myosin light chain, and troponin), biochemical assays for vascular diseases, however, have not been available due in part to a lack of specific markers for vascular disease. With the recent progress made in the field of vascular biology, markers specific to vascular components have become available. In this chapter, we review the rapidly accumulating knowledge in the field of biochemical markers in AAS and in particular in thoracic aortic diseases. We discuss the potential application of some of these biochemical markers, their advantages and disadvantages in the clinical practice, and outline areas for future research.

5.2.1 Smooth Muscle Myosin Heavy Chains

Smooth muscle myosin heavy chain (SMMHC), a structural protein found in SMCs, is released from the aortic medial SMC s on insult to the aortic wall [3, 55, 63, 69, 70, 118]. In 1995 an immunoassay of serum SMMHC was developed [44, 45]. Circulating levels of SMMHC are elevated in acute aortic dissection [99]. The assay showed a sensitivity of approximately 90% to detect the disease at a cutoff level of 2.5 ng/ml (the upper limit of the control population) during the initial 3 h after onset of symptoms and a specificity of 97% compared with healthy volunteers and of 83% compared with patients with acute myocardial infarction. Sensitivity decreased to 72.4% in the following 3 h and decreased to 30.3% thereafter (Fig. 5.4) [102]. The temporal course of circu-

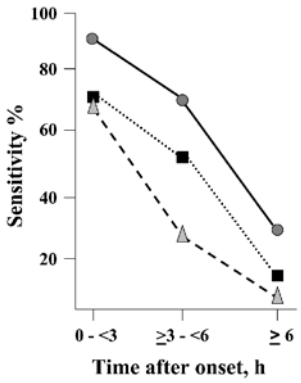


Fig. 5.4. Sensitivity of the smooth muscle myosin heavy chain (*SMMHC*) assay. Temporal sensitivity curves according to cut-off levels. *Solid line* cutoff level of 2.5 μg/l; *dotted line* cutoff level of 5.0 μg/l; and *dashed line* cutoff level of 10.0 μg/l. (Adapted from Suzuki et al. [102])

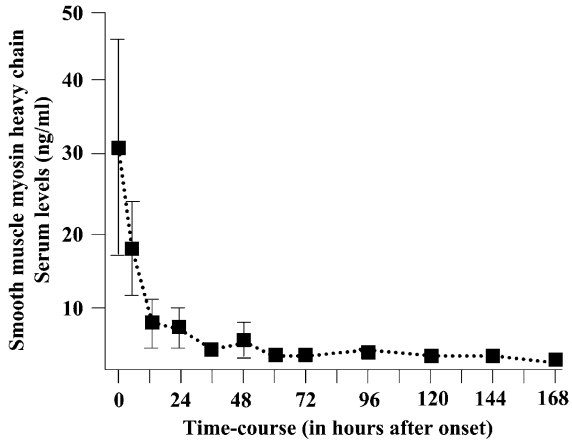


Fig. 5.5. Time course of serum SMMHC levels in patients with aortic dissection ($n=27$). The peak levels are at onset. Rapid reductions in levels are found during the first 24 h. (Adapted from Suzuki et al. [99])

lating SMMHC levels in patients with acute aortic dissection showed peak levels at onset with rapid normalization of levels within the initial 24 h (Fig. 5.5). The rapid decrease in SMMHC is likely due to the unique spatial localization of myosin within the muscle cells which affects its release into the circulation upon insult. Myosin in smooth muscle is loosely interspersed in the cell. Because of this distribution, upon cellular insult it is likely that smooth muscle myosin is rapidly released in a manner similar to cytosolic enzymes and proteins in acute myocardial infarction. Interestingly, patients with aortic dissection having negative levels were restricted to patients with distal De Bakey type III lesions. This is likely because the abdominal aorta upon arteriosclerosis change shows reduced content of smooth muscle, and therefore release of the protein is markedly reduced in these lesions [101]. Although the described assay of serum SMMHC was an early experimental assay which required 5 h for measurement, recent advances have allowed for a sensitive 30-min rapid assay suited for clinical use [101].

5.2.2 Soluble Elastin Fragments

Elastin is one of the major structural matrix proteins of the arterial wall [14, 20, 48, 74, 79, 85, 96, 117] (Fig. 5.6). Mature elastin is composed of soluble elastin subunits, which are intermolecularly cross-linked into a fibrous network (desmosine and isodesmosine formation) and thus construct a highly polymerized insoluble protein. The main pathological feature of the aortic media in acute aortic dissection is a higher grade of elastin degradation [88, 89, 92, 93]. Once an initial tear is formed, the dissection tends to expand to the degraded elastin layers, along with an inflammatory infiltrate, a major source of proteolytic enzymes such as elastases and metalloproteinases, which thus dramatically promote the fragmentation process of the elastin network in the media [68, 88, 89]. As a result, soluble elastin fragments (sELAF) are released into the circulating blood and are measurable in the serum [94]. Shinohara et al. [94] developed an enzyme-linked immunosorbent assay to measure sELAF in serum by using the newly created double monoclonal antibodies, which recognize the different epitopes of human aortic elastin. Using this system, when the cutoff point for positivity was set at the mean plus 3 times the standard deviation (SD) (i.e., 3SD above the mean in healthy subjects, at each age), they demonstrated that 64% of acute aortic dissection patients (88.9% of those with either an open or a partially open pseudolumen and 0% with a closed pseudolumen) within 48 h after the onset showed an increase in sELAF levels in serum and only 2% of the acute myocardial infarction patients were positive (Fig. 5.7). Discriminating acute aortic dissection from acute myocardial infarction is still a common clinical dilemma, and the differential diagnosis is critical, because the management and prognoses for each are quite different. Misdiagnosis of acute aortic dissection as acute myocardial infarction frequently results in catastrophic haemorrhage or an exacerbation of acute aortic dissection, especially when thrombolytic drugs are inappropriately administered [8, 12, 116]. A limitation of this assay is that it still takes at least 3 h to measure the sELAF level in serum and further efforts are being made to shorten the measurement time of the immunoassay system.

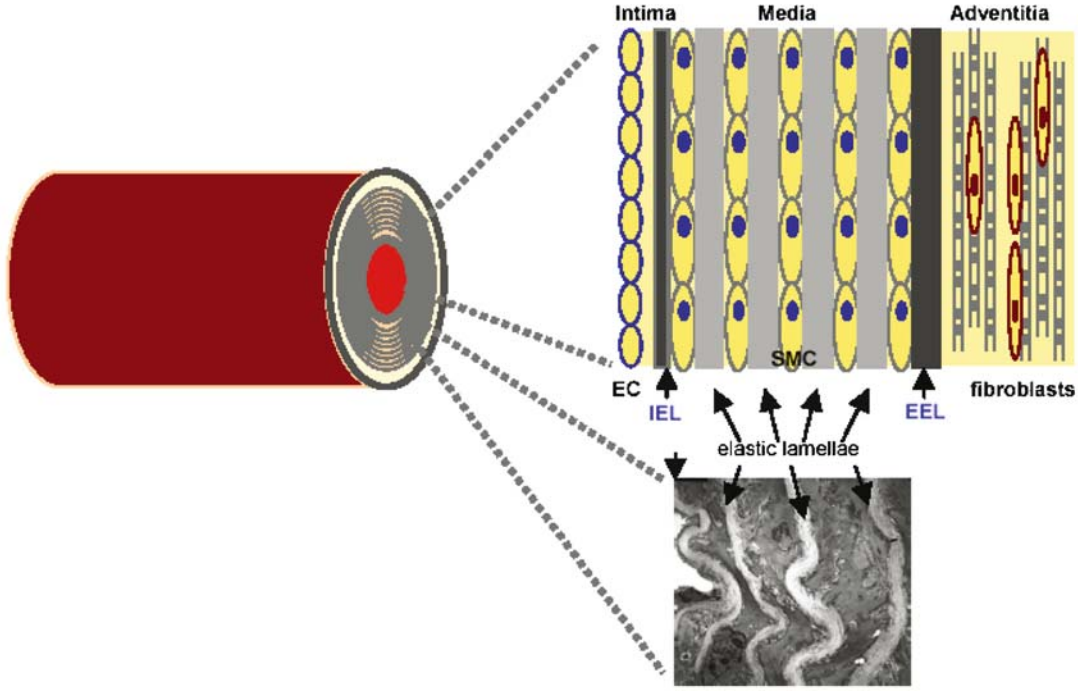


Fig. 5.6. Cartoon of a cross section through an artery. The tunica intima, tunica media, and tunica adventitia, and positions of the internal elastic lamina (*IEL*), external elastic lamina (*EEL*), and medial elastic lamellae are shown, together with a transmission electron micrograph of an arterial wall. (From Kielty [48])

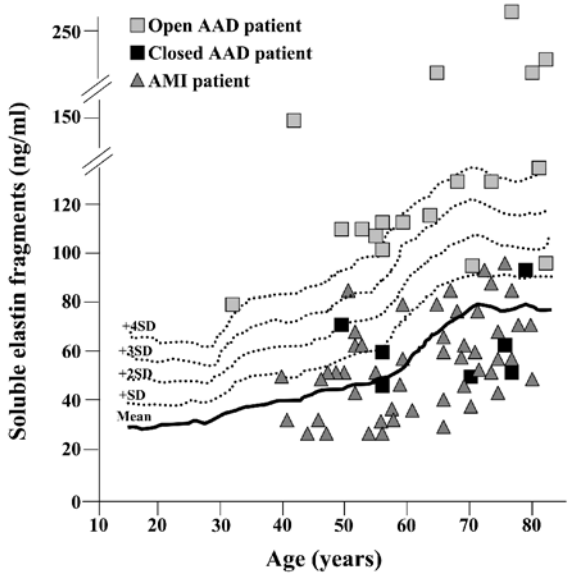


Fig. 5.7. Serum soluble elastin fragment (*sELAF*) levels in patients with acute aortic dissection (*AAD*; $n=25$) or acute myocardial infarction (*AMI*; $n=50$). *Lines* show the mean and mean + standard deviation (*SD*) to the mean + 4SD of sELAF levels at each age (range 15–83 years) for healthy control subjects. *Open AAD patients* are AAD patients with either an open or a partially open pseudolumen; *closed AAD patients* are AAD patients with a closed pseudolumen by thrombus formation. (Adapted from Shinohara et al. [94])

5.2.3 C-Reactive Protein

On the basis of the results of several prospective epidemiologic studies, C-reactive protein (CRP) has emerged as one of the most powerful predictors of cardiovascular disease [108]. CRP, named for its capacity to precipitate the somatic C-polysaccharide of *Streptococcus pneumoniae*, was the first acute-phase protein to be described, and is a sensitive systemic marker of inflammation and tissue damage. In healthy volunteer blood donors, the median concentration of CRP is 0.8 mg/l, but following an acute-phase stimulus, values may increase by as much as 10,000-folds, with de novo hepatic synthesis starting very rapidly, serum concentrations beginning to rise by about 6 h, and peaking around 48 h after a single stimulus. In most, but not all diseases, the circulating value of CRP much more accurately reflects on-going inflammation than do other biochemical parameters of inflammation, such as plasma viscosity or the erythrocyte sedimentation rate. This is because the plasma half-life of CRP is the same (about 19 h) under all conditions, and the sole determinant of the plasma concentration is therefore the synthesis rate, which, in turn, reflects the intensity of the pathological process(es) stimulating CRP production. The CRP value is thus a very useful nonspecific biochemical marker of inflammation, measurement of which contributes importantly to (1) screening for organic disease, (2) moni-

toring the response to treatment of inflammation and infection, and (3) detecting intercurrent infection in the few specific diseases characterized by modest or absent acute-phase responses to those diseases themselves [36].

The commercial availability of routine high-sensitivity assays for CRP has enabled a flood of studies demonstrating a powerful predictive relationship between increased CRP production, even within the range previously considered to be normal, and cardiovascular diseases and atherothrombotic events [36, 108].

Although, the association of acute-phase reaction and outcome of patients with acute vascular diseases is controversial, the prognostic value of CRP in patients with acute aortic aneurysm or dissection was investigated by some authors [59, 87]. Makita et al. [59] showed that the evaluation of CRP levels may serve as a useful marker for early and noninvasive detection of aortic events and for conservative management in patients with acute aortic dissection and intramural haematoma. They investigated the re-elevation, defined as an elevation of more than 1.0 mg/dl after the initial peak level, and the retarded recovery (until the initial peak had passed and thereafter once or twice a week until discharge) of CRP. Re-elevation and retarded recovery of CRP levels were considered to reflect an instability of intramural thrombus or haematoma, defined as enlargement of localized contrast filling, transition to classic dissection, or expansion of haematoma in the aortic wall. In classic dissection, the abnormal behaviour of CRP levels could be partly explained by gradual thrombosis in the false lumen. This issue was further investigated by Schillinger et al. [87], who demonstrated increased admission CRP values in patients with symptomatic aortic aneurysm/dissection were independently associated with poor prognosis. In fact, CRP levels higher than 6.3 mg/dl indicate a high risk for short-term mortality.

5.2.4 D-dimer

After the fibrin plug is created, the fibrinolytic system degrades the fibrin to produce fibrin-to-fibrin degradation products, such as D-dimer (Fig. 5.8); thus, levels of D-dimer reflect the extent of cross-linked fibrin turnover and activation of the haemostatic system. It has been shown to be highly sensitive and moderately specific for venous thromboembolic disease. Thus, the most common clinical use of D-dimer relates to its negative predictive value for deep vein thrombosis and pulmonary embolism. Over the last few years a number of studies have demonstrated that D-dimer may also enable the prediction of the complications of atherothrombosis, suggesting a significant association of D-dimer with the risk of coronary artery disease independent of classic risk factors. Moreover, elevated plasma D-dimer seems to be a marker of a systemic prothrombotic state [80]. High plasma levels of D-dimer were recognized in the Physician's Health Study as a strong, independent predictor of future coronary events [84], and this association was confirmed in other prospective cohort studies [28, 51]. A recent meta-analysis of six studies [16] reported that the odds ratio of D-dimer for cardiovascular disease was 1.67 (95% cardiac index 1.31–2.13), and the risk among the top third tertile of D-dimer was about 70% greater than that in the bottom tertile.

D-dimers are detectable at levels of more than 500 µg/l fibrinogen equivalent units in nearly all patients with venous thromboembolism. The sensitivity and the negative predictive value of the test for deep vein thrombosis and/or pulmonary embolism are more than 90% [33]. However, D-dimer is nonspecific. Elevated D-dimer levels generally can be seen with intravascular activation of the coagulation system and secondary fibrinolysis, in particular in patients with malignancies [15], disseminated intravascular coagulation [7], severe infections, complicated renal disease, recent trauma or surgery, and following fibrinolytic therapy. Different studies have demonstrated that highly elevated D-dimers values are also found in patients with acute aortic dissection. At a cutoff value of 500 µg/l, which has been previously proposed for the detection of pulmonary embolism [90], Eggebrecht et al. [22] found a sensitivity of 100% with a specificity of 67% for the presence of acute aortic dissection. In patients with acute chest pain and elevated D-dimers, acute aortic dissection should, thus, also be taken into account. This is of particular clinical importance because precipitate thrombolysis for misdiagnosed pulmonary embolism may have disastrous consequences in these patients [47]. It may be hypothesized that the elevation of D-dimers in acute aortic dissection is due to activation of the extrinsic pathway of the coagulation cascade by tissue factor, which is largely exposed at the site of the injured aortic wall (i.e., within the whole false lumen) [114]. The elevation of D-dimers would then reflect a

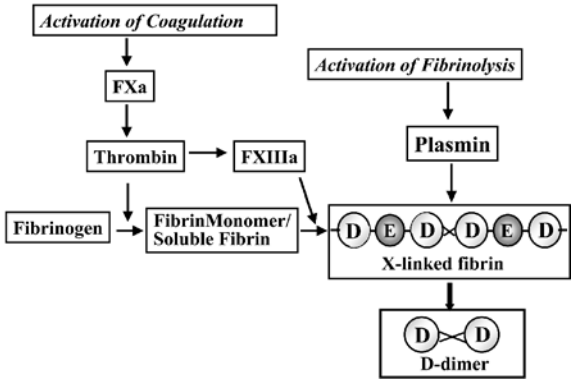


Fig. 5.8. Schematic diagram of D-dimer formation. *X-linked* cross-linked; *E* E domain; *D* D domain

profound fibrinolytic activity, which prevents thrombosis of the false lumen during the acute phase of aortic dissection. This is supported by clinical observations demonstrating that spontaneous false lumen thrombosis is only rarely observed (4% or less of patients) [24]. On the other hand, elevated D-dimer values may reflect systemic inflammatory reactions, which have been previously described in patients with acute aortic dissection [94]. Discrimination between acute and chronic aortic dissection has important prognostic and therapeutic implications, but may be difficult. Eggebrecht et al. [22] showed that D-dimers allow us to reliably differentiate acute from chronic aortic dissection. At the optimal cutoff value of 626 µg/l, there were only two false-positive results (sensitivity 100%, specificity 94%). The difference in D-dimers may be explained by the fact that the patent false lumen becomes endothelialized during the chronic course of aortic dissection; as a consequence, the coagulation cascade and fibrinolytic status are no longer activated [22].

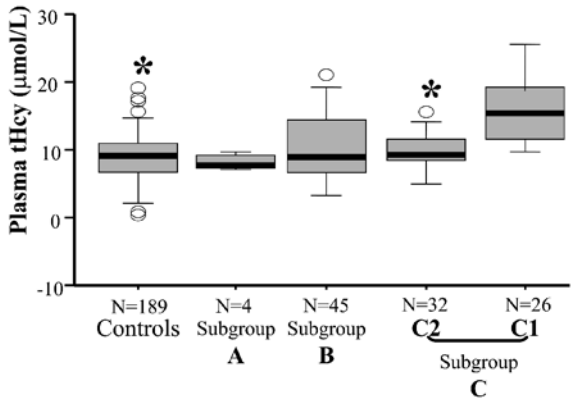


Fig. 5.9. Box-plots of the homocysteine (*tHcy*) plasma levels in patients with Marfan syndrome and control subjects. *A* no involvement of cardiovascular system; *B* mild involvement of cardiovascular system (involvement of mitral valve or pulmonary artery or descending thoracic aorta or abdominal aorta, and/or mild aortic dilatation less than 2.2 cm/m^2 body surface area); *C* major criteria (moderate to severe aortic dilatation more than 2.2 cm/m^2 body surface area or with aortic dissection); *C1* aortic dissection; *C2* no dissection. (Adapted from Giusti et al. [32])

5.2.5 Homocysteine

Homocysteine (Hcy) is a sulfur amino acid intermediate in the methylation and transsulfuration pathways of the methionine metabolism. In the transulfuration pathway, pyridoxine (vitamin B_6) is an essential cofactor, while in the remethylation pathway folate serves as a substrate and cobalamine (vitamin B_{12}) acts as a cofactor [92]. Moderate hyperhomocysteinemia, a common condition that occurs in approximately 5–7% of the general population, is a major independent risk factor for atherosclerosis and thrombosis [13]. The multisystem toxicity of Hcy is attributed to its spontaneous chemical reaction with many biologically important molecules, primarily proteins. Hcy plasma levels are influenced by several factors, including vitamins (vitamin B_{12}, vitamin B_6, folic acid), age, gender, and hormones; moreover, mutations in genes encoding enzymes involved in methionine metabolism, such as the methylenetetrahydrofolate reductase (MTHFR), cystathionine-β-synthase, methionine synthase, methionine synthase reductase and thymidylate synthase may play an important role. Thus, hyperhomocysteinemia is due to an interaction between environment and genome, the maximum gene involvement represented by homocystinuria, a metabolic hereditary autosomal recessive disorder [92] A growing body of evidence has shown a strong association between elevated plasma Hcy levels with vascular disease and its thrombotic complications [5, 37, 49, 113]. Data available in the literature suggest a role of hyperhomocysteinemia also in abdominal and thoracic aortic diseases [11, 32]. In particular, as a model of thoracic aorta dilation and dissection, Hcy was investigated in patients with MFS and it was demonstrated that Hcy levels were associated with the risk of severe cardiovascular manifestations or dissection (Fig. 5.9) [32]. Hcy was significantly higher also in patients with AAAs and was associated with the size of aneurysms [11]. It remains to be elucidated if this association is causal or simply an effect of the disease. A number of mechanisms may be evoked to explain these findings. An animal model demonstrated that hyperhomocysteinemia is able to induce a marked remodelling of the extracellular matrix of the arterial wall by inducing elastolysis through the activation of metalloproteinases. In addition, Hcy may directly affect fibrillin-1 or collagen by interfering with intramolecular and/or intermolecular disulfide bonds through disulfide exchange, or binding to free sulfydryl groups. If the usefulness of including Hcy determination in the clinical evaluation is confirmed, it will be possible to identify the potential candidates for a vitamin supplementation based on folic acid, vitamin B_6, and B_{12}.

5.2.6 Matrix Metalloproteinases

MMPs are endopeptidases that function in cell matrix turnover. Abnormal MMP activity has been implicated in the formation of atherosclerotic AAAs. Recent studies suggest that abnormal MMP activity may also be associated with the formation of atherosclerotic and non-atherosclerotic TAAs and dissections [39, 53, 56, 91] (Fig. 5.10). Boyum et al. [10] demonstrated that total MMP-2 and MMP-9 activity was greater in aneurysms associated with bicuspid valves when compared with

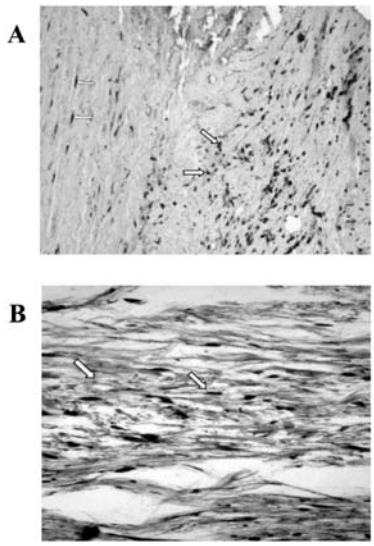


Fig. 5.10. **A** Intense matrix metalloproteinase 1 presence in smooth muscle cells (*thin arrows*) and inflammatory cells (*thick arrows*) in a patient with thoracic aortic aneurysm (×125). **B** Intense matrix metalloproteinase 9 presence in a smooth muscle cell network (*arrows*) in a patient with thoracic aortic dissection (×250). (From Koullias et al. [53])

those from tricuspid valves. This suggests that the previously documented abnormal elastic properties and the increased risk for aneurysm formation in patients with BAVs may reflect the increased activity of these matrix-degrading proteins within the aortic wall. Several risk factors for aneurismal dilatation, including hypertension and hyperhomocysteinemia, are known to induce the expression of MMPs. These data suggest the need of further study aimed to better understand the role of metalloproteinases, also in plasma, in AAS patients.

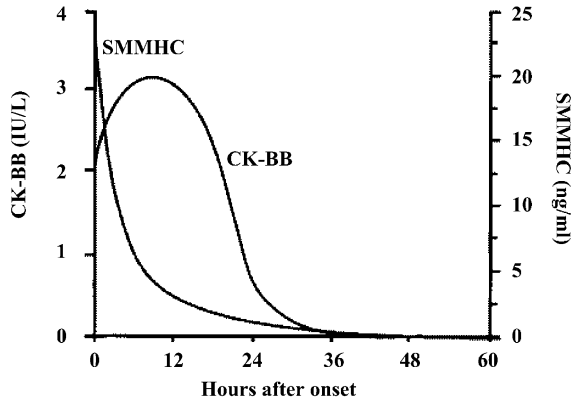


Fig. 5.11. Temporal profiles of SMMHC and creatinine kinase BB-isozyme (*CK-BB*) in acute aortic dissection. (Adapted from Suzuki et al. [101])

5.2.7 Other Biochemical Markers

Owing to their differential expression according to cell type, CK isozymes may represent possible markers for AAS. The BB-isozyme is preferentially expressed in smooth muscle and brain in contrast to the MB-isozyme, which is restricted to cardiac muscle and is used in the diagnosis of acute myocardial infarction, and the MM-isozyme, which is limited to skeletal muscle. A study on a limited number of patients showed that CK BB-isozyme is elevated in patients with aortic dissec-

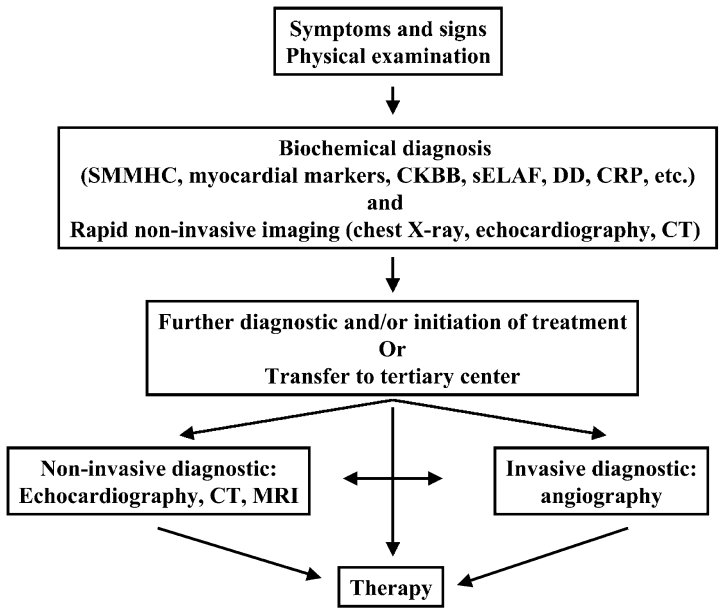


Fig. 5.12. Diagnostic flowchart of acute aortic dissection incorporating biochemical diagnosis. (Adapted from Suzuki et al. [101])

tion, suggesting its possible use in the clinical diagnosis [100]. The analysis showed that peak levels for CK BB-isozyme may be delayed compared with those for SMMHC (Fig. 5.11). Suzuki et al. [101] suggested that SMMHC and CK BB-isozyme could allow biochemical diagnosis of aortic dissection (Fig. 5.12).

Recent data showed that low serum albumin was independently related to the occurrence of aortic dissection [104]. It was suggested that low blood proteins may weaken the vessel wall structure. To the extent that blood albumin levels reflect nutritional intake, nutritional status may predispose to the fragility of the aortic wall.

5.3 Genetic Markers

Genetic markers will be subdivided into the following groups: (1) genes directly associated with monogenic heritable disorders as major genes; (2) polymorphic mutations inside genes predisposing to multifactorial disorders that, in some cases, can act as modifier mutations in monogenic disorders (Fig. 5.13). The characterization of a pathogenetic mutation in monogenic heritable disorders allows the better follow-up of patients and, in familial cases, the early identification of asymptomatic subjects in the younger generation at risk of developing acute aortic aneurysms/dissections. Moreover, it allows us to offer a service of prenatal diagnosis to the couple at risk or preimplantation. The detection of mutations in modifier genes hopefully will give the opportunity to identify targets for pharmacological treatments to reduce or slow down the progression of severe symptoms. Instead the identification of mutations predisposing to some multifactorial disorders helps as a genetic marker to better evaluate the percentage of risk to develop the disorder or a specific feature of the disorder. Moreover, with the large amount of information we are accumulating on the pharmacogenetics, the characterization of a number of polymorphisms in genes producing protein sensitive or susceptible to pharmacological therapy it allows us to select the best drug and the appropriate dose of a drug for each patient.

5.3.1 Genes Associated with Syndromic or Nonsyndromic Monogenic Disorders Presenting Aortic Aneurysms or Dissections

Among the classic aortic aneurysms/dissections, there is a group of heritable connective tissue disorders transmitted as an autosomal dominant trait represented by MFS, EDS, familial TAA, familial AAA, osteogenesis imperfecta, and PKD. Moreover, a neurological mental retardation, the fragile-X syndrome, and an anatomical congenital aortic valve malformation, the aortic bicuspid, also present aortic diseases. These monogenic disorders are mostly transmitted as autosomal traits. Most of them are due to mutations in extracellular matrix proteins that are important structural components of the aortic wall. The only exceptions are PKD, which is due to mutations in a protein that functions as a receptor to connect the extracellular matrix with the actin protein inside the cytoskeleton, and the fragile-X syndrome, which is due to mutations in the fragile mental retardation protein 1 (FMRP1), whose functions in the cardiovascular system are at present unknown, and the bicuspid aorta, whose genetic base is also unknown at

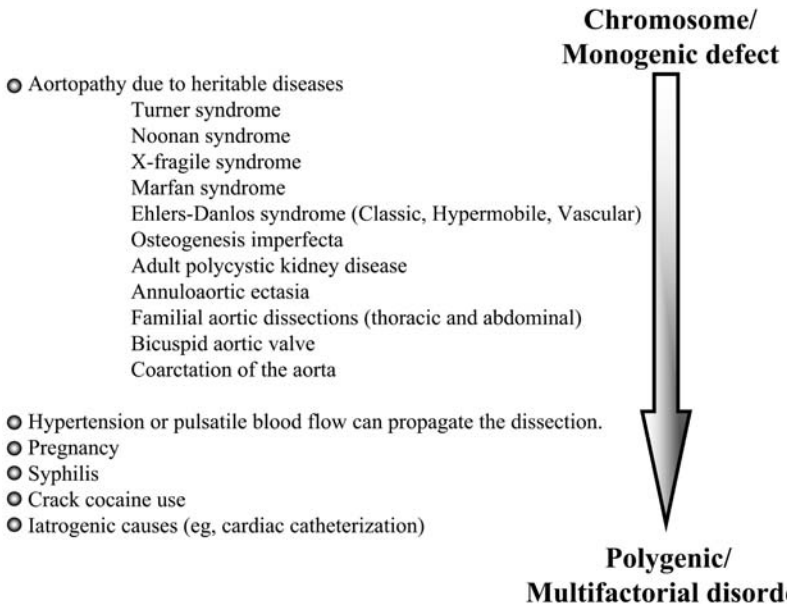


Fig. 5.13. Diseases affecting the media of the aorta with predisposition to dissection. Aortic dissection is commoner in patients with hypertension, connective-tissue disorders, congenital aortic stenosis, or bicuspid aortic valve, and in those with first-degree relatives with history of thoracic dissections

present. These disorders represent in vivo models in which the alterations are due in a high percentage of cases to mutations in one gene and in a low percentage to the genetic background (other minor genes) and to environmental factors. For this reason, the comparison between these mentioned disorders and the ones with a major multifactorial involvement such as AAAs or atherosclerotic aneurysms can help in better understanding the effect of molecules such as metalloproteinases and cytokines on the aortic wall. In a patient with a monogenic disorder, modifier genes will act on an already structurally altered wall accelerating the progress of the aneurysm; on the other hand, in a multifactorial disorder the damage caused to the wall is due to the long-term and continuous action of a large number of factors predisposing to the disease.

MFS is a multisystemic disorder with clinical major criteria affecting the cardiovascular system, the central nervous system, skeletal apparatus, and eyes. Mutations in the fibrillin 1 gene (FBN1) are associated with a high number of MFS patients. The fact that the mutations have not been detected in 100% of MFS patients can be due to a limitation of the mutation detection techniques used at present or to the existence of other major genes. Data from the literature showed that the sensitivity of conformation-sensitive gel electrophoresis (CSGE) is very high (16/17 mutations identified in 17 MFS patients in which the mutation was already detected) [52]. Another group demonstrated that by analysing the FBN1 gene with a first technique such as CSGE or single-strand conformation polymorphism they detected mutations in 73/93 patients with classic MFS; of the remaining 20 patients, 11 underwent direct sequencing analysis and nine were reanalysed with denaturing high-performance liquid chromatography. Seven out of 11 and five out of nine mutations were identified, reaching a total of 85/93 equal to 91% [57]. Very recently, a second Marfan or Marfanoid gene has been detected: the receptor 2 of β-transforming growth factor (TGFBR2) localized on chromosome 3p24-25 [66]. This second gene is probably associated with patients displaying skeletal and cardiovascular manifestations of MFS but further investigations are required to understand if it is also associated with the classic MFS or if it can act as a modifier gene among classic MFS patients or patients with MFS-related disorders.

The EDS include a heterogeneous group of disorders affecting skin, ligaments, joints, and blood vessels. The most recent classification recognizes six subtypes, most of which have been associated with mutations affecting one of the fibrillar collagens [6]. Aortic thoracic aneurysms/dissections can be the cause of death in many patients with vascular EDS and are present in 30% of classic and hypermobile EDS patients. The classic and hypermobile types are associated with mutations in COL5A1, COL5A2, and tenascin X genes [60, 61]. The vascular type is due to mutations in the COL3A1 gene [54].

OI, the brittle bone disease, is characterized by bone fragility, dentinogenesis imperfecta, deafness due to altered transmission, and blue sclerae; 30% of osteogenesis imperfecta patients can develop aortic dilatation. It is caused by mutations affecting COL1A1 and COL1A2, the two genes codifying for collagen type I. The aforementioned disorders together with Noonan syndrome, Turner syndrome, and fragile-X syndrome represent the group of aortic aneurysm associated with syndromic disorders.

Familial TAAs are characterized by thoracic aortic dilatation and mild skeletal alterations such as pectus and vertebral deformities, dolichostenomelia, arachnodactily, and pes planus. Genetic heterogeneity underlines the molecular bases of these disorders. FBN1 mutations have been detected in one familial case [29] and two sporadic cases [64] but other associated loci have been identified by linkage analysis on large families; they have been localized on chromosomes 11q23.2-q24 [83, 107]; 5q13-q14 [42], and 3p24-p25 [34]. This last locus could correspond to TGFBR2.

Aneurysmal degeneration in MFS patients is characterized by fragmented elastic fibres and abnormal accumulation of amorphous matrix [1]. Once the fibrillin-1 microfilaments do not connect elastin to SMCs, the cells produce matrix and matrix proteases in an attempt to remodel the tissue. The elastic fibre breakdown is accompanied by an inflammatory response starting from the adventitial surface and progressing into the media.

Mutations in genes associated with monogenic disorders that present aortic aneurysms/dissections can constitute a model to study other aneurysms due more to environments. The idea is due to the fact that the histopatological alterations are similar and that all kinds of aneurysms are associated with increased matrix proteases, especially metalloproteinase activity.

BAV is the commonest congenital heart malformation, with a prevalence of 1–2% in the population. It is associated with TAAs and dissections. A developmental defect of neural crest cells resulting in premature vascular SMCs (VSMCs) apoptosis has been hypothesized [9]. BAV can be associated with genetic syndromes such as Turner syndrome [65] and families with autosomal dominant transmission have been reported [91].

Both MFS and BAV aneurysms present, at a histology analysis, areas of CMN without inflammation. Immunohistochemical analysis shows intracellular accumulation of fibrillin, fibronectin, and tenascin in VSMCs that are not excreted since western blot analysis does not show any increase in these proteins. Moreover, MMP2 is increased in VMSCs of MFS patients in agreement with an increased VSMC apoptosis in MFS and BAV patients.

With regard to the aforementioned genes, a group of polymorphic mutations supposed to exert a milder effect have been described: further studies are needed in order to evaluate their role as genetic predisposing factors for multifactorial aortic diseases.

5.3.2 Polymorphic Mutations in Genes Predisposing to Alterations

It is well known that human genes present a high number of polymorphisms. These polymorphisms can be single nucleotide substitutions (SNPs) but also deletions or insertions of one to many nucleotides, even hundreds, inside a sequence repeat. These polymorphisms are often present in the introns or in the 5′ or 3′ untranslated regions, but SNPs can also be present in the coding sequences (exons) and in the regulatory regions such as the promoters.

In the last few years many of these polymorphisms have been detected but only in a small number of them have functional studies definitely demonstrated their pathogenecity: e.g., polymorphic SNPs inside a promoter can decrease or increase the transcription of a gene, therefore decreasing or increasing the quantity of the final product. These variations, which are usually mild, contribute to the clinical manifestation or to the progression of a multifactorial disease but can also act as modifiers in monogenic disorders.

Since AAAs represent a degenerative multifactorial group of disorders, many polymorphisms affecting genes encoding cytokines, chemokines involved in inflammatory reactions, metalloproteinases and their inhibitors, and proteins involved in the renin angiotensin system have already been described [27]. Among these polymorphisms some, such as the following, seem to exert important effects:

- A common polymorphism in the MTHFR gene (C677T) is known to cause mild hyperhomocysteinemia, especially in subjects with low folate intake [31]. Data on patients with AAA and MFS suggest that high Hcy plasma levels and the homozygous 677TT MTHFR genotype might be implicated in the weakening of the extracellular matrix of the vascular wall [11, 32].
- A functional polymorphism (C-1562T) in MMP9 was found preferentially associated with AAA patients. It can represent a genetic component contributing to susceptibility to vascular disease.
- CCR5 is a chemokine receptor that can be expressed on various cells such as macrophages, coronary endothelial cells, aortic SMC s and T cells. A common 32-bp deletion mutation in the CCR5 gene (D32), which causes truncation and loss of CCR5 receptors on lymphoid cell surfaces of homozygotes, was recently described [95]. It is more prevalent among AAAs.

The study of these polymorphisms or polymorphisms in other candidate genes might highlight associations also with TAAs/dissections.

5.4 Prospective New Tools to Identify New Biochemical and Genetic Markers

At the moment very few genetic and biochemical markers have been detected in TAAs, while many biochemical markers and few genetic markers have been found in AAAs; these last markers are similar to those found in atherosclerosis. The fact that TAA has a different molecular background from that found in AAA or atherosclerosis is in part explainable by the fact that the aortic wall has a different structural protein composition that can contribute to the different pathologies. To address the question of the presence of a different pathomolecular background one approach that has been used in the last few years is microarray technology such as messenger RNA (mRNA) expression profile and protein profile.

Recently, mRNA expression profile was determined on RNA extracted from thoracic and infrarenal abdominal aortic wall tissues of patients with degenerative aortic aneurysms (not with inherited connective tissue disorders) and controls with the aim of investigating and comparing profile-altered patterns in these two pathologies. Four patients with TAAs (two men, ages 49 and 78 years, and two women, ages 82 and 52 years), four with AAAs (two men, ages 84 and 80 years, and two women, ages 76 and 57 years), and four controls of RNA extracted from cadaveric organ transplant donors (three men, ages 42, 18, and 14 years) and one woman (age 36 years) were investigated. The analysis showed 9.5% (112/1,185) of the genes analysed were differentially expressed in thoracic aneurysm compared with in the controls; of the 112, 105 were overexpressed and seven were underexpressed. Instead 8.8% (104/1185) of the genes presented quantitative differences, with controls displaying (65) an increased mRNA and (39) a decreased mRNA expression. Only eight genes were severely altered in both pathologies and only four of them were increased in both aneurysms: MMP9, y-yes-1 oncogene, mitogen-activated protein kinase 9, and intercellular adhesion molecule 1/CD54. Instead, while the major increases in TAAs were reported for z and t isoforms of PKC, uracil-DNA glycosylase (a DNA repair enzyme), lymphotoxin-β, TNF-α, and CD27 (TNF receptor superfamily member-7), the greatest alterations in gene expression in AAAs were seen for MMP9/gelatinase B, CD86/B7-2 antigen, bystin-like, apolipoprotein E (Apo E), integrins b2 and B8, nonreceptor tyrosine kinase 1, Janus kinase 3, IL-8, and PKC-d. These data suggest that the two kinds of aneurysms have distinct pathomolecular mechanisms [2] (Fig. 5.14).

These are important data that need to be verified with gold standard techniques such as real-time PCR, northern blot analysis, western blot analysis, and other protein analysis. The major limits of the reported data

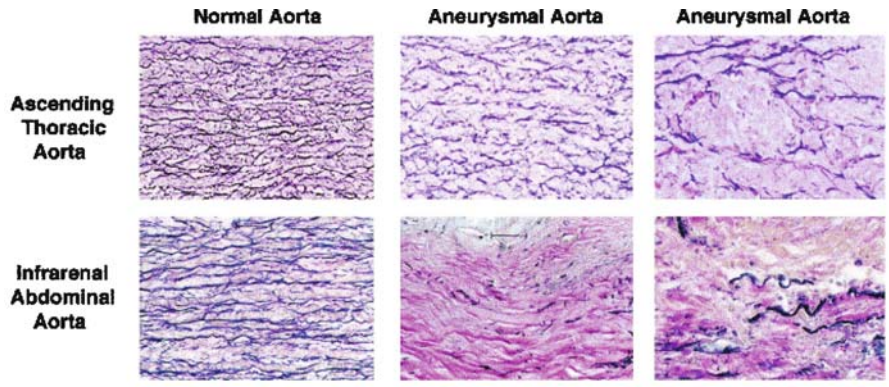


Fig. 5.14. Histopathology of aortic aneurysms. Representative sections of aortic wall tissue stained with Verhoeff van Geisen for elastin *(dark purple fibres)*. Compared with normal thoracic aorta, thoracic aortic aneurysm exhibited disruption, fragmentation, and disorganization of medial elastic fibres in the absence of significant inflammatory changes, along with other characteristic features of cystic medial necrosis (*upper panels*). Abdominal aortic aneurysm exhibited more extreme destruction of medial elastin and replacement by fibrocollagenous extracellular matrix (*pink*), along with depletion of medial smooth muscle cells and mononuclear inflammatory cell infiltration in direct association with areas of elastic fibre degeneration (*lower panels*). (From Absi et al. [2])

are the following: (1) the variable age of the patients with some young patients in which inherited connective tissue disorders cannot be totally excluded; (2) patients with AAAs have a more complicated history of degenerative disorders that can introduce many variables able to affect the mRNA expression profile; (3) the intraindividual variation seen among patients suggests a possible high variability among controls that has not been deeply analysed; (4) we do not know how many results obtained from experiments in vitro on cells or tissues really mimic human diseases [81].

Another relevant study on gene expression profiles in acutely dissected human aorta compared the aortic tissue of six patients (three men, ages 55, 50, and 41 years, and three women, ages 75, 57, and 66 years) vs that of six control multiorgan donors (four men, ages 30, 34, 48, and 65 years, and two women, ages 14 and 45 years). Of the 3,537 genes analysed 35% (1,250) were expressed in the aortic tissue and only 627 (17.7%) of them, for statistical reasons, were investigated further. Sixty-six genes turned out to present a significant different expression: 34 (5.4%) were overexpressed and 32 (5.1%) were expressed at a lower level in dissected aortas. Interestingly, among the downregulated genes several codify for extracellular matrix proteins such as elastin, fibulin 1, fibulin 5, fibronectin, microfibril-associated glycoprotein 4 (MAGP4), integrins a 7B, 5, and X, polycystin precursor, and selenoprotein P.

Fibrillins 1 and 2 have the same expression of the control, while many collagens are not detectable.

A second group that is downregulated is made of cytoskeleton and myofibrillar genes such as α-actinin 1 gene, two myosin regulatory chains, and tropomyosin β chain A.

Among the upregulated genes there are some involved in inflammation such as cytokines IL6 and IL8, MMP11 (MMPs 2, 3, 9, 12, and 13 are not detectable), and its inhibitor TIMP1. The proteins of the extracellular matrix displaying decreased mRNAs have functions related to cell adhesion and control of extracellular matrix integrity. It is noteworthy that polycystin, a large membrane-associated glycoprotein, acts as a matrix receptor to connect the extracellular matrix to the actin cytoskeleton through adhesion proteins [67]. Mutations in polycystin genes are associated with autosomal dominant PKD. Some families with PKD present aortic dissection, supra-aorta dissection, or cranial aneurysm; immunostaining of SMC with antibodies against polycystin showed that this protein is decreased in all these aneurysms together with some transmembrane and communication proteins, thus disturbing many tissue functions, such as response to injury.

In aortic dissection, cell motility seems altered in agreement with the decreased myosin mRNAs (proteins of motility) and α-actinin, an actinin binding protein that participates in the actin network formation.

Overall, dissection is associated with degradation of the aortic wall, inflammation, and cell proliferation. MMP11 degrades basement membrane components such as collagen IV and laminin and ground substances such as proteoglycan and gelatine; the data are in agreement with those of Sariola et al. [86].

Since little information is available on the role of MMPs in TAAs and dissections, MMP profile expression was investigated in a large number of patients (30 with thoracic aneurysm and 17 with thoracic dissection) by using tissue microarray immunostaining analysis. Seven controls of aortic tissue of patients in which vascular disease was excluded were used. As a result MMP-1, MMP-9, and TIMP-2 expression was increased in both groups. The MMP-9 to TIMP-1 ratio (a relative index of proteolytic state) was also increased in both groups.

Aortic dissection presented higher MMP-2 and MMP9 mRNA. In conclusion, increased proteolysis seems to play a role in the development and progression of the aortic aneurysm and dissection [53].

An important contribution to the understanding of the molecular mechanisms underline the AAS and to the identification and characterization of new biomarkers comes from mice models. Apo E in lipid metabolism has the role of an important mediator for the transport of circulating cholesterol; in fact, when it is decreased or absent the levels of cholesterol incresae. In addition, it has a role against inflammation; in fact, mice genetically deficient in Apo E spontaneously develop atherosclerosis in the arterial wall.

Brown Norway (BN) and BN Katholiek (BN/Ka) rat strains are both susceptible to develop lesions in the internal elastic lamina (IEL) of the aorta. BN/Ka rats carry a single point mutation in kininogen that causes a deficiency in both low and high molecular weight kininogen. The authors demonstrated that genetic defects causing kininogen deficiency cause the formation of aortic abdominal aneurysm but not the development of atherosclerosis. The aneurysm formation was associated with an increased elastolysis, elevated expression of MMP-2 and MMP-3, and decreased expression of TIMP-4. They observed changes in plasma cytokines: increased expression of IFN-γ and downregulation of GM-CSF and IL1-β are compatible with apoptotic vascular damage.

The fact that in response to an atherogenic diet the BN/Ka rats have an increase in the high-density lipoprotein-to-total cholesterol index, fatty liver and heart degeneration, and lipid deposition in the aortic media but no atherosclerotic plaque formation suggests that kininogen deficiency predisposes the vascular tissue to aneurysm but not to atherosclerotic lesions [43].

col1a1 is, with *col1a2*, one of the two genes that encode type I collagen, the most abundant and ubiquitous protein of the collagen family, and a structural component of the extracellular matrix. In a previous article [38] it was reported that a mutated *col1a1* allele missing a large fragment of intron 1 but still retaining the sequences required for a correct splicing underwent an age- and tissue-dependent decrease in expression. In this study, the aortic walls of mice homozygous for the deletion analysed by electron microscopy showed decreased collagen fibrils and less dense and irregular elastic fibrils. The *Col1A1* mRNA concentration appears to decrease with aging by northern blot analysis (2.5 months old a 29% decrease and 12 months old a 42% decrease). These data confirm the importance of regulatory sequences inside intron 1 that stabilize the mRNA during aging. Moreover collagen type I integrity is important for the integrity of the aortic wall [82]. These data in a mouse model are confirmed in humans by the fact that patients with brittle bone disease (osteogenesis imperfecta), a heritable connective tissue disorder due to mutations in COL1A1 or COL1A2 develop TAAs in 30% of cases.

In conclusion, many new data are coming from biochemical and genetic studies but still much work needs to be done to better understand the molecular bases underlying this group of pathologies. Molecular studies necessary to identify biochemical and genetic markers informative within the first hours of an emergency and for differential diagnosis are required. A correct clinical diagnosis will allow us to perform the right pharmacological/surgical therapy and follow-up. Moreover, the imaging analysis field is rapidly improving and hopefully will be of great help in the near future to recognize early tissue alterations associated with dissection. The aim is to develop a comprehensive integrated plan for the rational use of these biomarkers aimed at optimizing the management of this high-risk group of patients. It is hoped that the information provided in this chapter will contribute to achieving such a target.

References

1. Abraham PA, Perejda AJ, Carnes WH, Uitto J (1982) Marfan syndrome. Demonstration of abnormal elastin in aorta. J Clin Invest 70:1245–1252.
2. Absi TS, Sundt TM, Tung WS, Moon M, Lee JK, Damiano RR Jr, Thompson RW (2003) Altered patterns of gene expression distinguishing ascending aortic aneurysms from abdominal aortic aneurysms: complementary DNA expression profiling in the molecular characterization of aortic disease. J Thorac Cardiovasc Surg 126:344–357.
3. Aikawa M, Silvam PN, Kuro-o M et al (1993) Human smooth muscle myosin heavy chain isoforms as molecular markers for vascular development and atherosclerosis. Circ Res 73:1000–1012.
4. Anagnostopoulos CE, Prabhakar MJS, Kittle CF (1972) Aortic dissections and dissecting aneurysms. Am J Cardiol 30:263–273.
5. Bautista L, Arenas I, Penuela A, Martinez LX (2002) Total plasma homocysteine level and risk of cardiovascular disease: a meta-analysis of prospective cohort studies. J Clin Epidemiol 55:882–887.
6. Beighton P, De Paepe A, Steinmann B, Tsipouras P, Wenstrup RJ (1998) Ehlers-Danlos syndromes: revised nosology, Villefranche, 1997. Ehlers-Danlos National Foundation (USA) and Ehlers-Danlos Support Group (UK). Am J Med Genet 77:31–37.
7. Bick RL (1994) Disseminated intravascular coagulation: objective laboratory diagnostic criteria and guidelines for management. Clin Lab Med 14:729–768.
8. Blankenship JC, Almquist AK (1989) Cardiovascular complications of thrombolytic therapy in patients with a mistaken diagnosis of acute myocardial infarction. J Am Coll Cardiol 14:1579–1582.
9. Bonderman D, Gharehbaghi-Schnell E, Wollenek G, Maurer G, Baumgartner H, Lang IM (1999) Mechanisms underlying aortic dilatation in congenital aortic valve malformation. Circulation 99:2138–2143.
10. Boyum J, Fellinger EK, Schmoker JD, Trombley L, McPartland K, Ittleman FP, Howard AB (2004) Matrix metalloproteinase activity in thoracic aortic aneurysms associated with bicuspid and tricuspid aortic valves. J Thorac Cardiovasc Surg 127:686–691.

11. Brunelli T, Prisco D, Fedi S, Rogolino A, Farsi A, Marcucci R, Giusti B, Pratesi C, Pulli R, Gensini GF, Abbate R, Pepe G (2000) High prevalence of mild hyperhomocysteinemia in patients with abdominal aortic aneurysm. J Vasc Surg 32:531–536.
12. Butler J, Davies AH, Westaby S (1990) Streptokinase in acute aortic dissection. Br Med J 300:517–519.
13. Cattaneo M (1999) Hyperhomocyseinemia, atherosclerosis and thrombosis. Thromb Haemost 81:165–176.
14. Clark JM, Glagov S (1985) Transmural organization of the arterial media: the lamellar unit revisited. Arteriosclerosis 5:19–34.
15. Costantini V, Zacharski LR (1993) Fibrin and cancer. Thromb Haemost 69:406–414.
16. Danesh J, Whincup P, Walker M et al. (2001) Fibrin D-dimer and coronary heart disease: prospective study and meta-analysis. Circulation 103:2323–2327.
17. De Sa M, Moshkovitz Y, Butany J, David TE (1999) Histologic abnormalities of the ascending aorta and pulmonary trunk in patients with bicuspid aortic valve disease: clinical relevance to the Ross procedure. J Thorac Cardiovasc Surg 118:588–594.
18. Dietz HC (1996) Molecular etiology, pathogenesis and diagnosis of the Marfan syndrome. Prog Pediatr Cardiol 5:159–166.
19. Dietz HC, Pyeritz RE (2001) Marfan syndrome and relate disorders. In: Scriver CR (ed) The metabolic and molecular bases of inherited disease. McGraw-Hill, New York, pp 5287–5312.
20. Dobrin PB (1988) Mechanics of normal and diseased blood vessels. Ann Vasc Surg 2:283–294.
21. Eggebrecht H, Baumgart D, Schmermund A, Herold U, Hunold P, Jakob H, Erbel R (2003) Penetrating atherosclerotic ulcer of the aorta: treatment by endovascular stent-graft placement. Curr Opin Cardiol 18:431–435.
22. Eggebrecht H, Naber CK, Bruch C et al. (2004) Value of plasma fibrin D-dimers for detection of acute aortic dissection. J Am Coll Cardiol 44:804–809.
23. Elmore JR, Keister BF, Franklin DP, Youkey JR, Carey DJ (1998) Expression of matrix metalloproteinases and TIMPs in human abdominal aortic aneurysms. Ann Vasc Surg 12: 221–228.
24. Erbel R, Oelert H, Meyer J et al. (1993) Effect of medical and surgical therapy on aortic dissection evaluated by transesophageal echocardiography: implications for prognosis and therapy. Circulation 87:1604–1615.
25. Erbel R, Alfonso F, Boileau C et al. (2001) Diagnosis and management of aortic dissection. Eur Heart J 22:1642–1681.
26. Erdheim J (1929) Medionecrosis aortae idiopathica. Virchows Arch 273:454–479.
27. Faxon DP, Fuster V, Libby P et al. (2004) Atherosclerotic vascular disease conference: writing group III: pathophysiology. Circulation 109:2617–2625.
28. Folsom AR, Aleksic N, Park E et al. (2001) Prospective study of fibrinolytic factors and incident coronary heart disease: the atherosclerosis risk in communities (ARIC) study. Arterioscler Thromb Vasc Biol 21:611–617.
29. Francke U, Berg MA, Tynan K et al. (1995) A Gly1127Ser mutation in an EGF-like domain of the fibrillin-1 gene is a risk factor for ascending aortic aneurysm and dissection. Am J Hum Genet 56:1287–1296.
30. Furthmayr H, Francke U (1997) Ascending aortic aneurysm with or without features of Marfan syndrome and other fibrillinopathies: new insights. Semin Thorac Cardiovasc Surg 9:191–205.
31. Girelli D, Friso S, Trabetti E et al. (1998) Methylenetetrahydrofolate reductase C677T mutation, plasma homocysteine, and folate in subjects from northern Italy with or without angiographically documented severe coronary atherosclerotic disease: evidence for an important genetic-environmental interaction. Blood 91:4158–4163.
32. Giusti B, Porciani MC, Brunelli T, Evangelisti L, Fedi S, Gensini GF, Abbate R, Sani G, Yacoub M, Pepe G (2003) Phenotypic variability of cardiovascular manifestations in Marfan Syndrome. Possible role of hyperhomocysteinemia and C677T MTHFR gene polymorphism. Eur Heart J 24:2038–2045.
33. Goldhaber SZ, Simons GR, Elliott CG et al. (1993) Quantitative plasma D-dimer levels among patients undergoing pulmonary angiography for suspected pulmonary embolism. JAMA 270:2819–2822.
34. Hasham SN, Willing MC, Guo DC et al. (2003) Mapping a locus for familial thoracic aortic aneurysms and dissections (TAAD2) to 3p24-25. Circulation 107:3184–3190.
35. Henderson EL, Gang YJ, Sukhova GK, Whittemore AD, Knox J, Libby P (1999) Deathof smooth muscle cells and expression of mediators of apoptosis by T lymphocytes in human abdominal aortic aneurysms. Circulation 99:96–104.
36. Hirschfield GM, Pepys MB (2003) C-reactive protein and cardiovascular disease: new insights from an old molecule. Q J Med 96:793–807.
37. Homocysteine Studies Collaboration (2002) J Am Med Assoc 288:2015–2022.
38. Hormuzdi SG, Penttinen R, Jaenisch R, Bornstein P (1998) A gene-targeting approach identifies a function for the first intron in expression of the alpha1(I) collagen gene. Mol Cell Biol 18:3368–3375.
39. Ikonomidis JS, Gibson WC, Butler JE, McClister DM, Sweterlitsch SE, Thompson RP, Mukherjee R, Spinale FG (2004) Effects of deletion of the tissue inhibitor of matrix metalloproteinases-1 gene on the progression of murine thoracic aortic aneurysms. Circulation 110 (11 Suppl 1):II268–273.
40. Isotalo PA, Guindi MM, Bedard P, Brais MP, Veinot JP (1999) Aortic dissection: a rare complication of osteogenesis imperfecta. Can J Cardiol 15:1139–1142.
41. Jin P, Warren ST (2003) New insights into fragile X syndrome: from molecules to neurobehaviors. Trends Biochem Sci 28:152–158.
42. Kakko S, Raisanen T, Tamminen M et al. (2003) Candidate locus analysis of familial ascending aortic aneurysms and dissections confirms the linkage to the chromosome 5q13-14 in Finnish families. J Thorac Cardiovasc Surg 126:106–113.
43. Kaschina E, Stoll M, Sommerfeld M, Steckelings UM, Kreutz R, Unger T (2004) Genetic kininogen deficiency contributes to aortic aneurysm formation but not to atherosclerosis. Physiol Genomics 19:41–49.
44. Katoh H, Suzuki T, Hiroi Y et al. (1995) Diagnosis of aortic dissection by immunoassay for circulating smooth muscle myosin. Lancet 345:191–192.
45. Katoh H, Suzuki T, Yokomori K et al. (1995) A novel immunoassay of smooth muscle myosin heavy chain in serum. J Immunol Methods 185:57–63.
46. Keen RR, Dobrin PB (2000) Development of aneurysm. Landes Bioscience, Georgetown, TX.
47. Khoury NE, Borzak S, Gokli A et al. (1996) "Inadvertent" thrombolytic administration in patients without myocardial infarction: clinical features and outcome. Ann Emerg Med 28:553–554.
48. Kielty CM (2005) Applying elastic fibre biology in vascular tissue engineering. Philos Trans R Soc Lond Ser B (Theme issue): Engineering the heart.
49. Klerk M, Verhoef P, Clarke R, Blom HJ, Kok FJ, Schouten EG (2002) MTHFR 677C → T polymorphism and risk of coronary heart disease: a meta-analysis. J Am Med Assoc 288:2023–2031.

50. Koch A, Kunkel S, Pearce W, Shah M, Parikh D, Evanoff H, Haines GK, Burdick MD, Strieter RM (1993) Enhanced production of the chemotactic cytokines interleukin-8 and monocyte chemoattractant protein-1 in human abdominal aortic anurysms. Am J Pathol 142:1423–1431.
51. Koenig W, Rothenbacher D, Hoffmeister A et al. (2001) Plasma fibrin D-dimer levels and risk of stable coronary artery disease: Results of a large case-control study. Arterioscler Thromb Vasc Biol 21:1701–1705.
52. Korkko J, Kaitila I, Lonnqvist L, Peltonen L, Ala-Kokko L (2002) Sensitivity of conformation sensitive gel electrophoresis in detecting mutations in Marfan syndrome and related conditions. J Med Genet 39:34–41.
53. Koullias GJ, Ravichandran P, Korkolis DP, Rimm DL, Elefteriades JA (2004) Increased tissue microarray matrix metalloproteinase expression favors proteolysis in thoracic aortic aneurysms and dissections. Ann Thorac Surg 78:2106–2111.
54. Kuivaniemi H, Tromp G, Bergfeld WF, Kay M, Helm TN (1995) Ehlers-Danlos syndrome type IV: a single base substitution of the last nucleotide of exon 34 in COL3A1 leads to exon skipping. J Invest Dermatol 105:352–356.
55. Kuro-o M, Nagai R, Tsuchimochi H et al. (1989) Developmentally regulated expression of vascular smooth muscle myosin heavy chain isoforms. J Biol Chem 264:18272–18275.
56. Lesauskaite V, Tanganelli P, Sassi C, Neri E, Diciolla F, Ivanoviene L et al. (2001) Smooth muscle cells of the media in the dilative pathology of ascending thoracic aorta: morphology, immunoreactivity for osteopontin, matrix metalloproteinases, and their inhibitors. Hum Pathol 32:1003–1011.
57. Loeys B, De Backer J, Van Acker P, Wettinck K, Pals G, Nuytinck L, Coucke P, De Paepe A (2004) Comprehensive molecular screening of the FBN1 gene favors locus homogeneity of classical Marfan syndrome. Hum Mutat 24:140–146.
58. Lopez-Candales A, Holmes DR, Liao S, Scott MJ, Wickline SA, Thompson RW (1997) Decreased vascular smooth muscle cell density in medial degeneration of human abdominal aortic aneurysms. Am J Pathol 150:993–1007.
59. Makita S, Ohira A, Tachieda R et al. (2000) Behavior of C-reactive protein levels in medically treated aortic dissection and intramural hematoma. Am J Cardiol 86:242–244.
60. Malfait F, Coucke P, Symoens S et al. (2005) The molecular basis of classic Ehlers-Danlos syndrome: a comprehensive study of biochemical and molecular findings in 48 unrelated patients. Hum Mutat 25:28–37.
61. Mao JR, Taylor G, Dean WB et al. (2002) Tenascin-X deficiency mimics Ehlers-Danlos syndrome in mice through alteration of collagen deposition. Nat Genet 30:421–425.
62. Marsalese DL, Moodie DS, Lytle BW, Cosgrove DM, Ratliff NB, Goormastic M, Kovacs A (1990) Cystic medial necrosis of the aorta in patients without Marfan's syndrome: surgical outcome and long-term follow-up. J Am Coll Cardiol 16:68–73.
63. Miano JM, Cserjesi P, Ligon KL et al. (1994) Smooth muscle myosin heavy chain exclusively marks the smooth muscle lineage during mouse embryogenesis. Circ Res 75:803–812.
64. Milewicz DM, Michael K, Fisher N, Coselli JS, Markello T, Biddinger A (1996) Fibrillin-1 (FBN1) mutations in patients with thoracic aortic aneurysms. Circulation 94:2708–2711.
65. Miller MJ, Geffner ME, Lippe BM et al. (1983) Echocardiography reveals a high incidence of bicuspid aortic valve in Turner syndrome. J Pediatr 102:47–50.
66. Mizuguchi T, Collod-Beroud G, Akiyama T, Abifadel M, Harada N, Morisaki T, Allard D, Varret M, Claustres M, Morisaki H, Ihara M, Kinoshita A, Yoshiura K, Junien C, Kajii T, Jondeau G, Ohta T, Kishino T, Furukawa Y, Nakamura Y, Niikawa N, Boileau C, Matsumoto N (2004) Heterozygous TGFBR2 mutations in Marfan syndrome. Nat Genet 36:855–860.
67. Muller BT, Modlich O, Prisack HB, et al.. (2002) Gene expression profiles in the acutely dissected human aorta. Eur J Vasc Endovasc Surg 24:356–364.
68. Murray CA, Edwards JE (1973) Spontaneous laceration of ascending aorta. Circulation 47:848–858.
69. Nagai R, Larson DM, Periasamy M (1988) Characterization of a mammalian smooth muscle myosin heavy chain cDNA clone and its expression in various smooth muscle types. Proc Natl Acad Sci USA 85:1047:1051.
70. Nagai R, Kuro-o M, Babij P, Periasamy M (1989) Identification of two types of smooth muscle myosin heavy chain isoforms by cDNA cloning and immunoblot analysis. J Biol Chem 264:9734–9737.
71. Nakashima Y, Sueishi K (1992) Alterations of elastic architecture in the lathyritic rat aorta implies the pathogenesis of aortic dissecting aneurysm. Am J Pathol 140:959–969.
72. Nakashima Y, Shiokawa Y, Sueishi K (1990) Alterations of elastic architecture in human aortic dissecting aneurysm. Lab Invest 62:751–760.
73. Nataatmadja M, West M, West J, Summers K, Walker P, Nagata M, Watanabe T. (2003) Abnormal extracellular matrix protein transport associated with increased apoptosis of vascular smooth muscle cells in marfan syndrome and bicuspid aortic valve thoracic aortic aneurysm. Circulation 108 (Suppl 1):II329–334.
74. Neumann RE, Logan MA (1950) The determination of collagen and elastin in tissues. J Biol Chem 186:549–556.
75. Niwa K, Perloff JK, Bhuta SM, Laks H, Drinkwater DC, Child JS, Miner PD (2001) Structural abnormalities of great arterial walls in congenital heart disease: light and electron microscopic analyses. Circulation 103:393–400.
76. Nuenninghoff DM, Warrington KJ, Matteson EL (2003) Concomitant giant cell aortitis, thoracic aortic aneurysm, and aortic arch syndrome: occurrence in a patient and significance. Arthritis Rheum 49:858–861.
77. Palinski W (2004) Aneurysms: leukotrienes weaken aorta from the outside. Nat Med 10:896–898.
78. Pepin M, Schwarze U, Superti-Furga A, Byers PH (2000) Clinical and genetic features of Ehlers-Danlos syndrome type IV, the vascular type. N Engl J Med 342:673–680.
79. Powell JT, Vine N, Crossman M (1992) On the accumulation of D-aspartate in elastin and other proteins of the ageing aorta. Arteriosclerosis 97:201–208.
80. Prisco D, Antonucci E, Marcucci R, Pepe G (2000) D-dimers in the year 2000: current data and new perspectives. Ann Ital Med Int 15:267–272.
81. Pyeritz RE (2003) Express yourself – but consider the consequences. J Thorac Cardiovasc Surg 126:334–336.
82. Rahkonen O, Su M, Hakovirta H et al. (2004) Mice with a deletion in the first intron of the Col1a1 gene develop age-dependent aortic dissection and rupture. Circ Res 94:83–90.
83. Ramirez F, Dietz HC (2004) Therapy insight: aortic aneurysm and dissection in Marfan's syndrome. Nat Clin Pract 1:31–36.
84. Ridker PM, Hennekens CH, Cerskus A et al. (1994) Plasma concentration of cross-linked fibrin degradation product (D-dimer) and the risk of future myocardial infarction among apparently healthy men. Circulation 90:2236–2640.
85. Rucker RB, Tinker D (1977) Structure and metabolism of arterial elastin. Int Rev Exp Pathol 17:1–47.
86. Sariola H, Viljanen T, Luosto R (1986) Histological pattern and changes in extracellular matrix in aortic dissections. J Clin Pathol 39:1074–1081.

87. Schillinger M, Domanovits H, Bayegan K et al. (2002) C-reactive protein and mortality in patients with acute aortic disease. Intensive Care Med 28:740–745.
88. Schlatmann TJ, Becker AE (1977) Histologic changes in the normal aging aorta: implications for dissecting aortic aneurysm. Am J Cardiol 39:13–20.
89. Schlatmann TJ, Becker AE (1977) Pathogenesis of dissecting aneurysm of aorta: comparative histopathologic study of significance of medial changes. Am J Cardiol 39:21–26.
90. Schutgens RE, Ackermark P, Haas FJ et al. (2003) Combination of a normal D-dimer concentration and a non-high pretest clinical probability score is a safe strategy to exclude deep venous thrombosis. Circulation 107:593–597.
91. Segura AM, Luna RE, Horiba K, Stetler-Stevenson WG, McAlister HA, Willerson JT et al. (1998) Immunohistochemistry of matrix metalloproteinases and their inhibitors in thoracic aortic valves of patients with Marfan's syndrome. Circulation 98:II331–II338.
92. Selhub J (1999) Homocysteine metabolism. Ann Rev Nutr 19:217–246.
93. Shi GP, Sukhova GK, Grubb A, Ducharme A, Rhode LH, Lee RT, Ridker PM, Libby P, Chapman HA (1999) Cystatin C deficiency in human atherosclerosis and aortic aneurysms. J Clin Invest 104:191–197.
94. Shinohara T, Suzuki K, Okada M et al. (2003) Soluble elastin fragments in serum are elevated in acute aortic dissection. Aterioscler Thromb Vasc Biol 23:1839–1844.
95. Smith MW, Dean M, Carrington M et al. (1997) Contrasting genetic influence of CCR2 and CCR5 variants on HIV-1 infection and disease progression. Hemophilia growth and development study (HGDS), multicenter AIDS cohort study (MACS), multicenter hemophilia cohort study (MHCS), San Francisco City cohort (SFCC), ALIVE study. Science 277:959–965.
96. Spina M, Garbisa S, Zinnie J et al. (1983) Age-related changes in composition and mechanical properties of the tunica media of the upper thoracic human aorta. Arteriosclerosis 3:64–76.
97. Sukhova GK, Shi GP, Simon DI, Chapman HA, Libby P (1998) Expression of the elastolytic cathepsins S and K in human atheroma and regulation of their production in smooth muscle cells. J Clin Invest 102:576–583.
98. Sundt TM, Mora BN, Moon MR, Bailey MS, Pasque MK, Gay WA Jr (2000) Options for repair of a bicuspid aortic valve and ascending aortic aneurysm. Ann Thorac Surg 69:133.
99. Suzuki T, Katoh H, Watanabe M et al. (1996) Novel biochemical diagnostic method for aortic dissection: results of a prospective study using an immunoassay of smooth muscle myosin heavy chain. Circulation 93:1244–1249.
100. Suzuki T, Katoh H, Kurabayashi M et al. (1997) Biochemical diagnosis of aortic dissection by raised concentration of creatine kinase-BB-isozyme. Lancet 350:784–785.
101. Suzuki T, Katoh H, Nagai R (1999) Biochemical diagnosis of aortic dissection: from bench to bedside. Jpn Heart J 40:527–534.
102. Suzuki T, Katoh H, Tsuchio Y et al. (2000) Diagnostic implications of elevated levels of smooth muscle myosin heavy chain protein in acute aortic dissection: the smooth muscle myosin heavy chain study. Ann Intern Med 133:537–541.
103. Takagi H, Umemoto T (2005) Abdominal aortic aneurysm and autosomal-dominant polycystic kidney disease. Kidney Int 67:376.
104. Takeuchi T, Adachi H, Ohuchida M et al. (2004) A case-control study found that low albumin and smoking were associated with aortic dissection. J Clin Epidemiol 57:386–391.
105. Thompson RW, Lee JK, Curci JA (2000) The pathobiology of abdominal aoric aneurysms. In: Gewertz BL (ed) Surgery of the aorta and its branches. Saunders, Philadelphia, pp 75–106.
106. van der Loo B, Jenni R (2003) Acute aortic sindrome: proposal for a novel classification. Heart 89:928.
107. Vaughan CJ, Casey M, He J, Veugelers M et al. (2001) Identification of a chromosome 11q23.2-q24 locus for familial aortic aneurysm disease, a genetically heterogeneous disorder. Circulation 103:2469–2475.
108. Verma S, Szmitko PE, Ridker PM (2005) C-reactive protein comes of age. Nat Clin Pract 2:29–36.
109. Vilacosta I (2001) Acute aortic syndrome. Heart 85:365–368.
110. Vilacosta I (2003) Sindrome aortico agudo. Rev Esp Cardiol 56(Suppl 1):29–39.
111. Vilacosta I, San Roman JA, Aragoncillo P et al. (1998) Penetrating atherosclerotic aortic ulcer: documentation by transesophageal echocardiography. J Am Coll Cardiol 32:83–89.
112. von Kodolitsch Y, Schwartz AG, Nienaber CA (2000) Clinical prediction of acute aortic dissection. Arch Inter Med 160:2977–2982.
113. Wald DS, Law M, Morris JK (2002) Homocysteine and cardiovascular disease: evidence on causality from a meta-analysis. Br Med J 325:1202–1208.
114. Weber T, Hogler S, Auer J et al. (2003) D-dimer in acute aortic dissection. Chest 123:1375–1378.
115. Wegener M, Gorich J, Kramer S, Fleiter T, Tomczak R, Scharrer-Pamler R, Kapfer X, Brambs HJ (2001) Thrombus formation in aortic endografts. J Endovasc Ther 8:372–379.
116. Wilcox RG, von der Lippe G, Olsson CG et al. (1988) Trial of tissue plasminogen activator for mortality reduction in acute myocardial infarction: Anglo-Scandinavian study of early thrombolysis (ASSET). Lancet 2:525–530.
117. Wolinsky H, Glagov S (1967) A lamellar unit of aortic medial structure and function in mammals. Circ Res 20:99–111.
118. Yanagisawa M, Hamada Y, Katsuragawa Y et al. (1987) Complete primary structure of vertebrate smooth muscle myosin heavy chain deduced from its complementary DNA sequence. J Mol Biol 198:143–157.
119. Zhao L, Moos MPW, Grabner R et al. (2004) The 5-lipoxygenase pathway promotes pathogenesis of hyperlipidemia-dependent aortic aneurysm. Nat Med 10:966–973

Medical Aspect of the Aortic Diseases: the Follow-Up and Its Warnings

Guillaume Jondeau, Gabriel Delorme, Olivier Milleron and Jessica Wilson

6

Contents

6.1 Introduction

Traditionally, Marfan syndrome has always been associated with a high mortality rate, the result of aortic dissection and heart failure secondary to aortic dilatation: by the age of 40 years, 50% of men affected by Marfan syndrome were dead in a survey performed in 1972 [1]. But since the development of aortic surgery (Bentall intervention and more recently valve-sparing surgery), the life expectancy of Marfan syndrome patients has increased to more than 70 years [2], indicating that good medical and surgical management is efficient in these patients.

Marfan syndrome, a well-recognised disease with internationally recognised criteria [3], has been linked to an anomaly in fibrilin 1 [4]. However, this anomaly probably only accounts for a few of the degenerative aneurysms and dissections of the ascending aorta [5]. Another gene has also been linked to Marfan syndrome [6]. In addition, at least three other genetic localisations have been reported in familial forms of ascending aortic aneurysms or dissections [7, 7a], but most ascending aortic aneurysms remain of unknown aetiology. However, because the same mechanisms are probably involved in aortic dilatations of different aetiologies, the follow-up recommendations for Marfan syndrome are usually used for other aetiologies of aneurysm of the ascending aorta as well.

The mainstays of medical therapy are sports limitation, aiming at limiting stress on the aortic wall, and beta-blocking agents. Regular follow-up and aortic measurements are necessary to propose surgery before aortic dissection occurs. The aortic diameter is the single most important parameter for deciding surgery because the risk of dissection is greater as the aorta enlarges. This measurement should be standardised.

6.2 Positive Diagnosis of Marfan Syndrome, and the Importance of Familial Screening

Marfan syndrome is a polymorphic disease with large interfamilial and intrafamilial variability, complete penetrance and dominant autosomal transmission. Neo mutation may be responsible for 25% of the recognised cases. International criteria have been defined [3], with the aim of limiting overdiagnosis. To be diagnosed positive, a patient has to show major or minor features in at least three systems, including three major "criteria". The criteria are less stringent for patients with a family history as this is one of the major criteria (Table 6.1). However, because of the great variability of this disease and the progressive nature of the clinical features, inconclusive diagnosis accounts for 10% of patients coming to our out-patient clinic.

Familial screening should be systematic because of the genetic nature of Marfan syndrome. This often provides early recognition of affected individuals, allowing preventive measures and close follow-up before aortic complications. It is our experience that underdiagnosis could be improved by familial screening [8].

Table 6.1. Diagnostic criteria for Marfan syndrome [3]. The involvement of three systems with two major criteria is required for the diagnosis of Marfan syndrome

Skeletal system
A major criterion is defined by the presence of at least four of the following:
- Pectus carinatum
- Pectus excavatum severe enough to require surgery
- Reduced upper to lower segment ratio or arm span to height ratio greater than 1.05
- Positive wrist and thumb signs
- Reduced extension of the elbows (less than 170°)
- Medial displacement of the medial malleolus associated with pes planus
- Protrusio acetabuli of any degree (ascertained on radiographs, computed tomography, or MRI)

Involvement of the skeletal system is defined by the presence of two of the preceding features or the presence of one of the preceding features and two of the following: pectus excavatum not requiring surgery; joint hypermobility; high arched palate; facial features (at least two of the following: dolichocephaly; malar hypoplasia; enophtalmos, retrognathia; downslanting palpebral fissures)

Ocular system
A major criterion is defined by ectopia lentis of any degree
Involvement of the ocular system is defined by the presence of at least two of the following: flat cornea; increased axial length of the globe; hypoplastic ciliary muscle causing decreased miosis

Cardiovascular
A major criterion is defined by dilatation or dissection of the ascending aorta with or without aortic regurgitation and involving at least the sinuses of Valsalva

Involvement of the cardiovascular system requires the presence of at least one major criterion or one of the following: mitral valve prolapse with or without mitral regurgitation; dilatation of the main pulmonary artery, in the absence of valvular or peripheral pulmonic stenosis, under the age of 40 years; calcification of the mitral annulus under the age of 40 years; dilatation or dissection of the descending thoracic or abdominal aorta under the age of 40 years

Pulmonary system
Involvement is defined by either spontaneous pneumothorax or radiological evidence of apical blebs

Skin and teguments

Involvement is defined by either striae distensiae or a recurrent or incisional hernia

Dura
A major criterion is the presence of lumbosacral dural ectasia

Family and genetic history
A major criterion is defined by one of the following: a first-degree relative who independently meets diagnostic criteria for Marfan syndrome; the presence of a mutation in the *FBN1* gene that is likely to be pathogenic or the presence of a haplotype around the *FBN1* gene locus inherited by descent and unequivocally associated with diagnosed Marfan syndrome in the family

The occurrence of familial forms of aneurysm in more than 10% of the non-Marfan population [9] justifies the systematic screening of direct family members of patients with ascending aortic aneurysms. Familial forms of bicuspid aortic valves have been reported [10, 10a], and bicuspid aortic valves have been associated with alteration of the wall of the ascending aorta which is similar to that observed in Marfan syndrome (cystic medial necrosis) [11]. This histological anomaly and not the haemodynamic consequences of bicuspid aortic valves is responsible for aortic dilation. Other familial ascending aortic aneurysms have been recognised unrelated to bicuspid aortic valves or Marfan or Marfan-like disease [7, 12–14].

6.3 Aortic Anomaly in Marfan Syndrome

Aortic dissection and dilatation are mainly observed on the proximal part of the ascending aorta in patients with Marfan syndrome: this portion of the aorta is submitted to maximal haemodynamic stress, and is the richest in elastic fibres as well as in fibrillin 1. However, haemodynamic studies have clearly demonstrated that the entire aortic wall properties are altered [15, 16], even when the aortic diameter is within normal values [17]. Although less common, aortic dissection of the descending aorta also occurs in patients with Marfan syndrome [18]. It is interesting to note that although fibrilin is a ubiquitous molecule, wall properties of arteries others than the aorta are not altered in Marfan patients [15]. Therefore medical treatment and follow-up should be focused on the entire aorta.

It is generally assumed that patients with aortic dilatation who do not fulfil the Marfan criteria have abnormalities throughout the entire aortic wall. This has not been studied specifically, but is based on the facts that:
- Marfan syndrome, although clinically defined as a single entity, may be related to different genetic defects, and therefore includes different diseases (*FBN1* mutation, *TGFBR2* mutation or neither).
- Some overlap is seen in the clinical picture in patients with Marfan syndrome and nonsyndromic aortic dilation.
- Histology does not allow for recognition of Marfan syndrome, bicuspid aortic wall or dilation in relation with neither of these entities.

6.4 Exercise Limitation

Limitation of stress applied to the aortic wall may be achieved by limiting exercise and by beta-blocker therapy.

The avoidance of some exercise is based on the assumption that an increase in blood pressure is detrimental to patients because it favours aortic dilation, although no randomised data have been obtained. Actually the reports of the detrimental effect of intense sports are limited to case reports [19–22]. Nevertheless,

the pathophysiological background is strong enough to allow good convergence of views between recommendations [23, 24]. Recent recommendations have been published under the auspice of the American Heart Association [25].

"Burst" exertion (or sprinting), characterised by rapid acceleration and deceleration over short distances, should be avoided. Exercise of this type is encountered in a variety of sports, such as basketball (particularly full-court play), soccer, and tennis. Therefore, preference is given to recreational sporting activities such as informal jogging without a training regimen, biking on level terrain, or lap swimming, in which energy expenditure is largely stable and consistent, even over relatively long distances or periods of time.

Intense static (isometric) exertion, such as lifting free weights, may prove to be adverse by increasing wall stress and weakening the aortic media in patients with Marfan syndrome, particularly if aortic dilatation is already present.

Recreational sports are categorised with regard to high, moderate, and low levels of exercise and are graded on a relative scale (from 0 to 5) for eligibility with 0–1 indicating generally not advised or strongly discouraged, 4–5 indicating probably permitted, and 2–3 indicating intermediate and to be assessed clinically on an individual basis.

This classification is proposed for patients with no or only mild aortic dilation. Sports are classified as:

0: Body building, weightlifting, scuba diving
1: Ice hockey, rock climbing, windsurfing, surfing
2: Basketball, racquetball/squash, running (sprinting), skiing (downhill), skiing (cross-country), soccer, baseball/softball, motorcycling, sailing
3: Tennis (singles), touch (flag) football, biking, jogging, swimming (lap), hiking, horseback riding
4: Tennis (doubles), treadmill/stationary bicycle
5: Modest hiking, bowling, golf, Skating, snorkelling, brisk walking

Therefore, exercise limitation in patients with Marfan syndrome should be individualised, and the final decision is taken by the patients. They need to understand the deleterious effect of isometric exercise, competition, and the better tolerance of the endurance type of exercise, with limited intensity.

6.5 Medical Therapy

Medical therapy has been developed based on the assumption that aortic dilation and dissection are favoured by the repeated aortic stretch secondary to blood ejection by the left ventricle. Therefore, it was initially aimed at decreasing dp/dt and the rebound wave. The use of beta-blockers in this setting was reinforced by the observed benefit on turkeys prone to aortic dissection [26]. However, invasive haemodynamic measurements performed in patients scheduled for aortic surgery (and hence significant dilatation of the initial aorta) failed to demonstrate any significant decrease in dp/dt with acute injection of beta-blockers and actually showed an increase in the rebound wave, responsible, in conjunction with bradycardia, for an increase in pulse pressure [27]. It is therefore unclear if acute beta-blockade decreases the stress applied to the initial aorta during each systole. Beta-blockade may also prove beneficial through bradycardia; however, the importance of this mechanism has not been ascertained and is rarely quoted even if it is likely to be the main mechanism by which beta-blockers improve the prognosis of the patients. More recently, a beneficial effect of beta-blocking agents on aortic compliance of patients was proposed [28]. The proposed mechanism would be to acutely decrease blood pressure and, in the long term, limitation of aortic alteration and dilatation.

The benefits of beta-blockade in Marfan patients were evaluated during an open label, placebo control, parallel group study performed in 70 Marfan patients older that 12 years (Fig. 6.1) [29]. Propranolol was used at a dose aimed at limiting the peak exercise heart rate below 100 beats/min. The mean follow-up was 10 years. The mean slope of the regression line of the aortic-root dimensions, which reflects the rate of dilatation, was 3 times lower in the treatment group than in the control group, and end points (death, dissection, aortic dilatation over 60 mm or aortic regurgitation) tended to be lower in the treatment group (five including two not taking their pills vs nine controls). The effect of beta-blockade was observed irrespective of the importance of initial dilatation. Although the design of this pharmacological therapeutic study does not fulfil the criteria of modern studies, it was felt by the medical community to be sufficient to demonstrate the benefit of beta-blockers in adults, which are therefore recommended irrespective of the aortic diameter.

In children, no randomised study has ever been performed and discussion regularly recurs. Two retrospective analyses have suggested a benefit in children: one reporting a decrease in the rate of the aortic dilatation (absolute diameter and diameter normalised for age and body size) in female patients less than 17 years old or in male patients less than 19 years old when compared with children not receiving treatment [30]. The second study compared patients presenting under the age of 21 with contraindication to beta-blockade with patients who presented at a similar age and were given beta-blockade either at Johns Hopkins University or at the University of Tennessee [31]. The protective effect of beta-blockade was also evidenced in this study and appeared to be more pronounced when initiated earlier. It is therefore generally recommended that all Marfan patients in whom diagnosis is certain, adult as well as

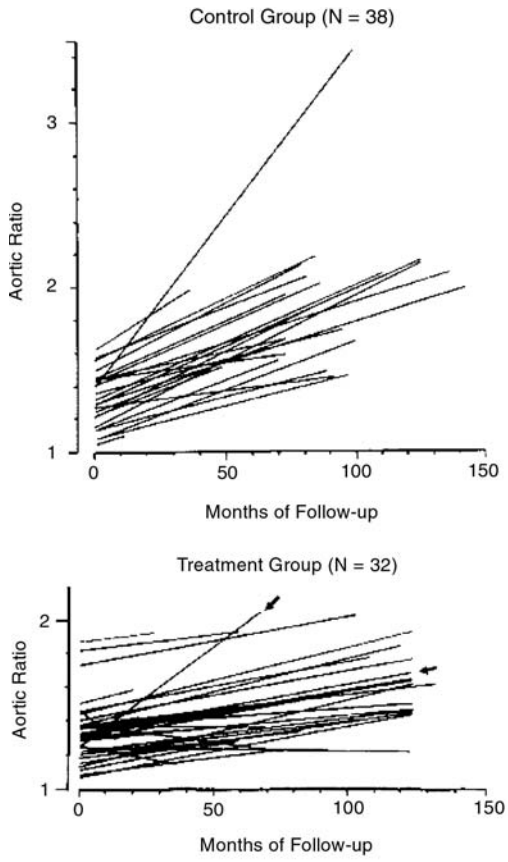


Fig. 6.1. Benefit of beta-blockade in patients receiving beta-blocker therapy [29]

children, should be treated with beta-blockade when tolerated although the consensus is less strict in younger patients without aortic dilatation.

The question arises as to what should be proposed to patients who do not tolerate the beta-blockers? Alternative therapy is proposed on the basis of the presupposed pathophysiological beneficial haemodynamic effect of beta-blockade: bradycardic calcium antagonists are usually used with the aim to decrease heart rate and to slow the left ventricular ejection. No study, however, has demonstrated their clinical benefit.

It has recently been reported that smooth muscle cells, cultured from aortic tissue of patients with Marfan syndrome, showed a shorter survival than smooth muscle cells obtained from normal aorta in the case of serum deprivation [32, 33]. This observation has been reproduced and it was shown that the use of angiotensin converting enzyme inhibition prolonged survival of these deprived cells to normal values [34]. This appeared to be the result of decreased stimulation of angiotensin II (ATII) type 2 receptors because sartans were devoid of this preventive effect, whereas ATII type 2 receptor blocker reproduced the beneficial effect of the angiotensin converting enzyme inhibition. Although obtained in a pure in vitro study, these results may suggest alternative or more likely additive therapy for patients with Marfan syndrome.

Recent studies in mouse models of Marfan syndrome has led to new understanding of the pathophysiology of this disease. Increased TGF-β signaling has been shown in Fbn1-hypomorphic mice in lung [34a] and in mitral valve tissue of knock-in mice harboring a missense mutation [34b]. These phenotypes were rescued by a TGF-β neutralizing antibody [34a,b]. Fibrillin-1 shares homology with latent TGF-β binding proteins (LTBPs), which bind to the small latent complex of TGF-β and sequestrate it to the extracellular matrix [34c]. Thus fibrillin-1 abnormalities may lead to altered sequestration of the latent form of TGF-β in the extracellular matrix and therefore increased TGF-β activity [34d]. This finding, in addition of the mutations in TGF beta-receptors 2 and 1 leading to aortic aneurysm alone or integrated into a Loyes Dietz syndrome, or a classical Marfan syndrome, challenges the classical thinking of fibrillinopathy leading to elastin misarrangement and therefore weakness of aortic wall. They indicate that TGF-β signaling abnormalities underlie the pathogenesis of Marfan syndrome, especially for some diseased organs. Finally, very recently, blocking angiotensin 2 type 1 receptors with losartan (antagonizing TGF-β pathway in some animal models) has been shown to limit the aortic dilation in the mouse model, when given very early on [34e]. Whether this finding will lead to modifications in management of Marfan syndrome and further aortic aneurysm in the man is the subject of clinical studies to be performed in the near future.

After surgery, the same precautions should prevail as only part of the abnormal aorta has been removed. Therefore beta-blockade and exercise limitation remain necessary.

Blood pressure control is absolutely critical in the Marfan population, and the prevalence of hypertension is increasing as life expectancy improves. It is of upmost importance in patients who have only part of their dissected aorta removed in surgery.

In these patients aortic dilatation often occurs inexorably and is usually maximal in the higher part of the descending thoracic aorta, often requiring surgery some years later. In our experience, 50% of the patients presenting dissection of the descending aorta, usually as an extension of a dissection of the ascending aorta, had been operated on or had died within 5 years. Beta-blockade and decreasing blood pressure are two of the few medical tools available to delay this high-risk surgery. We aim for a systolic blood pressure lower than 130 mmHg in this population, or lower if tolerated, and beta-blockade is mandatory.

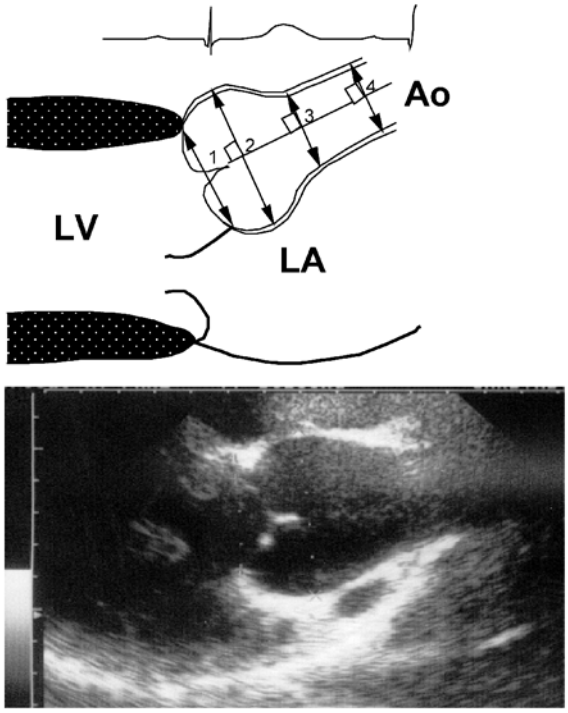


Fig. 6.2. Measurement of aortic diameter [39]

6.6 Follow-Up

The principal aim of follow-up is to propose surgery before aortic dissection has occurred. The aortic diameter is the principal predictor of aortic rupture or dissection [35]. In a large retrospective study gathering thoracic aortic aneurysms from different aetiologies, the risk for rupture or dissection was 6.9% per year, and death, rupture, or dissection was 15.6% per year for a size greater than 6.0 cm. The odds ratio for rupture increases 27-fold compared with lower values [36]. Similarly, patients operated on at the John Hopkins University had a greater risk of being operated on because of aortic dissection when the aortic diameter was greater [37]. Operative and postoperative mortality is higher when surgery is performed in an emergency setting. Lastly, the presence of dissection of the descending aorta is indicative of poor prognosis: in our experience, new surgery or death was encountered in 50% of the patients after 5 years. Therefore, measurement of the ascending aortic diameter is of critical importance for us to be able to propose timely surgery for replacement of the aortic root.

6.6.1 Technique of Measurement

Aortic root diameter can be measured using echocardiography, a computed tomography (CT) scan, or MRI. Transthoracic echocardiography remains the preferred investigation because of easy accessibility and good visualisation of the aortic root in most patients. However, in some patients, mainly as a result of chest deformation, it may be difficult to obtain a reliable aortic diameter using transthoracic echocardiography, in which case alternative techniques should be used (CT or MRI).

Whichever investigation is performed, great care must be taken to measure the diameter of the aorta in a plane which is perpendicular to the major axis of the vessel, during telediastole (Fig. 6.2): horizontal images, for example, such as those obtained from a CT scan before reconstruction, may show a distorted aortic root, obliquely imaged, which results in an overestimation of the aortic diameter. In any case, if doubt exists about the exact measurement of the aorta, the use of another technique to validate the figure obtained is recommended, at least for the first measurement. The same holds true when a brisk increase in diameter is observed during follow-up: confirmation of the evolution of the diameter should be obtained before surgery is considered.

However, the aortic dilatation may not be strictly symmetrical and the antero-posterior measurement made by echocardiography may then be a underestimation of the maximal aortic diameter at the level of the sinuses of Valsalva [38]. It appears therefore reasonable to systematically visualise the aortic root in the short-axis view to avoid gross underestimation of the maximal diameter in the case of frankly asymmetrical dilatation. The importance of a slight discrepancy is more difficult to evaluate as the validated prognostic marker is the antero-posterior diameter.

The aim for measuring the aortic diameter is twofold: first, to make the diagnosis of aortic dilatation, a major sign for the diagnosis of Marfan syndrome, and, second, to propose timely surgery.

The importance of normal values to recognise dilatation of the ascending aorta is obvious. Normal values have been published for adults and children, and are dependent on age and body surface area [39]. In adults the normal values from Roman et al. [39] are largely recognised as the standard. Specific nomograms for tall men (more than 189 cm) and women (more than 175 cm) have been proposed [40].

The normal values are more difficult to determine in children: it is our experience and that of others [41] that in some children an aorta initially considered as dilated according to the normal values proposed by Roman et al. is subsequently found to be within normal limits during follow-up. Other nomograms have been proposed with wider normal ranges [41]; the ratio of the sinus of Valsalva over the annulus has been found to be independent of age, height, and weight by some authors [42], and a ratio above 1.45 has been proposed as a diagnostic cutoff in children [43]. According to these authors, the principal limitation of this ratio is related to the dilatation of the aortic annulus, responsible

for aortic insufficiency. Normal values have been proposed by others for the aortic annulus [44]. Normalisation by the square root of the body surface area has also been proposed, with a mean normal value of 21 mm/m^2 [45].

6.6.2 Frequency for Follow-Up

Currently the recommended follow-up for aortic root measurement is once a year, when the aortic dilation is moderate. However, when the diameter comes to values close to surgical threshold, a 6-month interval follow-up is usually proposed. Similarly, when the aortic diameter appears to increase, the confirmation of the measurement using another technique is necessary and repeated measurements at 2-month intervals may be performed to confirm the evolution of the diameter and the indication for surgery or the stabilisation of the diameter at a new value, allowing for medical management.

6.6.3 Indications for Surgery

The indications for surgery are based on the appreciation of the risk of aortic dissection. Factors associated with increased risk are:

- First of all, the aortic diameter at the level of the sinuses of Valsalva (maximal diameter) [35] (cf. supra). The risk increases dramatically after 60 mm, although aortic dissection may occur when the aorta is of normal size [37]. Indications for surgery have been proposed in the past when the aortic diameter was 60 mm. With the progress in surgery, the limit of 55 mm has been proposed [46], and nowadays most teams would propose surgery when the aortic diameter is reaching 50 mm, as is stated in the recently published recommendations from the European Society of Cardiology [47], particularly if other risk factors are present. A proposition for standardisation of the aortic diameter by height has been made by Svensson and Khitin [48], who proposed that surgery should be considered when the ratio of the aortic area divided by the height is greater than 10 [r^2 (centimetres) $\times$ π/height (metres)]. However, the relation between aortic dilatation and the risk of aortic rupture is probably mediated both through the law of Laplace, which is independent of body size, and through the fragility of the aortic wall, which will be more important when the diameter of the aorta is greater than baseline values. This last phenomenon is better evaluated by the normalised aortic diameter, either by a ratio compared with the normal theoretical value, or by height or body surface area, depending on the authors. Therefore, the importance of normalising the aortic diameter for the purpose of timing surgery is not clear-cut.
- The fact that aortic dilatation is diffuse and goes beyond the sinuses of Valsalva on the ascending aorta has been associated with an increased risk for aortic dissection [35].
- A family history of aortic dissection [49], which is considered as an indication for earlier surgery, especially if the aortic diameter before dissection is known and is only mildly enlarged.
- Rapid dilation of the aorta.
- The absence of beta-blocker therapy.
- Probably aortic regurgitation. Beyond increasing the risk for aortic dissection through an increase in stroke volume, aortic regurgitation, in the long run, alters aortic leaflets, making valve-sparing intervention more difficult.
- Pregnancy (cf. infra) is a specific situation.

It is our current practice to propose surgery when the aortic diameter is above 50 mm, and we do not index this value for body size. Our experience is that with this threshold, aortic valve sparing operation is almost always possible and the risk for aortic dissection is minimal. However, aortic dissection may rarely occur after minimal dilatation of the aorta.

After surgery the patient remains at risk, as only part of the entirely abnormal aorta has been removed. Therefore, exercise limitation and beta-blocker therapy remain necessary. The diameter of the remaining native aorta should be checked using a CT scanner or MRI every few years. When dissection of the descending aorta is present, generally as an extension of a dissection of the ascending aorta, the aortic diameter should be checked every year, as dilatation usually inexorably occurs. As stated earlier, after 5 years, only 50% of the Marfan patients presenting a dissection of the descending aorta remained free of complication or surgery. The higher part of the descending aorta is usually where there is predominant dilatation and so should be checked. We usually propose surgery when the maximal diameter is above 60 mm.

6.6.3.1 Aortic Regurgitation

Aortic regurgitation may be related to different mechanisms. The first mechanism, aortic dilatation, particularly of the sino-tubular junction, leads to an increase in aortic orifice area and central, axial, aortic regurgitation. In this case the aortic regurgitation is roughly proportional to aortic dilatation. This is rare when the aortic diameter is lower than 40 mm, and is the rule when the aortic diameter is greater than 60 mm. The second mechanism which can be responsible for aortic regurgitation irrespective of the aortic diameter is the prolapse of an aortic leaflet leading to an eccentric regurgitant jet. Endocarditis should be prevented as soon as regur-

gitation is present, of either the aortic or the mitral valve.

Whatever the mechanism, the aortic regurgitation alters the aortic valve leaflets, so that long-term regurgitation renders valve-sparing operation difficult. The other classic complication of aortic regurgitation, i.e. heart failure, which was of major importance in the past [1], is now very seldom seen in adults. Indications for surgery are now almost always related to aortic dilation and not to heart failure or important aortic regurgitation. Important aortic regurgitation is sometimes encountered after valve-sparing surgery, and may necessitate replacement surgery.

6.6.3.2 Pregnancy

Pregnancy is associated with an increased risk of aortic dissection: combining the figures of the different series reported, a risk of around 4% can be calculated in women for each pregnancy. In these series, most of the women were unaware of the diagnosis, and were not receiving beta-blockers. The recommendation is to advise the risk of pregnancy as acceptable when the ascending aorta is less than 40 mm in diameter, and to advise against pregnancy when it is above 40–45 mm. Beta-blockers should be taken throughout pregnancy and after delivery, and close echocardiographic follow-up should be performed with examination after 3 and 6 months of pregnancy, and every month thereafter including once a month after delivery. Most of the reported dissections occurred during the third trimester and so delivery is generally induced to limit its duration. Caesarean section is recommended when the aortic diameter is more than 40 mm or is increasing rapidly. Every effort should be made to maintain constant blood pressure at delivery.

It has been proposed that pregnancy after preventive aortic surgery, particularly after valve-sparing operation, is low risk. However, part of the abnormal aorta remains in place, and one of our patients presented dissection of the descending aorta during pregnancy after preventive aortic valve sparing surgery.

6.6.3.3 Neonatal Marfan Syndrome

The neonatal form of Marfan disease is beyond the scope of this review. Aortic dilation is often present, but the cardiovascular manifestation is congestive heart failure secondary to mitral and aortic regurgitation. The prognosis is dismal, with death occurring within months, and the prevalence of neonatal mutation is much higher in this form of the disease than in the adult population.

6.7 Conclusion

Marfan syndrome is a genetic disease, the best recognised aetiology of ascending aortic aneurysm. Because of its genetic nature, familial screening is crucial to diagnose the disease before complications have occurred. Regular follow-up with echocardiography should allow timely surgery for aortic root replacement, ideally using a valve-sparing procedure. Beta-blockage and avoidance of violent sports are the mainstay of medical therapy and may delay surgery or even avoid it in some patients. Medical therapy and close follow-up should be maintained after surgery in all patients. Blood pressure control and close follow-up is of upmost importance in patients with persistent dissection of the descending thoracic aorta.

Patients with aortic aneurysm or dissection who do not fulfil the Marfan criteria and who have unknown aetiology, should also have systematic familial screening because of the familial pattern of inheritance in some cases.

References

1. Murdoch JL, Walker BA, Halpern BL, Kuzma JW, McKusick VA. Life expectancy and causes of death in the Marfan syndrome. N Engl J Med 1972; 286:804–808.
2. Silverman D, Burton K, Gray J, Bosner M, Kouchoukos N, Roman M, Boxer M, Devereux R, Tsipouras P. Life expectancy in the Marfan syndrome. Am J Cardiol 1995; 75:157–160.
3. De Paepe A, Devereux R, Dietz H, Hennekam R, Pyeritz R. Revised diagnostic criteria for the Marfan syndrome. Am J Hum Genet 1996; 62:417–426.
4. Dietz HC, Cutting GR, Pyeritz RE, Maslen CL, Sakai LY, Corson GM, Puffenberger EG, Hamosh A, Nanthakumar EJ, Curristin SM, et al. Marfan syndrome caused by a recurrent de novo missense mutation in the fibrillin gene [see comments]. Nature 1991; 352:337–339.
5. Januzzi JL, Marayati F, Mehta RH, Cooper JV, O'Gara PT, Sechtem U, Bossone E, Evangelista A, Oh JK, Nienaber CA, Eagle KA, Isselbacher EM. Comparison of aortic dissection in patients with and without Marfan's syndrome (results from the International Registry of Aortic Dissection). Am J Cardiol 2004; 94:400–402.
6. Mizuguchi T, Collod-Beroud G, Akiyama T, Abifadel M, Harada N, Morisaki T, Allard D, Varret M, Claustres M, Morisaki H, Ihara M, Kinoshita A, Yoshiura K, Junien C, Kajii T, Jondeau G, Ohta T, Kishino T, Furukawa Y, Nakamura Y, Niikawa N, Boileau C, Matsumoto N. Heterozygous TGFBR2 mutations in Marfan syndrome. Nat Genet 2004; 36:855–860.
7. Hasham SN, Willing MC, Guo DC, Muilenburg A, He R, Tran VT, Scherer SE, Shete SS, Milewicz DM. Mapping a locus for familial thoracic aortic aneurysms and dissections (TAAD2) to 3p24-25. Circulation 2003; 107:3184–3190.

7a. Zhu L, Vranckx R, Van Kien PK, Lalande A, Boisset N, Mathieu F, Wegman M, Glancy L, Gasc JM, Brunotte F, Bruneval P, Wolf JE, Michel JB, Jeunemaitre X. Mutations in myosin heavy chain 11 cause a syndrome associating thoracic aortic aneurysm/aortic dissection and patent ductus arteriosus. Nat Genet 2006; 38(3):343–349.

8. Hirtzlin I, Kiyeila-Loubaki F, Jondeau G. [Medical histories of patients with Marfan's syndrome]. Arch Mal Coeur Vaiss 2004; 97:855–860.
9. Coady MA, Davies RR, Roberts M, Goldstein LJ, Rogalski MJ, Rizzo JA, Hammond GL, Kopf GS, Elefteriades JA. Familial patterns of thoracic aortic aneurysms. Arch Surg 1999; 134:361–367.
10. Emanuel R, Withers R, O'Brien K, Ross P, Feizi O. Congenitally bicuspid aortic valves. Clinicogenetic study of 41 families. Br Heart J 1978; 40:1402–1407.

10a. Cripe L, Andelfinger G, Martin LJ, Shooner K, Benson DW. Bicuspid aortic valve is heritable. J Am Coll Cardiol 2004; 44(1):138–143.

11. Bauer M, Pasic M, Meyer R, Goetze N, Bauer U, Siniawski H, Hetzer R. Morphometric analysis of aortic media in patients with bicuspid and tricuspid aortic valve. Ann Thorac Surg 2002; 74:58–62.
12. Khau Van Kien P, Wolf JE, Mathieu F, Zhu L, Salve N, Lalande A, Bonnet C, Lesca G, Plauchu H, Dellinger A, Nivelon-Chevallier A, Brunotte F, Jeunemaitre X. Familial thoracic aortic aneurysm/dissection with patent ductus arteriosus: genetic arguments for a particular pathophysiological entity. Eur J Hum Genet 2004; 12:173–180.
13. Guo D, Hasham S, Kuang SQ, Vaughan CJ, Boerwinkle E, Chen H, Abuelo D, Dietz HC, Basson CT, Shete SS, Milewicz DM. Familial thoracic aortic aneurysms and dissections: genetic heterogeneity with a major locus mapping to 5q13-14. Circulation 2001; 103:2461–2468.
14. Vaughan CJ, Casey M, He J, Veugelers M, Henderson K, Guo D, Campagna R, Roman MJ, Milewicz DM, Devereux RB, Basson CT. Identification of a chromosome 11q23.2-q24 locus for familial aortic aneurysm disease, a genetically heterogeneous disorder. Circulation 2001; 103:2469–2475.
15. Jondeau G, Boutouyrie P, Lacolley P, Laloux B, Dubourg O, Bourdarias JP, Laurent S. Central pulse pressure is a major determinant of ascending aorta dilation in Marfan syndrome. Circulation 1999; 99:2677–2681.
16. Hirata K, Triposkiadis F, Sparks E, Bowen J, Wooley CF, Boudoulas H. The Marfan syndrome: abnormal aortic elastic properties. J Am Coll Cardiol 1991; 18:57–63.
17. Groenink M, de Roos A, Mulder BJ, Verbeeten B Jr, Timmermans J, Zwinderman AH, Spaan JA, van der Wall EE. Biophysical properties of the normal-sized aorta in patients with Marfan syndrome: evaluation with MR flow mapping. Radiology 2001; 219:535–540.
18. Hagan PG, Nienaber CA, Isselbacher EM, Bruckman D, Karavite DJ, Russman PL, Evangelista A, Fattori R, Suzuki T, Oh JK, Moore AG, Malouf JF, Pape LA, Gaca C, Sechtem U, Lenferink S, Deutsch HJ, Diedrichs H, Marcos y Robles J, Llovet A, Gilon D, Das SK, Armstrong WF, Deeb GM, Eagle KA. The International Registry of Acute Aortic Dissection (IRAD): new insights into an old disease. JAMA 2000; 283:897–903.
19. Bain MA, Zumwalt RE, van der Bel-Kahn J. Marfan syndrome presenting as aortic rupture in a young athlete: sudden unexpected death? Am J Forensic Med Pathol 1987; 8:334–337.
20. Patton DJ, Galliani CA, Johnson WH Jr, Hedlund GL. Sudden death in Marfan syndrome. AJR Am J Roentgenol 1995; 165:160.
21. Buchino JJ, Singer JI, Dixon WD. Case records of Wright State University: an unresponsive five-year-old boy. Pediatr Emerg Care 1998; 14:432–435.
22. Glorioso J Jr, Reeves M. Marfan syndrome: screening for sudden death in athletes. Curr Sports Med Rep 2002; 1:67–74.
23. Braverman AC. Exercise and the Marfan syndrome. Med Sci Sports Exerc 1998; 30:S387–395.
24. Mitchell JH, Haskell WL, Raven PB. Classification of sports. J Am Coll Cardiol 1994; 24:864–866.
25. Maron BJ, Chaitman BR, Ackerman MJ, Bayes de Luna A, Corrado D, Crosson JE, Deal BJ, Driscoll DJ, Estes NA, 3rd, Araujo CG, Liang DH, Mitten MJ, Myerburg RJ, Pelliccia A, Thompson PD, Towbin JA, Van Camp SP. Recommendations for physical activity and recreational sports participation for young patients with genetic cardiovascular diseases. Circulation 2004; 109:2807–2816.
26. Simpson CF, Boucek RJ. The B-aminopropionitrile-fed turkey: a model for detecting potential drug action on arterial tissue. Cardiovasc Res 1983; 17:26–32.
27. Yin FC, Brin KP, Ting CT, Pyeritz RE. Arterial hemodynamic indexes in Marfan's syndrome. Circulation 1989; 79:854–862.
28. Rios AS, Silber EN, Bavishi N, Varga P, Burton BK, Clark WA, Denes P. Effect of long-term beta-blockade on aortic root compliance in patients with Marfan syndrome. Am Heart J 1999; 137:1057–1061.
29. Shores J, Berger KR, Murphy EA, Pyeritz RE. Progression of aortic dilatation and the benefit of long-term beta-adrenergic blockade in Marfan's syndrome. N Engl J Med 1994; 330:1335–1341.
30. Rossi-Foulkes R, Roman MJ, Rosen SE, Kramer-Fox R, Ehlers KH, O'Loughlin JE, Davis JG, Devereux RB. Phenotypic features and impact of beta blocker or calcium antagonist therapy on aortic lumen size in the Marfan syndrome. Am J Cardiol 1999; 83:1364–1368.
31. Salim MA, Alpert BS, Ward JC, Pyeritz RE. Effect of beta-adrenergic blockade on aortic root rate of dilation in the Marfan syndrome. Am J Cardiol 1994; 74:629–633.
32. Sakomura Y, Nagashima H, Aoka Y, Uto K, Sakuta A, Aomi S, Kurosawa H, Nishikawa T, Kasanuki H. Expression of peroxisome proliferator-activated receptor-gamma in vascular smooth muscle cells is upregulated in cystic medial degeneration of annuloaortic ectasia in Marfan syndrome. Circulation. 2002; 106:I259–263.
33. Nataatmadja M, West M, West J, Summers K, Walker P, Nagata M, Watanabe T. Abnormal extracellular matrix protein transport associated with increased apoptosis of vascular smooth muscle cells in marfan syndrome and bicuspid aortic valve thoracic aortic aneurysm. Circulation 2003; 108(Suppl 1):II329–334.
34. Nagashima H, Sakomura Y, Aoka Y, Uto K, Kameyama K, Ogawa M, Aomi S, Koyanagi H, Ishizuka N, Naruse M, Kawana M, Kasanuki H. Angiotensin II type 2 receptor mediates vascular smooth muscle cell apoptosis in cystic medial degeneration associated with Marfan's syndrome. Circulation 2001; 104:I282–287.

34a. Neptune ER, Frischmeyer PA, Arking DE, et al. Dysregulation of TGF-beta activation contributes to pathogenesis in Marfan syndrome. Nat Genet 2003; 33:407–411.

34b. Ng CM, Cheng A, Myers LA, et al. TGF-beta-dependent pathogenesis of mitral valve prolapse in a mouse model of Marfan syndrome. J Clin Invest 2004; 114:1586–1592.

34c. Isogai Z, Ono RN, Ushiro S, et al. Latent transforming growth factor betabinding protein 1 interacts with fibrillin and is a microfibril-associated protein. J Biol Chem 2003; 278:2750–2757.

34d. Kaartinen V, Warburton D. Fibrillin controls TGF-beta activation. Nat Genet 2003; 33:331–332.

34e. Habashi JP, Judge DP, Holm TM, Cohn RD, Loeys BL, Cooper TK, Myers L, Klein EC, Liu G, Calvi C, Podowski M, Neptune ER, Halushka MK, Bedja D, Gabrielson K, Rifkin DB, Carta L, Ramirez F, Huso DL, Dietz HC. Losartan, an AT1 antagonist, prevents aortic aneurysm in a mouse model of Marfan syndrome. Science 2006; 312 (5770):117–121.

35. Roman MJ, Rosen SE, Kramer-Fox R, Devereux RB. Prognostic significance of the pattern of aortic root dilation in the Marfan syndrome. J Am Coll Cardiol. 1993; 22:1470–6.
36. Davies RR, Goldstein LJ, Coady MA, Tittle SL, Rizzo JA, Kopf GS, Elefteriades JA. Yearly rupture or dissection rates for thoracic aortic aneurysms: simple prediction based on size. Ann Thorac Surg 2002; 73:17–27; discussion 27–28.
37. Gott VL, Greene PS, Alejo DE, Cameron DE, Naftel DC, Miller DC, Gillinov AM, Laschinger JC, Pyeritz RE. Replacement of the aortic root in patients with Marfan's syndrome. N Engl J Med 1999; 340:1307–1313.
38. Meijboom LJ, Groenink M, van der Wall EE, Romkes H, Stoker J, Mulder BJ. Aortic root asymmetry in marfan patients; evaluation by magnetic resonance imaging and comparison with standard echocardiography. Int J Card Imaging 2000; 16:161–168.
39. Roman MJ, Devereux RB, Kramer-Fox R, O'Loughlin J. Two-dimensional echocardiographic aortic root dimensions in normal children and adults. Am J Cardiol 1989; 64:507–512.
40. Reed CM, Richey PA, Pulliam DA, Somes GW, Alpert BS. Aortic dimensions in tall men and women. Am J Cardiol 1993; 71:608–610.
41. Rozendaal L, Groenink M, Naeff MS, Hennekam RC, Hart AA, van der Wall EE, Mulder BJ. Marfan syndrome in children and adolescents: an adjusted nomogram for screening aortic root dilatation. Heart 1998; 79:69–72.
42. Sheil ML, Jenkins O, Sholler GF. Echocardiographic assessment of aortic root dimensions in normal children based on measurement of a new ratio of aortic size independent of growth. Am J Cardiol 1995; 75:711–715.
43. Mart CR, Khan SA, Smith FC, Kavey RE. A new on-line method for predicting aortic root dilatation during two-dimensional echocardiography in pediatric patients with Marfan syndrome using the sinus of valsalva to annulus ratio. Pediatr Cardiol 2003; 24:118–121.
44. el Habbal M, Somerville J. Size of the normal aortic root in normal subjects and in those with left ventricular outflow obstruction. Am J Cardiol 1989; 63:322–326.
45. Gutgesell HP, Rembold CM. Growth of the human heart relative to body surface area. Am J Cardiol 1990; 65:662–668.
46. Devereux RB, Roman MJ. Aortic disease in Marfan's syndrome. N Engl J Med 1999; 340:1358–1359.
47. Iung B, Gohlke-Barwolf C, Tornos P, Tribouilloy C, Hall R, Butchart E, Vahanian A. Recommendations on the management of the asymptomatic patient with valvular heart disease. Eur Heart J 2002; 23:1253–1266.
48. Svensson LG, Khitin L. Aortic cross-sectional area/height ratio timing of aortic surgery in asymptomatic patients with Marfan syndrome. J Thorac Cardiovasc Surg 2002; 123:360–361.
49. Silverman DI, Gray J, Roman MJ, Bridges A, Burton K, Boxer M, Devereux RB, Tsipouras P. Family history of severe cardiovascular disease in Marfan syndrome is associated with increased aortic diameter and decreased survival. J Am Coll Cardiol 1995; 26:1062–1067.

Spinal Cord Protection for Descending Aortic Surgery. Clinical and Scientific Basis for Contemporary Surgical Practice

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7

Contents

7.1 Introduction

Paraplegia has been a major concern of thoracic aortic surgeons ever since the first successful resection and replacement of a descending thoracic aneurysm in 1951 (which was, in fact, complicated by paraplegia [1]). Postoperative paraplegia remains the most devastating complication that faces patients undergoing surgery on the descending aorta because loss of lower-limb function imposes severe constraints on quality of life. Additionally, paraplegia is associated with higher postoperative mortality and morbidity.

Surgery on the thoracic aorta poses two distinct threats to the spinal cord. Firstly, to resect the aorta, the surgeon must temporarily interrupt lower-body aortic blood flow, rendering distal organs (including the spinal cord) ischemic intraoperatively. Secondly, replacement of the aorta may result in the permanent loss of spinal cord blood supply originating from the resected aortic segment. Being nervous tissue, the spinal cord tolerates ischemia poorly, and if infarction ensues, paraplegia results. In the early era of thoracic surgery, paraplegia rates in excess of 30% were reported, but with advances in surgical management, paraplegia rates below 10% became achievable in the 1980s [2].

In this chapter we review the contemporary anatomical and pathophysiological understanding of spinal cord blood supply, and present the scientific basis for clinical interventions used during descending aortic surgery to reduce the incidence of paraplegia.

7.2 Blood Supply of the Spinal Cord

7.2.1 Anatomy

The critical role of the descending aorta in the arterial blood supply of the spinal cord makes the spinal cord vulnerable to ischemia during disease processes or in-

terventions that involve the thoraco-abdominal aorta. The arterial supply to the spinal cord has been well studied [3]. The spinal cord is supplied via three longitudinal arteries: the anterior spinal artery, and the two posterior spinal arteries. The anterior artery is larger than the two posterior arteries, and provides 75% of spinal blood flow. There is little collateralization between the anterior and posterior arteries. Because the corticospinal tracts and motor neurons are largely supplied by the anterior spinal artery, it is occlusion or hypoperfusion of this vessel that is responsible for paraplegia. The anterior spinal artery is itself formed in the neck from the vertebral arteries, and continues caudally on the surface of the cord, receiving further blood supply via several segmental arteries (also called radicular arteries), which enter the spinal canal through the vertebral foramina [4]. These radicular arteries enter the cord in the three main regions of the spinal cord: cervical, thoracic and lumbar.

In the cervical region, the radicular arteries arise primarily from the vertebral, cerebellar, ascending cervical and other arteries, all of which arise from aortic arch vessels. As the input to the cervical cord is from the aortic arch, this part of the spinal cord is rarely compromised during descending aortic surgery. In contrast, in the thoracic and abdominal regions, the radicular arteries arise from the intercostal and lumbar arteries, which are branches of the descending aorta. The blood flow to the thoracic and lumbar cord therefore derives principally from the descending aorta, making this the region of the cord that is vulnerable during thoracic aortic surgery.

One segmental artery has assumed particular importance: the arteria radicularis magna (ARM), also known as the artery of Adamkiewicz, is an exceptionally large radicular artery that anastomoses into the mid-segment of the anterior spinal artery. Although large compared with other radicular arteries, the ARM is of variable diameter, ranging from 0.25 to 1.07 mm in cadaveric examinations [5]. Through the anterior spinal artery, the ARM supplies the majority of the flow to the lower thoracic and lumbar cord segments [3]. It can arise from any segmental artery between T7 and L4 on either side, or directly from the aorta, but frequently originates from one of the left segmental arteries between T8 and L1. In a study of 102 cadavers, Koshino et al. [6] found that approximately 70% of Adamkiewicz arteries originated from intercostal and/or lumbar arteries on the left side, frequently at the T8–L1 vertebral level.

Because the anterior spinal artery is generally continuous, loss of inflow from the Adamkiewicz artery alone does not generally result in paraplegia, since the anterior spinal artery will obtain sufficient inflow from the cervical and lumbar/hypogastric regions. On rare occasions, the anterior spinal artery may be poorly formed or discontinuous [4], so that loss of blood supply through the Adamkiewicz artery will render the lower anterior spinal territory ischemic. The incidence of discontinuous anterior spinal arteries is unknown, but two recent cadaveric studies did not find any instances of such discontinuity [5, 7]. Although the Adamkiewicz artery receives great prominence in anatomical texts, its importance is probably overstated. Some surgeons, notably Griepp et al. [8], have questioned the clinical importance accorded to this artery, as they have routinely ligated the presumed origins of this vessel without clinical consequence.

There is additionally an extensive collateral network of vessels surrounding the length of the vertebral column, and communicating with the spinal arteries, which provides an alternate route of blood supply [4, 7]. Arteries feeding this collateral network form the so-called extrasegmental or extrinsic supply to the cord, and include branches of the subclavian artery (other than the vertebral arteries), the posterior vertebral and retrovertebral vessels, the intercostal and lumbar arteries (other than the ARM), the hypogastric arteries and the median sacral artery.

This collateral network becomes clinically relevant during aortic surgery. During aortic clamping, part of the spinal blood supply will route via collaterals from the subclavian arteries [9], making it important to maintain adequate proximal pressures during cross-clamping. Additionally, if segmental blood inflow is lost (such as by endovascular stenting or open repair with division of intercostals), the extrinsic collateral network becomes a major route of blood supply to the mid-cord. Sufficiently high blood pressure is probably necessary to drive blood through these collaterals. This anatomical feature may explain the observation that delayed onset paraplegia after aortic repair is often preceded by hypotension [10] (since a low blood pressure may be insufficient to drive blood through these collaterals to the spinal cord). If the collateral network has previously been disrupted, such as by earlier abdominal or pelvic surgery, then the segmental blood flow assumes greater importance [11]: such patients may be more prone to paraplegia, particularly if segmental vessels are sacrificed.

7.2.2 Determinants of Spinal Blood Flow

As there are no modalities for direct measurement of spinal blood flow in man, current understanding derives from animal experiments and clinical extrapolations. The principal determinants of spinal blood flow are anatomical, physiological and pathological factors.

7.2.2.1 Integrity of Anatomical Pathways

Spinal cord blood flow depends upon anatomical integrity of the circulation described earlier. Anatomical in-

terruptions to the intrinsic or extrinsic blood pathways predispose to regional insufficiency in blood flow. Acute occlusion of intercostal or vertebral inflow (owing to trauma, dissection, endovascular stenting or surgery), in patients with such preexisting interruptions, can result in spinal cord infarction. In more chronic occlusions (which frequently occur in atherosclerotic aneurysms), spinal blood flow is maintained by collaterals which enlarge over time. The ability of the spinal cord to tolerate acute occlusion of the thoracic or lumbar inflow depends in part on the patency of collateral sources of blood supply, particularly the subclavian, vertebral, internal mammary, lumbar and hypogastric vessels. A higher incidence of paraplegia has been observed following endovascular repair of thoraco-abdominal aneurysms when there has been previous repair of an abdominal aortic aneurysm (and therefore sacrifice of the lumbar arteries) [12].

A closed arterial system is necessary to maintain spinal perfusion. If the segmental vessels are disrupted (by surgery or trauma), and bleeding freely, the pressure in the anterior spinal artery will decrease, and blood destined for the cord will flow in a retrograde direction into the thoracic cavity through the open blood vessels: this is the path of least resistance. A resultant drop in spinal blood flow then results because of a combination of the absence of input from the severed vessel and bleeding through the open vessel.

7.2.2.2 Blood Pressure

As is true of other organs, spinal blood flow demonstrates autoregulation, and maintains an adequate blood flow at arterial pressures between 50 and 135 mmHg in healthy adults. In animal models, when the blood pressure falls below 50 mmHg, spinal blood flow is increasingly compromised, with the incidence of spinal infarction rising steeply at blood pressures below 40 mmHg [13]. In patients with hypertension or severe atherosclerotic disease, autoregulation may be set at a higher level, such that higher blood pressures are required to maintain adequate flow. Clinically, a high incidence of spinal cord infarction (46%) has been observed on autopsy in patients who died after prolonged cardiac arrest or severe hypotensive episodes [14]; since spinal infarction is otherwise rare on necropsy, the likely explanation is a poor tolerance of spinal tissue to severe hypotension. Hypotension is often the cause of unexplained spinal infarction in patients who do not have vascular disease. Autoregulation may be abolished to some degree by trauma (including surgery), or by hypoxia and hypercarbia; in such instances, spinal blood flow is directly proportional to arterial blood pressure [15], making the cord sensitive to even small drops in arterial pressure.

7.2.2.3 Cerebrospinal Fluid Pressure

The effective spinal cord perfusion pressure is the difference between the mean arterial pressure and the cerebrospinal fluid (CSF) pressure. Because the spinal cord is in a closed rigid cavity, spinal cord perfusion pressure falls as the CSF pressure increases. It is not certain exactly what level of perfusion pressure is necessary to obtain effective cord perfusion, but extrapolation from clinical observations suggests that perfusion pressure should be greater than 40 mmHg for adequate spinal cord perfusion [16]. CSF pressure is particularly relevant in the setting of aortic surgery because the CSF pressure rises during aortic cross-clamping [17], and, since spinal arterial pressure is already decreased (because the distal aorta has been excluded with clamping), even small increases in CSF pressure may be sufficient to reduce spinal cord perfusion pressure below the limit required for autoregulation, resulting in reduced blood flow and spinal ischemia.

7.2.2.4 Other Factors

Other physiological determinants of spinal cord blood flow include carbon dioxide (flow increases with hypercarbia), hypoxia (flow increases), temperature (flow decreases with hypothermia, but metabolic requirements also decrease) and anesthesia (some agents, like thiopental, reduce blood flow). Vasodilators such as nitroprusside also reduce spinal cord perfusion pressure and hence spinal cord blood flow. This effect of nitroprusside is independent of its effect on systemic blood pressure, and is explained by vasodilatation of the distal aortic bed, which diverts blood from the cord and reduces distal blood pressure, hence reducing spinal perfusion pressure. Nitroprusside is also a cerebral vasodilator, which leads to increased CSF pressures [18, 19].

7.2.2.5 Effects of Aortic Cross-Clamping and Surgical Treatment

Aortic cross-clamping results in hypertension proximal to the clamp, and hypotension distal to the clamp. Cross-clamping therefore results in a reduction in spinal blood inflow from the thoracic and lumbar regions. The blood flow proximal to the clamp, including cerebral blood flow, increases, resulting in an increase in CSF pressure, which further reduces spinal perfusion pressure [13, 20]. The reduction in spinal perfusion pressure from aortic clamping is further exacerbated if the distal aorta or intercostals are bleeding freely, as a consequence of steal phenomena [21]. Avoidance of steal – for example, by clamping the distal aorta above the celiac arteries, or by clamping segmental vessels – has been shown to reduce spinal ischemia in pig models [9]. The severity of spinal cord ischemia is directly proportional to the duration of aortic clamping: this has

been shown in numerous animal models [17]. Clinical studies from the "clamp-and-sew" era confirm this relationship, and a higher incidence of paraplegia is found when cross-clamp times exceed 30 min [22, 23]. Most of these experiments and clinical series do not, however, reflect the complexities of modern clinical practice. In practice, the duration of aortic cross-clamping is also a marker of complexity of disease or procedure (such as the need for extensive thoraco-abdominal resection or multiple intercostal or visceral implantation), making it difficult to isolate the effect of ischemic time from that of other confounding factors. Additionally, with current spinal protection strategies, long periods of aortic cross-clamping can be well tolerated. More recent series incorporating the use of adjuncts have not found a relationship between extended cross-clamp times and neurological injury [24].

7.2.3 Monitoring of Spinal Cord Function

7.2.3.1 Sensory-Evoked Potentials

Popularized by Cunningham and associates in the early 1980s [25], somatosensory-evoked potentials (SSEPs or SEPs) record cortical stimulations through the scalp after peripheral electrical stimulation of the posterior tibial or peroneal nerves. The signal is transmitted through the posterior and lateral columns of the spinal cord, and recorded at the contralateral postcentral gyrus. Ischemia of the spinal cord results in a decrease in amplitude and prolonged latency of these potentials. But although SSEPs have been widely applied clinically for intraoperative monitoring, it has been observed that some patients who develop paraplegia never exhibit changes in intraoperatively monitored SSEPs [26–28]. This limitation of SSEPs can be explained anatomically. Since SSEPs are transmitted through the posterolateral tracts, they primarily reflect ischemia in the region of the posterior spinal arteries. The SSEPs are neither a sensitive nor a specific monitor of the corticospinal tracts in the anterior spinal cord (supplied by the anterior spinal artery), but it is the anterior cord which is usually the first region affected during spinal ischemia, and which causes paraplegia. Therefore, whilst SSEPs detect extensive spinal ischemia affecting global cord function, smaller degrees of ischemia limited to the anterior spinal motor territories may not be detected. In some cases, by the time the ischemia is sufficient to affect sensory transmission, the diagnosis has been sufficiently delayed that motor damage cannot be prevented. Also, SSEPs may produce false-positive results, since changes in sensory potentials can also originate from damage to the brain or to peripheral nerves (owing to acute cerebral events or limb ischemia, both of which can complicate aortic procedures) [29]. All these factors make interpretation of SSEPs complex and limit their clinical benefit. Because of these limitations, motor-evoked potentials (MEPs) were introduced to measure anterior cord function directly, rather than relying on monitoring of sensory pathways by SSEPs.

7.2.3.2 Motor-Evoked Potential

The MEP is a more logical way to detect impending paraplegia as it directly monitors nerve conduction in the corticospinal tract. Use of MEPs greatly increases the sensitivity and specificity of evoked potentials in detecting spinal ischemia compared with monitoring of SSEPs alone [28]. To detect MEPs, the motor cortex or spinal cord proximal to the aortic clamp level is stimulated, and potentials are recorded in the lower spinal cord, peripheral nerves or muscles. Unlike the SSEP, which may have a slow response time, inadequate cord perfusion can result in loss of MEPs within as little as 1 min [30]. As with SSEPs, monitoring of MEPs is also complex, with limitations and confounding factors [31–33]: these include interactions with drugs, unreliability during profound hypothermia, conflicting results in animal experiments and the observation that detection of abnormal MEPs, even with subsequent normalization following adjustment in surgical management, does not necessarily avert paraplegia. The use of MEPs is not universal, and has not been shown to reduce paraplegia rates; some groups achieve low paraplegia rates without the use of MEP monitoring. Although MEPs do provide interesting information regarding spinal cord ischemia, and also provide reassurance that surgical adjunctive measures are working effectively, it has not been proven that clinical benefit derives directly from the information they provide, or from the surgical or medical interventions they may trigger. In most series in which MEPs were monitored, there was also extensive use of adjuncts, making it difficult to attribute any clinical outcomes to use of MEP measurement.

Nevertheless, evoked-potential monitoring remains the only practical method of rapidly detecting spinal cord ischemia in a clinical setting. At least in some patients, this technique has the potential to detect significant spinal cord ischemia and allow remedial measures to be undertaken. In clinical practice, SSEPs are measured concurrently with MEPs, the information from one complementing the other. Where changes in evoked potentials are noted, prompt remedial intervention is instituted (such as change in clamping or intercostal management strategy, blood pressure control, systemic cooling or CSF drainage), particularly if the changes followed a specific surgical maneuver or surgical event, or if MEP/SSEP changes were accompanied by alteration in monitored hemodynamic or other patient parameters. If no clear precipitating factor is found, and all adjuncts are deemed to be working satisfactorily, then consideration is given to the possibility of a brain or peripheral event. Evoked-potential monitoring may

be continued in the postoperative period until the patient can be evaluated clinically if the cord is thought to be particularly vulnerable (such as following complex repair or multiple intercostal artery ligation).

7.2.3.3 Other Approaches

Other experimental approaches of monitoring cord spinal function include measurement of surface spinal oxygen tension, intrathecal oxygen levels, hydrogen ion electrode techniques and F-wave polysynaptic response complex monitoring [34]. The clinical role of these techniques is not established, and aside from application of the hydrogen electrode technique by Svensson [35], their use is confined to laboratory studies. Examination of various biochemical markers in the blood and CSF has been undertaken [36–38], but none have been sufficiently predictive of cord function for routine clinical use.

7.3 Strategies to Minimize Duration of Cord Ischemia

7.3.1 Clamp-and-Sew Techniques

Exclusion of the diseased aorta with clamps, and expeditious anastomosis with limited cross-clamp time, was the original method for repair of aneurysms. This technique was used exclusively by many surgeons for even the most extensive thoraco-abdominal aneurysms during the 1960s and 1970s. No adjuncts are employed. Modifications of this technique include that of Cooley, in which only a single proximal clamp is placed, and the distal body is exsanguinated whilst performing both proximal and distal anastomoses. The rationale for distal exsanguination is that free drainage of the intercostal and lumbar arteries would decrease CSF and central venous pressures, thus offering spinal protection [39]. It is more probable that the low incidence of paraplegia in Cooley's series was because of the short spinal cord ischemic times (average 26 min and as short as 11 min [40]) rather than use of distal exsanguination.

This technique of spinal management relies exclusively on minimizing the ischemic time. As clamp times approach and exceed 30 min, the risk of paraplegia is significantly increased [22, 23] such that a necessary component of the clamp-and-sew approach is the ability to perform all anastomoses in less than 30 min. But if repair is unexpectedly protracted or complicated, the risk of paraplegia will increase. Data suggest that the application of a normothermic clamp-and-sew technique to all patients results in overall higher paraplegia rates, a risk that is largely reduced by use of adjuncts [24, 41–43]. For these reasons, many surgeons have abandoned isolated simple clamp-and-sew techniques for the safety margin offered by distal perfusion or methods involving hypothermia. Some groups have persevered in the clamp-and-sew technique and continue to report excellent results [22, 40, 44].

7.3.2 Sequential Aortic Clamping

In this approach, aortic clamps are applied sequentially while performing the proximal anastomosis, reimplanting intercostals and reimplanting visceral segments, such that at any given time, only a short segment of aorta is excluded, allowing perfusion of segmental and visceral branches except in the area being worked on. Some form of distal bypass ensures perfusion to the lower body. A variation of this technique is to perfuse segmental vessels through side-arm grafts or to direct cannulae whilst performing the aortic anastomoses [45].

7.3.3 Endovascular Therapies

Endovascular stenting provides a useful model for studying spinal cord ischemia. As there is no significant aortic occlusion, distal and proximal cord perfusion are maintained. Sources of alterations in spinal blood flow during the procedure are therefore minimal; the only relevant spinal cord ischemia arises from the sudden loss of blood supply from the intercostals (compared with open surgical repair, where aortic clamping results in wider loss of blood inflow). The paraplegia rate for endovascular stent grafting has yet to be established. Published data suggest an extremely low paraplegia rate. In one review, 18 of 26 published series reported no paraplegia; the remaining eight studies reported paraplegia rates of 3–7% [46]. Studies with small numbers of patients and zero complication rates, however, often do not reflect the true scenario, and underestimate the true event rate [47, 48]. It is likely that the literature is biased, and that series from groups with higher paraplegia rates are not being reported or published. A voluntary registry in Europe reported a higher paraplegia rate of 4% in 249 stent grafts placed in atherosclerotic aneurysms [49], supporting the presence of bias in the published literature. The true risk of paraplegia is therefore not insignificant, but is likely less than seen with open surgery.

The lower incidence of paraplegia with the endovascular approach suggests that spinal cord ischemia is largely related to aortic clamping and cord hypoperfusion during lower body circulatory arrest or bypass. Hypoperfusion due to hypotension in the perioperative period is also generally absent in endovascular approaches (but is not infrequent after open repair due to

hypovolemic, cardiogenic and septic causes); the likelihood of better postoperative perfusion may further explain the lower incidence of paraplegia after stent grafting. The endovascular approach also differs importantly from open surgery in that the sudden loss of intercostal blood flow does not allow for steal syndromes [50], lending support to surgical techniques, such as those of Griepp et al. [21], that include division of intercostal arteries prior to opening of the aneurysm or aortic clamping. The complete absence of paraplegia in some endovascular series of as many as 100 patients [46] suggests that loss of intercostal perfusion of the spinal cord generally does not result in paraplegia (questioning the rationale for routine implantation of these vessels).

The observation of some cases of paraplegia with endovascular grafting, however, implies that, at least in some patients, loss of intercostal blood supply to the cord can, by itself, result in spinal infarction. This may occur in patients in whom the distal spinal or collateral system is anatomically deficient [4], or has previously been compromised by disease or surgery [12]. Although the logical extension is that this observation supports intercostal reimplantation, it cannot be asserted with any certainty that intercostal implantation would necessarily have prevented such events: the patients with paraplegia following endovascular stent grafting may represent the same subset of patients who would have become paraplegic with open repair regardless of the surgical approach (as all surgical approaches have a consistent basal paraplegia rate of about 5% which has not been influenced by technique or adjuncts). Sophisticated analysis and modeling of large datasets of endovascular and open repairs should identify similarities and differences between patients who become paraplegic with either approach, and may help in advancing the understanding of the surgical importance of the intercostal spinal cord blood supply, and also help to determine whether there are any patients in whom paraplegia is almost certain regardless of the therapeutic approach. Systematic application of magnetic resonance angiography prior to aneurysm repair may identify anatomical patterns of the spinal circulation that render patients more vulnerable to paraplegia. Because we are currently unable to identify those susceptible patients in whom intercostal occlusion will result in spinal infarction, some groups are selectively employing adjunctive measures for endovascular stent graft procedures, such as use of CSF drainage, permissive hypertension and permissive hypothermia.

7.4 Strategies to Reduce Severity of Cord Ischemia

7.4.1 Distal Perfusion Techniques

Distal perfusion techniques perfuse the abdominal aorta during the period of aortic cross-clamping, supplying blood to the spinal cord via the lumbar and hypogastric vessels. Although distal perfusion techniques were used by some surgeons in the 1960s, they were not widely adopted because the results were variable, with some suggestion that distal perfusion was ineffective, and resulted in higher paraplegia rates [51]. At that time, however, cardiopulmonary bypass and anesthetic management were in their early stages. It took until the late 1980s for sufficient clinical data to emerge and for techniques to be sufficiently standardized to enable consistent results to be achieved [52]. There is now abundant experimental and clinical evidence that these techniques do reduce the incidence of paraplegia compared with the simple clamp-and-sew approach. Notably, data from studies that included both distal perfusion and clamp-and-sew procedures have demonstrated that the exponential rise in paraplegia rates when clamp times exceed 30 min with clamp-and-sew does not occur when distal perfusion is used [23, 41, 53].

7.4.1.1 Passive Shunts

Historically, passive shunts were the method of choice for distal perfusion. Shunts, such as the Gott shunt, were connected to the aorta or its major limb branches proximal and distal to the clamped aorta, thereby providing blood flow to the distal aorta during clamping. These shunts were relatively simple to apply, and did not require perfusionist support. They were also versatile, since various limb arteries, such as axillary, femoral and iliac, could be used in preference to the aorta. Because of resistance to flow by the shunt, which was narrow relative to the aorta, however, the blood flow and blood pressure in the distal aorta were variable, and significantly less than in the proximal aorta. The proximal aorta may not be sufficiently decompressed, increasing cardiac afterload and CSF pressure, and distal perfusion may be suboptimal. Although the proximal pressures may be manipulated by pharmacological means, the control of distal flows and pressures is difficult and unreliable. In one series, the flow through the shunt, as measured using a flowmeter in 40 patients, varied from 1,100 to 4,000 ml/min [54]. For these reasons, whilst passive shunting may provide increased spinal protection compared with clamp-and-sew techniques, its use has been largely superseded by active bypass [52]. Occasionally, passive shunts may still be preferred, such as in trauma cases where cardiopulmonary

bypass is not immediately available or heparinization is not desirable (heparin-coated cardiopulmonary bypass circuits may obviate the need for heparinization and may be preferable).

7.4.1.2 Active Distal Bypass

Active bypass to the distal aorta overcomes the unpredictability of passive bypass. Blood is drained from the left atrium, and returned to the distal aorta, or to the femoral or iliac arteries. By adjusting the pump flow rate, the distal aortic pressure can be maintained between 60 and 70 mmHg, and by using a combination of partial exsanguination from the left atrium and retransfusion of blood, the proximal pressures are maintained at 70–80 mmHg [8]. Pharmacological agents are used minimally. Experimentally, it has been demonstrated that distal perfusion at pressures of 60 mmHg increases spinal cord perfusion when compared with clamp-and-sew approaches [55, 56]. Some have argued that the time spent performing anastomoses is generally short and inconsequential, questioning the need for distal bypass in all cases [57]. Indeed, a recent analysis of aneurysms confined to the thoracic aorta by Coselli et al. [44] compared 46 patients who had distal bypass with 341 patients where a clamp-and-sew approach was used, and did not find any difference in the incidence of neurological injury. Aside from CSF drainage in 7% of patients, and mild hypothermia, no other adjuncts were used, and intercostals were rarely reattached, suggesting that distal bypass is probably not mandatory in straightforward thoracic repairs [44]. An earlier analysis from the same group, however, did find a lower paraplegia rate using left heart bypass in patients with thoraco-abdominal aneurysms (involving the visceral aorta) [58], confirming the role of distal perfusion in extensive repairs. Even with a brief period of clamping for the proximal anastomosis, an extra 10 min or so added to a 20 min or greater period of ischemia during distal and intercostal reconstruction can prolong the spinal ischemic period beyond 30 min, with the attendant increasing risk of paraplegia. For this reason, many surgeons advocate distal bypass for most descending aorta resections other than simple repairs, in which ischemia time will almost certainly not exceed 25 min. Because unexpected delays and difficulties can emerge, however, many would recommend use of distal bypass in all patients. One understated benefit of distal bypass is the maintenance of renal and gastrointestinal perfusion, with a reduced incidence of renal dialysis compared with clamp-and-sew techniques [41]. Possibly other adjunctive measures may obviate the need for distal bypass; some groups employing a clamp-and-sew approach without bypass use alternative adjunctive measures such as regional or systemic hypothermia [59].

An alternative distal bypass technique is to use the right atrium (via the femoral vein) for venous drainage. By obviating the need for left atrial cannulation, the risk of air embolism is minimized. This technique also allows prompt conversion to cardiopulmonary bypass if required. However, this approach requires full heparinization, and incorporation of an oxygenator in the bypass circuit.

7.4.1.3 Selective Spinal Cord Perfusion

Some workers further attempt to reduce spinal cord ischemia by continuously perfusing the lower intercostal arteries. Experimentally, it has been demonstrated in pigs that segmental artery perfusion can protect the spinal cord for up to 60 min of ischemia [60]. But in this study, the control group had simple aortic cross-clamping without distal perfusion, which is not reflective of the clinical scenario, where adjuncts are frequently used. Selective spinal cord perfusion has been applied clinically utilizing special cannulae [61], or through a Dacron graft [62]. Benefits of this approach have not been demonstrated. The lack of demonstrable additional benefit with intercostal artery perfusion adds to the debate regarding the value of interventions involving intercostal vessels as a means to prevent paraplegia. Retrograde spinal cord perfusion via the hemiazygous system is also being investigated, but has also not been shown to be protective [63].

7.4.2 Physiological Adjuncts

7.4.2.1 Mild to Moderate Systemic Hypothermia

Abundant animal and clinical studies have shown that deep hypothermia protects neural tissues from ischemic injury during periods of circulatory arrest [34]. The basis for the protective effect of hypothermia is a combination of various mechanisms including reduced metabolic rate, inhibition of release of excitatory neurotransmitters (particularly glutamate) and reduced production of superoxide anions [64]. Although most of the experimental work on neuronal protection has concerned deep hypothermia, it has also been demonstrated experimentally that mild to moderate degrees of hypothermia [32–35 °C) also afford spinal cord protection [65–67]. Moderate hypothermia has been an integral part of our operative strategy to minimize cord injury since the early 1990s, and it is achieved by a combination of permissive hypothermia and active cooling using a cooling blanket and a heat-exchanger in the distal bypass circuit if necessary [8]. Clinical studies comparing systemic hypothermia with normothermia have not shown a difference in paraplegia outcome [68]; although one study did report fewer transient neurological deficits in patients with moderate hypothermia, paraplegia rates were similar [69]. However, virtually all animal studies on hypothermia have shown that spinal

cord hypothermia, achieved via whatever means, reduces spinal injury; notably, none of these studies has shown a higher incidence of spinal injury with hypothermia [34]. The inability to demonstrate benefit in clinical studies is likely due to lack of statistical power, and reflects the success of modern surgical techniques and adjunctive measures in minimizing the incidence of paraplegia. Many surgeons extend the use of hypothermia to all patients because it is simple to apply, and has potential benefit and negligible risk (cardiac arrhythmias are rare, even with core temperature as low as 30 °C [70]).

7.4.2.2 Profound Hypothermia and Circulatory Arrest

Greater degrees of hypothermia afford more protection to neural tissue, with the advantage that even longer periods of ischemia are tolerated, compared with normothermic techniques. Because ventricular fibrillation or severe bradycardia is invariable with profound hypothermia, total body circulatory arrest is necessarily a component of this technique. Some groups, notably those of Kouchoukos et al. [71, 72], advocate routine application of deep hypothermic circulatory arrest (DHCA) for treatment of complex thoraco-abdominal aneurysms. Depending upon the extent of aortic replacement and vessel reimplantation, the whole procedure may be undertaken during circulatory arrest, or, for more extensive thoraco-abdominal procedures, circulation is resumed after completion of the proximal and intercostal anastomoses. The advantages of this approach, in terms of spinal protection, are a more uniform cooling of the cord, avoidance of the need for selective intercostal or visceral perfusion, and ability to perform all aortic and intercostal anastomoses open, without circulation, thus avoiding potential for steal. Kouchoukos et al. [73] reported a series of 211 patients undergoing repair under DHCA with a paraplegia rate of 3%. Technically, this approach is also less cumbersome, since it avoids the use of additional adjuncts. However, the requirement for full cardiopulmonary bypass and profound hypothermia introduces new problems and potential complications, such as coagulaopathy, cardiac dysfunction (due to ventricular distension during cooling), brain injury and possibly higher infection risk. The results in the literature are mixed, and there are several small series reporting high morbidity and mortality with this technique [34]. For this reason, most surgeons reserve DHCA techniques for only the most complex cases.

7.4.2.3 Regional Cooling

Direct cooling of the spinal cord has been applied in both the laboratory and the clinical setting, and has the theoretical advantage of deep cooling of the spinal cord whilst avoiding the drawbacks of profound systemic hypothermia. Cooling of the spinal cord has been achieved in the experimental or clinical setting by direct perfusion of intercostal arteries with cold blood [61], indirect perfusion by infusing cold blood into the clamped aneurysm [74], retrograde perfusion through hemiazygous veins [75], infusion of cold saline through an epidural [59] or subdural [76] catheter, and external application of ice packs around the lower spine [77]. Of these methods, the most systematically applied in the clinical setting has been the technique of Cambria et al. [78], in which normal saline at 4 °C is continuously infused into the epidural space through a catheter. Using epidural cooling with CSF drainage, segmental artery reimplantation and almost exclusive use of a clamp-and-sew technique without distal bypass (in 98% of patients), Cambria et al. [57] reported a paraplegia rate of 2% in 170 cases. The major risk with this approach is a potential for an increase in CSF pressure: this explains the necessity for CSF pressure monitoring and drainage. Their data show that epidural cooling is an effective method of spinal protection, and may offer an alternative to distal bypass. Whilst regional cooling has been shown to be a safe alternative to distal perfusion in the majority of cases, it is not known whether it adds further protection if used in addition to distal perfusion. One group has employed a combined approach of distal bypass and epidural cooling in 40 patients, with one instance of paraplegia [79], but there are presently no available data comparing a combined approach with either distal bypass alone or epidural cooling alone.

7.4.2.4 Cerebrospinal Fluid Drainage

Drainage of CSF during aortic procedures was introduced to prevent the rise in CSF pressure (and consequent reduction in spinal perfusion pressure) that often occurs during aortic cross-clamping or in the early postoperative period. With this technique, a catheter is inserted into the lumbar spinal canal, and small amounts of spinal fluid (up to 50 ml prior to aortic clamping, 50 ml during aortic clamping and a maximum of 20 ml/h in the postoperative period) are withdrawn on an intermittent basis to maintain CSF pressures below 10 mmHg. The rationale for using CSF drainage in clinical practice arises largely from a wealth of data from animal studies demonstrating improved spinal perfusion and less neurological injury when CSF drainage is utilized [34]. Drainage of CSF minimizes any deleterious effect caused by a rise in CSF pressure during clamping, optimizes spinal cord perfusion and ameliorates the potentially deleterious effect of spinal cord edema in the early postoperative period. Although its scientific basis was well documented in the 1960s [1], and several groups have employed it routinely since the 1980s [80], controversy still exists regarding the use of CSF drainage, since some surgeons who do not employ it still obtain good results. Opponents of routine

CSF drainage argue that the excellent results achieved by those employing its use may merely reflect the benefits derived from the other adjunctive measures they use (as there are few surgeons who rely on CSF drainage as the sole protective strategy), that complications of CSF drainage, although rare, can be catastrophic (and occasionally fatal) and that the clinical data supporting its use are weak, particularly for less extensive thoraco-abdominal aneurysms [81]. Indeed, in the face of other adjunctive measures, the incremental benefit from CSF drainage is probably small, and some would argue that its implementation does not always justify the risk [81]. Although a systematic review of 14 published studies favored CSF drainage – with a pooled odds ratio of 0.30 for the likelihood of paraplegia compared with no CSF drainage [82] – the studies were generally methodologically deficient, and empirical testing demonstrated the existence of publication bias (implying that studies which showed poor results with CSF drainage were not being published) [82].

The use of CSF drainage as a therapeutic measure for delayed-onset paraparesis or paraplegia after open or endovascular repair is more accepted: there are several published case reports and anecdotal accounts of successful reversal of paraplegia by employing CSF drainage [83–87]. With CSF drainage, up to 50% of delayed-onset paraplegia can be successfully reversed [88]; in contrast, reversal of paraplegia was rare in the era when CSF drainage was not being employed [26]. The clinical observation of reversal of paraplegia with reduction of CSF pressure confirms the hypothesis that CSF drainage does increase spinal cord perfusion in the clinical setting, and can impact on neurological outcome. Other clinical correlates include the study by Wada et al. [16], in which they manipulated mean arterial pressures and CSF pressures intraoperatively, and found that ischemic SSEPs normalized when a combination of CSF drainage and arterial pressure manipulation was used to obtain a spinal perfusion pressure above 40 mmHg. On the basis of their data, spinal perfusion pressure should always be maintained above 40 mmHg, confirming previous similar observations from animal studies. Manipulation of spinal perfusion pressure assumes greater importance in patients with respiratory compromise, as autoregulation of spinal blood flow is lost with hypoxia and hypercarbia, making spinal blood flow more sensitive to changes in perfusion pressure [15]. Since not all cases of spinal ischemia are accompanied by increased CSF pressure, however, CSF drainage alone cannot be relied upon to prevent or reverse paraplegia, and should be regarded as part of a multimodality approach to preventing spinal cord injury.

7.4.3 Management of Segmental Arteries

One of the more controversial aspects of surgical technique for treating thoraco-abdominal aneurysms is the management of the intercostal arteries. Although several experimental studies have shown improved spinal cord protection with intercostal reimplantation, there has been difficulty transferring the results to the clinical setting as most animal studies do not mimic the clinical situation. In animal experiments, the interventions used are often limited to those being tested, whilst in practice a multitude of adjuncts are used; the aorta, intercostal and spinal vasculature are generally disease-free and without collaterals, unlike the clinical scenario, where patients may have occlusive atherosclerotic disease; and the relevance of the intercostal blood supply may differ from its impact in humans. The clinical literature also does not provide robust evidence on which to base intercostal management strategy. Consequently, surgical opinion is widely varied. Three major schools of thought exist amongst surgeons: some believe the intercostal arteries should always be reimplanted, some reimplant vessels selectively and others rarely reimplant these arteries.

7.4.3.1 Systematic Reimplantation of Segmental Vessels

Using this approach, the segmental arteries from T7 or T8 to as low as L2 (depending on the extent of resection) are reimplanted. Systematic intercostal implantation is an integral component of the technique of several of the larger published series in the literature, such as those of Kouchoukos et al. [73], Coselli et al. [44], Jacobs et al. [89], Kuniyoshi et al. [90] and Cambria et al. [91]. These groups all report paraplegia rates below 10%, which they attribute in part to their intercostal reimplantation strategy. Advocates of this strategy believe this component of the surgery to be so crucial to avoiding paraplegia that they recommend an aggressive approach of implantation in almost all patients, including endarterectomy of the aorta if the intercostal orifices are occluded [32, 92]. Published series on intercostal reimplantation are, however, heavily confounded, because all studies report use of several other adjunctive measures, any of which could have contributed to the observed low incidence of paraplegia. Indeed, successful intercostal reimplantation does not result in revascularization of the Adamkiewicz artery in all patients. In one cadaveric study, the Adamkiewicz artery arose outside the levels of T7–L1, the usual scope of reimplantation, in 45% of cases [7], suggesting that any strategy of routine reimplantation of segmental arteries may miss the origin of the Adamkiewicz artery in a substantial proportion of cases. Similarly, preoperative studies of spinal cord blood supply failed to localize the artery of Adamkiewicz in 25–40% of patients, and where the

artery is present, it may be occluded [93]. At least in some patients, reimplanting the intercostals will therefore have no bearing on spinal cord blood supply, since the implanted segment will contain no meaningful source of spinal cord blood flow (some other radicular arteries may be reimplanted, but these generally make only a minimal contribution to the spinal blood supply) [3, 4]. We would argue that the numbers needed to be treated probably do not justify the effort and risk of routine implantation in every patient. If one compares series with routine reimplantation [89] with those where no intercostals were reimplanted [8], one can calculate that almost 200 intercostals must be reimplanted to prevent a single case of paraplegia. It could, however, be argued that the intercostals, if reimplanted, would contribute some blood flow indirectly to the cord via the collateral network.

There are no comparative clinical studies that show convincing benefit of intercostal reimplantation. Although a few retrospective series have identified non-implantation of intercostal vessels as a risk factor for developing paraplegia, such an association is likely spurious and confounded. In those series, the non-reimplanted group either represented a historical cohort at a time when adjuncts were not utilized [94], or were patients in whom reimplantation was not technically feasible or the disease or surgical procedure was thought too complex to allow implantation [57, 95]. In these studies, therefore, the non-reimplanted group consisted of patients who were already at higher risk of paraplegia. Although intercostal reimplantation is widely practiced, examination of the literature suggests that it is not essential for a significant proportion of patients.

7.4.3.2 Selective Reimplantation of Segmental Vessels

Selective reimplantation has been advocated because of the drawbacks of systematic reimplantation: longer aortic clamp times, which potentially increase the paraplegia risk, use of large aortic wall patches, which may predispose to future aneurysmal dilatation of the included aortic wall, and extra anastomoses, which increase the potential for bleeding. Because anatomical understanding of the spinal circulation suggests that not all patients will achieve useful anterior spinal cord revascularization as the result of intercostal reimplantation, systematic reimplantation would subject some patients to unnecessary risks without any potential for benefit. For example, in a preoperative magnetic resonance angiography study of 120 patients, Kawaharada et al. [96] identified a cohort of patients who might not benefit from intercostal reimplantation, including 17% of patients in whom the ARM could not be localized and 18% in whom the anterior spinal artery was continuous and well collateralized. Some surgeons attempt to identify the critical segmental vessels, and selectively reimplant them. Traditionally, which vessels were important was decided intraoperatively, by observing the intercostals and reimplanting the larger vessels and those with greatest back-bleeding. Other surgeons based their decisions on the extent of resection, reimplanting vessels only during extensive thoraco-abdominal resections. Anatomical studies have, however, shown no correlation between the size of the intercostals and the likelihood of their feeding the ARM [6]. The assumption that the arteries with greatest back-bleeding are those that should be implanted is also flawed, since the presence of bleeding after aortic transection implies that a vessel is well collateralized and is effectively stealing blood retrograde from the spinal cord: such vessels can be ligated without consequence. In contrast, vessels that do not back-bleed suggest a lack of collateralization, and their reimplantation may improve spinal circulation.

Most surgeons favoring selective reimplantation do not rely on intraoperative assessment, but undertake preoperative angiography to localize the ARM. Preoperative localization helps target intercostal reimplantation (such that only a few intercostal arteries are reimplanted, rather than a larger patch of up to eight pairs of arteries). Although this approach has several theoretical advantages, no difference has been demonstrated in clinical outcome between patients who had preoperative localization compared with those who did not [93]. And, in patients who underwent angiography, those in whom the ARM was identified did not have a better outcome than those in whom it could not be localized [97, 98]. In practice, many surgeons who favor localization of the ARM still persist with mass intercostal reimplantation if the ARM cannot be visualized preoperatively [93, 99, 100], presumably because of the possibility of a false-negative study, or because the surgeons are strongly biased toward intercostal reimplantation. In most series, therefore, selective implantation does not succeed in reducing the proportion of patients revascularized, but is more often used as a research tool. It does allow implantation of only a few intercostals in patients in whom the ARM is localized, instead of the mass reimplantation which would otherwise have been performed.

7.4.3.3 Sacrificing of Segmental Vessels

Systematic sacrifice of intercostal vessels has been employed by Griepp et al. [8, 21] and Galla et al. [101]. Intercostal reimplantation is not an integral part of their technique, and is only undertaken if evoked potentials suggest spinal ischemia when intercostal arteries are occluded. With this approach, the lower vessels are temporarily occluded in a stepwise and gradual manner prior to aortic clamping. Vessels are occluded in triplets every 10 min, after which motor and sensory potentials are recorded. If the evoked potentials remain normal

after 5 min of occlusion, then these vessels are sacrificed. The process is repeated until all vessels have been sacrificed, so that by the time of aortic clamping, the spinal cord has (depending upon the extent of resection) lost most or all of its intercostal blood supply for a period of time. In practice, changes in evoked potentials are rare. The advantages of the Griepp approach include minimization of aortic cross-clamp time (and hence minimization of the overall duration of spinal ischemia), minimization of steal (as all intercostals are ligated prior to aortic transection) and prevention of unnecessary reimplantation of intercostals (with its attendant risks). The postoperative spinal circulation is more predictable, and is not subject to abrupt changes resulting from problems with intercostal reimplantation (such as acute occlusion from thrombosis, which has been postulated as one mechanism for delayed-onset paraplegia [10]). Other potential advantages are avoidance of technical problems associated with performing anastomoses or oversewing intercostals in a severely atherosclerotic aneurysm, and the absence of residual aortic tissue in the replaced segment of aorta.

The experience of Griepp et al. differs notably from that of Jacobs et al. [89], who also monitor evoked potentials to help guide intercostal implantation. Although Jacobs's group generally advocates systematic reimplantation of intercostals where feasible [102], they assess the spinal blood supply using a technique in which the aorta is double-clamped sequentially in segments from proximal to distal, and evoked potentials are recorded to determine if an excluded segment of the aorta contains intercostals that are worth reimplanting [89]. Interestingly, 41% of Jacobs's patients developed abnormal MEP levels with the exclusion of the aortic segment between T5 and L1, whereas it was unusual to get MEP changes with intercostal clamping in Griepp's series. The major difference between the two approaches seems to be the mass occlusion of all vessels in Jacobs's series [89], as opposed to a stepwise occlusion with Griepp's technique, suggesting that the gradual approach to division of the intercostals may be a crucial component of the Griepp technique [8]. Additionally, with mass exclusion of the T5–L1 segment, there may be potential for steal away from the spinal cord, via the ARM and its feeding vessels, into the other intercostal arteries in the excluded aortic segment. The rarity of changes in MEPs using the Griepp approach, compared with the relatively frequent occurrence with the Jacob approach, warrants further study into the effects of various approaches to sequential clamping of intercostal vessels.

The low paraplegia rates achieved with systematic sacrifice of segmental vessels challenges the widely held view [34] that intercostal reimplantation is a mandatory component of extended thoraco-abdominal repairs, although the notion that the entire T5–L1 segmental vessels can be disconnected from the aorta without consequence may seem implausible to the surgeons who employ routine reimplantation. Systematic stepwise sacrifice of segmental vessels does, however, have logical foundations in both experimental and clinical studies. As early as 1964, Edwards and Killen [103] showed that a staged approach – tying of the eight highest intercostals on the first day, and returning a day later to tie the remaining – reduced the paraplegia rate following segmental artery sacrifice in dogs. They postulated that dividing the intercostals in a staged approach allows the collaterals to progressively take up the new burden of flow. In a human cadaveric study, Biglioli et al. [7] perfused the spinal cord through either the vertebral or the lumbar inflow, and demonstrated that the entire spinal cord was still satisfactorily perfused after all the segmental arteries had been divided, with the dye flowing through the extensive collateral network along the cord and vertebral column. Animal models have shown that these collaterals are sufficient to supply the cord after division of all segmental vessels [9]. The extensive atherosclerotic disease seen in many of the aneurysms may already have limited the thoracic component of spinal cord blood supply so that the collateral network may be even more developed [93], and division of segmental vessels is inconsequential. Ischemic preconditioning, which has been shown experimentally to offer some spinal cord protection [104–107], could contribute to the success of the Griepp approach: the intercostal inflow to the cord is lost for an interval before the definitive ischemia of aortic cross-clamping. Finally, the observed low incidence of paraplegia following endovascular stenting [108], particularly in patients with acute dissection – who are generally not well collateralized – suggests that sudden occlusion of the lower thoracic intercostals does not compromise spinal blood flow in the manner that would have been expected if the ARM had as pivotal a role as generally believed.

Sacrificing of the intercostal inflow to the spinal circulation, however, means that part of the thoracic cord is totally dependent upon extrasegmental supply and inflow from the cervical and hypogastric/lumbar arteries postoperatively. The spinal perfusion pressure therefore assumes greater importance as the principal determinant of spinal blood flow to critical regions. For this reason, evoked potentials are monitored until the patient is awake and can be evaluated neurologically. Mean arterial pressures are kept in a supranormal range (80–90-mmHg mean) and, with CSF drainage, cerebrospinal pressures are kept below 10 mmHg. Sustained hypotension in the absence of the intercostal inflow will almost certainly result in paraparesis, which, if untreated, could develop into paraplegia.

An alternative approach of sacrificing segmental approaches is that of Cooley [40], in which a single clamp is applied, and the aneurysm opened, allowing the distal aorta to exsanguinate. The proximal and distal graft anastomoses are then performed, and the intercostals are oversewn *after* aortic continuity has been estab-

lished. This technique differs from that of Griepp in the nonuse of adjuncts, and the allowance of free bleeding from the intercostals during construction of both anastomoses. Cooley postulates that the free bleeding from the intercostals reduces CSF pressure [39], and that oversewing the vessels before performing the distal and proximal aortic anastomoses increases the CSF pressure during the critical period of aortic clamping. This would imply that CSF drainage must be an integral part of the Griepp approach and any other techniques in which intercostal supply is occluded during aortic clamping. Cooley's hypothesis has not been proven, however, and his results have generally not been replicated.

7.4.4 Pharmacological Adjuncts

The potential spinal cord protective effect of various pharmacological agents has been widely investigated in both the experimental and the clinical setting. Thus far, no pharmacological agents have consistently been found to be of benefit. The areas of investigation have included prolongation of the safe period of aortic clamping, attenuation of the spinal cord injury caused by ischemia, attenuation of reperfusion injury, and prevention of secondary problems – such as edema – that may compound a primary ischemic insult [109]. The cascade that leads to neuronal death after ischemia consists of several pathways that provide potential areas for pharmacologic intervention. Whilst some agents have been shown to be beneficial in the laboratory setting, clinical use is often hampered by toxicity and side effects associated with the dose needed to achieve the desired effects. Consequently, of the hundreds of agents tested in the laboratory, only a few have made it into the clinical arena, and the use of pharmacological adjuncts remains largely investigational [110].

Corticosteroids have been the most widely used pharmacological agents clinically. Their use is an extension of their utility in the setting of spinal cord trauma. Methylprednisolone is the steroid of choice because, in addition to its anti-inflammatory properties, experimental studies suggest an antioxidant property which inhibits spinal tissue lipid peroxidation, one of the postulated key events in the secondary posttraumatic degenerative cascade [111]. The clinical basis for the use of steroids in trauma arose largely from the National Acute Spinal Cord Injury (NASCIS) trials of the 1980s, which found benefits in neurological recovery in patients given steroids within 14 h of spinal cord injury [112]. There are, however, no clinical studies showing that steroids actually help to *prevent* occurrence of spinal injury if given before the insult, and evidence that they attenuate the subsequent injury is weak. Indeed, the benefits of steroids in the setting of neuronal trauma are debatable, with heavily conflicting data in the literature [113–115]. There is also the possibility that steroids could be harmful: they have potent adverse effects, and also have an impact, sometimes deleterious, on numerous beneficial cellular pathways in the injured or postsurgical patient. The use of steroids in neuronal injury has recently been brought into question by an international multicenter trial of steroid therapy vs placebo in 10,008 patients with head injury, which did not find any benefit of steroid administration [116]. In fact, the investigators found a higher mortality rate in patients who received steroids. The harmful effect of steroids in the setting of head injury raises questions about their use in spinal injury [116, 117]. Further studies should clarify the role of steroids as spinal protective agents in aortic surgery, but with modern adjuncts, and considering the negative evidence from clinical studies in trauma (from where steroid use in aortic surgery derives), one must conclude that it is unlikely that steroids provide substantial additional benefit. For these reasons, steroids are not relied upon as a major means of spinal protection.

Other drugs used in the clinical setting include intrathecal papaverine [118] and intravenous naloxone [42]. There is an experimental basis for a spinal protective effect of these drugs, and lower paraplegia rates were noted with these agents compared with rates with historical series. But groups employing these drugs use them as adjuncts to CSF drainage and hypothermia, making it impossible to isolate the effect of the pharmacological agent. Neither drug has achieved widespread use.

7.5 Special Phenomena

7.5.1 Steal

Steal is one concept that unifies most of the various strategies that have been successful at reducing paraplegia rates. Steal is a pathological process whereby increased blood flow through a low-resistance vascular bed is sufficient to direct flow away from a critical region: in this setting, the spinal cord [119]. The various connections of the spinal cord arterial supply mean that blood can be diverted toward and away from the spinal cord, and toward and away from other competing vascular beds in the cervical, thoracic and lumbar/hypogastric regions. Spinal cord steal syndromes are well described in the medical literature as a cause of acute paraplegia in patients with aortic coarctation, in whom the spinal arteries act preferentially as collaterals diverting available blood flow from the upper aorta to supply the lower body, rather than the spinal cord [119].

The importance of steal syndromes in the context of aortic surgery has been less appreciated, and although

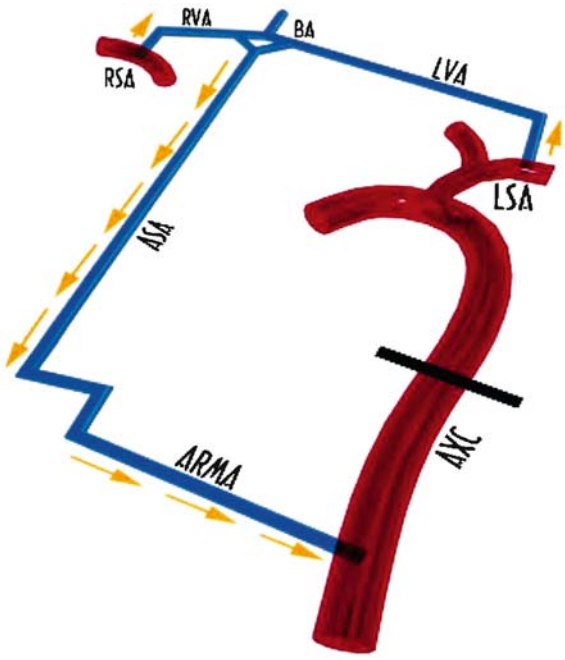

Fig. 7.1. Steal phenomenon in the excluded part of the aorta. A rerouting through the anterior spinal artery (*ASA*) and the arteria radicularis magna artery (*ARMA*) steals blood from the spinal cord. *LSA* left subclavian artery, *RSA* right subclavian artery, *LVA* left vertebral artery, *RVA* right vertebral artery, *BA* basilar artery, *AXC* aortic clamping. (From Biglioli et al. [7])

Table 7.1. Potential mechanisms by which steal may be minimized in selected contemporary series

Surgeon	Mechanism
Cambria [91]	Occlusion of critical intercostal vessels with balloon catheters upon opening the aneurysm
Coselli [92]	Selective intercostal perfusion, then sequential clamping of graft after intercostal reattachment
Griepp [21]	Ligation of segmental vessels prior to opening of the aneurysm
Jacobs [89]	Double cross-clamping and sequential clamping
Kouchoukos [73]	Proximal anastomosis and intercostal reimplantation are done on deep hypothermic circulatory arrest, so there is no possibility of steal. Intercostal flow is restored when circulation is resumed for the abdominal procedure
Kuniyoshi [90]	Intercostals are snared with purse-string sutures and tourniquets after the aneurysm is opened, mainly to assess the motor-evoked potentials as a guide to intercostal reimplantation, but tourniquets are maintained until implantation
Motoyoshi [79]	Inlets of critical intercostal arteries are cannulated, ostensibly for hemostasis, using small occlusive catheters
Schepens [122]	Double cross-clamping and sequential clamping

the possibility of steal as a cause of paraplegia after aortic resection was suggested by Cole and Gutelius [1] in 1969, it was largely unacknowledged until recently. Cole and Gutelius [1] had suggested that use of the left subclavian artery for distal perfusion resulted in steal away from the anterior spinal artery, compounding the spinal hypoperfusion of cross-clamping. In the early 1990s, Wadouh et al. [120] revisited the concept of steal, suggesting that spinal cord injury during aortic clamping resulted from a steal phenomenon. Using a pig model, they demonstrated that clamping of the aorta at T3–T4 resulted in decreased oxygen tension on the spinal cord surface, but that exclusion of the thoracic aorta by a second clamp at L1 restored oxygen tension almost to the original level. They concluded that after aortic cross-clamping, blood tends to drain away from the spinal cord rather than supplying it longitudinally. These experiments suggested that simple clamp techniques, especially where a proximal clamp only is applied, may result in more steal away from the cord compared with other approaches. Christiansson et al. [9] replicated the findings of Wadouh et al. with intrathecal oxygen measurement, but in addition, using spectral Doppler analysis, they demonstrated reversal of flow through the intercostal arteries after application of the proximal clamp. Using aortic injection and spinal artery perfusion in cadavers, Biglioli et al. [7] demonstrated the anatomical existence of a functional steal pathway (Fig. 7.1) whereby the ARM steals blood from the spinal cord during aortic clamping.

Another potential steal pathway is into the open thoracic cavity. If the aneurysm is opened prior to ligation of segmental arteries, back-bleeding is evident from the intercostal and lumbar orifices in the aorta. As there is no resistance to blood flow from these segmental vessels, blood from the anterior spinal artery will preferentially bleed out into the thorax through the ARM, thus compounding the spinal ischemia that has already resulted from loss of intercostal supply from the excluded aortic segment [21].

The clinical existence of spinal steal as a possible cause of neurological injury is supported by the relatively low incidence of paraplegia in endovascular stent graft procedures, which avoid steal entirely. Many of the current surgical strategies of spinal protection that have yielded low paraplegia rates with open repair deliberately or inadvertently incorporate measures that reduce spinal cord steal (Table 7.1).

One series that raises doubt about the existence of clinical steal syndrome as a cause of neurological injury is Cooley's single clamp with distal exsanguination approach [121], as intercostals bleeding freely during aortic clamping. Using this approach, Cooley and colleagues reported an 8.3% incidence of spinal cord dys-

function in 132 patients. Aside from this series, there are no large published series that report low paraplegia rates with permissive intraoperative steal. It seems prudent therefore to include measures to minimize steal in spinal protection strategies.

7.5.2 Delayed Paraplegia

Compared with the other aspects of spinal protection, which have made substantial progress in the last 2 decades, the occurrence of delayed paraplegia remains an enigma, with little understanding about its mechanism and how it may be prevented [123]. There are only a handful of published clinical studies examining delayed paraplegia. Its occurrence seems sporadic, and does not appear to be prevented by the use of adjuncts. The exact incidence of delayed paraplegia is unknown, but there are multiple case reports and anecdotal accounts of patients becoming paraplegic days or even weeks after apparently successful thoraco-abdominal aortic repair. Unlike for other aspects of spinal protection, there are no satisfactory animal models to investigate delayed paraplegia. Our understanding of delayed paraplegia is consequently very limited. It is not known which patients are vulnerable, why they are vulnerable or how long the vulnerability persists.

In a review of five patients who developed new paraplegia 1–27 days after surgery, Maniar et al. [10] could not identify any aspects of their operative strategy or patient pathology that may have predisposed to the neurological injury, except the occurrence of hypotension in three patients. Three of the five had undergone intercostal reimplantation, including the two patients in whom there was no documented hypotension. None of the patients had intercostal angiography, so thrombosis of these vessels could not be excluded. This is interesting, because it reminds us that intercostal reimplantation does not eliminate delayed paraplegia. At least in theory, if intercostal reimplantation has been successful (assuming there has been no technical or thromboembolic obstruction), the spinal cord should be close to the same blood supply as it was prior to surgery, and should be no more vulnerable than it was prior to surgery. The explanation probably does not therefore lie solely in the anatomical blood supply. It seems more likely that the spinal cord suffers some insult during ischemia or reperfusion that affects its autoregulatory capacity or its ability to tolerate relative degrees of hypotension. Use of adjuncts during surgery and operative factors such as cross-clamp duration probably have no bearing on paraplegia occurring more than 1 or 2 days after surgery [123]. Indeed, delayed paraplegia is well described after endovascular repairs, where these operative factors do not exist. The paraplegia is therefore likely to have a pathophysiological explanation in the residual postoperative blood supply to the spinal cord and its ability to maintain adequate spinal cord perfusion under varying physiological and pathological conditions. In a series of 854 patients operated over 10 years, of whom 21 developed delayed-onset neurological deficit, Estrera et al. [88] found only the extent of aneurysm and history of aortic dissection to be predictors of delayed paraplegia. Notably, operative factors such as distal aortic perfusion time, aortic cross-clamp time and intercostal artery reattachment were not associated with delayed paraplegia. As in the series of Maniar et al. [10], Estrera et al. were also unable to define the direct factors that precipitated the paraplegia.

As delayed paraplegia seems to occur universally regardless of surgical (or endovascular) technique, and bears no apparent relationship to the manner in which the spinal circulation was dealt with during surgery, it appears that some patients have a more vulnerable spinal blood supply than others. Estrera et al. [88] did find an interesting association: although the use of adjuncts had decreased the overall paraplegia rate, there was a paradoxically higher incidence of delayed paraplegia in patients in whom they used adjuncts compared with those who had a clamp-and-sew repair. This led Estrera et al. to postulate that the use of adjuncts may be creating a new group of paraplegic patients: patients who would otherwise have developed immediate paraplegia if adjuncts had not been used, but who now recover from surgery without deficit, only to succumb to what is an inevitable outcome hours or days later. In other words, there may be a group of patients whose spinal cords will not tolerate the insult of aortic resection. Further study of patients with delayed paraplegia may help define such patients. Conversely, one could conclude that our adjuncts are far from perfect: in those patients with delayed paraplegia, they only succeeded in temporarily mitigating – but not eliminating – the ischemic insult, hence the need for further refinement and developments of adjunctive measures.

Although hypotension causing spinal cord ischemia is widely held to be the most likely mechanism for delayed paraplegia, early series found that the traditional approaches to treating paraplegia (improving blood pressure, giving steroids and providing physical therapy) were generally unsuccessful in reversing neurological deficits [26]. This suggests that hypotension alone is not the mechanism for delayed paraplegia, since successful reversal should otherwise have been observed in many cases.

With the advent of CSF drainage, numerous reports of successful reversal of delayed paraplegia emerged in the literature [83, 88]. In the series of Estrera et al. [88], paraplegia resolved in 57% of patients treated with combined CSF drainage, blood pressure stabilization and improved oxygen delivery. The relatively frequent observation of an increased CSF pressure in patients with delayed paraplegia suggests that additional spinal

mechanisms may be contributory. Safi et al. [124] labeled this the spinal compartment syndrome, postulating that CSF hypertension, possibly due to spinal cord edema, was the cause of delayed paraplegia.

Delayed paraplegia remains ill-understood: the mechanisms are probably complex, and may not be restricted to anatomical and physiological factors. For example, a substantial number of patients, almost 50%, do not respond to CSF drainage and blood pressure optimization [88], suggesting that, at least in those patients, there are other overriding factors. Whilst the seemingly formidable task in the 1970s of refining adjuncts and reducing the burden of paraplegia [51] has largely been achieved, it seems that, as immediate paraplegia becomes infrequent, delayed paraplegia will increase to become the major challenge confronting descending aortic surgery. Further experimental and clinical studies of the spinal circulation and the pathophysiology of spinal cord ischemia and paraplegia are clearly required. As most centers can only accrue small numbers of cases, pooled data may offer the only hope of understanding and solving the problem of delayed paraplegia. Azizzadeh et al. [83] have proposed a national database for delayed paraplegia, with the hope that collective experience will provide data to allow better understanding and investigation of potential preventive and therapeutic measures.

Delayed paraplegia serves as a reminder that our understanding of spinal cord ischemia is incomplete, and that our current spinal protective strategies are far from perfect. Although great strides have been made in the last 30 years, continuing study of the anatomical, physiological, cellular and epidemiological determinants of spinal cord injury is necessary, and should form the foundations for a new era in spinal protection that unifies the various concepts, controversies and techniques of the current era. The ultimate goal would be to make it possible to identify the patients particularly vulnerable to paraplegia, and to define the anatomical, physiological or cellular basis of such vulnerability so that the surgeon is able to tailor the operative and spinal protection strategy to the individual patient.

References

1. Cole PT, Gutelius JR. Neurologic complications of operations on the descending thoracic aorta. Can J Surg 1969; 12(4):435–443.
2. Crawford ES. Symposium: prevention of complications of abdominal aortic reconstruction. Introduction. Surgery 1983; 93(1 Pt 1):91–96.
3. Turnbull IM. Chapter 5. Blood supply of the spinal cord: normal and pathological considerations. Clin Neurosurg 1973; 20:56–84.
4. Lazorthes G, Gouaze A, Zadeh JO, Santini JJ, Lazorthes Y, Burdin P. Arterial vascularisation of the spinal cord. Recent studies of the anatomic substitution pathways. J Neurosurg 1971; 253–262.
5. Morishita K, Murakami G, Fujisawa Y, Kawaharada N, Fukada J, Saito T et al. Anatomical study of blood supply to the spinal cord. Ann Thorac Surg 2003; 76(6):1967–1971.
6. Koshino T, Murakami G, Morishita K, Mawatari T, Abe T. Does the Adamkiewicz artery originate from the larger segmental arteries? J Thorac Cardiovasc Surg 1999; 117(5):898–905.
7. Biglioli P, Roberto M, Cannata A, Parolari A, Fumero A, Grillo F, et al. Upper and lower spinal cord blood supply: the continuity of the anterior spinal artery and the relevance of the lumbar arteries. J Thorac Cardiovasc Surg 2004; 127(4):1188–1192.
8. Griepp RB, Ergin MA, Galla JD, Lansman S, Khan N, Quintana C, et al. Looking for the artery of Adamkiewicz: a quest to minimize paraplegia after operations for aneurysms of the descending thoracic and thoracoabdominal aorta. J Thorac Cardiovasc Surg 1996; 112(5):1202–1213.
9. Christiansson L, Ulus AT, Hellberg A, Bergqvist D, Wiklund L, Karacagil S. Aspects of the spinal cord circulation as assessed by intrathecal oxygen tension monitoring during various arterial interruptions in the pig. J Thorac Cardiovasc Surg 2001; 121(4):762–772.
10. Maniar HS, Sundt TM, III, Prasad SM, Chu CM, Camillo CJ, Moon MR, et al. Delayed paraplegia after thoracic and thoracoabdominal aneurysm repair: a continuing risk. Ann Thorac Surg 2003; 75(1):113–119.
11. Strauch JT, Spielvogel D, Lauten A, Zhang N, Shiang H, Weisz D, et al. Importance of extrasegmental vessels for spinal cord blood supply in a chronic porcine model. Rev Port Cir Cardiothorac Vasc 2003; 10(4):185–191.
12. Gravereaux EC, Faries PL, Burks JA, Latessa V, Spielvogel D, Hollier LH, et al. Risk of spinal cord ischemia after endograft repair of thoracic aortic aneurysms. J Vasc Surg 2001; 34(6):997–1003.
13. Taira Y, Marsala M. Effect of proximal arterial perfusion pressure on function, spinal cord blood flow, and histopathologic changes after increasing intervals of aortic occlusion in the rat. Stroke 1996; 27(10):1850–1858.
14. Duggal N, Lach B. Selective vulnerability of the lumbosacral spinal cord after cardiac arrest and hypotension. Stroke 2002; 33(1):116–121.
15. Afifi S. Pro: cerebrospinal fluid drainage protects the spinal cord during thoracoabdominal aortic reconstruction surgery. J Cardiothorac Vasc Anesth 2002; 16(5):643–649.
16. Wada T, Yao H, Miyamoto T, Mukai S, Yamamura M. Prevention and detection of spinal cord injury during thoracic and thoracoabdominal aortic repairs. Ann Thorac Surg 2001; 72(1):80–84.
17. Gelman S. The pathophysiology of aortic cross-clamping and unclamping. Anesthesiology 1995; 82(4):1026–1060.
18. Marini CP, Levison J, Caliendo F, Nathan IM, Cohen JR. Control of proximal hypertension during aortic cross-clamping: its effect on cerebrospinal fluid dynamics and spinal cord perfusion pressure. Semin Thorac Cardiovasc Surg 1998; 10(1):51–56.
19. Marini CP, Grubbs PE, Toporoff B, Woloszyn TT, Coons MS, Acinapura AJ, et al. Effect of sodium nitroprusside on spinal cord perfusion and paraplegia during aortic cross-clamping. Ann Thorac Surg 1989; 47(3):379–383.
20. Saether OD, Juul R, Aadahl P, Stromholm T, Myhre HO. Cerebral haemodynamics during thoracic- and thoracoabdominal aortic aneurysm repair. Eur J Vasc Endovasc Surg 1996; 12(1):81–85.
21. Griepp RB, Ergin MA, Galla JD, Klein JJ, Spielvogel D, Griepp EB. Minimizing spinal cord injury during repair of descending thoracic and thoracoabdominal aneurysms: the Mount Sinai approach. Semin Thorac Cardiovasc Surg 1998; 10(1):25–28.

22. Biglioli P, Spirito R, Porqueddu M, Agrifoglio M, Pompilio G, Parolari A, et al. Quick, simple clamping technique in descending thoracic aortic aneurysm repair. Ann Thorac Surg 1999; 67(4):1038–1043.
23. Schepens MA, Defauw JJ, Hamerlijnck RP, De Geest R, Vermeulen FE. Surgical treatment of thoracoabdominal aortic aneurysms by simple crossclamping. Risk factors and late results. J Thorac Cardiovasc Surg 1994; 107(1):134–142.
24. Safi HJ, Winnerkvist A, Miller CC, III, Iliopoulos DC, Reardon MJ, Espada R, et al. Effect of extended cross-clamp time during thoracoabdominal aortic aneurysm repair. Ann Thorac Surg 1998; 66(4):1204–1209.
25. Cunningham JN Jr, Laschinger JC, Merkin HA, Nathan IM, Colvin S, Ransohoff J, et al. Measurement of spinal cord ischemia during operations upon the thoracic aorta: initial clinical experience. Ann Surg 1982; 196(3):285–296.
26. Crawford ES, Mizrahi EM, Hess KR, Coselli JS, Safi HJ, Patel VM. The impact of distal aortic perfusion and somatosensory evoked potential monitoring on prevention of paraplegia after aortic aneurysm operation. J Thorac Cardiovasc Surg 1988; 95(3):357–367.
27. Galla JD, Ergin MA, Lansman SL, McCullough JN, Nguyen KH, Spielvogel D, et al. Use of somatosensory evoked potentials for thoracic and thoracoabdominal aortic resections. Ann Thorac Surg 1999; 67(6):1947–1952.
28. Meylaerts SA, Jacobs MJ, van I, V, De Haan P, Kalkman CJ. Comparison of transcranial motor evoked potentials and somatosensory evoked potentials during thoracoabdominal aortic aneurysm repair. Ann Surg 1999; 230(6):742–749.
29. Guerit JM, Verhelst R, Rubay J, Khoury G, Matta A, Dion R. Multilevel somatosensory evoked potentials (SEPs) for spinal cord monitoring in descending thoracic and thoraco-abdominal aortic surgery. Eur J Cardiothorac Surg 1996; 10(2):93–103.
30. Reuter DG, Tacker WA Jr, Badylak SF, Voorhees WD III, Konrad PE. Correlation of motor-evoked potential response to ischemic spinal cord damage. J Thorac Cardiovasc Surg 1992; 104(2):262–272.
31. De Haan P, Kalkman CJ, de Mol BA, Ubags LH, Veldman DJ, Jacobs MJ. Efficacy of transcranial motor-evoked myogenic potentials to detect spinal cord ischemia during operations for thoracoabdominal aneurysms. J Thorac Cardiovasc Surg 1997; 113(1):87–100.
32. Jacobs MJ, Meylaerts SA, De Haan P, de Mol BA, Kalkman CJ. Strategies to prevent neurologic deficit based on motor-evoked potentials in type I and II thoracoabdominal aortic aneurysm repair. J Vasc Surg 1999; 29(1):48–57.
33. Sueda T, Okada K, Watari M, Orihashi K, Shikata H, Matsuura Y. Evaluation of motor- and sensory-evoked potentials for spinal cord monitoring during thoracoabdominal aortic aneurysm surgery. Jpn J Thorac Cardiovasc Surg 2000; 48(1):60–65.
34. Juvonen T, Biancari F, Rimpilainen J, Satta J, Rainio P, Kiviluoma K. Strategies for spinal cord protection during descending thoracic and thoracoabdominal aortic surgery: Up-to-date experimental and clinical results – a review. Scand Cardiovasc J 2002; 36(3):136–160.
35. Svensson LG. Intraoperative identification of spinal cord blood supply during repairs of descending aorta and thoracoabdominal aorta. J Thorac Cardiovasc Surg 1996; 112(6):1455–1460.
36. Anderson RE, Winnerkvist A, Hansson LO, Nilsson O, Rosengren L, Settergren G, et al. Biochemical markers of cerebrospinal ischemia after repair of aneurysms of the descending and thoracoabdominal aorta. J Cardiothorac Vasc Anesth 2003; 17(5):598–603.
37. Shiiya N, Kunihara T, Miyatake T, Matsuzaki K, Yasuda K. Tau protein in the cerebrospinal fluid is a marker of brain injury after aortic surgery. Ann Thorac Surg 2004; 77(6):2034–2038.
38. van Dongen EP, Ter Beek HT, Boezeman EH, Schepens MA, Langemeijer HJ, Aarts LP. Normal serum concentrations of S-100 protein and changes in cerebrospinal fluid concentrations of S-100 protein during and after thoracoabdominal aortic aneurysm surgery: Is S-100 protein a biochemical marker of clinical value in detecting spinal cord ischemia? J Vasc Surg 1998; 27(2):344–346.
39. Scheinin SA, Cooley DA. Graft replacement of the descending thoracic aorta: results of "open" distal anastomosis. Ann Thorac Surg 1994; 58(1):19–22.
40. Cooley DA, Golino A, Frazier OH. Single-clamp technique for aneurysms of the descending thoracic aorta: report of 132 consecutive cases. Eur J Cardiothorac Surg 2000; 18(2):162–167.
41. Schepens MA, Vermeulen FE, Morshuis WJ, Dossche KM, van Dongen EP, Ter Beek HT, et al. Impact of left heart bypass on the results of thoracoabdominal aortic aneurysm repair. Ann Thorac Surg 1999; 67(6):1963–1967.
42. Tefera G, Acher CW, Wynn MM. Clamp and sew techniques in thoracoabdominal aortic surgery using naloxone and CSF drainage. Semin Vasc Surg 2000; 13(4):325–330.
43. Safi HJ, Miller CC, III, Huynh TT, Estrera AL, Porat EE, Winnerkvist AN, et al. Distal aortic perfusion and cerebrospinal fluid drainage for thoracoabdominal and descending thoracic aortic repair: ten years of organ protection. Ann Surg 2003; 238(3):372–380.
44. Coselli JS, LeMaire SA, Conklin LD, Adams GJ. Left heart bypass during descending thoracic aortic aneurysm repair does not reduce the incidence of paraplegia. Ann Thorac Surg 2004; 77(4):1298–1303.
45. Walterbusch G, Fromke J, Sydow M. A simple method to reduce ischemic time of the spinal cord in extensive thoracoabdominal aneurysm operations. Thorac Cardiovasc Surg 2003; 51(1):46–48.
46. Lee JT, White RA. Current status of thoracic aortic endograft repair. Surg Clin North Am 2004; 84(5):1295.
47. Hanley JA, Lippman-Hand A. If nothing goes wrong, is everything all right? Interpreting zero numerators. JAMA 1983; 249(13):1743–1745.
48. Anyanwu AC, Treasure T. Unrealistic expectations arising from mortality data reported in the cardiothoracic journals. J Thorac Cardiovasc Surg 2002; 123(1):16–20.
49. Leurs LJ, Bell R, Degrieck Y, Thomas S, Hobo R, Lundbom J. Endovascular treatment of thoracic aortic diseases: combined experience from the EUROSTAR and United Kingdom thoracic endograft registries. J Vasc Surg 2004; 40(4):670–679.
50. Grabenwoger M, Hutschala D, Ehrlich MP, Cartes-Zumelzu F, Thurnher S, Lammer J, et al. Thoracic aortic aneurysms: treatment with endovascular self-expandable stent grafts. Ann Thorac Surg 2000; 69(2):441–445.
51. Crawford ES, Rubio PA. Reappraisal of adjuncts to avoid ischemia in the treatment of aneurysms of descending thoracic aorta. J Thorac Cardiovasc Surg 1973; 66(5):693–704.
52. Ergin MA, Galla JD, Lansman SL, Taylor M, Griepp RB. Distal perfusion methods for surgery of the descending aorta. Semin Thorac Cardiovasc Surg 1991; 3(4):293–299.
53. von Oppell UO, Dunne TT, De Groot KM, Zilla P. Spinal cord protection in the absence of collateral circulation: meta-analysis of mortality and paraplegia. J Card Surg 1994; 9(6):685–691.
54. Verdant A, Page A, Cossette R, Dontigny L, Page P, Baillot R. Surgery of the descending thoracic aorta: spinal cord protection with the Gott shunt. Ann Thorac Surg 1988; 46(2):147–154.
55. Laschinger JC, Cunningham JN Jr, Nathan IM, Knopp EA, Cooper MM, Spencer FC. Experimental and clinical assessment of the adequacy of partial bypass in mainte-

nance of spinal cord blood flow during operations on the thoracic aorta. Ann Thorac Surg 1983; 36(4):417–426.
56. Elmore JR, Gloviczki P, Harper CM Jr, Murray MJ, Wu QH, Bower TC et al. Spinal cord injury in experimental thoracic aortic occlusion: investigation of combined methods of protection. J Vasc Surg 1992; 15(5):789–798.
57. Cambria RP, Davison JK, Carter C, Brewster DC, Chang Y, Clark KA, et al. Epidural cooling for spinal cord protection during thoracoabdominal aneurysm repair: a five-year experience. J Vasc Surg 2000; 31(6):1093–1102.
58. Coselli JS, LeMaire SA. Left heart bypass reduces paraplegia rates after thoracoabdominal aortic aneurysm repair. Ann Thorac Surg 1999; 67(6):1931–1934.
59. Cambria RP, Davison JK. Regional hypothermia for prevention of spinal cord ischemic complications after thoracoabdominal aortic surgery: experience with epidural cooling. Semin Thorac Cardiovasc Surg 1998; 10(1):61–65.
60. Meylaerts SA, De Haan P, Kalkman CJ, Jaspers J, Vanicky I, Jacobs MJ. Prevention of paraplegia in pigs by selective segmental artery perfusion during aortic cross-clamping. J Vasc Surg 2000; 32(1):160–170.
61. Ueda T, Shimizu H, Mori A, Kashima I, Moro K, Kawada S. Selective perfusion of segmental arteries in patients undergoing thoracoabdominal aortic surgery. Ann Thorac Surg 2000; 70(1):38–43.
62. Sueda T, Morita S, Okada K, Orihashi K, Shikata H, Matsuura Y. Selective intercostal arterial perfusion during thoracoabdominal aortic aneurysm surgery. Ann Thorac Surg 2000; 70(1):44–47.
63. Winnerkvist A, Bartoli S, Iliopoulos DC, Hess KR, Miller CC, Safi HJ. Spinal cord protection during aortic cross clamping: retrograde venous spinal cord perfusion, distal aortic perfusion, and cerebrospinal fluid drainage. Scand Cardiovasc J 2002; 36(1):6–10.
64. Kataoka K, Yanase H. Mild hypothermia–a revived countermeasure against ischemic neuronal damages. Neurosci Res 1998; 32(2):103–117.
65. Wakamatsu H, Matsumoto M, Nakakimura K, Sakabe T. The effects of moderate hypothermia and intrathecal tetracaine on glutamate concentrations of intrathecal dialysate and neurologic and histopathologic outcome in transient spinal cord ischemia in rabbits. Anesth Analg 1999; 88(1):56–62.
66. Matsumoto M, Iida Y, Sakabe T, Sano T, Ishikawa T, Nakakimura K. Mild and moderate hypothermia provide better protection than a burst-suppression dose of thiopental against ischemic spinal cord injury in rabbits. Anesthesiology 1997; 86(5):1120–1127.
67. Strauch JT, Lauten A, Spielvogel D, Rinke S, Zhang N, Weisz D, et al. Mild hypothermia protects the spinal cord from ischemic injury in a chronic porcine model. Eur J Cardiothorac Surg 2004; 25(5):708–715.
68. von Segesser LK, Marty B, Mueller X, Ruchat P, Gersbach P, Stumpe F, et al. Active cooling during open repair of thoraco-abdominal aortic aneurysms improves outcome. Eur J Cardiothorac Surg 2001; 19(4):411–415.
69. Svensson LG, Khitin L, Nadolny EM, Kimmel WA. Systemic temperature and paralysis after thoracoabdominal and descending aortic operations. Arch Surg 2003; 138(2):175–179.
70. Cooley DA, Jones BA. Use of selective hypothermia to protect the spinal cord during resection of thoracoabdominal aneurysms. Tex Heart Inst J 2000; 27(1):29–31.
71. Kouchoukos NT, Wareing TH, Izumoto H, Klausing W, Abboud N. Elective hypothermic cardiopulmonary bypass and circulatory arrest for spinal cord protection during operations on the thoracoabdominal aorta. J Thorac Cardiovasc Surg 1990; 99(4):659–664.
72. Kouchoukos NT. Hypothermic circulatory arrest and hypothermic perfusion for extensive disease of the thoracic and thoracoabdominal aorta. Jpn J Thorac Cardiovasc Surg 1999; 47(1):1–5.
73. Kouchoukos NT, Masetti P, Murphy SF. Hypothermic cardiopulmonary bypass and circulatory arrest in the management of extensive thoracic and thoracoabdominal aortic aneurysms. Semin Thorac Cardiovasc Surg 2003; 15(4):333–339.
74. Sueda T, Okada K, Orihashi K, Sugawara Y, Kouchi K, Imai K. Cold blood spinal cord plegia for prediction of spinal cord ischemia during thoracoabdominal aneurysm repair. Ann Thorac Surg 2002; 73(4):1155–1159.
75. Winnerkvist A, Bartoli S, Iliopoulos DC, Hess KR, Miller CC, Safi HJ. Spinal cord protection during aortic cross clamping: retrograde venous spinal cord perfusion, distal aortic perfusion, and cerebrospinal fluid drainage. Scand Cardiovasc J 2002; 36(1):6–10.
76. Meylaerts SA, Kalkman CJ, De Haan P, Porsius M, Jacobs MJ. Epidural versus subdural spinal cord cooling: cerebrospinal fluid temperature and pressure changes. Ann Thorac Surg 2000; 70(1):222–227.
77. Motoyoshi N, Sakurai M, Hayashi T, Aoki M, Abe K, Itoyama Y, et al. Establishment of a local cooling model against spinal cord ischemia representing prolonged induction of heat shock protein. J Thorac Cardiovasc Surg 2001; 122(2):351–357.
78. Cambria RP, Davison JK, Zannetti S, L'Italien G, Brewster DC, Gertler JP, et al. Clinical experience with epidural cooling for spinal cord protection during thoracic and thoracoabdominal aneurysm repair. J Vasc Surg 1997; 25(2):234–241.
79. Motoyoshi N, Takahashi G, Sakurai M, Tabayashi K. Safety and efficacy of epidural cooling for regional spinal cord hypothermia during thoracoabdominal aneurysm repair. Eur J Cardiothorac Surg 2004; 25(1):139–141.
80. Hollier LH, Moore WM. Avoidance of renal and neurologic complications following thoracoabdominal aortic aneurysm repair. Acta Chir Scand Suppl 1990; 555:129–135.
81. Wallace L. Con: cerebrospinal fluid drainage does not protect the spinal cord during thoracoabdominal aortic reconstruction surgery. J Cardiothorac Vasc Anesth 2002; 16(5):650–652.
82. Cina CS, Abouzahr L, Arena GO, Lagana A, Devereaux PJ, Farrokhyar F. Cerebrospinal fluid drainage to prevent paraplegia during thoracic and thoracoabdominal aortic aneurysm surgery: a systematic review and meta-analysis. J Vasc Surg 2004; 40(1):36–44.
83. Azizzadeh A, Huynh TT, Miller CC, III, Safi HJ. Reversal of twice-delayed neurologic deficits with cerebrospinal fluid drainage after thoracoabdominal aneurysm repair: a case report and plea for a national database collection. J Vasc Surg 2000; 31(3):592–598.
84. Bhama JK, Lin PH, Voloyiannis T, Bush RL, Lumsden AB. Delayed neurologic deficit after endovascular abdominal aortic aneurysm repair. J Vasc Surg 2003; 37(3):690–692.
85. Hill AB, Kalman PG, Johnston KW, Vosu HA. Reversal of delayed-onset paraplegia after thoracic aortic surgery with cerebrospinal fluid drainage. J Vasc Surg 1994; 20(2):315–317.
86. Kasirajan K, Dolmatch B, Ouriel K, Clair D. Delayed onset of ascending paralysis after thoracic aortic stent graft deployment. J Vasc Surg 2000; 31(1 Pt 1):196–199.
87. Oberwalder PJ, Tiesenhausen K, Hausegger K, Rigler B. Successful reversal of delayed paraplegia after endovascular stent grafting. J Thorac Cardiovasc Surg 2002; 124(6):1259–1260.
88. Estrera AL, Miller CC, III, Huynh TT, Azizzadeh A, Porat EE, Vinnerkvist A, et al. Preoperative and operative predictors of delayed neurologic deficit following repair of thoracoabdominal aortic aneurysm. J Thorac Cardiovasc Surg 2003; 126(5):1288–1294.

89. Jacobs MJ, de Mol BA, Elenbaas T, Mess WH, Kalkman CJ, Schurink GW, et al. Spinal cord blood supply in patients with thoracoabdominal aortic aneurysms. J Vasc Surg 2002; 35(1):30–37.
90. Kuniyoshi Y, Koja K, Miyagi K, Shimoji M, Uezu T, Arakaki K, et al. Prevention of postoperative paraplegia during thoracoabdominal aortic surgery. Ann Thorac Surg 2003; 76(5):1477–1484.
91. Cambria RP, Clouse WD, Davison JK, Dunn PF, Corey M, Dorer D. Thoracoabdominal aneurysm repair: results with 337 operations performed over a 15-year interval. Ann Surg 2002; 236(4):471–479.
92. Coselli JS, Moreno PL. Descending and thoracoabdominal aneurysm. In: Cohn LH, Edmonds HL Jr, editors. Cardiac surgery in the adult. New York: McGraw-Hill; 2003. p. 1169–1190
93. Williams GM, Roseborough GS, Webb TH, Perler BA, Krosnick T. Preoperative selective intercostal angiography in patients undergoing thoracoabdominal aneurysm repair. J Vasc Surg 2004; 39(2):314–321.
94. Ross SD, Kron IL, Parrino PE, Shockey KS, Kern JA, Tribble CG. Preservation of intercostal arteries during thoracoabdominal aortic aneurysm surgery: a retrospective study. J Thorac Cardiovasc Surg 1999; 118(1):17–25.
95. Svensson LG, Hess KR, Coselli JS, Safi HJ. Influence of segmental arteries, extent, and atriofemoral bypass on postoperative paraplegia after thoracoabdominal aortic operations. J Vasc Surg 1994; 20(2):255–262.
96. Kawaharada N, Morishita K, Hyodoh H, Fujisawa Y, Fukada J, Hachiro Y, et al. Magnetic resonance angiographic localization of the artery of Adamkiewicz for spinal cord blood supply. Ann Thorac Surg 2004; 78(3):846–851.
97. Savader SJ, Williams GM, Trerotola SO, Perler BA, Wang MC, Venbrux AC, et al. Preoperative spinal artery localization and its relationship to postoperative neurologic complications. Radiology 1993; 189(1):165–171.
98. Minatoya K, Karck M, Hagl C, Meyer A, Brassel F, Harringer W, et al. The impact of spinal angiography on the neurological outcome after surgery on the descending thoracic and thoracoabdominal aorta. Ann Thorac Surg 2002; 74(5):S1870–1872.
99. Heinemann MK, Brassel F, Herzog T, Dresler C, Becker H, Borst HG. The role of spinal angiography in operations on the thoracic aorta: myth or reality? Ann Thorac Surg 1998; 65(2):346–351.
100. Kawaharada N, Morishita K, Fukada J, Yamada A, Muraki S, Hyodoh H, et al. Thoracoabdominal or descending aortic aneurysm repair after preoperative demonstration of the Adamkiewicz artery by magnetic resonance angiography. Eur J Cardiothorac Surg 2002; 21(6):970–974.
101. Galla JD, Ergin MA, Lansman SL, McCullough JN, Nguyen KH, Spielvogel D, et al. Use of somatosensory evoked potentials for thoracic and thoracoabdominal aortic resections. Ann Thorac Surg 1999; 67(6):1947–1952.
102. Jacobs MJ, Mess WH. The role of evoked potential monitoring in operative management of type I and type II thoracoabdominal aortic aneurysms. Semin Thorac Cardiovasc Surg 2003; 15(4):353–364.
103. Edwards RH, Killen DA. Prevention of spinal cord ischemia incident to extensive mobilization of the thoracic aorta from the posterior parietes. Surg Forum 1964; 15:285–287.
104. Isbir CS, Ak K, Kurtkaya O, Zeybek U, Akgun S, Scheitauer BW, et al. Ischemic preconditioning and nicotinamide in spinal cord protection in an experimental model of transient aortic occlusion. Eur J Cardiothorac Surg 2003; 23(6):1028–1033.
105. Sirin BH, Ortac R, Cerrahoglu M, Saribulbul O, Baltalarli A, Celebisoy N, et al. Ischaemic preconditioning reduces spinal cord injury in transient ischaemia. Acta Cardiol 2002; 57(4):279–285.
106. Ueno T, Chao ZL, Okazaki Y, Itoh T. The impact of ischaemic preconditioning on spinal cord blood flow and paraplegia. Cardiovasc Surg 2001; 9(6):575–579.
107. Zvara DA, Colonna DM, Deal DD, Vernon JC, Gowda M, Lundell JC. Ischemic preconditioning reduces neurologic injury in a rat model of spinal cord ischemia. Ann Thorac Surg 1999; 68(3):874–880.
108. Bush RL, Lin PH, Lumsden AB. Endovascular treatment of the thoracic aorta. Vasc Endovascular Surg 2003; 37(6):399–405.
109. De Haan P. Pharmacologic adjuncts to protect the spinal cord during transient ischemia. Semin Vasc Surg 2000; 13(4):264–271.
110. Reece TB, Kern JA, Tribble CG, Cassada DC. The role of pharmacology in spinal cord protection during thoracic aortic reconstruction. Semin Thorac Cardiovasc Surg 2003; 15(4):365–377.
111. Hall ED. The effects of glucocorticoid and nonglucocorticoid steroids on acute neuronal degeneration. Adv Neurol 1993; 59:241–248.
112. Bracken MB, Shepard MJ, Collins WF, Holford TR, Young W, Baskin DS, et al. A randomized, controlled trial of methylprednisolone or naloxone in the treatment of acute spinal-cord injury. Results of the Second National Acute Spinal Cord Injury Study. N Engl J Med 1990; 322(20):1405–1411.
113. Lammertse DP. Update on pharmaceutical trials in acute spinal cord injury. J Spinal Cord Med 2004; 27(4):319–325.
114. Bracken MB. Steroids for acute spinal cord injury. Cochrane Database Syst Rev 2002; (3):CD001046.
115. Hurlbert RJ. The role of steroids in acute spinal cord injury: an evidence-based analysis. Spine 2001; 26(24 Suppl):S39–46.
116. Roberts I, Yates D, Sandercock P, Farrell B, Wasserberg J, Lomas G, et al. Effect of intravenous corticosteroids on death within 14 days in 10,008 adults with clinically significant head injury (MRC CRASH trial): randomised placebo-controlled trial. Lancet 2004; 364(9442):1321–1328.
117. Sauerland S, Maegele M. A CRASH landing in severe head injury. Lancet 2004; 364(9442):1291–1299.
118. Svensson LG. An approach to spinal cord protection during descending or thoracoabdominal aortic repairs. Ann Thorac Surg 1999; 67(6):1935–1936.
119. Taylor CL, Selman WR, Ratcheson RA. Steal affecting the central nervous system. Neurosurgery 2002; 50(4):679–688.
120. Wadouh F, Wadouh R, Hartmann M, Crisp-Lindgren N. Prevention of paraplegia during aortic operations. Ann Thorac Surg 1990; 50(4):543–552.
121. Cooley DA. Single-clamp repair of aneurysms of the descending thoracic aorta. Semin Thorac Cardiovasc Surg 1998; 10(1):87–90.
122. Schepens M, Dossche K, Morshuis W, Heijmen R, van Dongen E, ter Beek H, et al. Introduction of adjuncts and their influence on changing results in 402 consecutive thoracoabdominal aortic aneurysm repairs. Eur J Cardiothorac Surg 2004; 25(5):701–707.
123. Huynh TT, Miller CC, III, Safi HJ. Delayed onset of neurologic deficit: significance and management. Semin Vasc Surg 2000; 13(4):340–344.
124. Safi HJ, Miller CC, III, Azizzadeh A, Iliopoulos DC. Observations on delayed neurologic deficit after thoracoabdominal aortic aneurysm repair. J Vasc Surg 1997; 26(4):616–622.

Deep Hypothermia and Circulatory Arrest

Pieter J. A. van der Starre

8

Contents

8.1 Introduction

The technique of deep hypothermia and circulatory arrest (DHCA) was first described by Drew et al. [12] in 1959. Children undergoing surgery for tetralogy of Fallot were cooled to 12 °C (nasopharyngeal), allowing a circulatory arrest time of 1 h.

The application of DHCA in adult patients undergoing surgery of the aortic arch was first reported by Griepp et al. [22] in 1975. This technique allowed performance of open distal anastomosis in type A aortic dissections, and better visualization of the aortic arch.

The main disadvantages of DHCA include coagulopathy, increased cardiopulmonary bypass (CPB) time, and renal and neurological dysfunction [15]. In this discussion we will focus on neurological and renal dysfunction, which are the main risk factors for increased morbidity and mortality in DHCA surgery.

8.2 Ischemic Brain

The vulnerability of the brain during circulatory arrest has been a great concern. Even at brain temperatures as low as 18 °C, the safe arrest time is considered to be not longer than between 30 and 40 min. An additional factor in the incidence of cerebral damage is the increasing age of the patients [52].

When the brain is deprived of blood flow it immediately lacks oxygen. The pathophysiologic consequences of oxygen deprivation of the brain are summarized in Table 8.1. ATP depletion leads to failure of the Na^+K^+-ATPase pump, which leads to the accumulation of Na^+ and Cl^- intracellularly, followed by cell swelling and neuron depolarization. This depolarization causes an influx of Ca^{2+} ions, which activates phospholipases, resulting in the production of free fatty acids, particularly arachidonic acid. The hydrolysis of membranes leads to the disruption of mitochondria and plasma membranes. During reperfusion arachidonic acid is further metabolized to prostaglandins, thromboxane, leukotrienes and free radicals. All these reactions result in an additional accumulation of Ca^{2+} ions in the cytoplasm [42, 43].

Glutamate and aspartate are major excitatory amino acids in the brain responsible for neurological processes such as memory cognition and consciousness. During ischemia, excessive activation and the presynaptic release of these excitatory amino acids, which activate postsynaptic *N*-methyl-D-aspartate (NMDA) and α-amino-3-hydroxy-5-methyl-4-isoxazolepropionate (AMPA) receptors, lead to an efflux of K^+ and influx of Na^+ and Ca^{2+} ions [44], causing neuronal injury and death. This is particularly true for the hippocampus, a region of the brain which is extremely vulnerable to ischemia [4].

During ischemic conditions glucose is metabolized in an anaerobic way to lactate, which accumulates in

Table 8.1. Pathophysiological events during brain ischemia

ATP depletion
Na^+K^+-ATPase pump failure
Intracellular ionic accumulation
Ca^{2+} accumulation
Membrane disruption
N-Methyl-D-aspartate/α-amino-3-hydroxy-5-methyl-4-isoxazolepropionate receptor activation
Lactate accumulation
Free-radical generation

the neurons and causes cell swelling and denaturation of proteins and enzymes.

The most important free radicals are the superoxide radicals, which are mainly produced during reperfusion when xanthine is catalyzed to urate and O_2^- is reduced to O_2. They attack membranes, leading to the further disruption of intracellular organelles and cell death. This phenomenon is called reperfusion injury.

8.2.1 Hypothermia

To protect the brain against ischemia, several different techniques are available, of which hypothermia is a standard, well-accepted application. To be able to establish the precise temperature of the brain, it is important to know which monitoring site is the most accurate for this purpose. The routinely used sites include esophageal, rectal, bladder, nasopharyngeal, pulmonary arterial and skin temperature. Several studies have compared the efficacy of the different monitoring sites in indicating the temperature of the brain, particularly in the dynamic phase of cooling and rewarming. Although core temperature sites, in particular bladder and esophageal temperature, may reflect accurately the changes in body temperature during moderate hypothermia [51, 54], the accurate estimation of brain temperature site is still a matter of debate. The only available study in which brain temperature was directly measured during DHCA included patients undergoing surgical clipping of a cerebral aneurysm [58]. Routine monitoring sites, including tympanic temperatures, underestimated or overestimated brain temperature with relatively large differences between individual patients. Although the authors recommended at least three monitoring sites during DHCA surgery, the additional 5–10 min of cooling as suggested by the accompanying editorial may be beneficial, although no data are yet available [27].

8.2.2 Monitoring

Although the effective time of arrest of cerebral perfusion has been substantially shortened by the application of antegrade low-flow cold blood cerebral perfusion, it is still important to assess cerebral temperature as accurately as possible. In our practice at Stanford this includes the measurement of bladder temperature, venous perfusate temperature, and two tympanic temperatures.

Since hypothermia is applied for brain protection by diminishing cerebral oxygen consumption ($CMRO_2$), it is appealing to the degree of depression of the electrical signaling obtained during cooling. The use of electroencephalography (EEG) has been advocated, but EEG only records postsynaptic potentials of cortical neurons and not the metabolic status of basal structures. During cooling the EEG becomes isoelectric between 20 and 18 °C, but consistency of variation during hypothermia is unproven. The association between intraoperative EEG changes and postoperative neurological deficit is weak. Still, EEG is used to determine electrical silence before DHCA, and to assess the effects of additional pharmacological protective strategies [59].

Recently the bispectral index (BIS), derived from the analysis of phase and frequency interrelationships of EEG waves, was studied in patients undergoing cardiac surgery with CPB, and it showed a reduced need for anesthetics after CPB compared with before CPB [39]. This important observation was confirmed in our patients, using the patient state index (PSI) instead of the BIS [13]. Monitoring DHCA patients with PSI revealed that after rewarming and termination of CPB, the level of anesthetic sedation may last several hours without any additional administration of anesthetics. This might be due to the combination of deep hypothermia and pharmacological protection with barbiturates, which is our common practice. Since anesthetics may cause myocardial depression and unwanted hypotension owing to vasodilatation, monitors such as BIS and PSI have the capacity to improve outcome by preventing unnecessary anesthetic intervention in the early post-CPB period. A typical example of a PSI registration is presented in Fig. 8.1.

A second monitoring method, which is studied intensively, is jugular venous bulb oxygen saturation ($SjVO_2$). $SjVO_2$ is measured by inserting a catheter percutaneously in the internal jugular vein, and advancing it in a retrograde fashion into the jugular bulb. The actual measurements of $SjVO_2$ are performed intermittently by sampling from the catheter, or continuously by using a fiberoptic catheter [46]. During cerebral cooling cerebral metabolic rate and cerebral oxygen extraction both decrease, resulting in an increase in $SjVO_2$. Some authors suggest cooling to DHCA should continue until $SjVO_2$ has increased to at least 95%, indicating sufficient global cerebral hypothermia, although regional differences will still be undetected [23].

The cerebral protective effect of hypothermia is undisputed [6], but the accurate temperature to guarantee maximal protection during DHCA is unknown. Hypothermia not only lowers the brain energy demands by lowering $CMRO_2$, but also provides protection by reducing excitatory neurotransmitter release, decreasing free-radical production, and maintaining cellular integrity [7].

Most authors indicate that DHCA is started at a temperature of 15–20 °C measured at core, tympanic, or both sites [10, 52, 47]. Studies on neurological deficit after DHCA conclude that an arrest time of 25–30 min is probably the maximal tolerated ischemic period, particularly for the brain. The duration of DHCA time and the age of the patients are reported to be the most important risk factors for mortality and postoperative neurological deficit [10, 15, 52].

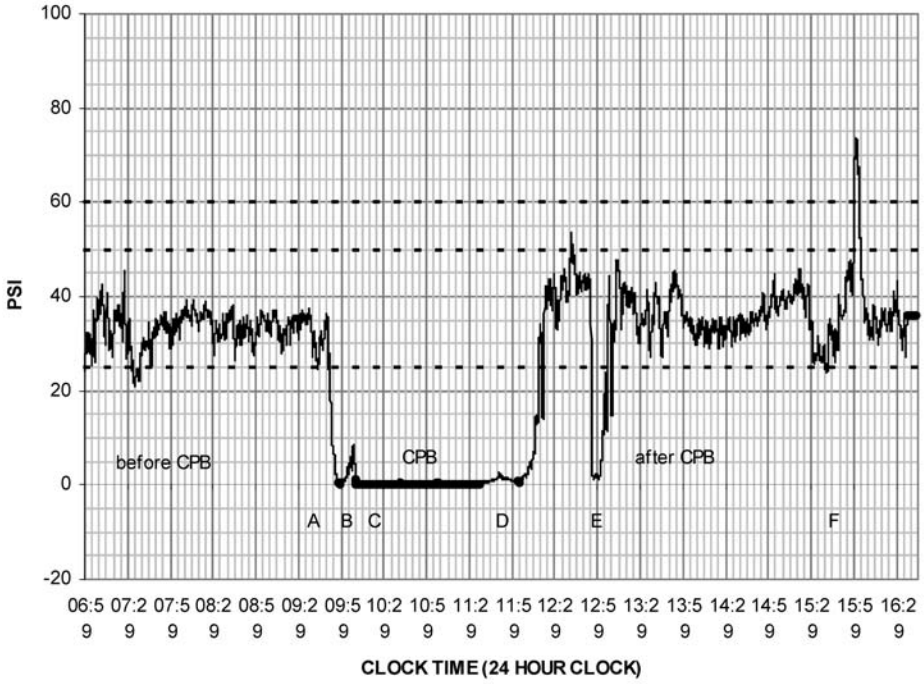

Fig. 8.1. Typical recording of patient state index (*PSI*) during surgery with deep hypothermic circulatory arrest. *A* start of cardiopulmonary bypass (*CPB*) and cooling; *B* deep hypothermic circulatory arrest; *C* start of antegrade cerebral perfusion; *D* start of rewarming; *E* 2 mg midazolam intravenously; *F* start of 50 µg/kg/min propofol

To diminish cerebral arrest time, perfusion of the brain during deep hypothermia has been implemented including retrograde cerebral perfusion (RCP) or antegrade cerebral perfusion (ACP). Recent reports indicate the superiority of ACP [40, 50, 56], with neurologic deficit rates of 5–8% [10] and transient brain dysfunction of 10–30% [15, 50]. Cerebral autoregulation is significantly better preserved with ACP compared with RCP or with no selective cerebral perfusion [47]. An alternative approach using the axillary artery for antegrade perfusion during DHCA shows promising results [34], even in emergency conditions [63].

In spite of these improvements, the substantial residual neurologic problems after surgery with deep hypothermia have inspired researchers to focus on the rewarming phase after circulatory arrest. Several studies using $SjVO_2$ monitoring have reported significant venous desaturation during rewarming [9, 33]. Apparently there is a discrepancy between oxygen demand and supply in this crucial phase, which was reported to be prevented by mild hypercapnia [25], with a critical limit of desaturation defined at 50% [9]. Changing the rate of rewarming had no effect on the reduction of jugular venous saturation, indicating that a relative impairment of cerebral blood flow in the presence of marked hemodilution may be responsible for this phenomenon. There are no convincing data that jugular venous desaturation is related to postoperative neurologic deficit, but a study using preoperative MRI suggests that patients with greater preoperative abnormalities had higher degrees of desaturation during rewarming [20]. Since patients undergoing surgery of the aortic arch may show preoperative impairment of cerebral perfusion, they represent a vulnerable group for venous jugular desaturation during rewarming after DHCA. Large, prospective, multicenter studies may show a relationship between these two variables.

8.2.3 Pharmacological Protection

Because deep hypothermia, including ACP, often still leads to unwanted neurological outcome in circulatory arrest, additional methods of neuroprotection are applied, including pharmacological interventions. Probably the most controversial approach is the use of barbiturates, particularly thiopentone. In theory barbiturates have an interesting protective profile including a reduction of $CMRO_2$ and cerebral blood flow, effects on free fatty acid and free-radical metabolism, reduction of cerebral edema, and suppression of seizure activity [32]. In a rat model of cerebral ischemia, thiopentone attenuated Ca^{2+} influx in the hippocampus and cortex, probably owing to inhibition of calcium channels and NMDA receptors [64].

Barbiturates have been extensively studied in animal models of focal ischemia [42, 43] with varying success.

CBP, with its tendency to produce substantial amounts of microemboli, may serve as a reliable human model for focal cerebral ischemia. Nussmeier et al. [49] were among the first to report beneficial effects of thiopentone in the prevention of neuropsychiatric complications in cardiac surgery, but a similar study by Zaidan et al. [65] could not substantiate this finding.

The cerebral protective effects of barbiturates in global ischemia have been studied in various models including humans after cardiac arrest [5]. All the trials failed to demonstrate an improvement in outcome. There are no randomized clinical studies showing advantageous effects of barbiturates in DHCA patients, and it has even been suggested that barbiturates may jeopardize the energy state of the brain in these conditions [55]. Still, in a survey on current practice, 35% of the respondents believed there to be sufficient evidence to support the use of barbiturates in aortic surgery with DHCA [11]. As potential support for the use of barbiturates, it could be stated that they have been shown to be protective in incomplete, focal ischemia in specific settings as are present during CBP, because of multiple emboli. In addition, they may be helpful in protecting the brain during rewarming after DHCA, particularly in the early phase, when the aforementioned observed jugular venous oxygen desaturation indicates a lack in oxygen delivery.

Since Ca^{2+} ions play a major role in the devastating effect of cerebral ischemia, several studies have been conducted on the effects of calcium antagonists as neuroprotectants. Nimodipine, which has neuroprotective effects in decreasing vasospasm after subarachnoid hemorrhage, has been shown to have some efficacy in improving cognitive outcome after CBP [16], but no studies in patients undergoing DHCA have been reported. Unfortunately, a study involving patients undergoing valve replacement had to be terminated because of substantial complications in the nimodipine-treated patients [38].

Another Ca^{2+} channel blocker, magnesium, showed evidence of protection to the neurons of the hippocampus in rats in anoxic conditions, in contrast to nimodipine, which showed no protection at all [29]. This can be explained by the blockade of all voltage-sensitive and NMDA-activated neuronal Ca^{2+} channels by magnesium, whereas nimodipine only blocks voltage-sensitive channels.

In view of its typical local anesthetic properties, lidocaine has the potential of a powerful neuroprotective agent. It blocks selectively Na^{+} channels in neuronal membranes. In animal models high doses of lidocaine induce isoelectric EEG, indicating a pronounced reduction in $CMRO_2$. In this respect it mimics the effects of hypothermia, but unlike the barbiturates, lidocaine can further reduce metabolic rate by 15–20% [2]. This is mainly attributed to its capacity to reduce ion leaks and energy requirements for the $Na^{+}K^{+}$-ATPase pumps. In many respects lidocaine may be an adjuvant to hypothermia in protecting the brain during ischemia. In a dog model studying lidocaine at doses of 4 mg/kg before DHCA and 2 mg/kg at the start of reperfusion, the neurological deficit scores in the treatment group were significantly better than in the placebo group [67]. In two recent human studies, a continuous lidocaine infusion of 1 mg/min during and after cardiac surgery resulted in better short-term cognitive outcome [41, 61]. These promising results should lead to human multicenter trials on the neuroprotective effects of lidocaine during DHCA.

In the cascade of events during brain ischemia with an important role for NMDA and AMPA receptors, it is understandable that antagonists of these receptors have been extensively studied in the prevention of adverse neurological outcomes. Remacemide, an NMDA antagonist, was studied during coronary bypass surgery, and showed beneficial effects as a neuroprotective agent [1], but follow-up is lacking. It is also unknown if these results can be extrapolated to DHCA patients. Other studies with NMDA antagonists, including ketamine, had to be discontinued because of toxicity or hallucinogenic side effects [57].

Steroids, in particular dexamethasone and methylprednisolone, are routinely used during DHCA surgery [11], mainly because they counteract the systemic inflammatory response (SIRS) during and after CBP. Brain ischemia is considered to be a combination of embolization and SIRS, and steroids have previously been shown to improve neurological outcome in DHCA patients [36].

In several animal studies dexmedetomidine, a selective α_2-adrenoreceptor agonist, showed strong neuroprotective properties in focal as well as global ischemia [35]. Inhibition of ischemia-induced norepinephrine release may be associated with these effects, particularly in the hippocampus, an extremely vulnerable region in the brain, as described earlier. There are no data concerning the potential protecting role of dexmedetomidine in brain ischemia, but its pharmacological profile makes it a very interesting compound to study in this context.

8.2.4 Aprotinin

The use of antifibrinolytics in cardiac surgery is a well-accepted technique to reduce perioperative blood loss and to minimize blood transfusions [37]. Since profound hypothermia induces coagulopathy by kinin and kallikrein activation, platelet dysfunction and fibrinolysis, and since circulatory arrest causes an increase of activated protein C and the endothelial release of tissue-type plasminogen activator, the administration of antifibrinolytics in these conditions seems to be appropriate.

Unfortunately, concern about the potential prothrombotic properties of antifibrinolytics, specifically aprotinin, has provoked controversy about their use. In earlier studies aprotinin was related to adverse outcomes, including mortality, renal dysfunction, and thrombotic complications [60, 62]. It is generally accepted that these complications were due to inadequate heparinization. In later retrospective studies, in which the heparin dose was optimized, aprotinin had no deleterious effect on organ function, and mostly diminished blood loss and transfusions [21]. Since aprotinin has additional anti-inflammatory properties, its use in DHCA surgery is even more attractive since DHCA causes a profound form of vascular endothelial injury and apoptosis in various organs [8]. Larger, multicenter studies should be initiated to end the controversy.

Anesthetics, including inhalation agents and opioids, and potent intravenous sedatives, such as etomidate and propofol, all diminish $CMRO_2$, and in doing so may exert neuroprotective properties. In animal models most anesthetics suppress brain concentrations of catecholamines and glutamine during incomplete ischemia [14].

Similar to the experiences with thiopentone, propofol did not show protection against neuropsychiatric dysfunction following cardiac surgery in humans [53].

An exciting new development is the so-called preconditioning effect of inhalation agents. Ischemic preconditioning of the myocardium was first described by Murry et al. [45], who described the protective effect of brief periods of previous ischemia against a subsequent, more prolonged period of myocardial ischemia. Ischemic stimuli cause the release of adenosine, bradykinin, noradrenaline, and free radicals. Through intracellular messenger systems, such as protein kinase C, ATP-sensitive potassium (K^+) channels on the sarcolemma and mitochondria are activated, preventing the influx of calcium into the cytosol.

Halogenated agents, such as isoflurane and sevoflurane, have been shown to mimic this preconditioning effect and to protect the myocardium during ischemic episodes and reperfusion [30]. In a recent study sevoflurane also showed renal protective properties, although the mechanism behind this observation is not yet clear [28]. It is tentative to assume that similar preconditioning effects by inhalation agents may be true during brain ischemia. In animal studies isoflurane and sevoflurane pretreatment protected the brain against ischemia [3], with an identical underlying mechanism as in myocardial tissues [31, 66].

8.3 Ischemic Kidney

Acute renal failure is most often due to a combination of hypotension, hypovolemia, and dehydration. The heterogenous blood flow in the kidney is responsible for heterogenous oxygen delivery, and the medullary ascending limb of Henle's loop is particularly vulnerable to hypoxia. During DHCA the kidney is not perfused, but the hypothermia should protect it from injury. Since it is not clear at what temperature this protective mechanism is most effective, additional pharmacological protection is applied.

The two most important components in preserving renal function are mannitol and furosemide.

8.3.1 Mannitol

Osmotic diuresis with mannitol is considered to protect the kidney by lowering renal vascular resistance and preserving tubular integrity. It may also reduce endothelial cell edema by preventing sludging in the circulation of the medulla. In addition, mannitol is a free-radical scavenger [18]. The optimal protective dose is assessed at 0.5 mg/kg.

8.3.2 Furosemide

Renal oxygen consumption is mainly determined by persisting glomerular filtration and the active transport, including reabsorption, of solute across the membranes. Although the blood flow to the kidneys is abolished during DHCA causing a cessation of glomerular filtration, it might be particularly important during reperfusion to block oxygen consumption by means of loop diuretics. For example, furosemide not only blocks reabsorption, but also increases renal blood flow, probably mediated by prostaglandins [48]. The combination of furosemide and mannitol has shown to preserve renal function in ischemic conditions [26]. The optimal protective dose is assessed at 1 mg/kg, which is often divided into a preischemic and a postischemic dose.

8.3.3 Vasodilators

Although dopamine dilates renal arterioles, increases renal blood flow, and has anti-aldosterone activity, its role as a renal protecting compound is questionable. Low-dose dopamine (0.5–3 µg/kg/min) did not show any benefit in preventing renal failure in surgical patients, presumably because it has a mixed specificity for DA_1 receptors, DA_2 receptors and α_1-adrenergic receptors [19].

Fenoldopam, a highly selective DA_1 receptor agonist, has a similar vasodilating profile as dopamine. In patients undergoing cardiac or aortic surgery it showed protective properties for the kidney during ischemia [17, 24]. The recommended effective dose is 0.03–1

μg/kg/min. There are no data available about the use of fenoldopam in DHCA surgery.

8.4 Conclusion

From the available studies concerning patients undergoing surgery with DHCA one can conclude that two major issues have been involved in the improvement of outcome: the application of selective ACP, and the recognition of cerebral ischemia during the rewarming phase.

Apart from the hypothermia, additional pharmacological protection has not been shown to be effective in reducing adverse neurological outcome, although most clinicians administer barbiturates, steroids, and lidocaine before the ischemic event.

It is challenging to address the potential protective properties of halogenated anesthetics such as isoflurane and sevoflurane since the concept of protective ischemic preconditioning by these compounds is well established in other organs, particularly in the heart.

A second interesting approach is a study of the potentially protective role of dexmedetomidine, a selective α_2-adrenorecptor agonist, since recent animal studies suggest protective properties in the hippocampus, an extremely vulnerable region in cerebral ischemic conditions.

Eventually the outcome of these forms of surgery may be improved by better monitoring techniques. The assessment of the optimal protective brain temperature is still difficult, not only before, but also after the circulatory arrest phase. $SjVO_2$ monitoring may become mandatory, informing the perfusionist during rewarming about the oxygen balance in the brain. New EEG processing monitors like the BIS or the PSI have the ability to inform the anesthesiologist about the anesthetic state of the brain, and may prevent unnecessary administration of anesthetics.

Owing to the application of selective ACP and the shortening of the duration of cerebral ischemia, there is more focus on the fate of other organ systems after the phase of circulatory arrest. In particular, renal failure is an important risk factor, and the pharmacological protection of the kidney with mannitol, furosemide, and potentially fenoldopam should always be considered.

References

1. Arrowsmith JE, Harrison MJG, Newman SP, Stygall J, Timberlake N, Pugsley WB (1998) Neuroprotection of the brain during cardiopulmonary bypass. A randomized trial of remacemide during coronary artery bypass in 171 patients. Stroke 29:2357–2562.
2. Astrup J, Sorensen PM, Sorensen HR (1981) Inhibition of cerebral oxygen and glucose consumption in the dog by hypothermia, pentobarbital, and lidocaine. Anesthesiology 55:263–268.
3. Blanck TJ, Haile M, Xu F (2000) Isoflurane pre-treatment ameliorates postischemic neurologic dysfunction and preserves hippocampal Ca^{2+}/calmodulin-dependent protein kinase in a canine cardiac arrest model. Anesthesiology 93:1285–1293.
4. Bokesch PM, Marchand J, Seirafi PA, Deiss JM, Warner KG, Bronson RT, Kream RM (1996) Immediate-early gene expression in ovine brain after cardiopulmonary bypass and hypothermic circulatory arrest. Anesthesiology 85:1439–1446.
5. Brian Resuscitation Clinical Trial 1 Study Group (1986) Randomized clinical study of thiopental loading in comatose survivors of cardiac arrest. N Eng J Med 314:397–403.
6. Busto R, Dietrich W, Globus M, Ginsberg M (1989) The importance of brain temperature in cerebral ischemic injury. Stroke 20:1113–1114.
7. Busto R, Globus M, Dietrich W, Martinez E, Valdez I, Ginsber M (1989) Effect of mild hypothermia on ischemia-induced release of neurotransmitters and free fatty acids in rat brain. Stroke 20:904–910.
8. Cooper WA, Duarte IG, Thourani VH, Nakamura M, Wang N-P, Brown WM, Gott JP, Vinten-Johansen J, Guyton RA (2000) Hypothermic circulatory arrest causes multisystem vascular endothelial dysfunction and apoptosis. Ann Thorac Surg 69:696–703.
9. Croughwell ND, Frasco P, Blumenthal JA, Leone BJ, White WD, Reves JG (1992) Warming during cardiopulmonary bypass is associated with jugular bulb desaturation. Ann Thorac Surg 53:827–832.
10. Czerny M, Fleck T, Zimpfer D, Dworschak M, Hofmann W, Hutschala D, Dunkler D, Ehrlich M, Wolner E, Grabenwoger M (2003) Risk factors of mortality and permanent neurologic injury in patients undergoing ascending aortic and arch repair. J Thorac Cardiovasc Surg 126:1296–1301.
11. Dewhurst AT, Moore SJ, Liban JB (2002) Pharmacological agents as cerebral protectants during deep hypothermic circulatory arrest in adult thoracic aortic surgery. Anesthesia 57:1016–1021.
12. Drew CE, Keen G, Benazon DB (1959) Profound hypothermia. Lancet 1:745–748.
13. Edmonds HL (2001) Advances in neuromonitoring for cardiothoracic and vascular surgery. J Cardiothorac Vasc Anesth 15:241–250.
14. Engelhard K, Werner C, Hoffman W, Matthes B, Blobner M, Kochs E (2003) The effect of sevoflurane and propofol on cerebral neurotransmitter concentrations during cerebral ischemia in rats. Anesth Analg 97:1155–1161.
15. Fleck TM, Czerny M, Hutschala D, Koinig H, Wolner E, Grabenwoger M (2003) The incidence of transient neurologic dysfunction after ascending aortic replacement with circulatory arrest. Ann Thorac Surg 76:1198–1202.
16. Forsman M, Tubylewicz OB, Semb G, Steen PA (1990) Effects of nimodipine on cerebral blood flow and neuropsychological outcome after cardiac surgery. Br J Anaesth 65:514–520.
17. Garwood S, Swamidoss CP, Davis EA, Samson L, Hines RL (2003) A case series of low-dose fenoldopam in seventy cardiac surgical patients at increased risk of renal dysfunction. J Cardiothorac Vasc Anesth 17:17–21.
18. Gelman S (1998) Ischemic insult, kidney viability, and renal function. Anesth Analg 86:1–2.
19. Goldberg LI (1988) Dopamine and new dopamine analogs: receptors and clinical applications. J Clin Anesth 1:66–74.
20. Goto T, Yoshitake A, Baba T, Shibata Y, Sakata R, Uozomi H (1997) Cerebral ischemic disorders and cerebral oxygen balance during cardiopulmonary bypass surgery: pre-

operative evaluation using magnetic resonance imaging and angiography. Anesth Analg 84:5–11.
21. Green JA, Spiess BD (2003) Current status of antifibrinolytics in cardiopulmonary bypass and elective deep hypothermic circulatory arrest. Anesthesiol Clin North Am 21:527–551.
22. Griepp RB, Stinson EB, Hollingworth JF, Buehler D (1975) Prosthetic replacement of the aortic arch. J Thorac Cardiovasc Surg 70:1051–1063.
23. Griepp RB, Ergin MA, McCullough JN, Nguyen KH, Juvonen T, Chang N, Griepp EB (1997) Use of hypothermic circulatory arrest for cerebral protection during aortic surgery. J Card Surg 12 (Suppl):312–321.
24. Halpenny M, Rushe C, Breen P, Cunningham AJ, Boucher-Hayes D, Shorten GD (2002) The effects of fenoldopam on renal function in patients undergoing elective aortic surgery. Eur J Anesthesiol 19:32–39.
25. Hänel F, von Knobelsdorff G, Werner C, Schulte am Esch J (1998) Hypercapnia prevents jugular bulb desaturation during rewarming from cardiopulmonary bypass. Anesthesiology 89:19–23.
26. Hanley MJ, Davidson K (1981) Prior mannitol and furosemide infusion in a model of ischemic acute renal failure. Am J Physiol 241:556–564.
27. Hindman BJ, Dexter F (1995) Estimating brain temperature during hypothermia. Anesthesiology 82:329–330.
28. Julier K, Da Silva R, Garcia C, Bestmann L, Frascarolo P, Zollinger A, Chassot-P-G, Schmid E, Turina MI, Von Segesser LK, Pasch T, Spahn DR, Zaugg M (2003) Preconditioning by sevoflurane decreases biochemical markers for myocardial and renal dysfunction in coronary artery bypass graft surgery: a double-blinded, placebo-controlled, multicenter study. Anesthesiology 98:1315–1327.
29. Kass IS, Cottrell JE, Chambers G (1988) Magnesium and cobalt, not nimodipine, protect neurons against anoxic damage in the rat hippocampal slice. Anesthesiology 69:710–715.
30. Kato R, Fox P (2002) Myocardial protection by anesthetic agents against ischemia-reperfusion injury: an update for anesthesiologists. Can J Anaesth 49:777–791.
31. Kehl F, Payne RS, Roewer N, Schurr A (2004) Sevoflurane-induced preconditioning of rat brain in vitro and the role of K (ATP) channels. Brain Res 17:76–81.
32. Kelly BJ, Luce JM (1993) Current concepts in cerebral protection. Chest 103:1246–1254.
33. Kiziltan HT, Baltali M, Koca D, Oner S, Sener M, Tasdelen A (2003) Reduced jugular venous oxygen saturation during rewarming from deep hypothermic circulatory arrest: cerebral overextraction? Cardiovasc Surg 11:213–217.
34. Kouchoukos NT, Masetti P (2003) Total aortic arch replacement with a branched graft and limited circulatory arrest of the brain. J Thorac Cardiovasc Surg 128:233–237.
35. Kuhmonen J, Pokorny J, Miettinen R, Haapalinna A, Jolkkonen J, Riekkinen P, Sivenius J (1997) Neuroprotective effects of dexmedetomidine in the gerbil hippocampus after transient global ischemia. Anesthesiology 87:371–37.
36. Langley SM, Chai PJ, Jaggers JJ, Ungerleider RM (2000) Preoperative high dose methylprednisolone attenuates the cerebral response to deep hypothermic circulatory arrest. Eur J Cardiothorac Surg 17:279–286.
37. Laupacis A, Fergusson D (1997) Drugs to minimize perioperative blood loss in cardiac surgery: meta-analyses using perioperative blood transfusion as outcome. Anesth Analg 85:1258–1267.
38. Legault C, Furberg C, Wagenknecht L, Rogers A, Stump D, Coker L, Troost B, Hammon J (1996) Nimodipine neuroprotection in cardiac valve replacement. Report of an early terminated trial. Stroke 27:593–598.
39. Lundell JC, Scuderi PE, Butterworth JF (2001) Less isoflurane is required after than before cardiopulmonary bypass to maintain a constant bispectral index value. J Cardiothorac Vasc Anesth 15:551–554.
40. Matalanis G, Hata M, Buxton BF (2003) A retrospective study of deep hypothermic circulatory arrest, retrograde, and antegrade cerebral perfusion in aortic arch surgery. Ann Thorac Cardiovasc Surg 9:174–179.
41. Mitchell SJ, Pellett O, Gorman (1999) Cerebral protection by lidocaine during cardiac operations. Ann Thorac Surg 67:1117–1124.
42. Mitchenfelder JD, Milde JH, Sundt TM (1976) Cerebral protection by barbiturate anesthesia. Use of middle cerebral artery occlusion in Java monkeys. Arch Neurol 33:345–350.
43. Murdoch J, Hall R (1990). Brain protection: physiological and pharmacological considerations. Can J Anaesth 37:663–671.
44. Murkin J (1995) Neuroprotection, anaesthesia, and the brain. Can J Anaesth 42:R109–R113.
45. Murry CE, Jennings RB, Reimer KA (1986) Preconditioning with ischemia. A delay of lethal cell injury in ischemic myocardium. Circulation 74:1124–1136.
46. Nakajima T, Kuro M, Hayashi Y (1992) Clinical evaluation of cerebral oxygen balance during cardiopulmonary bypass: on-line continuous monitoring of jugular venous oxyhemoglobin saturation. Anesth Analg 74:630–635.
47. Neri E, Sassi C, Barabesi L, Massetti M, Pula G, Buklas D, Tassi R, Giomarell P (2004) Cerebral autoregulation after hypothermic circulatory arrest in operations on the aortic arch. Ann Thorac Surg 77:72–80.
48. Nies AS, Gal J, Fadul S, Gerber JG (1983) Indomethacin-furosemide interaction: the importance of renal blood flow. J Pharmacol Exp Ther 226:27–32.
49. Nussmeier NA, Arlund C, Slogoff SL (1986) Neuropsychiatric complications after cardiopulmonary bypass: cerebral protection by a barbiturate. Anesthesiology 64:165–170.
50. Okita Y, Minatoya K, Tagusari O, Ando M, Nagatsuka K, Kitamura S (2001) Prospective comparative study of brain protection in total aortic arch replacement: deep hypothermic circulatory arrest with retrograde cerebral perfusion or selective antegrade cerebral perfusion. Ann Thorac Surg 72:72–79.
51. Ramsay JG, Ralley FE, Whalley DG, DelliColli P, Wynands JE (1985) Site of monitoring and prediction of afterdrop after open heart surgery. Can Anaesth Soc J 32:607–612.
52. Reich DL, Uysal S, Sliwinski M, Ergin MA, Kahn RA, Konstadt SN, McCullough J, Hibbard MR, Gordon WA, Griepp RB (1999) Neuropsychological outcome after deep hypothermic circulatory arrest in adults. J Thorac Cardiovasc Surg 117:156–163.
53. Roach GW, Newman MF, Murkin JM, Martzke J, Ruskin A, Li J, Guo A, Wisniewski A, Mangano DT (1999) Ineffectiveness of burst suppression therapy in mitigating perioperative cerebrovascular dysfunction. Anesthesiology 90:1255–1264.
54. Robinson J, Charlton J, Seal R, Spady D, Hoffres MR (1998) Oesophageal, rectal, axillary, tympanic and pulmonary artery temperatures during cardiac surgery. Can J Anaesth 45:317–323.
55. Siegman M, Anderson R, Balaban R, Ceckler T, Clark R, Swain J (1992) Barbiturates impair cerebral metabolism during hypothermic circulatory arrest. Ann Thorac Surg 54:1131–1136.
56. Sinatra R, Melina G, Pulitana I, Fiorani B, Ruvolo G, Marino B (2001) Emergency operation for acute type A aortic dissection: neurologic complications and early mortality. Ann Thorac Surg 71:33–38.
57. Small DL, Buchan AM (1996) Mechanisms of cerebral ischemia: intracellular cascades and therapeutic interventions. J Cardiothorac Vasc Anesth 10:139–146.

58. Stone JG, Young WL, Smith CR, Solomon RA, Wald A, Ostapkovich N, Shrebnick DB (1995) Do standard monitoring sites reflect true brain temperature when profound hypothermia is rapidly induced and reversed. Anesthesiology 82:344–351.
59. Stump DA, Jones TJJ, Rorie KD (1999) Neurophysiologic monitoring and outcomes in cardiovascular surgery. J Cardiothorac Vasc Anesth 13:600–613.
60. Sundt T, Kouchoukos N, Saffitz J, Murphy SF, Wareing TH, Stahl DJ (1993) Renal dysfunction and intravascular coagulation with aprotinin and hypothermic circulatory arrest. Ann Thorac Surg 55:1418–1424.
61. Wang D, Wu X, Li J, Xiao F, Liu X, Men M (2002) The effect of lidocaine on early postoperative cognitive dysfunction after coronary artery bypass surgery. Anesth Analg 95:1134–1141.
62. Westaby S (1997) Coagulation disturbances in profound hypothermia: the influence of antifibrinolytic therapy. Semin Thorac Cardiovasc Surg 9:246–256.
63. Whitlark J, Goldman SM, Sutter FP (2000) Axillary artery cannulation in acute ascending aortic dissections. Ann Thorac Surg 69:1127–1129.
64. Zahn RZ, Fukiwara N, Endoh H, Yamakura T, Taga K, Fukuda S, Shimoji K (1998) Thiopental inhibits increases in $[Ca^{2+}]i$ induced by membrane depolarization, NMDA receptor activation, and ischemia in rat hippocampal and cortical slices. Anesthesiology 89:456–466.
65. Zaidan JR, Klochany A, Martin WM, Ziegler JS, Harless DM, Andrews RB (1991) Effects of thiopental on neurological outcome following coronary artery bypass grafting. Anesthesiology 74:406–411.
66. Zhao P, Zuo Z (2004) Isoflurane preconditioning induces neuroprotection that is inducible nitric oxide synthase-dependent in neonatal rats. Anesthesiology 101:695–703.
67. Zhou Y, Wang D, Du M, Zhu J, Shan G, Ma D, Xie D, Ma Q, Hu X, Li J (1998) Lidocaine prolongs the safe duration of circulatory arrest during deep hypothermia in dogs. Can J Anaesth 45:692–698

Anaesthetic Management of the Endovascular Thoracic Aorta

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Contents

9.1 Introduction

Open surgical treatment of the thoracic aorta is associated with important complications: death rate 3–12%, perioperative infarctions 2%, respiratory failure up to 43%, renal failure, 7%, paraplegia 4–7%, cerebral complications 0.5%. When it is feasible, endovascular treatment can considerably lighten the therapeutic management. At the same time the anaesthetic procedure is simplified, even though it must take into account a possible surgical conversion. The requirements of the procedure must be known in order to ensure its good management. The procedure is performed either in a radiology intervention room or in an operating room. This means that the conditions for imaging can be limited in the surgical room, whereas they are ideal in the case of surgical conversion. Nevertheless, this is exceptional.

9.2 Requirements

1. The procedure could be conducted in an angiosuite or an operating room. If it takes place in a radiology department, the angiosuite has to be set up like an operating room in order to ensure its safe management. The ventilation must be standardised so that the air is renewed in conformity with the rules of hygiene and evacuation of anaesthetic gas. The anaesthetic fluids must be available: oxygen, medical air, nitrous oxide and medical vacuum. Of course, the material necessary for haemodynamic monitoring, ventilation and reanimation must be ready and in good order. This means regular maintenance and checking. Making X-ray acquisition from several angles requires frequent movements of the table. As well as the lengthwise movements of the table, arched movements for the oblique shots are often required. It is necessary to verify that these movements do not cause an accidental extubation of the patient and that the pipes of the respirator can move freely according to the movements of the table.

On the other hand, in the operating room, it is difficult to move easily the portable C-arm to obtain the best quality of imaging, as we get in the angiosuite.

2. The possibility of an open surgical conversion. Even though it is theoretical, the possibility of an open surgical conversion arising from a complication during the intervention must be kept in mind. All of the anaesthetic management should be done with this in view. In our experience of more than 150 thoracic stent-grafts, no conversion to open thoracic surgery was necessary. It is true that in the ideal conditions, the risk of an aortic rupture is very low. On the other hand, by using large introducers, the risk of an iliac rupture is more frequent and it could be necessary to repair it either with a surgical bypass or with a covered stent. The anaesthetic team must be prepared for this eventuality to replace blood loss if significant and control vital signs using inotropic drugs if necessary.

3. Teamwork. The procedure necessitates the participation of several teams: anaesthetists, surgeons, radiologists, and sometimes cardiologists for transoesophageal echography (TEE). The TEE is often used to obtain an excellent image of the lesion before and after stent-graft deployment and to detect an eventual endo-leak. This topic is extensively illustrated in the chapter of this book by Massabuau.

4. The position and the impossibility to estimate the duration. The procedure is carried out in a supine position on an angiography table. This uncomfortable position must be maintained during the whole process, i.e.

the insertion of the stent-graft but also the exploratory, preimplantation phases and the radiological controls. It is impossible to predict exactly the intervention duration but it should roughly be estimated between 30 and 100 min. Of course, during the learning stages these times can be longer, which is why we strongly suggest doing the procedure under general anaesthesia. The angiographic controls also demand apnoea and complete immobility, which are other arguments for doing so.

5. The temperature. The loss of heat is taken into account by the heating of the upper part of the body by a system of propelled air. The ideal positioning of the heater is hindered by the movements of the radiology table.

Problems caused by the patient. Even though stent-graft therapy is rapidly growing, it is still mainly proposed to patients with potential surgical risks. The preprocedure consultation with the anaesthetist is thus mandatory with full-medical history and complete physical examination. Polyarterial damage, although not specific to this context, must be kept in mind. The cardiac function should be closely examined, usually by an echocardiogram. Simple laboratory tests such as blood cell count, electrolytes, serum creatine, prothrombine time and activated partial thromboplastine time should be done to complete the examination. During the consultation, the patient should be clearly informed of the implications of the procedure.

6. Problems caused by the patient. The intravenous access should be of a good calibre (cathlon diameter 18). The arterial pressure should be followed through a catheter into the radial artery. In most cases only the right radial artery or the right ulnar artery will be useable. The left radial or humeral artery is most often used for the imaging controls. We also introduce a central venous catheter in the internal jugular vein. It is best for this catheter have two lumens; one for central venous pressure which would become indispensable in the case of an open conversion; the second for the injection of inotropic support if necessary.

7. Injection of iodine contrast agent. Of course, iodine contrast agent is used throughout the procedure. Its effect on renal function is well known especially in elderly polyvascular patients already showing a certain degree of renal insufficiency. Cockcroft's formula enables one to easily estimate the renal clearance and define the patient's real kidney function. Good hydration and creatinine surveillance are necessary. The administration of 600 mg *N*-acetylcystein the day before and on the day of the examination has been reported to prevent renal failure. The use of low osmolarity contrast agents and the reduction of the doses associated with adequate hydration are the best methods to reduce renal complications.

8. Anticoagulation. Anticoagulation using heparin is necessary prior to stent-graft deployment. A bolus injection of 5,000 U of heparin is done before femoral clamping. Usually, one injection is enough for the whole intervention. Unfortunately the uses of anticoagulants decreases the immediate formation of the perigraft thrombus in the aneurysm. Even if the thrombosis is not complete, the use of TEE gives an idea of the subsequent evolution. The presence of a slow motion and turbulence inside the sac is a good predictive factor for secondary thrombosis. In the same way TEE evaluates the cardiac function. In the immediate postprocedure period, anticoagulation follow-up is ensured by the association of low molecular weight heparin until rising and aspirin. It should be noted that in some circumstances for traumatic cases, we can use only 1,000 U of heparin to avoid iliac thrombosis and haemorrhage complications. In this situation, a rapid deployment of the stent-graft is essential in order to reduce the occlusion to a minimum.

9. Haemodynamic requirements. As in all anaesthetic interventions, stable blood pressure is necessary. One must be particularly careful of a sudden blood pressure rise during the stent-graft insertion especially in the case of a traumatic rupture or aortic dissection because of vascular fragility related to these pathologies. Also the success of the procedure depends on meticulous positioning and the absence of migration of the prosthesis when it is released. A systolic arterial pressure of 80 mmHg is generally sufficient to avoid migration. Several methods are used: the deepening of the anaesthesia by halogens (sevoflurane by increasing the maximum alveolar concentration), or injection of calcic inhibiters nicardipine, beta blockers, trinitrine, or more rarely sodium nitroprussiate.

In order to further reduce the parietal tension on the aorta, some authors proposed creating asystoly during the deployment, particularly in the first-generation-stent-grafts where balloon modelling was used. Different methods have been described in the literature, especially induction of ventricular fibrillation or injection of adenosine [1–4]. The first method has the disadvantage of being aggressive since the induction of a ventricular fibrillation is done using a Swan–Ganz catheter as well as a defibrillation by two external electrodes. A moderate hypothermia (34°) is also induced, with a reactionary phase of arterial hypertension. The injection of a bolus of 60 mg of adenosine has also been proposed to induce asystoly in a few seconds. The patient returns to a normal rhythm after 45 s. The secondary effects of ventricular fibrillation can be considerable. Particular attention must be paid to asthmatics. After the procedure, it is essential to maintain a normal arterial pressure.

10. Bleeding. Moderate bleeding can occur during the stent-graft placement. It is usually less than that which occurs during open surgery [5]. The blood loss usually occurs at the site of the femoral introducer. Since the intervention takes place, the anaesthesiologists must be particularly attentive to this blood loss and to the risk of hypovolemia which it could provoke.

The use of a cell-saver could be considered, particularly in the case of vascular access complication.

11. Medullar protection. As in the case of surgery, medullar complications have been described after the implantation of a stent-graft [6]. The rate of paraplegias seems to be from 0 to 4%, according to the kind of injuries treated, and is particularly frequent when thoracic and abdominal aorta are treated. These rates are inferior to those of surgery and can be explained by the absence of an aortic clamp. The mechanism of medullar injuries is ambiguous: the covering of the intercostal arteries or the Adamkiewicz artery, the absence of collateral arteries and an arterial hypotension. One of the decisive factors of spinal cord ischemia is the reduction of the pressure of the medullar perfusion defined as the gradient between the average arterial pressure and the pressure of the cerebrospinal fluid. For this reason, in order to improve the medullar perfusion, a preventive cerebrospinal fluid drainage could be proposed for high-risk patients [7] or in the case of appearance of paraplegia [8]. Although it has been contested [9], this technique, widely used in surgery, has seen the number of paraplegias reduced.

The method consists of placing an 18G catheter intrathecal after an L4–L5 punction using a Tuohy 14G needle. Cerebrospinal fluid drainage is done for a threshold value of 10 mmHg.

This method does have risks. It can be the origin of infectious complications [10], or rachidian hematomas [11]. This latter problem is crucial as we need to use heparin during the procedure. Secondary paraplegias resulting from the withdrawal of the catheter have also been described [12].

The administration of a strong dose of methylprednisolone (30 mg/kg) has been suggested as a preventive treatment [7]. In the same way, Naloxone has been used [13], but at this time there are no arguments in favour of a possible pharmacological protection.

12. Antibioprophylaxia is used by general agreement in cardio ascular surgery (1.5 g of cephalosporin at the induction, to be renewed 2 h later).

9.3 The Anesthesia Techniques

The anaesthesia techniques should be guided by the objectives of the procedure, that is, immobility, apnea and the patient's comfort.

9.3.1 General Anaesthesia

It is best suited to the objectives but its use must be dictated by the conditions. The induction anaesthesia is carried out using rapidly eliminated products and keeping haemodynamic stability. The painless procedure does not necessitate the use of important doses of morphine. The anaesthesia is maintained using halogens, without maintaining the curarisation.

9.3.2 Local Anaesthesia and Diazanalgesia

In some cases it is possible to carry out the procedures under diazanalgesia, if there is no TEE, which is uncomfortable for the patient.

9.3.3 Loco-regional Anaesthesia

A thoracic epidural anaesthesia with the patient awake could be used, but in this context we would not advise it. The carrying out of a thoracic epidural combined with a general anaesthesia could have the advantage of provoking postprocedure analgesia.

9.4 Postoperative Treatment

The immediate postoperation supervision consists primarily in supervising the awakening but also in following the arterial pressure and it maintenance below 130 mmHg, and a neurological monitoring in case of paraplegia. This supervision is best carried out in an intensive care unit for the first few hours.

In the following days the patient should remain hospitalised with, in addition to neurological and vital signs monitoring, the monitoring of temperature and blood cell count

The onset of an inflammatory syndrome is nearly constant after the insertion of an aortic stent-graft [14]. It causes fever, hyperleucocytosis and increase of C-reactive protein, and increase of C-reactive protein and the interleukins, especially IL-6 and IL-8, is observable without any bacterial infection. Normally moderate, it diminishes after a few days, either spontaneously or with the administration of nonsteroidal anti-inflammatory treatment.

This hyperthermia can sometimes require supplementary oxygen for patients with respiratory or cardiac complications and can even be the source of hypoxia, of tachyarrhythmia or of angina pectoris. Its aetiology is still hypothetical. Some say it could be an immunity reaction to the material used or a secondary cellular reaction to the manipulation of the aneurismal sac

After the implantation of an aortic endoprothesis, an activation of coagulation with a thrombopenia has been observed [15]. This postoperative syndrome, although rare, can give rise to a consumptive coagulopathy [16].

9.5 Conclusion

The anaesthetic management of patients undergoing endovascular treatment is greatly simplified compared with that for patients undergoing open surgery. Nevertheless, the procedure is mainly reserved for patients with high morbidity risk or in a traumatic context. A general anaesthesia enables the insertion of the stent-graft in a highly comfortable condition for the patient and the operators, even more so since it is now possible to moderate the depth of the anaesthesia and to ensure a high degree of security, especially haemodynamic stability.

The evaluation of the technique will enable us to better pinpoint the indications. Should the procedure be extended to patients in good medical condition, or should it still mainly be reserved for older patients with associated comorbidity, which incurs supplementary constraints for the anaesthetic management?

References

1. Baker AB, Bookallil MJ, Lloyd G. Intentional asystole during endoluminal thoracic aortic surgery without cardiopulmonary bypass. Br J Anaesth 1997; 78:444–448.
2. Hashimoto T, Young WL, Aagaard BD, Joshi S, Ostapkovich N, Pile-Spellman J. Adenosine-induced ventricular asystole to induce transient profound systemic hypotension in patients undergoing endovascular therapy. Anesthesiology 2000; 93:998–1001.
3. Kahn RA, Marin ML, Hollier LH, Parson R, Griepp R. Induction of ventricular fibrillation to facilitate endovascular stent graft repair of thoracic aortic aneurysms. Anesthesiology 1998; 88:534–536.
4. Weigand MA, Motsch J, Bardenheuer HJ. Adenosine-induced transient cardiac arrest for placement of endovascular stent-grafts in the thoracic aorta. Anesthesiology 1998; 89:1037.
5. Zarins CK, White RA, Schwarten D, Kinney E, Diethrich EB, Hodgson KJ, Fogarty TJ. AneuRx stent graft vs. open surgical repair of abdominal aortic aneurysms: multicenter prospective clinical trial. J Vasc Surg 1999; 29:292–308.
6. Fuchs RJ, Lee WA, Seubert CN. Transient paraplegia after stent grafting of a descending thoracic aortic aneurism treated with cerebrospinal fluid drainage. J Clin Anesth 2003; 15:59–63.
7. Kahn RA, Faries PL, Leibowitz AB. Anesthetic techniques for endovascular repair of thoracic aortic aneurysms: influence of endovascular device design and prevention of spinal cord ischemia. 2001 ASA meeting abstracts.
8. Ortiz-Gomez JR, Gonzalez-Solis FJ, Fernandez-Alonzo L. Reversal of acute paraplegia with cerebrospinal fluid drainage after endovascular thoracic aneurysm repair. Anesthesiology 2001;9 5:1288–1289.
9. Ling E, Arellano R. Systematic overview of the evidence supporting the use of cerebrospinal fluid drainage in thoracoabdominal aneurysm surgery for prevention of paraplegia. Anesthesiology 2000; 93:1115–1122.
10. Coplin WM, Avellino AM, Kim DH, Winn HR, Grady MS. Bacterial minigitis associated with lumbar drains: a retrospective cohort study. J Neurol Neurosurg Psychiatry 1999; 67:468–473
11. Weaver KD, Wiserman DB, Farber M, Ewend MG, Marston W, Keagy BA. Complication of lumbar drainage after thoracoabdominal aortic aneurysm repair. J Vasc Surg 2001; 34:623–627.
12. Heller LB, Chaney MA. Paraplegia immediately following removal of a cerebrospinal fluid drainage catheter in a patient after thoracoabdominal aortic aneurysm surgery. Anesthesiology 2001; 95:1285–1287.
13. Killen DA, Weinstein CL, Reed WA. Reversal of spinal cord ischemia resulting from aortic dissection. J Thorac Cardiovasc Surg 2000; 119:1049–1052.
14. Zimmer S, Heiss MM, Schardey HM, Weilbach C, Faist E, Lauterjung L. Inflammatory syndrome after endovascular implantation of an aortic stent – a comparative study. Langenbecks Arch Chir Suppl Kongressbd 1998; 115(Suppl I):13–17.
15. Shimazaki T, Ishimaru S, Kawaguchi S, Yokoi Y, Watanabe Y. Blood coagulation and fibrinolytic response after endovascular stent grafting of thoracic aorta. J Vasc Surg 2003; 37(6):1213–1218.
16. Cross KS, Bouchier-Hayes D, Leahy AL. Consumptive coagulopathy following endovascular stent repair of abdominal aortic aneurysm. Eur J Vasc Endovasc Surg 2000; 19(1):94–95.

Surgical Treatment

Hans-Joachim Schäfers

10

Contents

10.1 Introduction

The treatment of aortic arch aneurysms by aortic replacement was first attempted in the 1950s utilizing temporary shunts or selective perfusion of the supraaortic vessels to maintain cerebral circulation [1, 2]. The introduction of deep hypothermic circulatory arrest greatly facilitated aortic repair, which was standardized in the 1980s [3, 4]. Several technical modifications have been proposed in the past 20 years, some of which seem to be of benefit in special situations. Research in the past 15 years has focused on cerebral protection in order to minimize the risk of neurological complications further. Today replacement of the aortic arch for degenerative aneurysm has become a standard and reproducible surgical procedure with low mortality and morbidity.

10.2 Prevalence, Symptoms

While the exact prevalence of aortic arch aneurysms is unknown, they are less frequent than aneurysms of the ascending or the infrarenal aorta [5]. This is due to the fact that aneurysms of the aortic arch may easily be overlooked in the course of cardiologic diagnostic studies, and an arch aneurysm is rarely diagnosed on a rou-

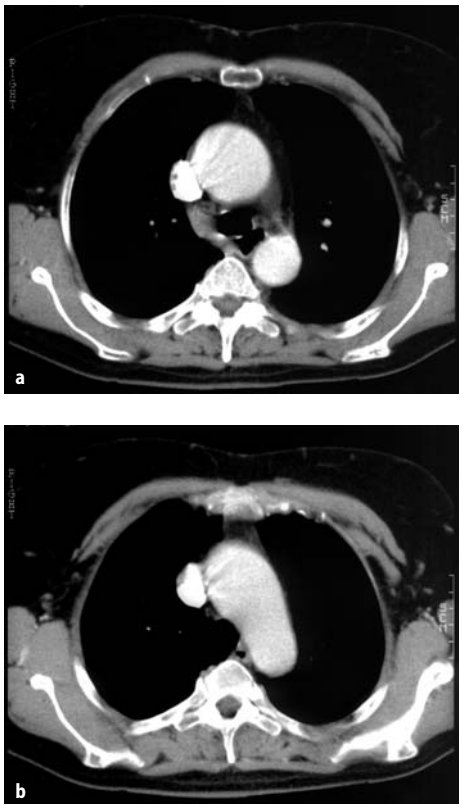

Fig. 10.1. Typical computed tomography of the chest with contrast in a 65-year-old patient with a true proximal aortic aneurysm. The main involvement is in the ascending aorta, and this patient can be treated by ascending and partial arch replacement

tine chest radiograph performed for other reasons. Most frequently, arch aneurysms are found as an extension of proximal or distal aortic aneurysms (Fig. 10.1). Degenerative aneurysms of the arch are commonly asymptomatic. Occasionally, hoarseness due to stretching of the left recurrent laryngeal nerve leads to the diagnosis of arch aneurysm. Symptoms, such as chest pain, mostly occur once the aneurysm has either ruptured or perforated into a mediastinal structure.

10.3 Pathology

As in ascending aortic aneurysms, atherosclerosis and connective tissue disorders are the two most frequent underlying diseases [5, 6]. Luetic aneurysms have become a rarity. Morphologically, degenerative aneurysms of the aortic arch are mainly seen in two distinct forms. The majority of aneurysms are fusiform and thus so-called true aneurysms. They are rarely found isolated in the arch, but most often represent the arch extension of proximal, or – less frequently – distal aortic aneurysms (Fig. 10.2). The combination of both proximal and distal aneurysmal disease is not infrequent and is often referred to as mega-aortic syndrome. Saccular aneurysms are seen in the aortic arch as in other parts of the distal aorta [7]. They most frequently arise from a ruptured atherosclerotic plaque, and consequently are not encompassed by all layers of the vascular wall (Fig. 10.3).

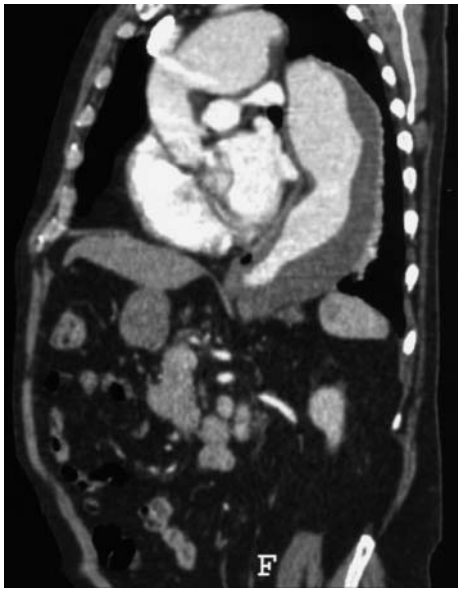

Fig. 10.2. Two-dimensional reconstruction of computed tomography of the chest of a 74-year-old patient with a true distal aortic aneurysm beginning in the arch and extending into the distal thoracic aorta. A one-stage operation could be performed through the left chest. Because of the risk of embolism and the presence of chronic obstructive lung disease a two-stage approach with total arch replacement followed by distal repair seems advisable

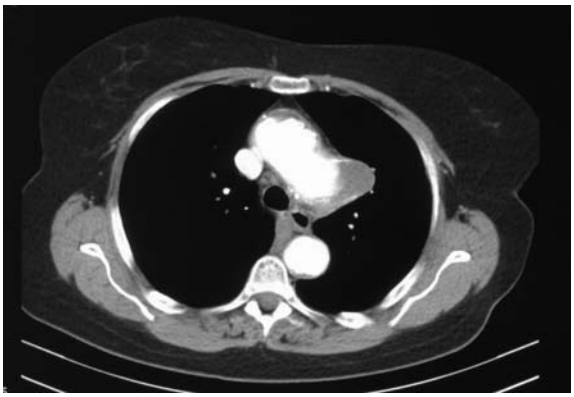

Fig. 10.3. Severe atherosclerosis in a 68-year-old patient with hoarseness of 3 months' duration. There is moderate dilatation of the arch and a saccular aneurysm, which measured over 3 cm in its largest diameter. The vascular wall of the arch exhibits marked atheroma with a relevant chance of embolism. The lowest risk of stroke can probably be achieved by total arch replacement including the use of retrograde perfusion

Both forms of aneurysms are consequences of atherosclerosis, and aortic arch aneurysm is thus accompanied by other manifestations of atherosclerosis in a significant proportion of individuals. Most important are coronary heart disease and cerebrovascular disease; impaired renal function is usually an indicator of marked, generalized atherosclerosis.

10.4 Prognosis, Indication for Treatment

The prognosis of these aneurysms largely depends on their tendency to rupture or originate acute dissection. Some information exists on the spontaneous prognosis of true aneurysms [6, 8], even though the data is very limited compared with the prognostic information on coronary heart or valve disease. On the basis of the information available it seems to be clear that these aneurysms tend to grow in size and rupture or dissect with increasing frequency once a diameter of approximately 5 cm has been exceeded [6, 8, 9]. However, the available studies either do not differentiate between proximal and distal aneurysms or fail to clearly point out similarities or differences between, for example, proximal aorta and arch. There is only minimal information on the natural fate of saccular or false aneurysms of the arch [7]. Since the aneurysmal wall is not composed of all three vascular wall layers it is reasonable to assume a higher tendency to rupture compared with true aneurysms. At this time, however, it is absolutely unclear at what size a decision in favor of surgery should be made.

The decision for surgical treatment not only depends on the natural prognosis, but also on the complication

rate of surgical treatment. In this context not only hospital mortality, but also the occurrence of stroke has to be taken into consideration. Some data indicate that a diameter of more than 5.5–6 cm warrants aortic replacement [9]. Nonetheless we realize that the objective information on which these decisions are based is incomplete, and prospective, randomized interventional studies are required in order to define the cutoffs for or against surgical treatment.

We currently decide for surgery once a diameter of 5 cm for true aneurysms and 3 cm for false aneurysms is exceeded, and if the anticipated combined rate of unwanted major complications (death and stroke) does not exceed 4–5%.

10.5 Diagnostic Investigations

A computed tomography (CT) scan of the chest will be available for almost all patients at the time of referral. It gives almost all the information necessary regarding the aorta itself, i.e., diameters, extension of the aneurysmatic process, and anatomical relationship with neighboring structures including the chest wall. If not already available, a CT or an MRI scan should be available before every operation performed on an elective basis. It is of vital importance when planning any aortic reoperation in order to be able to develop the operative strategy including entry into the chest.

Coronary heart disease and chronic obstructive pulmonary disease are the two commonest associated entities. Carotid artery disease is less common, and the role of carotid stenosis or its treatment in the context of aortic surgery has not been well defined.

It is advisable to perform an echocardiogram and a left heart catheterization for every patient over the age of 40 years scheduled for elective arch surgery. If coronary artery or heart valve disease is documented, it will also influence the type of procedure to be performed. An aneurysm of the distal arch can be reached well through a left-sided incision; in the presence of significant coronary disease it is better approached through a sternotomy. In the presence of severe left ventricular dysfunction without correctable cardiac disease, the patient's prognosis will primarily be determined by this factor, and one should reconsider a decision for surgical treatment of the arch aneurysm.

The results of pulmonary function testing will similarly influence the decision for surgery. The presence of chronic obstruction lung disease has been shown to have an adverse effect on postoperative long-term survival even in patients that appeared to be good or reasonable surgical candidates. More importantly, severe pulmonary dysfunction may carry a prognosis that is worse than that of the aneurysmal disease, and it is doubtful whether the patient will benefit from any procedure. The presence of respiratory limitations must also be taken into consideration in choosing the surgical approach; a median sternotomy is much better tolerated in these instances than a bilateral or posterolateral incision.

We try to be thorough in our diagnostic workup in order to be able to make the best decision possible before performing an extensive operation. In addition to CT, every patient undergoes pulmonary function testing, Doppler examination of the carotid arteries, an echocardiogram, and left heart catheterization. An aortogram is only performed if stenosis of an arch vessel is suspected on clinical grounds or by Doppler studies.

10.6 Cerebral Protection

Cerebral protection is of central importance in surgery of the aortic arch [10, 11]. Historically the first approach to be utilized was antegrade perfusion of the supraaortic vessels in order to completely avoid interruption of cerebral blood flow. Although this made the first replacements of the arch possible, it never gained wide acceptance. The concept of hypothermic circulatory arrest was based on the early investigations of Bigelow [12] and others [13, 14], who found that decreased body temperature markedly increased the tissue tolerance to ischemia. In the 1980s, most surgeons used hypothermic circulatory arrest only, and reproducible operations on the aortic arch became feasible [3, 4]. It became clear, however, that hypothermia alone did not provide unlimited cerebral protection, and there was still a relevant risk of stroke.

For many years it was believed that a nasopharyngeal temperature of 16–18 °C allowed up to 60 min of circulatory arrest and was thus "safe." Further clinical experience led to the realization that not only mortality, but most importantly the risk of stroke increased with the duration of circulatory arrest if arrest times exceeded 45 min [15, 16]. More recent follow-up information and neuropsychological testing results showed that the risk of stroke and also neurological dysfunction including confusion increases beyond arrest times of 20–30 min [17–19]. Most importantly, a significant proportion of patients who have recovered from confusion are later compromised by permanent cognitive dysfunction [19]. On the basis of clinical data from aortic surgery, an arrest time of 20–30 min thus appears safe [18]; this, however, has not been unequivocally proven. The experience with hypothermic circulatory arrest in conjunction with pulmonary thromboendarterectomy for chronic pulmonary embolism creates an even more confusing picture. In these operations a circulatory arrest time of 40 min is not uncommon, and in more than 160 patients treated in our institution there has been no stroke, and confusion has occurred in less than

3% of the patients. Thus, the true safe duration of hypothermic circulatory arrest is still unknown.

Retrograde perfusion was first used by Ueda et al. [20] in order to provide cerebral blood supply during the period of antegrade circulatory arrest. It was shown to provide cooling of the brain and was felt to also provide some protection against embolism of air and atherosclerotic debris. Cerebral edema can occur, however, and close monitoring of central venous pressure as the retrograde perfusion pressure is necessary [21]. Subsequent animal research and clinical studies indicated that the evidence of blood flow and thus oxygen supply to the brain was weak or nonexistent [22–24]. Thus, the exact role of retrograde perfusion in cerebral protection is currently unclear, but it provides additional cerebral cooling and minimizes the possibility of emboli [21].

Antegrade perfusion – historically the first technique of neuroprotection – has recently been used again with increasing enthusiasm. Several groups proposed a drastic reduction in the incidence of stroke and temporary neurological dysfunction [25–28]. It was also felt that the degree of hypothermia necessary for adequate cerebral protection was less and thus the time of extracorporeal circulation reduced. There are, however, still concerns over the possibility of embolism during introduction of the perfusion catheters and subsequent perfusion. Several clinical series, in which a definite advantage of antegrade perfusion was found, were characterized by long times required for arch repair in excess of 45 or even 60 min [29–32]. It is unclear whether these times were prolonged because of the presence of perfusion cannulae in the field, or rather by careful performance of difficult operative procedures.

Currently the risk of stroke is approximately 3–5% in many series for arrest times of up to 30 min, regardless of the type of cerebral protection used [25, 33, 34]. The risk of stroke appears to be primarily related to the presence of atherosclerotic risk factors and the age of the patient [16]. While this risk is not negligible, it compares with an incidence of 2–3% after coronary surgery or aortic valve replacement in patients of similar age groups [35]. Only if anticipated interruption of cerebral blood flow exceeds 30–40 min, antegrade perfusion gives a clear advantage over deep hypothermic circulatory arrest alone. Retrograde cerebral perfusion appears to be of benefit only if the risk of embolic stroke is high, such as in the presence of abundant atherosclerotic debris in the lumen of the aortic arch [36].

It is at present unclear whether cerebral ischemic tolerance can be extended by pharmacologic adjuncts. On the basis of animal experiments, barbiturates, corticosteroids, and even lidocaine have been proposed for this purpose. There is evidence that the reduction of excitation (e.g., by barbiturates) does indeed reduce neuronal oxygen requirement and prolongs the safe duration of cerebral ischemia [37]. It is unclear, however, whether this effect is also present when the patient has been anesthetized with other narcotics. Corticosteroids have been used by several groups without clear clinical evidence of their effect [38, 39]. Recent data suggest that steroids would probably have to be administered several hours before the operation to limit potential cerebral damage [39]. The insufflation of CO_2 has been used increasingly in order to minimize air embolism [40]. The effect has not been clearly proven in prospective studies, but its use leads to a remarkable reduction of intracardiac bubbles, as documented by transesophageal echocardiography.

For partial arch replacement, the anticipated arrest time in our hands is almost always less than 20 min; in this situation we employ hypothermic arrest with a nasopharyngeal temperature of 19–21 °C. In most patients with degenerative aneurysm who require total arch replacement, an arrest time of less than 30 min will be necessary, and again hypothermic circulatory arrest with a nasopharyngeal temperature of 16–18 °C is used. If unforeseen problems are encountered during dissection of the arch already under conditions of arrest, a Dacron graft is anastomosed in end-to-end fashion to the origins of the supraaortic branches (Fig. 10.11). Antegrade perfusion of the arch vessels can then be resumed either via the axillary artery or by direct cannulation of the graft itself. This will then give sufficient time for most of the arch repair procedure to be completed without the pressure of cerebral ischemic time. We utilize retrograde perfusion only if marked atheromas are present in the lumen of the arch in order to minimize the risk of embolism.

10.7 Operative Technique

10.7.1 Incision

The choice of incision primarily depends on the exact procedure planned, taking into consideration exposure, morbidity of the incision itself, and the options to minimize neurologic complications. As a rule, a median sternotomy provides excellent exposure for any procedure involving the proximal or total arch. A left posterolateral thoracotomy in the fourth or fifth intercostal space provides excellent exposure for a distal arch procedure, especially if additional surgery is necessary on the descending aorta. It also allows total arch replacement to the level of the distal ascending aorta. A bilateral thoracotomy gives easy access for any procedure on the thoracic aorta [41] except for more complex operations on the aortic root.

The morbidity of the incision is primarily related to the degree of respiratory impairment. The median sternotomy leads to minimal impairment; a lateral thoracotomy will reduce postoperative FEV1 by 20–30%. This

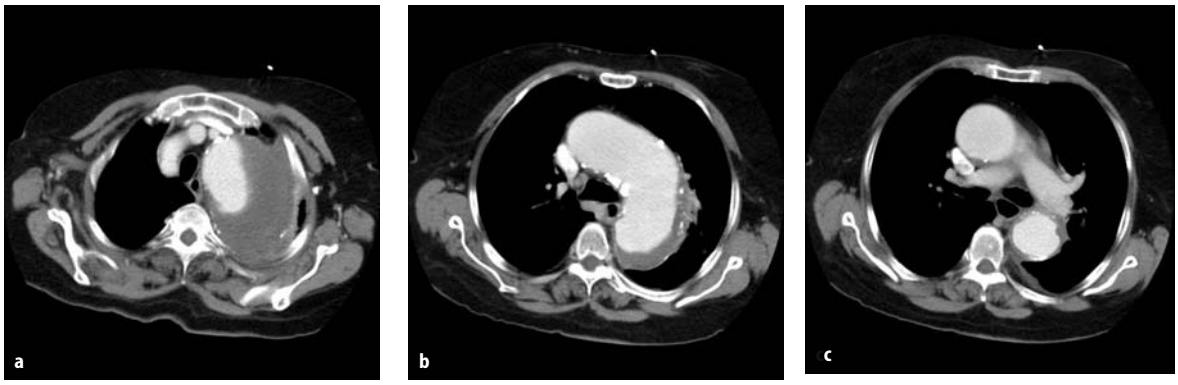

Fig. 10.4. True aneurysm of the aortic arch and proximal descending aorta. The patient had become symptomatic with hemoptysis and had been referred on an emergency basis. The apex of the left hemithorax is filled by the aneurysm, the increased antero-posterior diameter in **c** underlines the presence of significant obstructive lung disease. Aortic replacement through a left thoracotomy would be associated with an increased risk of embolism during retrograde perfusion. The diameter of the distal aorta is acceptable at the level of the left pulmonary artery and can thus be reached from a median sternotomy as part of total arch replacement

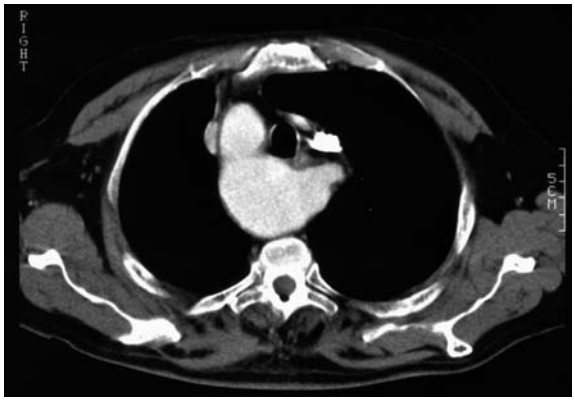

Fig. 10.5. Congenital anomalies may pose difficulties for surgical exposure, as in this patient with distal arch aneurysm, right-sided descending aorta, and an aberrant left subclavian artery. A bilateral thoracotomy is probably the best approach for these anatomical variant

can lead to dyspnea, atelectasis, hypoxemia, and prolonged mechanical ventilation and intensive-care stay. A bilateral thoracotomy has been used infrequently for aortic surgery]41]. In pulmonary surgery it has been shown to be associated with the highest degree of postoperative pain and pulmonary impairment. The limited experience in aortic surgery seems to confirm this impression.

We thus use a median sternotomy in most instances of arch replacement if the distal anastomosis is at the level of or superior to the left pulmonary artery (Fig. 10.4). In the remaining patients we prefer the bilateral thoracotomy because of exposure, the possibility of antegrade perfusion, and facilitated deairing of left heart and aortic arch (Fig. 10.5).

10.7.2 Cannulation

The place of arterial cannulation has become an important aspect of aortic arch surgery irrespective of the type of cerebral protection to be used. Traditionally, femoral arterial cannulation was the standard in most aortic procedures. In the past 10–15 years it has been realized that this could contribute to an increased incidence of neurological complications, possibly due to embolization of chronic thrombus or atherosclerotic debris from the descending aorta during perfusion with retrograde flow [42, 43]. Cannulation of the proximal aorta – either in a normal segment or direct cannulation of the aneurysm – has repeatedly been shown to be associated with decreased risk of stroke. Most recently, cannulation of the right axillary artery either directly or via a short vascular graft anastomosed to the artery has become an alternative, and is not only used in acute dissection, but also in the presence of arch aneurysm [42, 43].

For reasons of simplicity, we cannulate the aorta in almost all instances. If this is impossible or inadvisable, such as in reoperations with close proximity between the aorta and the chest wall, an 8-mm graft is connected to the subclavian/axillary artery and cannulated directly. The use of a graft minimizes the risk of trauma to the axillary artery and facilitates decannulation.

10.8 Type of Replacement

The type of replacement has been the subject of continuing controversy. After the introduction of the deep hypothermic circulatory arrest, orthotopic tubular replacement of the aortic arch became the standard, at

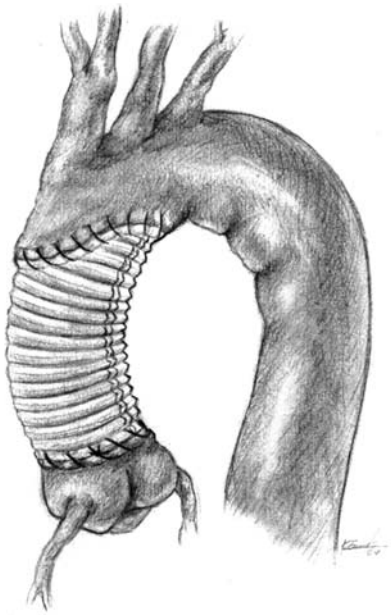

Fig. 10.6. Schematic drawing of ascending and partial arch replacement. The exact level of the distal anastomosis has little or no impact on morbidity or mortality

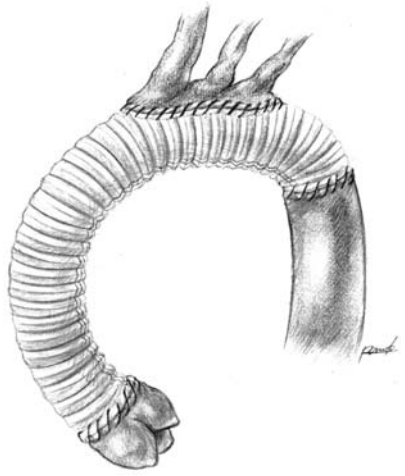

Fig. 10.7. Schematic drawing of total arch replacement with one anastomosis to the descending aorta and a second connection for reimplantation of the supraaortic vessels

least in the hands of most European and American groups. Partial or complete replacement of the arch was performed, depending on the pathology of the arch to be treated. Partial arch replacement consisted of an open oblique anastomosis to any level of the arch, and the procedure was termed proximal arch, subtotal arch, or hemiarch replacement (Fig. 10.6).

Complete replacement implies an end-to-end anastomosis to the descending aorta with implantation of a patch of aortic wall carrying the origins of the supraaortic branches into the graft (Fig. 10.7). By contrast, several Japanese surgeons have preferred individual connections of the supraaortic vessels to side arms of a trifurcated aortic graft [27]. The Griepp group [44] proposed a similar approach with individual anastomoses to the arch vessels in a more individualized fashion.

The evidence produced by the different groups with heterogenous patient populations is not very clear regarding superiority of one approach over others. It is quite apparent, however, that partial replacement of the arch in the form of an open anastomosis carries the least technical difficulty, is least prone to surgical hemorrhage, and can be performed in the shortest time. In fact, the time necessary to perform this anastomosis is more or less identical to the duration of circulatory arrest necessary to install perfusion catheters, if selective antegrade cerebral perfusion is utilized.

For complete arch replacement, traditional tubular replacement with patch implantation of the arch vessels is still the standard. This can be performed within a period of 25–30 min, thus carrying a minimal risk of temporary or permanent neurological dysfunction. If longer times for repair are anticipated, a modification used by the New York group appears as the best alternative [10, 34]. In this technique, the origins of the supraaortic vessels are mobilized with a patch of aortic wall. An oblique anastomosis is created between a 16–18-mm graft and the aortic patch, reqiring approximately 10–15–min of arrest. Antegrade perfusion can then be resumed via this graft or the axillary artery, and a second graft (22–26 mm) is anastomosed to the descending aorta (Fig. 10.11). Both grafts are then connected, either during continuous perfusion via the right axillary artery or during another brief period of arrest.

The concept of an elephant trunk extension of the graft into the descending aorta (Figs. 10.8, 10.9) was developed by Borst et al. [45] in order to facilitate subsequent downstream aortic replacement. For total arch replacement the graft is invaginated and placed in the descending aorta. The anastomosis is created between the fold and the descending aorta. The graft is then unfolded for implantation of the supraaortic vessels.

Saccular aneurysms often occur in the presence of marked atheroma in the wall of the aortic arch. In order to prevent cerebral embolism, total arch replacement with an anastomosis to aortic wall of reasonable quality appears as the best solution. Alternatively, separate anastomoses may be created at the level of the individual supraaortic branches, where the degree of atherosclerosis is usually less pronounced. If the aortic wall is of reasonable quality, the false aneurysm may also be treated by implantation of a Dacron patch into the margins of the intact vascular wall (Fig. 10.10). This approach requires the shortest arrest time for completion.

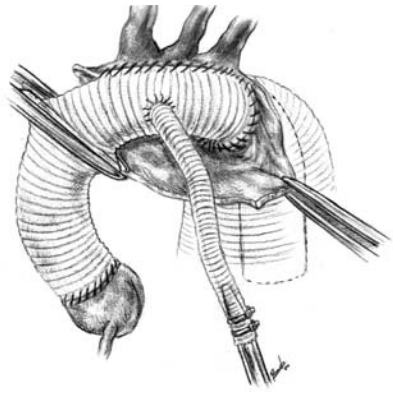

Fig. 10.8. Schematic drawing of total arch replacement with the elephant trunk modification. The extension of the graft in the descending aorta facilitates later distal aortic replacement. The arterial perfusion cannula can be introduced into a side arm of the graft as shown in this illustration. Alternatively, it may be inserted directly into the graft through a stab incision or via the right axillary artery

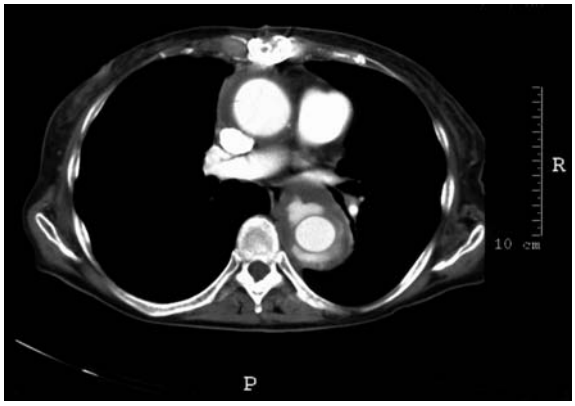

Fig. 10.9. Computed tomography of the chest after total arch replacement with an elephant trunk. The graft extension can be seen easily; there is the of beginning thrombosis of the aortic lumen around the trunk

We commonly perform standard replacement of the aortic arch with one anastomosis to the descending aorta and a second connection between the graft and a patch of aortic wall carrying the origins of the supraaortic vessels. With this standardized approach the circulatory arrest time is less than 30 min in almost all instances, and our stroke risk has been low. If this is difficult, such as in acute dissection, we resort to the two-graft modification with one graft connected in an oblique fashion to the aortic patch with the brachiocephalic vessels (Fig. 10.11). A second graft is anastomosed to the descending aorta, and the grafts are then connected.

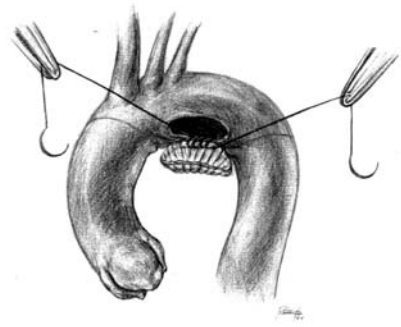

Fig. 10.10. Schematic drawing of patch repair for saccular aneurysm of the aortic arch. This may be helpful if inflammatory changes make dissection of the arch difficult for total arch replacement. There are, however, few data on the long-term durability of this repair

Fig. 10.11. Schematic drawing of the modified technique for total arch replacement which limits the necessary time of interruption of cerebral blood flow. In the first step an oblique end-to-end anastomosis is created between the aortic button carrying the origins of the head and neck vessels. Antegrade perfusion of the head can then be resumed through the right axillary artery (as shown) or by direct cannulation of the graft. A second graft is then anastomosed to the descending aorta, and the grafts are connected. This technique not only limits the duration of cerebral ischemia, but also facilitates surgical hemostasis at the distal anastomosis to the descending aorta

10.9 Results

Hospital mortality mainly depends on the urgency of the operation, age, and the presence and degree of atherosclerosis. Elective arch replacement is possible with a mortality rate of 2–6%. In patients over the age of 80 years, mortality may be as high as 8–15%. In

emergency situations, the presence or absence of shock prior to the operation appears to be the primary determinant of survival.

In our own 9-year experience consisting of approximately 800 thoracic aortic operations for aneurysm or dissection, 524 were performed on patients with degenerative aneurysm of the proximal aorta. Of these, 217 patients underwent elective arch replacement. Hospital mortality has been low despite the need for concomitant mitral and coronary artery bypass surgery. For elective ascending aortic replacement, early mortality was 4.6% (14/307), compared with 2.0% for partial arch replacement (3/148) and 5.8% (4/69) for total arch replacement. Thus, mortality was not increased by the addition of arch replacement with circulatory arrest compared with replacement of the ascending aorta only.

The published incidence of stroke varies considerably between series and ranges from 2 to 8% [15, 16, 19, 20, 25–32]. The incidence of stroke in our experience is identical between ascending aortic and arch replacement (2.1 vs. 2.0%). The incidence of temporary neurologic dysfunction seems to depend on similar factors and patient age [19]. In our series the risk of developing temporary neurologic dysfunction including confusion was higher after arch repair with circulatory arrest (8.3 vs. 12.1%). By multivariate analysis, the presence of peripheral vascular disease was the only risk factor for stroke. Age and indicators of generalized atherosclerosis were significant risk factors for the development of temporary neurologic dysfunction. There was no relationship between hypothermic circulatory arrest and temporary neurologic dysfunction. Persistent dysfunction of the left recurrent laryngeal nerve was seen in three patients after total arch replacement, and this incidence of 4% is lower than that seen with descending aortic and arch replacement through the left chest.

10.10 Conclusions

Replacement of the aortic arch for degenerative aneurysms is a standardized procedure which can be performed with a low risk. Both operative technique and cerebral discussion are still the subject of controversial discussion. In many patients standard arch replacement using hypothermic arrest yields excellent results. Technical modifications should be kept in mind to be able to apply an individualized approach to patient and aortic pathology in difficult situations.

References

1. Cooley DA, Mahaffey DE, De Bakey ME. Total excision of the aortic arch for aneurysm. Surg Gynecol Obstet 1955; 101(6):667–672.
2. De Bakey ME, Crawford ES, Cooley DA, Morris GC Jr. Successful resection of fusiform aneurysm of aortic arch with replacement by homograft. Surg Gynecol Obstet 1957; 105(6):657–664.
3. Ott DA, Frazier OH, Cooley DA. Resection of the aortic arch using deep hypothermia and temporary circulatory arrest. Circulation 1978; 58(3 Pt 2):I227–I231.
4. Livesay JJ, Cooley DA, Duncan JM, Ott DA, Walker WE, Reul GJ. Open aortic anastomosis: improved results in the treatment of aneurysms of the aortic arch. Circulation 1982; 66(2 Pt 2):I122–I127.
5. Bickerstaff LK, Pairolero PC, Hollier LH, Melton LJ, Van Peenen HJ, Cherry KJ, et al. Thoracic aortic aneurysms: a population-based study. Surgery 1982; 92(6):1103–1108.
6. Coady MA, Rizzo JA, Goldstein LJ, Elefteriades JA. Natural history, pathogenesis, and etiology of thoracic aortic aneurysms and dissections. Cardiol Clin 1999; 17(4):615–635.
7. Taylor BV, Kalman PG. Saccular aortic aneurysms. Ann Vasc Surg 1999; 13(6):555–559.
8. Dapunt OE, Galla JD, Sadeghi AM, Lansman SL, Mezrow CK, de Asla RA, et al. The natural history of thoracic aortic aneurysms. J Thorac Cardiovasc Surg 1994; 107(5): 1323–1332.
9. Coady MA, Rizzo JA, Elefteriades JA. Developing surgical intervention criteria for thoracic aortic aneurysms. Cardiol Clin 1999; 17(4):827–839.
10. Ergin MA, Griepp EB, Lansman SL, Galla JD, Levy M, Griepp RB. Hypothermic circulatory arrest and other methods of cerebral protection during operations on the thoracic aorta. J Card Surg 1994; 9(5):525–537.
11. Griepp RB. Cerebral protection during aortic arch surgery. J Thorac Cardiovasc Surg 2001; 121(3):425–427.
12. Bigelow WG, Lindsay WK, Greenwood WF. Hypothermia; its possible role in cardiac surgery: an investigation of factors governing survival in dogs at low body temperatures. Ann Surg 1950; 132:849–866
13. Borst HG, Schaudig A, Rudolph W. Arteriovenous fistula of the aortic arch: repair during deep hypothermia and circulatory arrest. J Thorac Cardiovasc Surg 1964; 48:443–447.
14. Lillehei CW, Todd DB Jr, Levy MJ, Ellis RJ. Partial cardiopulmonary bypass, hypothermia, and total circulatory arrest. A lifesaving technique for ruptured mycotic aortic aneurysms, ruptured left ventricle, and other complicated cardiac pathology. J Thorac Cardiovasc Surg 1969; 58(4):530–544.
15. Ehrlich MP, Ergin MA, McCullough JN, Lansman SL, Galla JD, Bodian CA, et al. Predictors of adverse outcome and transient neurological dysfunction after ascending aorta/hemiarch replacement. Ann Thorac Surg 2000; 69(6):1755–1763.
16. Ergin MA, Galla JD, Lansman L, Quintana C, Bodian C, Griepp RB. Hypothermic circulatory arrest in operations on the thoracic aorta. Determinants of operative mortality and neurologic outcome. J Thorac Cardiovasc Surg 1994; 107(3):788–797.
17. Reich DL, Uysal S, Sliwinski M, Ergin MA, Kahn RA, Konstadt SN, et al. Neuropsychologic outcome after deep hypothermic circulatory arrest in adults. J Thorac Cardiovasc Surg 1999; 117(1):156–163.
18. McCullough JN, Zhang N, Reich DL, Juvonen TS, Klein JJ, Spielvogel D, et al. Cerebral metabolic suppression during

hypothermic circulatory arrest in humans. Ann Thorac Surg 1999; 67(6):1895–1899.
19. Ergin MA, Uysal S, Reich DL, Apaydin A, Lansman SL, McCullough JN, et al. Temporary neurological dysfunction after deep hypothermic circulatory arrest: a clinical marker of long-term functional deficit. Ann Thorac Surg 1999; 67(6):1887–1890.
20. Ueda Y, Miki S, Kusuhara K, Okita Y, Tahata T, Yamanaka K. Surgical treatment of aneurysm or dissection involving the ascending aorta and aortic arch, utilizing circulatory arrest and retrograde cerebral perfusion. J Cardiovasc Surg (Torino) 1990; 31(5):553–558.
21. Reich DL, Uysal S, Ergin MA, Griepp RB. Retrograde cerebral perfusion as a method of neuroprotection during thoracic aortic surgery. Ann Thorac Surg 2001; 72(5):1774–1782.
22. Duebener LF, Hagino I, Schmitt K, Sakamoto T, Stamm C, Zurakowski D, et al. Direct visualization of minimal cerebral capillary flow during retrograde cerebral perfusion: an intravital fluorescence microscopy study in pigs. Ann Thorac Surg 2003; 75(4):1288–1293.
23. Ehrlich MP, Hagl C, McCullough JN, Zhang N, Shiang H, Bodian C, et al. Retrograde cerebral perfusion provides negligible flow through brain capillaries in the pig. J Thorac Cardiovasc Surg 2001; 122(2):331–338.
24. Tanoue Y, Tominaga R, Ochiai Y, Fukae K, Morita S, Kawachi Y, et al. Comparative study of retrograde and selective cerebral perfusion with transcranial Doppler. Ann Thorac Surg 1999; 67(3):672–675.
25. Kazui T, Washiyama N, Muhammad BA, Terada H, Yamashita K, Takinami M, et al. Total arch replacement using aortic arch branched grafts with the aid of antegrade selective cerebral perfusion. Ann Thorac Surg 2000; 70(1):3–8.
26. Hagl C, Ergin MA, Galla JD, Lansman SL, McCullough JN, Spielvogel D, et al. Neurologic outcome after ascending aorta-aortic arch operations: effect of brain protection technique in high-risk patients. J Thorac Cardiovasc Surg 2001; 121(6):1107–1121.
27. Ueda T, Shimizu H, Hashizume K, Koizumi K, Mori M, Shin H, et al. Mortality and morbidity after total arch replacement using a branched arch graft with selective antegrade cerebral perfusion. Ann Thorac Surg 2003; 76(6):1951–1956.
28. Di Eusanio M, Wesselink RM, Morshuis WJ, Dossche KM, Schepens MA. Deep hypothermic circulatory arrest and antegrade selective cerebral perfusion during ascending aorta-hemiarch replacement: a retrospective comparative study. J Thorac Cardiovasc Surg 2003; 125(4):849–854.
29. Bachet J, Guilmet D, Goudot B, Dreyfus GD, Delentdecker P, Brodaty D, et al. Antegrade cerebral perfusion with cold blood: a 13-year experience. Ann Thorac Surg 1999; 67(6):1874–1878.
30. Di Eusanio M, Schepens MA, Morshuis WJ, Di Bartolomeo R, Pierangeli A, Dossche KM. Antegrade selective cerebral perfusion during operations on the thoracic aorta: factors influencing survival and neurologic outcome in 413 patients. J Thorac Cardiovasc Surg 2002; 124(6):1080–1086.
31. Kazui T, Yamashita K, Washiyama N, Terada H, Bashar AH, Suzuki T, et al. Usefulness of antegrade selective cerebral perfusion during aortic arch operations. Ann Thorac Surg 2002; 74(5):S1806–1809.
32. Takahara Y, Mogi K, Sakurai M, Nishida H. Total aortic arch grafting via median sternotomy using integrated antegrade cerebral perfusion. Ann Thorac Surg 2003; 76(5):1485–1489.
33. Coselli JS, LeMaire SA. Experience with retrograde cerebral perfusion during proximal aortic surgery in 290 patients. J Card Surg 1997; 12(2 Suppl):322–325.
34. Strauch JT, Spielvogel D, Lauten A, Galla JD, Lansman SL, McMurtry K, et al. Technical advances in total aortic arch replacement. Ann Thorac Surg 2004; 77(2):581–589.
35. Reich DL, Bodian CA, Krol M, Kuroda M, Osinski T, Thys DM. Intraoperative hemodynamic predictors of mortality, stroke, and myocardial infarction after coronary artery bypass surgery. Anesth Analg 1999; 89(4):814–822.
36. Safi HJ, Letsou GV, Iliopoulos DC, Subramaniam MH, Miller CC, III, Hassoun H, et al. Impact of retrograde cerebral perfusion on ascending aortic and arch aneurysm repair. Ann Thorac Surg 1997; 63(6):1601–1607.
37. Siegman MG, Anderson RV, Balaban RS, Ceckler TL, Clark RE, Swain JA. Barbiturates impair cerebral metabolism during hypothermic circulatory arrest. Ann Thorac Surg 1992; 54(6):1131–1136.
38. Langley SM, Chai PJ, Jaggers JJ, Ungerleider RM. Preoperative high dose methylprednisolone attenuates the cerebral response to deep hypothermic circulatory arrest. Eur J Cardiothorac Surg 2000; 17(3):279–286.
39. Shum-Tim D, Tchervenkov CI, Laliberte E, Jamal AM, Nimeh T, Luo CY, et al. Timing of steroid treatment is important for cerebral protection during cardiopulmonary bypass and circulatory arrest: minimal protection of pump prime methylprednisolone. Eur J Cardiothorac Surg 2003; 24(1):125–132.
40. Goldstein LJ, Davies RR, Rizzo JA, Davila JJ, Cooperberg MR, Shaw RK, et al. Stroke in surgery of the thoracic aorta: incidence, impact, etiology, and prevention. J Thorac Cardiovasc Surg 2001; 122(5):935–945.
41. Kouchoukos NT, Masetti P, Rokkas CK, Murphy SF. Single-stage reoperative repair of chronic type A aortic dissection by means of the arch-first technique. J Thorac Cardiovasc Surg 2001; 122(3):578–582.
42. Sabik JF, Lytle BW, McCarthy PM, Cosgrove DM. Axillary artery: an alternative site of arterial cannulation for patients with extensive aortic and peripheral vascular disease. J Thorac Cardiovasc Surg 1995; 109(5):885–890.
43. Strauch JT, Spielvogel D, Lauten A, Lansman SL, McMurtry K, Bodian CA, et al. Axillary artery cannulation: routine use in ascending aorta and aortic arch replacement. Ann Thorac Surg 2004; 78(1):103–108.
44. Spielvogel D, Strauch JT, Minanov OP, Lansman SL, Griepp RB. Aortic arch replacement using a trifurcated graft and selective cerebral antegrade perfusion. Ann Thorac Surg 2002; 74(5):S1810–1814.
45. Borst HG, Walterbusch G, Schaps D. Extensive aortic replacement using “elephant trunk” prosthesis. Thorac Cardiovasc Surg 1983; 31(1):37–40.

The New Wave of Elephant Trunk Technique

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11

Contents

11.1 The Conventional Elephant Trunk Technique

Anatomy determines that the proximal segment of the descending aorta is less accessible via median sternotomy than the aortic arch. Therefore most surgeons prefer a multiple-stage approach to treat combined lesion of the aortic arch and the descending aorta. The introduction of the elephant trunk technique by Borst et al. [4] in 1983 has greatly facilitated surgery on this kind of pathology. The basic principle of the Borst operation for the replacement of the aortic arch resides in the protrusion of a length of tubing into the downstream aorta distal to the actual graft to aortic anastomosis at the level of the left subclavian artery. In the subsequent operation performed through lateral thoracotomy, the graft segment in the descending aorta may be used for further replacing the diseased vessel. More importantly, the difficult and often dangerous dissection of the original distal graft to aortic anastomosis is avoided.

After earlier publications from our own group and Crawford's landmark paper published in 1990, this method became more and more popular for treating patients with complex aortic diseases [1, 3, 5, 8–10, 26, 27, 31]. Today, the elephant trunk operation is employed in the two classic conditions: aneurysms and chronic dissection of (1) the aortic arch and (2) the descending thoracic aorta involving the respective downstream portions of the vessel. It may also be chosen for selected patients with acute proximal and distal dissection [9, 23, 24].

Meanwhile, several modifications of the original technique have been reported. Coselli et al. [8] introduced the reversed elephant trunk technique, while Carrel et al. [5, 6] described a bidirectional variant for the replacement of the descending aorta, thereby facilitating second- and third-stage procedures for the replacement of the aortic arch and the thoracoabdominal aorta.

The idea of using an elephant trunk prosthesis as a stent graft, introduced into the descending aorta, was born and popularized by Buffolo's group [23, 24], who employed this approach in a large series of patients with acute type B dissection. Along with the advent of transfemoral stent grafts for the treatment of descending aortic aneurysms it became even possible to securely anchor a stent graft in an elephant trunk prosthesis previously placed during arch surgery [11].

Even though complications following the insertion of elephant trunk grafts have been rare and appear largely avoidable, concerns were reported with regard to increased tension on the suture line distal to the left subclavian artery, thereby increasing the risk of rupture at or near that site during the waiting period for the second-stage operation [18, 32]. This fear has prompted further modifications of the original technique by preparing this anastomosis at an upstream and less dilated aortic level. Thus, Svensson et al. [32] have suggested placing the anastomosis in the aortic arch between the left carotid artery and the left subclavian artery. Another, even more radical approach in this regard was published by Kuki et al. [18], who reported a series of 17 patients in whom the elephant trunk anastomosis was made at the base of the innominate artery. Using this technique, they reconnected the supraaortic branches to the ascending aortic vascular graft by three small-caliber interposition grafts. The authors suggest that this modification yields a secure and rapid anastomosis, and reduces the risk of aortic tearing even in the case when the suture line that is tailored down to the smaller size of the graft [18]. While the length of the elephant trunk depends on the extent of the downstream aortic enlargement and should be at least

7–8 cm according to Borst's original suggestion, the technical modification described by Kuki et al. requires a length of about 15 cm. Here may reside a potential problem of this variant, because a long elephant trunk is more likely to cause complications due to kinking and graft occlusion. This suspicion is supported by Crawford's finding that there are increased risks of peripheral embolisation caused by flapping action of the elephant trunk and paraplegia as a result of clot formation around the graft, if the trunk is too long [10].

Another concern with regard to staged repair of extensive thoracic aortic aneurysms using the conventional elephant trunk operation resides in the fact that the risks of two major surgical procedures and the risk during the time interval between the two interventions add up cumulatively. This was highlighted in a more recent report by Estrera et al. [12]. They calculated early mortality rates of 9% after the stage one operation and 7% mortality after the stage two procedure. Among the 124 patients who survived the stage one operation, there were 56 patients discharged from hospital who failed to return for the second-stage repair. In this group of patients follow-up surveys at 5 years revealed as many as 18 out of 56 (32.1%) deaths. In addition, a mortality rate within the small time window between 4 and 6 weeks following the stage one operation of 8% with the majority of fatalities due to aortic rupture clearly indicates the limitations of staged approaches. A similar observation was made by Schepens et al. [29], who reported survival rates between 80 and 90% in patients who completed the stage two procedure within 4 years, compared with as low as 50% survival in patients, who did not.

11.2 The Frozen Elephant Trunk Technique

The complications that may be attributed to the elephant trunk itself and the cumulative risks of the staged approach are drivers for change towards new procedures and implants, which allow for risk reduction in the surgical treatment of large aortic aneurysms. Extensive one-stage repair techniques performed through a clamshell incision or through the left chest bear remarkable technical challenges and risks, too [17, 19, 28, 35]. They may therefore be limited to selected patients.

A new wave of the elephant trunk technique that may accomplish this goal approached with reports using a new type of homemade vascular prosthesis carrying a stent at its distal end. Suto et al. [30] described a patient with an aneurysm of the distal aortic arch and the descending aorta which was replaced via median sternotomy during circulatory arrest by antegrade implantation of a Gianturco stent connected to a conventional vascular prosthesis. Based on Buffolo's earlier experience and Kato's description of endovascular covered stent grafting through median sternotomy, Usui et al. [33] reported a series of 12 patients who underwent implantation of a covered stent graft for distal aortic arch aneurysm via median sternotomy under pigtail catheter guidance. Two patients in this cohort underwent additional procedures such as aortic arch replacement and aortocoronary bypass grafting, respectively. Shortly thereafter, Orihashi et al. [22] published a report on a cohort of 15 patients, mainly with descending aortic aneurysms not treatable with transfemoral stent grafts. Again, homemade grafts were prepared from a Gianturco stent introduced in a conventional vascular prosthesis prior to antegrade implantation during circulatory arrest. Almost half of the patients underwent additional procedures, including ascending and/or aortic arch replacement using separate vascular grafts, which were connected to the stented graft in the descending aorta. While these reports describe the use of the frozen elephant trunk technique in patients with aneurysms or chronic dissections, more recent publications focus on its use in patients with acute A aortic dissection, too [15, 16, 21]. Both, early and midterm results using this approach appear favourable, particularly with regard to the promotion of thrombus formation in the false channel. In the vast majority of patients in the study of Ishihara et al. [15] the false channel had even disappeared as distal as at the diaphragmatic aortic level at a maximum follow-up at 38 months postoperatively. In accordance with this finding, Kato et al. [16] observed a marked reduction of the diameter of the false lumen in the descending aorta excluded by the stent graft in their cohort comprising 19 patients. Whether these promising results justify the use of a frozen elephant trunk in patients with arch tears only or possibly in all patients with acute type A dissection is debatable. Given the fact, that up to 25% of patients who undergo ascending aortic replacement with an open distal anastomosis of the proximal aortic arch will develop critical downstream dilatation of native dissected aortic segments, this option should be taken into consideration [14].

11.3 Own Experience Employing the Frozen Elephant Trunk Technique Using a Hybrid Prosthesis with a Stented and a Nonstented End

11.3.1 Patients and Surgery

Between September 2001 and April 2004, 22 patients with combined pathologies of the aortic arch and the descending aorta were operated on using a "hybrid prosthesis" (Chavan–Haverich endograft, Curative, Dresden, Germany) made of a woven vascular prosthesis with stainless steel stents affixed to the inner aspects

Fig. 11.1. The "hybrid prosthesis" (Chavan-Haverich endograft, Curative, Dresden, Germany) was made of a woven vascular prosthesis with stainless steel stents affixed to the inner aspects at its distal end

at its distal end (Fig. 11.1). The mean patient age was 62 years (range, 47–77 years). There were seven patients who were older than 70 years. Nine patients were women. The majority of patients ($n=11$) presented with type A aortic dissection, ten in its chronic form and one with its acute variant. The second most frequent pathology ($n=7$) was an aneurysm proximal and distal of the left subclavian artery. A smaller cohort ($n=4$) presented with chronic aortic dissection type B. Additional cardiac pathology comprised severe coronary artery disease in nine patients and aortic valve disease in three patients.

The diameters of the stents within the hybrid prosthesis ranged between 30 and 46 mm and the stents had a length of 22 mm each. The proximal portion of the hybrid prosthesis was not stented and consisted of a Dacron sleeve ready for conventional surgical handling.

The delivery system comprised a flexible 39-French (F) outer sheath, a 34-F inner sheath, as well as a central pusher. Withdrawal of the outer sheath while holding the inner sheath and the pusher steady released the stented portion of the hybrid prosthesis. The proximal Dacron tube was then released by pulling back both sheaths simultaneously while holding the pusher steady. Spiral computed tomographic angiography of the thoracic aorta was performed preoperatively to assess the extent of the aneurysm and/or dissection as well as to determine the appropriate stent graft size.

All patients were operated on using cardiopulmonary bypass. Central cannulation of the ascending aorta and the right atrium was preferred. In three patients who underwent resternotomy the groin vessels were cannulated before, because an ascending aortic aneurysm encroached upon the sternum. Then, core cooling was accomplished to 25 °C rectal temperature. After induction of cardioplegic cardiac arrest, cardiopulmonary bypass was discontinued. The aortic arch was then opened longitudinally. Selective antegrade cerebral perfusion

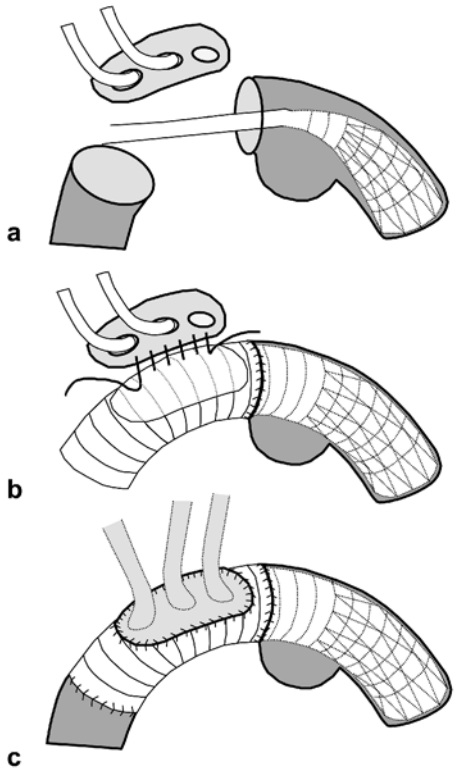

Fig. 11.2. a The stented end of the hybrid prosthesis is deployed in the descending aorta distal of the dilated segment. Selective antegrade cerebral perfusion is accomplished during hypothermic circulatory arrest. **b** After suturing the hybrid prosthesis circumferentially into the descending aorta directly distal of the origin of the left subclavian artery, the supraaortic branches are reimplanted into the graft as a single tissue patch. **c** The reconstruction may then be completed at any desired level of the ascending aorta while cardiopulmonary bypass is reestablished

with cold blood at 15 °C and a volume of 250–450 ml/min was initiated after ostial cannulation of the left common carotid artery and the brachiocephalic trunk. Then, the stented end of the hybrid prosthesis was deployed in the descending aorta. In the first five patients it was implanted over an antegradely placed superstiff guide wire. Prompted by perforation of the aortic wall with the introducer system in a patient with a tortuous descending aorta, a through-and-through transfemoral guide-wire technique was employed in all subsequent patients.

The distal landing site of the graft was at or above the tenth thoracic vertebra in all patients. After deployment, the stented portion of the prosthesis was modulated onto the aortic wall with the help of an appropriately sized balloon catheter (Medtronic, USA). Then, the nonstented Dacron graft segment was sutured circumferentially to the aorta distal to the origin of the left subclavian artery before the supraaortic branches were reimplanted enbloc into an appropriately sized

window of the graft. A proximal graft-to-aortic anastomosis at any desired level of the ascending aorta completed the repair (Fig. 11.2). In six patients with previously implanted valved conduits a graft-to-graft anastomosis was sutured accordingly.

In 20 patients the entire aortic arch and the proximal segment of the descending aorta were replaced using this procedure. In ten of them the ascending aorta had to be replaced additionally.

In two other patients with aneurysms limited to the proximal descending aorta, implantation of the hybrid prosthesis into the descending aorta was enabled by a limited, 3–4-cm-long longitudinal T-shaped incision of the aortic arch. The nonstented endograft segment was sutured circumferentially distal to the level of the left subclavian artery before the aortotomy was closed. One of the two patients required additional complete myocardial revascularization and the other aortic valve replacement for aortic valve stenosis using a biological aortic valve prosthesis. Except for these two patients there were ten other patients who required additional procedures (myocardial revascularization, eight patients; aortic valve replacement, two patients).

11.3.2 Results and Follow-Up

There were no intraoperative deaths. The implantation of the prosthesis was successful in all but one patient. This patient presented with marked kinking of the descending aorta distal of the aneurysmatic segment to be excluded. Implantation was attempted over an antegradely placed guide wire. The tip of the introducer system could not be advanced beyond the kinked segment; thus, perforation of the aortic wall occurred at this point, and required surgical repair and additional transfemoral stent-graft implantation to bridge the perforated and aneurysmatic segment. In all subsequent patients the transfemoral through-and-through guidewire technique for the implantation of the stented segment of the hybrid prosthesis in the descending aorta (s. a.) was used.

In one patient with chronic aortic dissection type A the aortic wall of the false lumen directly distal to the origin of the left subclavian artery was accidentally injured during surgical preparation. Even though this laceration was sutured and the further course of the operation was uneventful, the patient died from fatal bleeding into the left hemithorax 2 days postoperatively. Autopsy revealed that exsanguination was caused by a reopening of the repaired segment.

The mean duration (± standard deviation) of total cardiopulmonary bypass time, aortic cross-clamp time, hypothermic circulatory arrest time, antegrade selective cerebral perfusion time and the time required for the deployment of the stented end of the hybrid prosthesis were 239 ± 76, 136 ± 43, 74 ± 19, 62 ± 14 and 12 ± 5 min respectively. Reexploration for bleeding was necessary in two patients.

Four patients awoke with central neurological dysfunction. In two of them, it was transient and resolved completely before discharge. Two of the four patients had a history of cerebrovascular events with anatomical correlates in the preoperative computed tomography scan of the brain. Documented (by direct laryngoscopy) left recurrent nerve paralysis occurred in two patients.

There was no late mortality after a mean follow-up of 14 months. Postoperative computed tomography scans revealed completed thrombus formation in the perigraft space around the stented segment of the hybrid prosthesis in the descending aorta in all seven patients with atherosclerotic aneurysms. The same holds true for the arch aneurysms in two patients with associated type B aortic dissections.

In the remaining 12 patients with aortic dissections in follow-up, initiation of thrombus formation in the false lumen in the descending aorta up to the level of the stents was noted in all but one patient, who exhibited a small endoleak into the false lumen at the origin of the left subclavian artery; otherwise, the false lumen was thrombosed. As the patient refused a reintervention, the exact aetiology of the endoleak remains unclear.

In one patient with chronic aortic dissection type A, the stented segment of the graft could not be anchored successfully in a previously implanted thoracoabdominal aortic vascular graft. The stents slipped proximally during and after release, giving rise to a distal endoleak. This was treated 2 weeks later by placing a commercially available endograft (Talent endograft, Medtronic) transfemorally, thus extending the hybrid endograft distally into the thoracoabdominal graft. At discharge, he still presented with a type III endoleak, which was found to be reduced to a tiny contrast extravasation at 6-months follow-up. As the actual aneurysm has thrombosed and its size remains constant, the patient is being treated conservatively at present.

11.4 Comment

In Sect. 11.3 we described our approach that allows for definite treatment of lesions of the aortic arch and beyond during a single-stage procedure by using a hybrid prosthesis, which combines the features of a stent graft and a conventional vascular prosthesis. The stented distal segment of the hybrid prosthesis is implanted into the descending aorta through the opened aortic arch under fluoroscopic control, while the proximal nonstented segment is used for conventional replacement of the upstream aorta. The procedure is performed through median sternotomy, thereby facilitating additional surgery on the heart and/or the ascending aorta.

In this series of 22 patients, implantation of the hybrid prosthesis was successful in all but one patient with pronounced tortuosity of the descending aorta. With the through-and-through transfemoral guide-wire technique (s. a.) we have used ever since, no malpositioning of the stented segment of the hybrid prosthesis occurred anymore.

The conventional elephant trunk operation necessitates a reoperation through lateral thoracotomy, because the perigraft space around the elephant trunk remains perfused, thereby promoting further aneurysmatic dilatation of that aortic segment [12, 17, 20]. As opposed to this, the "frozen" elephant trunk technique as described here allows for progressive thrombus formation in the perigraft space in the descending aorta up to the level of the stents. Widening of the descending aorta has not been observed in our patients, regardless of whether thrombus formation was complete or still incomplete. This observation suggests that the stents within the distal segment of the hybrid prosthesis are effective in preventing retrograde flow into the aneurysm.

Owing to the necessity of mounting the hybrid prosthesis in an adequately flexible and thin delivery system, we utilized Dacron (0.36 mm in width) which is thinner than the Dacron used in conventional aortic surgery. In addition to pretreatment with collagen during fabrication of the hybrid prosthesis, extra sealing of the graft with fibrin glue was necessary in some cases to render the graft completely haemostatic.

While the perioperative mortality rate of 4.5% is very acceptable, the incidence of stroke in four out of 22 patients remains a concern, even though in two of the four patients symptoms resolved completely and two had had previous cerebrovascular incidents. The circulatory arrest time of 70 min on average has to be regarded as a risk factor for stroke despite the routine use of selective antegrade cerebral perfusion [2]. Deployment of the stented segment of the hybrid prosthesis currently takes 15–20 min. Further reduction of this time is therefore desirable, because this will shorten the phase of circulatory arrest, thereby lowering the central neurological risk [13].

No patient in our series developed paraplegia as a result of spinal cord injury. Even though this result is in line with those of endovascular stent grafting of descending aortic aneurysms it is still intriguing in view of the significant paraplegia rates reported with open surgical approaches similar to ours [21, 25, 34, 36]. One aspect that could have reduced the risk of spinal cord injury in our series was the keeping of exclusion criteria with regard to the extent of the descending aortic aneurysm to be treated together with a stent-graft fabrication that was adjusted specifically to the patient's individual pathology. Therefore, this treatment was limited to patients with aneuryms involving only the first half of the descending aorta regardless of their size. The proximal extent of the aneurysm with regard to arch involvement was not critical, because the quality of the anastomosis distal to the origin of the subclavian artery depends on the condition of the aortic tissue rather than on the actual aortic diameter at that segment.

In the two patients with aneurysms limited to the descending aorta, other options such as retrograde or isolated antegrade stent-graft implantation with or without transposition of the subclavian artery would have been conceivable treatment alternatives to our approach. We believe, however, that the favourable results that can be obtained with circulatory arrest at moderate hypothermia and selective cerebral perfusion in surgery involving the aortic arch well justifies the technique described here [2, 13]. The use of the hybrid prosthesis enables safe anchoring of its proximal vascular graft segment by a circumferential, hand-sewn anastomosis distal to the origin of the left subclavian artery at the expense of a probably somewhat extended circulatory arrest time, when compared with the time required for antegrade implantation of a conventional stent graft with or without its fixation by internal stay sutures. In addition, both patients presented with landing zones distal to the left subclavian artery too short to allow for safe anchoring of a conventional stent graft. Therefore, we considered both antegrade and retrograde implantation of a conventional stent graft as suboptimal treatment options. On the other hand, transpositioning of the left subclavian artery *together* with conventional stent grafting is not less complex in comparison with the implantation of a hybrid prosthesis when other car-

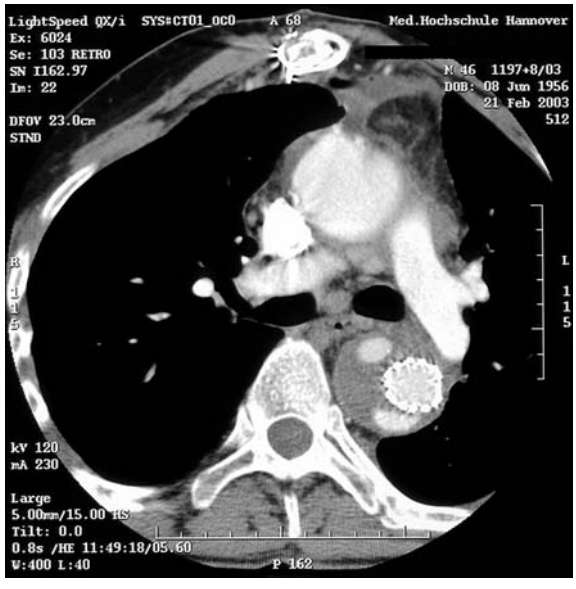

Fig. 11.3. Contrast computed tomography scans of a patient with a chronic aortic dissection type A following implantation of a hybrid prosthesis. The perigraft space around the stented segment of the hybrid prosthesis in the descending aorta is thrombosed partially at 1 week postoperatively

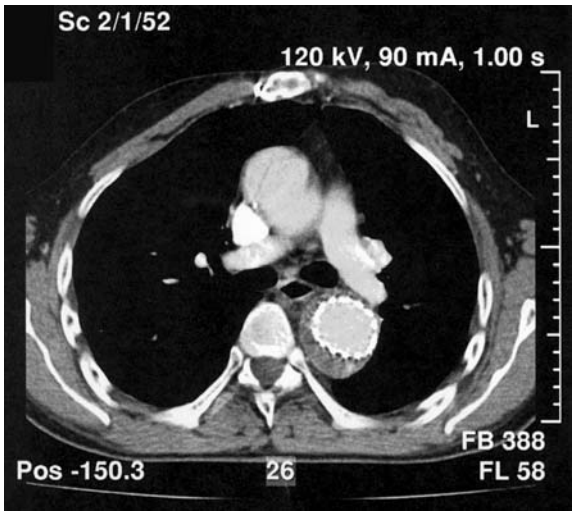

Fig. 11.4. At 10 months postoperatively the perigraft space is thrombosed completely. The diameter of the stented segment of the hybrid prosthesis became wider when compared with that 1 week postoperatively after complete unfolding of the stent. Compared with the status 1 week postoperatively, the diameter of the aneurysm in the descending aorta is now reduced

diac pathologies are treated simultaneously using extracorporeal circulation.

Similar to observations during follow-up after endovascular stent grafting we observed either advanced (Fig. 11.3) or completed thrombus formation around the frozen elephant trunk after the mean follow-up of 14 months that has accumulated so far (Fig. 11.4) [7]. In some cases we found additional shrinkage of the thrombosed aneurysms, which is a common finding after endovascular stent grafting, too [37].

Both phenomena, thrombus formation of the perigraft space and shrinkage of the excluded aneurysm, are indicative for a reduction of aortic wall stress, thereby reducing the risk of rupture of the stented aortic segment. This finding together with a relatively low perioperative mortality and morbidity support the therapeutic concept of a single-stage antegrade combined open and endovascular repair of complex thoracic aortic aneurysms using a hybrid prosthesis or other variants summarized under the term frozen elephant trunk technique. Further evaluation of this treatment modality appears therefore warranted.

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References

1. Ando M, Takamoto S, Okita Y, Morota T, Matsukawa R, Kitamura S (1998) Elephant trunk procedure for surgical treatment of aortic dissection. Ann Thorac Surg 66(1):82–87.
2. Bachet J, Guilmet D, Goudot B, Dreyfus GD, Delentdecker P, Brodaty D, Dubois C (1999) Antegrade cerebral perfusion with cold blood: a 13-year experience. Ann Thorac Surg 67(6):1874–1878; discussion 1891–1874.
3. Borst HG (1999) The elephant trunk operation in complex aortic disease. Curr Opin Cardiol 14(5):427–431.
4. Borst HG, Walterbusch G, Schaps D (1983) Extensive aortic replacement using "elephant trunk" prosthesis. Thorac Cardiovasc Surg 31(1):37–40.
5. Carrel T, Althaus U (1997) Extension of the "elephant trunk" technique in complex aortic pathology: the "bidirectional" option. Ann Thorac Surg 63(6):1755–1758.
6. Carrel T, Berdat P, Kipfer B, Eckstein F, Schmidli J (2001) The reversed and bidirectional elephant trunk technique in the treatment of complex aortic aneurysms. J Thorac Cardiovasc Surg 122(3):587–591.
7. Chavan A, Lotz J, Oelert F, Galanski M, Haverich A, Karck M (2003) Endoluminal treatment of aortic dissection. Eur Radiol 13(11):2521–2534. Epub 2003 Jun 2517.
8. Coselli JS, Oberwalder P (1998) Successful repair of mega aorta using reversed elephant trunk procedure. J Vasc Surg 27(1):183–188.
9. Coselli JS, Buket S, Djukanovic B (1995) Aortic arch operation: current treatment and results. Ann Thorac Surg 59(1):19–26; discussion 26–17.
10. Crawford ES, Coselli JS, Svensson LG, Safi HJ, Hess KR (1990) Diffuse aneurysmal disease (chronic aortic dissection, Marfan, and mega aorta syndromes) and multiple aneurysm. Treatment by subtotal and total aortic replacement emphasizing the elephant trunk operation. Ann Surg 211(5):521–537.
11. Dake MD, Miller DC, Mitchell RS, Semba CP, Moore KA, Sakai T (1998) The "first generation" of endovascular stent-grafts for patients with aneurysms of the descending thoracic aorta. J Thorac Cardiovasc Surg 116(5):689–703; discussion 703–684.
12. Estrera AL, Miller CC, 3rd, Porat EE, Huynh TT, Winnerkvist A, Safi HJ (2002) Staged repair of extensive aortic aneurysms. Ann Thorac Surg 74(5):S1803–1805; discussion S1825–1832.
13. Griepp RB (2001) Cerebral protection during aortic arch surgery. J Thorac Cardiovasc Surg 121(3):425–427.
14. Heinemann M, Laas J, Karck M, Borst HG (1990) Thoracic aortic aneurysms after acute type A aortic dissection: necessity for follow-up. Ann Thorac Surg 49(4):580–584.
15. Ishihara H, Uchida N, Yamasaki C, Sakashita M, Kanou M (2002) Extensive primary repair of the thoracic aorta in Stanford type A acute aortic dissection by means of a synthetic vascular graft with a self-expandable stent. J Thorac Cardiovasc Surg 123(6):1035–1040.
16. Kato M, Kuratani T, Kaneko M, Kyo S, Ohnishi K (2002) The results of total arch graft implantation with open stent-graft placement for type A aortic dissection. J Thorac Cardiovasc Surg 124(3):531–540.
17. Kouchoukos NT, Masetti P, Rokkas CK, Murphy SF (2001) Single-stage reoperative repair of chronic type A aortic dissection by means of the arch-first technique. J Thorac Cardiovasc Surg 122(3):578–582.
18. Kuki S, Taniguchi K, Masai T, Yokota T, Yoshida K, Yamamoto K, Matsuda H (2002) An alternative approach using long elephant trunk for extensive aortic aneurysm: elephant trunk anastomosis at the base of the innominate artery. Circulation 106(12 Suppl 1):I253–258.

19. Massimo CG, Presenti LF, Favi PP, Crisci C, Cruz Guadron EA (1993) Simultaneous total aortic replacement from valve to bifurcation: experience with 21 cases. Ann Thorac Surg 56(5):1110–1116.
20. Minale C, Splittgerber FH, Wendt G, Messmer BJ (1994) One-stage intrathoracic repair of extended aortic aneurysms. J Card Surg 9(5):604–613.
21. Mizuno T, Toyama M, Tabuchi N, Wu H, Sunamori M (2002) Stented elephant trunk procedure combined with ascending aorta and arch replacement for acute type A aortic dissection. Eur J Cardiothorac Surg 22(4):504–509.
22. Orihashi K, Sueda T, Watari M, Okada K, Ishii O, Matsuura Y (2001) Endovascular stent-grafting via the aortic arch for distal aortic arch aneurysm: an alternative to endovascular stent-grafting. Eur J Cardiothorac Surg 20(5):973–978.
23. Palma JH, Almeida DR, Carvalho AC, Andrade JC, Buffolo E (1997) Surgical treatment of acute type B aortic dissection using an endoprosthesis (elephant trunk). Ann Thorac Surg 63(4):1081–1084.
24. Palma JH, Carvalho AC, Buffolo E, Almeida DR, Gomes WJ, Brasil LA (1998) Endoscopic placement of stents in aneurysms of the descending thoracic aorta. Ann Thorac Surg 66(1):256–258.
25. Palma JH, de Souza JA, Rodrigues Alves CM, Carvalho AC, Buffolo E (2002) Self-expandable aortic stent-grafts for treatment of descending aortic dissections. Ann Thorac Surg 73(4):1138–1141; discussion 1141–1132.
26. Safi HJ, Miller CC 3rd, Iliopoulos DC, Letsou GV, Baldwin JC (1997) Staged repair of extensive aortic aneurysm: improved neurologic outcome. Ann Surg 226(5):599–605.
27. Saitoh H, Ezure M, Takeshita M, Mizuno A (1993) [Surgical treatment for impending rupture of distal aortic arch aneurysm: a case report using "elephant trunk" prosthesis]. Kyobu Geka 46(12):1044–1047.
28. Sasaguri S, Fukuda T (1998) Is the elephant trunk technique really necessary for extensive arch aneurysm? Ann Thorac Surg 65(5):1512–1513.
29. Schepens MA, Dossche KM, Morshuis WJ, van den Barselaar PJ, Heijmen RH, Vermeulen FE (2002) The elephant trunk technique: operative results in 100 consecutive patients. Eur J Cardiothorac Surg 21(2):276–281.
30. Suto Y, Yasuda K, Shiiya N, Murashita T, Kawasaki M, Imamura M, Takigami K, Sasaki S, Matsui Y, Sakuma M (1996) Stented elephant trunk procedure for an extensive aneurysm involving distal aortic arch and descending aorta. J Thorac Cardiovasc Surg 112(5):1389–1390.
31. Svensson LG (1992) Rationale and technique for replacement of the ascending aorta, arch, and distal aorta using a modified elephant trunk procedure. J Card Surg 7(4):301–312.
32. Svensson LG, Kaushik SD, Marinko E (2001) Elephant trunk anastomosis between left carotid and subclavian arteries for aneurysmal distal aortic arch. Ann Thorac Surg 71(3):1050–1052.
33. Usui A, Tajima K, Nishikimi N, Ishiguchi T (1999) Implantation of an endovascular covered stent-graft for distal aortic arch aneurysm via midsternotomy under pigtail catheter guidance. Eur J Cardiothorac Surg 16(3):356–358.
34. Usui A, Fujimoto K, Ishiguchi T, Yoshikawa M, Akita T, Ueda Y (2002) Cerebrospinal dysfunction after endovascular stent-grafting via a median sternotomy: the frozen elephant trunk procedure. Ann Thorac Surg 74(5):S1821–1824; discussion S1825–1832.
35. Westaby S, Katsumata T (1998) Proximal aortic perfusion for complex arch and descending aortic disease. J Thorac Cardiovasc Surg 115(1):162–167.
36. Won JY, Lee DY, Shim WH, Chang BC, Park SI, Yoon CS, Kwon HM, Park BH, Jung GS (2001) Elective endovascular treatment of descending thoracic aortic aneurysms and chronic dissections with stent-grafts. J Vasc Interv Radiol 12(5):575–582.
37. Yamazaki I, Imoto K, Suzuki S, Ichikawa Y, Karube N, Manabe T, Noishiki Y, Kondo J, Takanashi Y (2001) Mid-term results of stent-graft repair for thoracic aortic aneurysms: computed tomographic evaluation. Artif Organs 25(3):223–227.

Management of the Horizontal Aorta with the Inoue Branched Stent-Graft

Kanji Inoue, Hiroaki Hosokawa, Kenichi Abe, Takeshi Kimura

12

Contents

12.1 Introduction

Currently, the standard treatment of thoracic aortic aneurysms is surgery with artificial graft replacement, for which perioperative mortality rates of 5–35% have been documented in multicenter reports [2, 3, 12, 14, 18, 19]. Despite recent progress of thoracic aortic surgery, complications are still prevalent in repair of aortic arch aneurysms [3, 6, 15]. Endovascular stent-grafting of aortic aneurysms is an attractive alternative to conventional surgical therapy [1, 5, 17]. This approach potentially offers the benefits of remarkably reduced patient physical and psychic burden, shortened procedure time, reduced operative risk, and lower cost compared with conventional surgery. With regard to thoracic aortic aneurysm repair, Dake et al. [4] first demonstrated the clinical feasibility with Dacron-covered, self-expanding, stainless steel straight stent-grafts in 13 cases with descending thoracic aortic aneurysms. However, endovascular repair with straight stent-grafts is limited to the descending aortic aneurysms because the great vessels arising from the ascending aorta and transverse arch are occluded by the stent-graft [13]. Therefore, the development of a branched stent-graft has been eagerly awaited for treating aortic arch aneurysms.

In 1996 we reported the first clinical application of a branched stent-graft for a patient with a type B dissection originating just beyond the left subclavian artery [7]. The successful endovascular repair with the single-branched stent-graft led to the obliteration of the dissection. Several modifications in stent-graft designs and catheter techniques enabled total arch reconstruction with a triple-branched stent-graft [10]. We describe herein our experience with the use of the Inoue branched stent-graft for the treatment of horizontal aneurysms.

12.2 Materials and Methods

12.2.1 Inoue Branched Stent-Graft

The stent-graft is composed of crimped woven polyester graft material, the outside surface of which is encircled with multiple successive rings of nickel titanium wire [8]. The graft is extremely flexible to conform to the tortuous aortic arch. The first and second rings from the edge are covered by polyester graft fabrics to provide effective, secure friction seals against the aortic wall. The middle rings prevent the graft from collapsing because of the outside pressure during long-term use. Although the graft rings are easily visible under fluoroscopy, radiopaque gold markers are sutured to the two terminal rings and the center line along the greater curvature of the stent-graft to further facilitate graft visualization during the procedure.

As shown in Fig. 12.1, the branched stent-graft has a main graft body and short branches. The single-branched stent-graft, which has a branch extending into one of the great vessels arising from the aortic arch, is

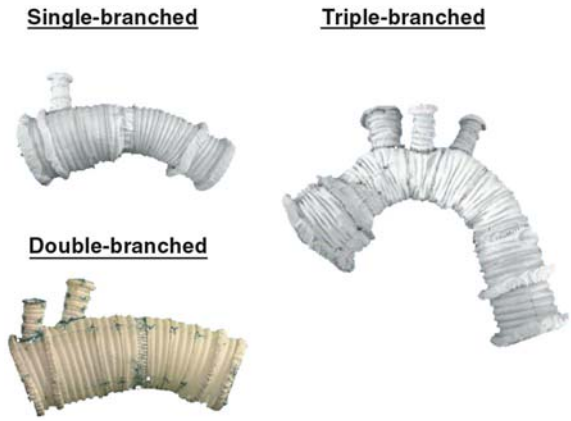

Fig. 12.1. Inoue branched stent-graft. The stent-graft is composed of a woven Dacron fabric graft supported by multiple rings of nickel titanium wire

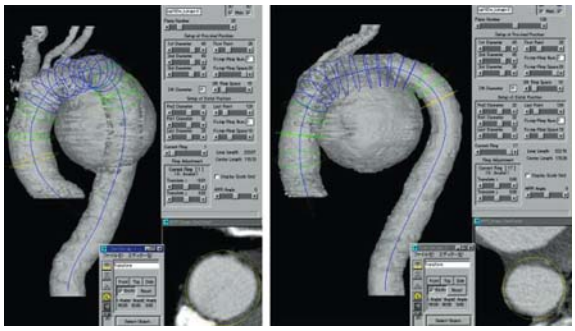

Fig. 12.2. A computer-assisted design system of stent-grafts for aortic aneurysms. A designed stent-graft can be virtually implanted into the aortic aneurysm

mainly placed into the distal arch including the left subclavian artery and the descending thoracic aorta. The double- and triple-branched stent-grafts have branches extended into two or three great vessels of the aortic arch.

The stent-graft is custom-made according to the state of the individual patient's pathology. Aortic arch aneurysms have highly complex anatomic characteristics; therefore, a precise stent-graft design is crucial to achieve complete aneurysm exclusion. The length, diameter, and taper of the stent-graft, and the landing zone are determined using a computer-assisted stent-graft design system. With the system, a suitable stent-graft can be designed by simulating the stent-graft in a three-dimensional aortic aneurysm model constructed from helical computed tomography images on a computer display (Fig. 12.2). The main graft body is 22–44 mm in diameter and 50–300 mm long. The side branch is 8–18 mm in diameter and 15–40 mm long.

12.2.2 Inoue Stent-Graft Delivery System

The delivery apparatus includes a detachable carrying wire, a detachable traction wire, a delivery sheath, a tapered dilator, and a loading cartridge.

The detachable carrying wire is attached to the proximal end of the main stent-graft body. It functions to deliver the stent-graft to the optimal point. The wire has a 21-gauge nitinol hollow shaft and a J-tip flexible tube is attached to its tip to prevent injury to the aortic wall.

The detachable traction wire is constructed of a 3-F polyethylene tube with multilumen and is attached to each distal end of the main graft body and branches. For the traction catheters of each branch, a guidewire is connected to its distal end, which facilitates catching the tip by a snare wire inserted through the brachial artery or the left carotid artery. The traction wire connected to the main graft body allows length adjustment by pushing it up after stent-graft deployment if spinal cord ischemia occurs. Reducing the length of the graft reduces the risk of spinal cord damage.

A 22-F or a 24-F delivery sheath is used for thoracic use.

12.2.3 Aortic Arch Reconstruction with Single-Branched Stent-Grafts

The endovascular catheter technique with a single-branched stent-graft is usually performed under local anesthesia in the angiography suite. Before the insertion of the stent-graft, a carrying wire is attached to the proximal end of the main graft body and a traction wire is also attached to each distal end of the main body and branch (Fig. 12.3). The main graft body and branch are individually constricted using a thread and a 0.020-mm nickel titanium wire in such a way that the stent-graft does not spontaneously expand after its release from the sheath. A 10-F guiding catheter is then set over the traction wire connected to the branch. And then, a 3-F detachable tag wire is connected to the tip of the carrying catheter, which serves to lead the stent-graft toward the ascending aorta beyond the bend of the distal arch.

After initial arteriography, 200 U of heparin per kilogram of body weight is administrated and surgical exposure of the common femoral artery is made. A delivery sheath is introduced into the descending thoracic aorta via the groin incision and then the detachable tag wire connected to the carrying wire is advanced through the sheath. A snare wire is then inserted into a 7-F guiding catheter which is inserted from a left brachial artery puncture site to capture the free end of the detachable tag wire. The constricted stent-graft is loaded into the cartridge, introduced into the sheath,

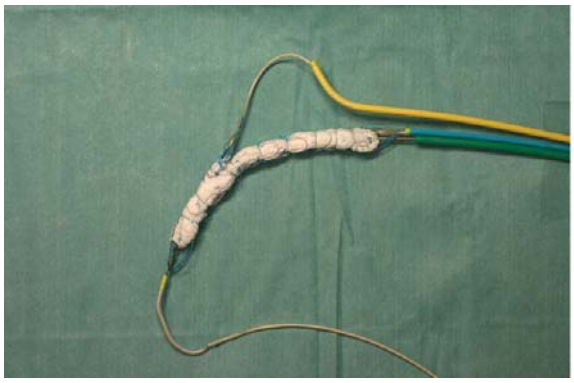

Fig. 12.3. A constricted single-branched stent-graft and its delivery system. A carrying wire is attached to the proximal end of the stent-graft and a traction wire is at each distal end of the stent-graft

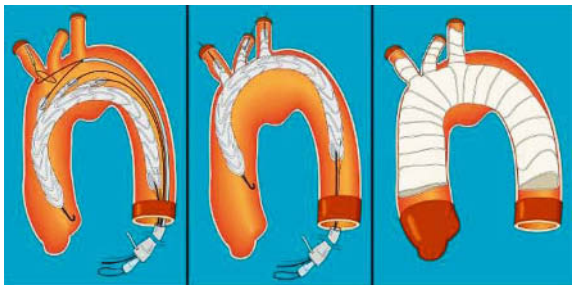

Fig. 12.4. Technique of triple-branched stent-graft implantation. The free end of a traction wire attached to the tip of the branches is caught by a snare wire

and advanced into the descending aorta with the aid of the carrying wire, and released from the sheath. The stent-graft is further advanced toward the ascending aorta with the aid of the tag wire. Once the branch tip is placed near the left subclavian artery, the tag wire is detached from the carrying wire and removed, leaving the 7-F guiding catheter in the left brachial artery. Subsequently, the free end of the traction wire attached to the sidearm is folded back, inserted again into the 10-F guiding catheter which has been previously set, and advanced to the distal arch so that its free end can be caught and pulled back using a snare wire which is inserted through the 7-F guiding catheter from a left brachial artery puncture site. After confirmation of the location of the stent-graft with angiography, the stent-graft is deployed by removal of the 0.20-mm nickel titanium wires being used to constrict it. The main graft body and branch are fully dilated by means of balloon inflation. Finally, angiography is performed to assess technical adequacy, the carrying wire and traction wires are removed and then the arteriotomy site is repaired.

12.2.4 Aortic Arch Reconstruction with Double-Branched or Triple-Branched Stent-Grafts

The double-branched or triple-branched stent-graft is implanted in a manner similar to that of the single-branched stent-graft. Figure 12.4 shows the method of placing the triple-branched stent-graft. The procedure is performed under general or epidural anesthesia depending on the individual patient's clinical condition. With the aid of its carrying system, the constricted stent-graft is delivered to the descending thoracic aorta via a 22-F or a 24-F sheath, released from the sheath, and then further advanced into the ascending aorta. Then, each sidearm is positioned one by one into the aortic branch by pulling back each traction wire attached to its tip with snare wires inserted from bilateral brachial artery and left carotid artery puncture sites. Then, the main graft body is deployed, and subsequently each branch is deployed. After all graft sections have been deployed, the stent-graft is pressed against the aortic and arterial walls by balloon inflation. At this point, adenosine is administered intravenously to induce temporary asystole, which reduces the risk of graft migration, when it is necessary.

12.2.5 Countermeasure Against Distal Embolization

Although endovascular repair may be associated with lower morbidity and mortality than conventional surgical approaches, the treatment has inherent complications. Our prime concern of late has been cerebral vascular accidents. The cerebral incidents are most likely caused by cerebral embolization. Especially, our technique needs catheter manipulation in diseased aortic arch containing mural thrombus and atherosclerotic debris. We have therefore developed a filter device to minimize the risk of massive embolization [16, 20].

The filter device is constructed of a polyester mesh with a nitinol wire ring. The filters are connected to a 0.014-in. wire which is used as a guidewire. There are two types of filter devices: detachable and undetachable (Fig. 12.5). Detachable ones are placed into the carotid arteries and detached from the guidewire so as not to interrupt catheter manipulation associated with stent-graft placement (Fig. 12.6). Undetachable ones are placed into the celiac axis, the superior mesenteric artery, and the unilateral renal artery to protect visceral organs. After endovascular grafting is terminated, the filters are retrieved from the arteries (Fig. 12.7). Macroscopic embolic particles were captured in the filters. In our preliminary clinical trial, the newly developed protection device seemed to be effective and safe; however, further clinical data will be necessary to confirm its general utility.

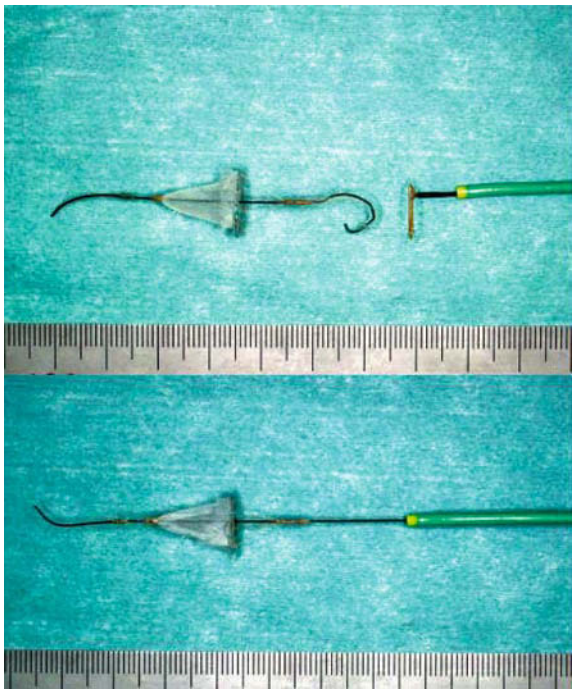

Fig. 12.5. Newly designed filter device

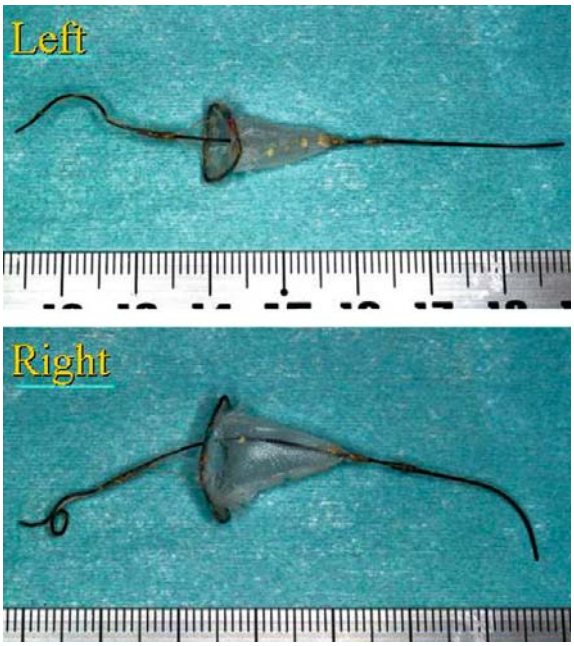

Fig. 12.7. Macroscopic view of embolic particles captured by filter devices

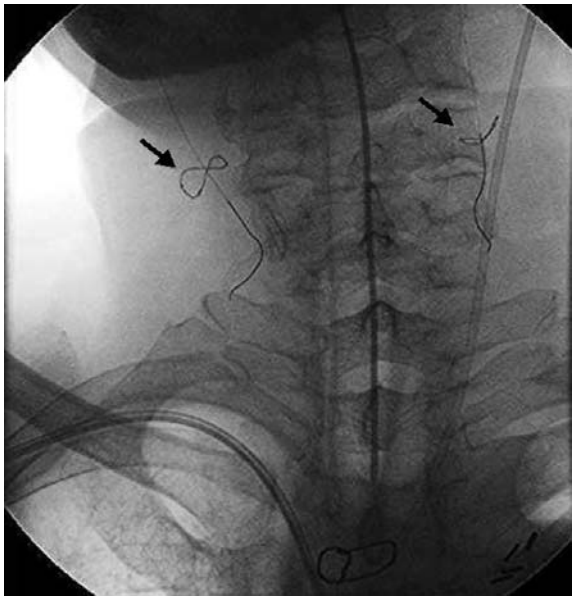

Fig. 12.6. Fluoroscopic image after filter deployment in the carotid arteries

12.2.6 Patients and Anatomic Criteria for Endovascular Repair

Between November 1995 and March 2002, the procedure was attempted in 48 patients with aortic arch aneurysms. The mean age of the patients was 68 years (range, 21–87), with a male-to-female ratio of 5:1. Etiologies included atherosclerosis in 26 patients, chronic aortic dissection in 15 patients, and posttraumatic or false aneurysm in seven patients. Because of the experimental nature of this procedure, it was mainly performed for high-risk surgical patients. The anatomic criteria are as follows:

1. For placement of a single-branched or a double branched stent-graft, both the proximal and the distal landing zones should be at least 1 cm long.
2. If a single-branched stent-graft is to be employed, ideally, the front part of the proximal landing zone (the segment between the origin of the left subclavian artery and the left carotid artery) and the back part of the proximal landing zone (the segment between the origin of the left subclavian artery and the proximal aspect of the aneurysm) should each be more than 5 mm in length.
3. For placement of a triple-branched stent-graft, a proximal landing zone at least 3-cm long and a distal landing zone at least 1 cm long must be present.
4. The caliber of the normal artery selected for sidearm implantation must be 8 mm or more in diameter.

5. The caliber of the iliac and the femoral arteries must be sufficient to accept the delivery sheath.
6. Acute aortic dissections are excluded because the intimal flap is flimsy and easily injured by the edge of the stent-graft. However, it usually thickens in the chronic phase. Patients with chronic type B aortic dissections are therefore suitable candidates even if they have very small true lumen with compression of the large false lumen.
7. Patients with connective tissue disorders (e.g., Marfan's syndrome) are excluded.

12.3 Outcome

12.3.1 Immediate Results and In-Hospital Course

Single-branched stent-graft placement was technically successful in 86% (30/35 patients), double-branched in 67% (2/3 patients), and triple-branched in 70% (7/10) of patients (Fig. 12.8). The procedure was terminated before completion in nine patients, either because of a complication (one patient) or because the stent-graft did not pass through the delivery sheath used (eight patients). There were three deaths in the perioperative period. The causes were rupture of the coiled external iliac artery, acute pancreatitis due to microembolization, and massive bleeding from the left carotid artery puncture site.

Other major complications included stroke in one patient, reversible neurological event in one patient, new aortic dissection in one patient, rupture of the external iliac artery in one patient, and severe graft stenosis in one patient. Of the major complications, the arterial rupture during the withdrawal of the delivery sheath was successfully managed by stent-grafting of the external iliac artery and the severe graft stenosis at the main graft body was corrected by deployment of metal stents.

12.3.2 Clinical Follow-Up

Follow-up for a period averaging 37 months (range, 4 months to 8.5 years) was available for 37 patients of the 39 patients in whom the procedure was completed; one died of acute pancreatitis in the perioperative period and one was lost to follow-up. There were three procedure-related deaths. The causes were infection in one patient, rupture of the treated aneurysm in one patient, and helium gas embolism during secondary stent-graft intervention in one patient. Four late deaths occurred from other causes (two due to pneumonia, one due to colon cancer, one due to rupture of a concomitant abdominal aortic aneurysm). Four patients had persistent endoleaks; three patients were successfully treated by additional catheter-based interventions.

Late graft disruption, which was caused by the defect of the graft fabric on the manufacturing process, occurred in eight patients. Of the eight patients, six received second stent-graft intervention; one died and five were successfully treated by the placement of an overlapping stent-graft. Of the remaining two patients, one died of aneurysm rupture and the other declined further intervention. The other major complications included late graft thrombosis of the left subclavian artery in one patient with freedom from symptoms and late endoleak in one patient. The leakage caused by a gap between the stent-graft and the aorta at the proximal edge was eliminated by the placement of a straight stent-graft.

With regard to changes in the maximum diameter of the aneurysm sac as assessed by computed tomography, 18 of the 37 patients (49%) had a reduction (Fig. 12.9), 12 patients (32%) had no change, and seven patients (19%) had an increase (one with a persistent leak, two with late graft disruption, three with no demonstrable endoleak, one with residual reentries in a type B aortic dissection).

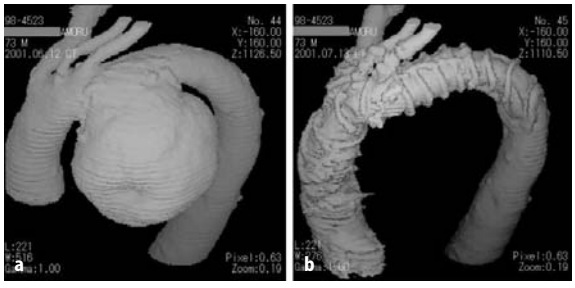

Fig. 12.8. Triple-branched stent-graft for treatment of aortic arch aneurysm. **a** Computed tomography (*CT*) image demonstrates a huge transverse aortic arch aneurysm. **b** CT image obtained after stent-graft placement shows complete exclusion of the aneurysm

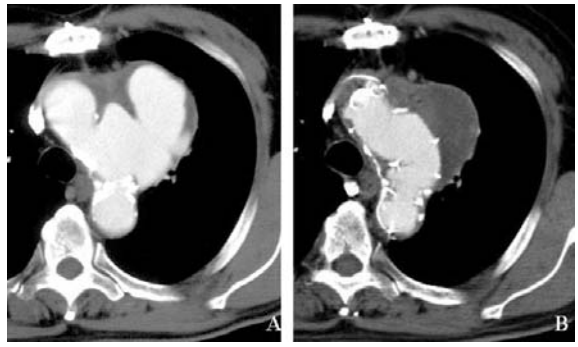

Fig. 12.9. Triple-branched stent-graft for treatment of aortic arch aneurysm. **A** CT image demonstrates a transverse aortic arch aneurysm. **B** CT image obtained 2 years after stent-graft placement shows aneurysm shrinkage

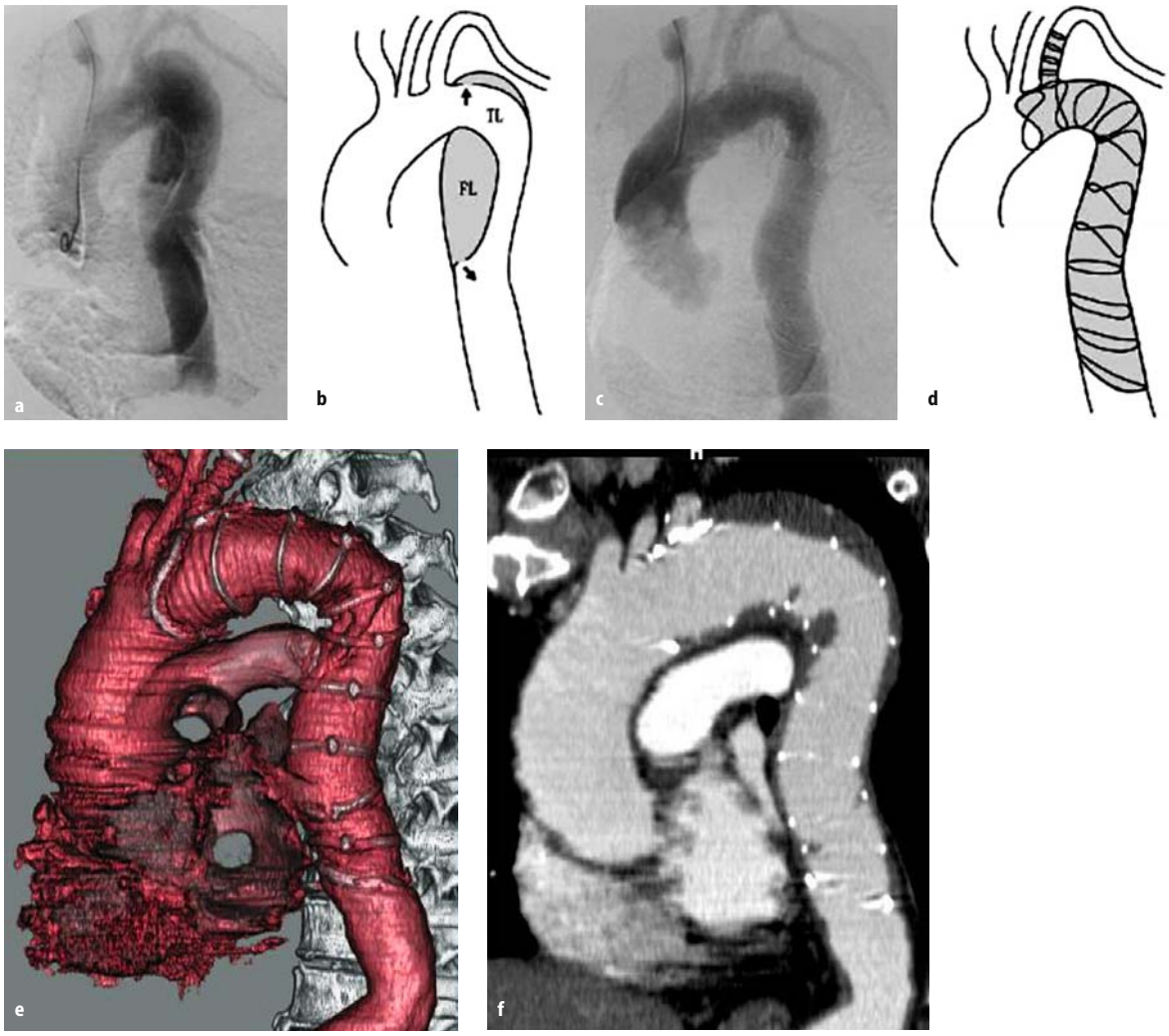

Fig. 12.10. Aortograms in a 51-year-old woman with a type B dissection: **a, b** aortogram shows the entry just beyond the left subclavian artery; **c, d** aortogram after the procedure shows a good flow of contrast medium through the single-branched stent-graft with no leakage into the false lumen. **e, f** CT images taken 8 years after single-branched stent-graft placement reveals a shrinkage of the false lumen, with absence of contrast enhancement into the false lumen

12.4 Conclusion

Endovascular repair with a branched stent-graft has the advantage of being remarkably less invasive compared with conventional surgical treatment and is applicable to complex aneurysms such as aortic arch aneurysms [9, 11]. Considering most of the patients in our series were at surgical high risk, the immediate and follow-up results of endovascular repair with the Inoue branched stent-graft appear to be favorable (Fig. 12.10). However, further technical refinements and extensive clinical trials will be needed before the procedure can become the primary treatment for horizontal aneurysms.

Acknowledgements. The authors thank Yuki Yoshida for the English translation of the manuscript.

References

1. Blum U et al. (1997) Endoluminal stent-grafts for infrarenal abdominal aortic aneurysms. N Eng J Med 336:13–20.
2. Crawford ES et al. (1979) Treatment of aneurysm of transverse aortic arch. J Thorac Cardiovasc Surg 78:383–393.
3. Crawford ES et al. (1989) Surgical treatment of aneurysm and/or dissection of the ascending aorta, transverse aortic arch, and ascending aorta and transverse aortic arch: factors influencing survival in 717 patients. J Thorac Cardiovasc Surg 98:659–674.
4. Dake MD et al. (1994) Transluminal placement of endovascular stent-graft for the treatment of descending thoracic aortic aneurysms. N Eng J Med 331:1729–1734.

5. Dotter CT (1969) Transluminally-placed coilsoring endoarterial tube grafts: long-term patency in canine popliteal artery. Invest Radiol 4:329–332.
6. Ergin MA et al. (1994) Hypothermic circulatory arrest in operations on the thoracic aorta: determinants of operative mortality and neurologic outcome. J Thorac Cardiovasc Surg 107:788–799.
7. Inoue K et al. (1996) Clinical endovascular placement of branched graft for type B aortic dissection. J Thorac Cardiovasc Surg 112:1111–1113.
8. Inoue K et al. (1997) Clinical application of transluminal endovascular graft placement for aortic aneurysms. Ann Thorac Surg 63:522–528.
9. Inoue K et al. (1997) Transluminal endovascular branched graft placement for a pseudoaneurysm: reconstruction of the descending thoracic aorta including the celiac axis. J Vasc Cardiovasc Surg 114:859–861.
10. Inoue K et al. (1999) Aortic arch reconstruction by transluminally placed endovascular branched stent graft. Circulation 100(Suppl II):316–321.
11. Inoue K et al. (2001) Successful endovascular repair of juxtarenal and suprarenal aortic aneurysms with a branched stent graft. J Vasc Surg 33:1087–1092.
12. Miller DC et al. (1979) Operative treatment of aortic dissections: experience with 125 patients over a sixteen-year period. J Thorac Cardiovasc Surg 78:365–382.
13. Mitchell RS et al. (1996) Endovascular stent-graft repair of thoracic aortic aneurysm. J Thorac Cardiovasc Surg 111:1054–1062.
14. Moreno-Cabral CE et al. (1984) Degenerative and atherosclerotic aneurysms of the thoracic aorta: determinants of early and late surgical outcome. J Thorac Cardiovasc Surg 88:1020–1032.
15. Okita Y et al. (1998) Mortality and cerebral outcome in patients who underwent aortic arch operations using deep hypothermic circulatory arrest with retrograde cerebral perfusion: no relation of early death, stroke, and delirium to the duration of circulatory arrest. J Thorac Cardiovasc Surg 115:129–138.
16. Ohki T et al. (1999) Efficacy of a filter device in the prevention of embolic events during carotid angioplasty and stenting: an ex vivo analysis. J Vasc Surg 30:1034–1044.
17. Parodi JC et al. (1991) Transfemoral intraluminal graft implantation for abdominal aortic aneurysms. Ann Vasc Surg 5:491–499.
18. Pressler V, McNamara JJ (1985) Aneurysm of the thoracic aorta. Review of 260 cases. J Thorac Cardiovasc Surg 89:50–54.
19. Skupin M et al. (1990) Results of surgical repair for 110 thoracic aortic aneurysms. J Thorac Cardiovasc Surg 38:175–180.
20. Theron JG et al. (1996) Carotid artery stenosis: treatment with protected balloon angioplasty and stent placement. Radiology 201:627–636.

Distal Aortic Perfusion and Selective Visceral Perfusion

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Contents

13.1 Introduction

Thoracoabdominal aortic aneurysm repair was first performed by Etheredge [1] in 1955. Using a temporary shunt to divert blood flow from the distal thoracic aorta to the distal abdominal aorta, Etheredge excised a thoracoabdominal aortic aneurysm and restored blood flow by inserting a homograft tube. De Bakey reported a similar shunt and homograft technique in 1956. Later that year, De Bakey [2] began to use a Dacron tube graft that was sewn to the descending thoracic aorta and infrarenal abdominal aorta, and sequentially performed separate bypass grafts of the celiac, superior mesenteric and both renal arteries. This became the mainstay of thoracoabdominal aortic aneurysm repair in its new beginning, because of its relative simplicity and reduced ischemic insult to the viscera and kidneys. In 1965, Crawford and the Baylor group then started to set the standard in thoracoabdominal aortic surgery, as they recruited large volumes of patients. Crawford's technique stemmed primarily from the early works of Matas and Carrell, and encompassed three basic principles of aortic surgery: the inclusion technique, use of a Dacron tube graft conduit, and reimplantation of visceral and renal arteries. In 1888, Matas [3] had first repaired an aneurysm of the brachial artery within the walls of the aneurysm, an inclusion technique later termed as endoaneurysmorrhaphy. On the other hand, direct reattachment of visceral arteries to a hole made in the prosthetic graft was pioneered by Carrell [4], who had experimented with different methods for reattaching smaller vessels to larger ones, at the turn of the twentieth century. Creech [5] reported his approach for thoracoabdominal aortic aneurysm repair, in 1966. Thoracoabdominal aortic repair in this early time, however, was still very arduous, an extremely lengthy procedure, and associated with severe ischemia of the spinal cord, viscera and kidneys.

Connolly et al. [6] of Irvine, California, were the first to use the pulsatile left heart bypass as an adjunct for repair of the descending thoracic aneurysm. Korompai [7], at Scott and White Clinic in Temple, used an ingenious method to perfuse the viscera, by diverting blood from the descending thoracic aorta via a branched cannula connected to the celiac axis, superior mesenteric and both renal arteries. In the mid-1970s, after trying out various adjuncts, Crawford et al. [8] settled on the clamp-and-go technique, because this simplified the procedure, shortened the length of the operation and produced good results. The modern era of repair of thoracoabdominal aortic aneurysm was then ushered in. However, high rates of postoperative paraplegia remained, and adjuncts continued to be explored widely into the 1980s.

The original experimental work of Spencer, Cunningham, Laschinger and others at John Hopkins University enlightened the surgical community to the significance of intercostal artery reattachment in thoracoabdominal aortic repair. Subsequently, Cunningham et al. [9, 10] proposed the combined use of distal aortic perfusion and somatosensory-evoked potential (SSEP) to identify the artery of Adamkiewicz. In contrast, Crawford et al. [11] reported high rates of false positives and false negatives in SSEP changes when correlated with postoperative neurological deficit. In 1988, Hollier [12], while at the Mayo Clinic, established the use of perioperative ce-

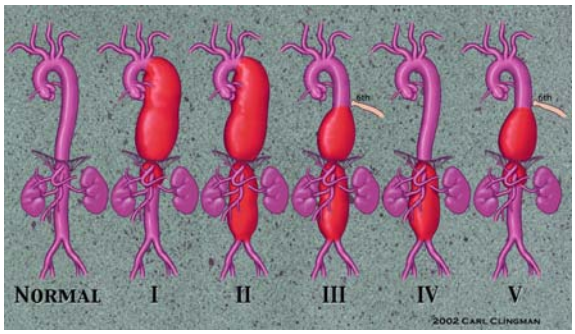


Fig. 13.1. Thoracoabdominal aortic aneurysm classification. Extent *I*, distal to the left subclavian artery to above the renal arteries. Extent *II*, distal to the left subclavian artery to below the renal arteries. Extent *III*, from the sixth intercostal space to below the renal arteries. Extent *IV*, from the 12th intercostal space to the iliac bifurcation (total abdominal aorta). The original Crawford classification comprises extent I to extent IV. We have since added extent *V*, from below the sixth intercostal space to above the renal arteries

rebrospinal fluid (CSF) drainage, and reported a dramatic reduction in the incidence of paraplegia. In a subsequent randomized clinical trial, Crawford et al. [13] showed that CSF drainage provided no significant benefit; however, intraoperative CSF drainage was allowed only up to 50 mL, and this limitation may have been the reason for the negative result of their study. Because adjuncts had been up to now largely unsatisfactory, protection of the spinal cord by simply reducing the aortic cross-clamp time became the focus. To minimize the ischemic time to aortic segments, sequential clamping of the aorta was essential to the clamp-and-go technique. Also during this period, the classification of the extent of thoracoabdominal aortic aneurysms (Fig. 13.1) was solidified, to permit meaningful comparisons between various surgical groups and methods [14].

The 1990s were characterized by further experiments with adjuncts, and different centers concentrated on different techniques, including hypothermia [15, 16] and regional spinal cord cooling [17]. Crawford's cumulative work was reviewed by Svensson et al. [18] in a landmark paper published in 1993. The incidence of neurological deficit was correlated with the extent of aneurysm, clamp time, rupture, age, proximal aortic aneurysm and renal dysfunction [18]. Simple clamp-and-go technique was virtually abandoned [16, 17,19]. In 1992, after several years of animal experiments and promising clinical results reported by ourselves and other investigators, we adopted the combined adjunct distal aortic perfusion and CSF drainage for all patients undergoing thoracoabdominal aortic repair [19, 20]. We then observed considerable improvement in patient outcome. In this chapter, we will discuss the adjuncts of distal aortic perfusion, CSF drainage, moderate hypothermia and visceral perfusion, and review their impact on neurological deficits and organ protection.

13.2 Operative Technique and Adjuncts

The patient is brought to the operating room and placed in the supine position on the operating table and prepared for surgery. The right radial artery is cannulated for continuous arterial pressure monitoring. General anesthesia is induced. Endotracheal intubation of the patient is established using a double lumen tube for selective right lung ventilation during surgery. A sheath is inserted in the internal jugular vein, and a Swan–Ganz catheter is floated into the pulmonary artery for continuous monitoring of the central venous and pulmonary artery pressures. Large-bore central and peripheral venous lines are established for fluid and blood replacement therapy. Temperature probes are placed in the patient's nasopharynx and bladder (or rectum). Electrodes are attached to the scalp for an electroencephalogram (EEG) and along the spinal cord for SSEP to assess the central nervous system and spinal cord function, respectively. Although a detailed account of the essential anesthetic care during thoracoabdominal aortic repair is beyond the scope of this chapter, the importance of adequate maintenance of systemic arterial pressure with judicious blood transfusion cannot be overemphasized, as perfusion of vital organs depends on the systemic pressure.

13.2.1 Cerebrospinal Fluid Drainage

When the descending thoracic aorta is cross-clamped, the spinal cord is rendered ischemic because of decreased perfusion to the spinal cord and consequent increased CSF pressure. The rationale for our use of CSF drainage is to increase the spinal cord perfusion pressure directly with distal aortic perfusion, and indirectly by reducing CSF pressure. Once all catheters, probes

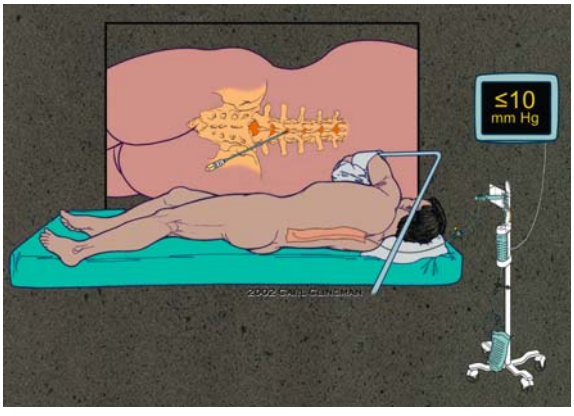


Fig. 13.2. Placement of the lumbar catheter in the third or fourth lumbar space to provide cerebrospinal fluid drainage and pressure monitoring

and lines are in place, we reposition the patient on his or her right side, flexing the knees to open the space between the vertebrae. The anesthesiologist inserts a catheter in the third or fourth lumbar space and advances it for about 5 cm (Fig. 13.2). CSF pressure is kept below 10 mmHg throughout the surgery and for 3 days postoperatively. Systemic hypotension is avoided during and after surgery to prevent additional hypoperfusion of the spinal cord.

13.2.2 Thoracoabdominal Incision

Once the lumbar catheter is in place, we readjust the patient's position on the operating table. The right lateral decubitus position is maintained on a bean bag, and the patient's shoulders are placed at a right angle to the edge of the table, with the left hip flexed at 60° to allow access to both groins. The patient is sterilely cleansed and draped in the usual sterile fashion. We tailor the incision to fit the extent of the aneurysm (Fig. 13.3). A full thoracoabdominal incision begins between the spine and vertebral border of the left scapula, curves along the sixth rib across the costal cartilage in an oblique line to the umbilicus, and then continues below the umbilicus to just above the symphysis pubis. Resection of the sixth rib facilitates exposure and is routinely performed for all thoracoabdominal aortic repair, except extent IV. Usually, a full thoracoabdominal exploration is necessary for extents II, III and IV. A modified thoracoabdominal incision begins in the same way as a full thoracoabdominal incision, but ends at the costal cartilage or above the umbilicus. A self-retaining retractor placed firmly on the edges of the incision maintains full thoracic and abdominal exposure during the procedure. The left lung is deflated. Mobilization of the aorta begins at the level of the hilum of the lung, cephalad to the proximal descending thoracic aorta. We identify the ligamentum arteriosum and transect it, taking care to avoid injury to the adjacent left recurrent laryngeal nerve. The extent of the distal abdominal aneurysm is assessed. For modified thoracoabdominal exploration, the diaphragm is retracted downward to expose the infradiaphragmatic aorta. When the aortic aneurysm extends below the renal arteries, we continue the full thoracoabdominal exploration below the diaphragm.

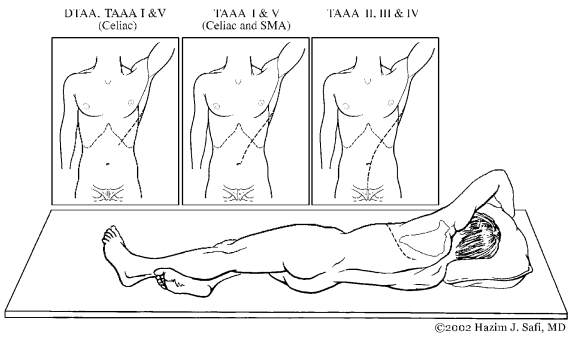


Fig. 13.3. Thoracoabdominal incisions tailored for aneurysm extent (see text)

13.2.3 Diaphragm Preservation

We have found that diaphragm preservation during thoracoabdominal aortic repair results in earlier weaning from mechanical ventilation, and consequently a shorter length of hospital stay [21, 22]. Since 1994, rather than dividing the diaphragm, we cut only the muscular portion, leaving the central tendinous portion intact and preserving the phrenic nerve (Fig. 13.4). This technique permits maintenance of pulmonary mechanics that more closely reflect normal function, and hence we are able to wean patients earlier from mechanical ventilation. After cutting only the muscular portion of the diaphragm, a retroperitoneal plane is developed, mobilizing the spleen, bowel loops and left kidney to the right side of the abdominal aorta (medial visceral rotation).

13.2.4 Distal Aortic Perfusion

Aortic cross-clamping not only causes distal end-organ ischemia, but can also lead to proximal systemic hypertension and left ventricular distension. Left ventricular distension can lead to increased wall stress and decreased subendocardial perfusion. To protect the spinal

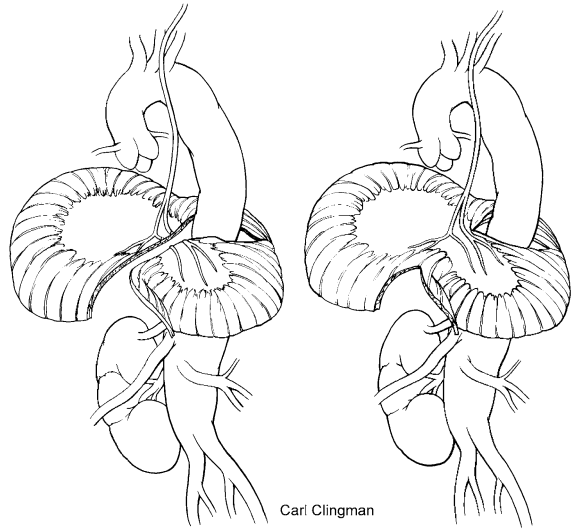


Fig. 13.4. Previously the diaphragm was completely divided (*left*); currently only the muscular portion of the diaphragm is cut

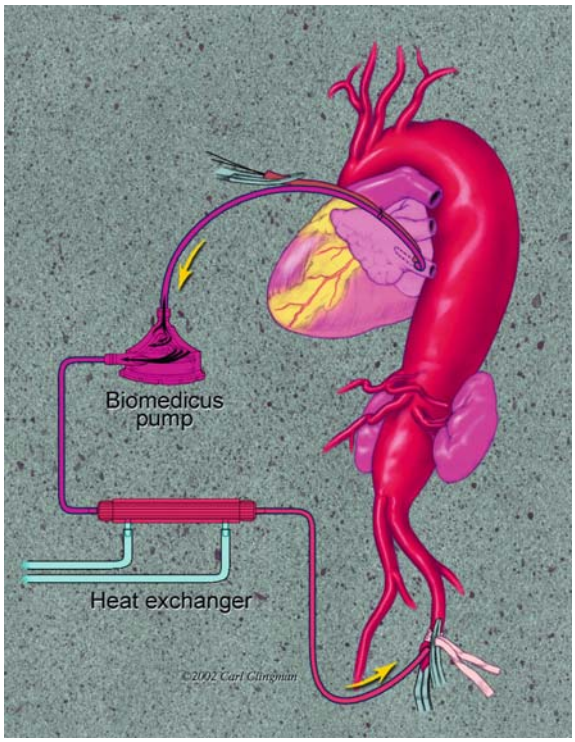


Fig. 13.5. Distal aortic perfusion from the left pulmonary vein to the left femoral artery

cord, reduce proximal hypertension, minimize cardiac ischemia and "unload" the heart, we routinely use distal aortic perfusion. Afterload-reducing pharmacologic agents such as nitrates are frequently used to further protect the heart. But we no longer use nitroprusside as an afterload-reducing agent, as we have observed precipitous systemic hypotension and a paradoxical increase in CSF pressure associated with its use. Occasionally, severe cardiac dysfunction may require mechanical support utilizing intraaortic balloon counterpulsation. To prepare for distal aortic perfusion the patient receives a dose of 1 mg/kg of heparin as an anticoagulant. The pericardium is opened posterior to the left phrenic nerve to allow direct visualization of the pulmonary veins and left atrium. The lower pulmonary vein is cannulated and a cannula is inserted and connected to a BioMedicus pump with an on-line heat exchanger (Fig. 13.5). Two potential problems can arise if the pericardium is not opened properly: first, the cannula is placed mistakenly in the pericardial space rather than the pulmonary vein, and concealed leakage from the pulmonary vein after the cannula is removed can cause pericardial tamponade (Fig. 13.6). To complete the distal aortic perfusion circuit, the left common femoral artery is exposed, and arterial inflow from the pump is generally established through the left common femoral artery. When the left femoral artery is not accessible (e.g., in the presence of an existing femoral prosthetic

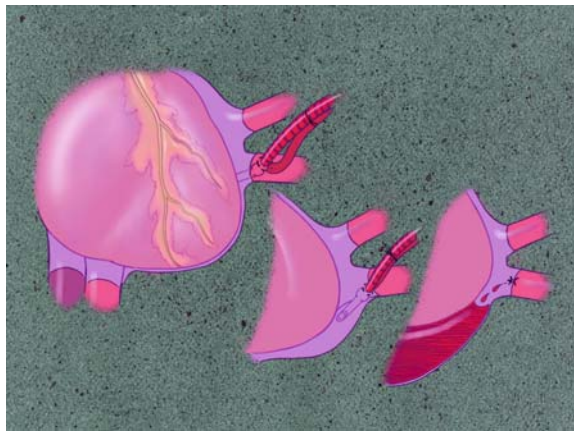


Fig. 13.6. The pericardium is opened for cannulation of the left lower pulmonary vein (*left*). If the pericardium is not properly opened (*middle*), tamponade can occur with concealed leakage from the pulmonary vein after decannulation (*right*)

graft or severe arteriosclerotic occlusive disease), the abdominal aorta or distal thoracic aorta is used instead. Distal aortic perfusion is initiated. We use passive moderate hypothermia (i.e., the patient's body temperature is allowed to drift to 32–34 °C). Body temperature drop below 32 °C is avoided to prevent the occurrence of ventricular arrhythmias. Our perfusion circuit includes a heat exchanger to permit active warming.

13.2.5 Sequential Cross-Clamping

We use sequential aortic cross-clamping to minimize organ ischemia, beginning either proximal or distal to left subclavian artery and at the mid-descending thoracic aorta (Fig. 13.7 a). The proximal aortic neck is transected completely and separated from the underlying esophagus to prevent the formation of esophageal-graft fistula (Fig. 13.7 b). To replace the aorta we use a woven Dacron tube graft that is either infiltrated with gelatin or impregnated with collagen. We suture the proximal graft to the descending thoracic aorta using a 3-0 or a 2-0 monofilament polypropylene suture in a running fashion. Distal aortic perfusion provides continuous perfusion to the spinal cord, viscera and kidneys during this period. After completion of the proximal anastomosis, the distal clamp is released and reapplied onto the abdominal aorta above the celiac axis.

13.2.6 Reattachment of Intercostal Arteries

Next, we reattach the patent intercostal arteries. We identify the lower intercostal arteries for reattachment to the graft. Most commonly the anterior radicular artery (also known as the artery of Adamkiewicz), the

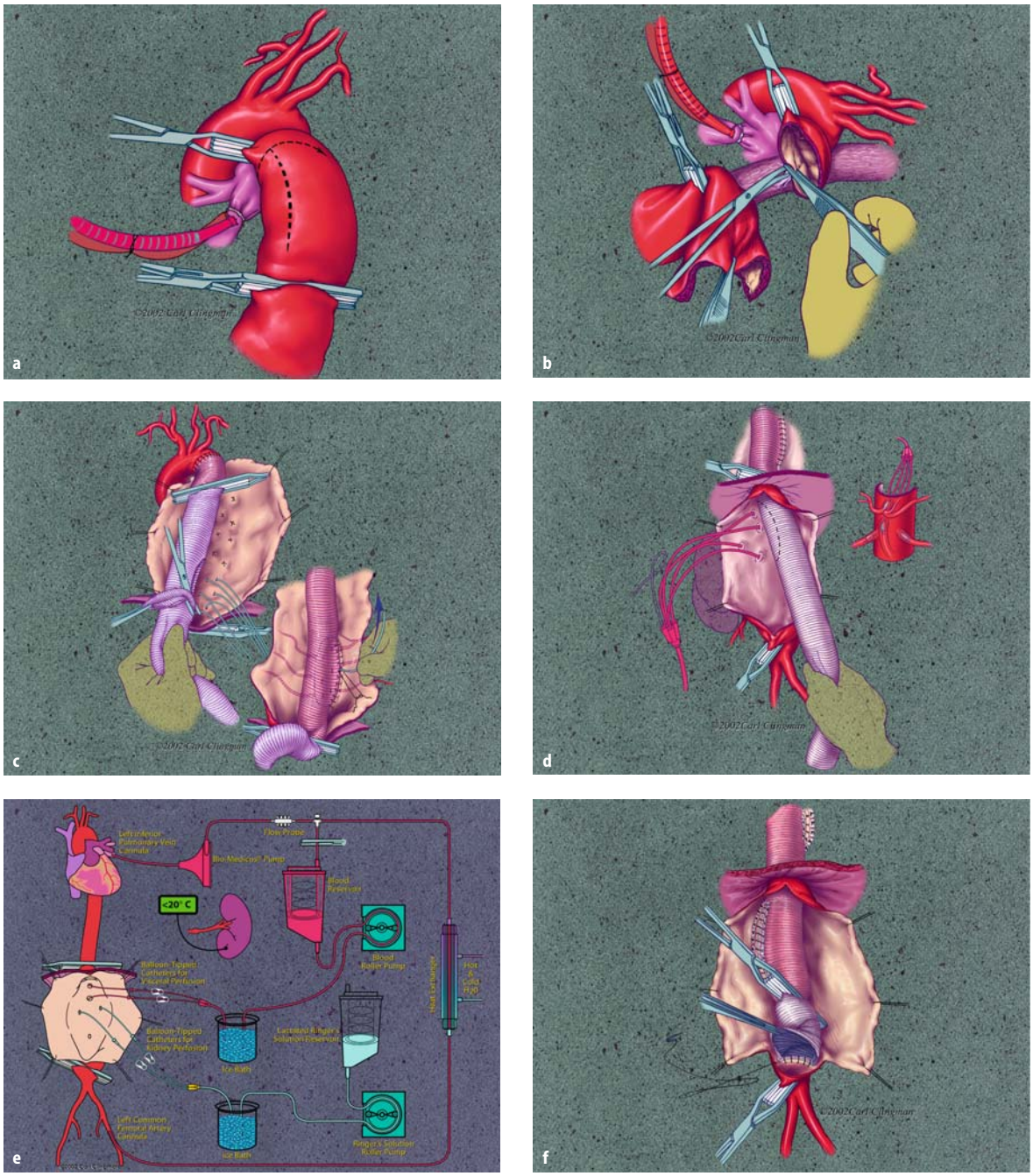


Fig. 13.7. a Application of the proximal and distal clamps in sequential clamping, and the proximal part of the aneurysm is opened. **b** The aorta is completely transected and separated from the esophagus. **c** An elliptical hole is cut in the graft, and the lower intercostal arteries are reattached as a patch to the graft. **d** The proximal clamp is placed beyond the intercostal anastomosis, and the distal clamp is on the distal infrarenal aorta. Catheters are inserted into the celiac, superior mesenteric, and renal arteries to permit perfusion. An elliptical hole is made in the graft for reimplantation of the visceral and renal arteries. **e** Integrated visceral perfusion and cooling circuit. Cold lactated Ringer's solution (4 °C) is used to cool the kidneys to approximately 15 °C, and the viscera is perfused with cold blood (4 °C). The lower extremities continue to be warmed. **f** Once the visceral and renal arteries have been reimplanted to the aortic graft, the proximal clamp is applied beyond this anastomosis, and the distal anastomosis is fashioned from a graft to the infrarenal aorta

major arterial blood supply to the spinal cord, takes its origin from one of the lower intercostal arteries (T9–T12) with or without additional collateral branches from nearby intercostal arteries. Reimplantation of intercostal arteries to the aortic graft therefore plays a critical role in spinal cord protection. Paradoxically before we began to use adjuncts, reattachment of intercostal arteries was shown to be a risk factor for postoperative neurological deficit, owing to the longer period of unprotected cross-clamp time required to perform this task. However, several years after implementing CSF drainage and distal aortic perfusion we studied the relationship of neurological deficits to ligation, reimplantation and preexisting occlusion of intercostal arteries in patients undergoing thoracoabdominal aortic repair. We found that ligation of patent lower intercostal arteries (T9–T12) increased the risk of paraplegia [23]. Therefore, we reattach all patent lower intercostal arteries from T9 to T12, either together as a patch to an elliptical side hole made in the Dacron graft or, if the intercostal arteries are too far apart, separately as buttons or using interposition bypass grafts (Fig. 13.7 c). Backbleeding from patent intercostal arteries can be minimized with temporary placement and inflation of balloon catheters (size 3F) prior to reimplantation. In general, we ligate the upper (above T8) intercostal arteries. If the lower intercostal arteries are occluded we reimplant the patent upper intercostal arteries, because these arteries may have assumed a critical collateral system to the anterior spinal artery. After completion of the intercostal reattachment, the proximal clamp is released from the aorta and reapplied onto the aortic graft below the intercostal patch, restoring pulsatile flow to the reattached intercostal arteries.

13.2.7 Visceral and Renal Perfusion

The distal clamp is moved onto the distal abdominal aorta below the renal arteries, the upper abdominal aortic aneurysm is opened and the walls are retracted, using 2-0 retraction sutures. The celiac, superior mesenteric and both renal arteries are identified and perfused through individual no. 9 or no. 12 Pruitt (Cryolife, St. Petersburg, FL, USA) catheters (Fig. 13.7 d). Currently, we perfuse the celiac and superior mesenteric arteries with cold blood. For the kidneys, an initial bolus of 300–800 mL of cold lactated Ringer's solution is infused into the left and right renal arteries, followed by additional periodic 100-mL aliquots as needed, to maintain renal temperature around 15 °C (Fig. 13.7 e). Renal temperature is monitored directly by inserting a temperature probe in the left renal cortex. The flow rate is approximately 200 and 150 mL/min for the renal and visceral arteries, respectively.

The aortic graft is passed through the aortic hiatus. A side hole is made in the graft and the visceral and renal arteries are reattached as an island. Alternatively, separate bypass grafts to the individual artery may be necessary if they are not in close proximity. Once the visceral anastomosis is completed, the clamp is moved down on the graft to restore the pulsatile flow to the viscera and renal arteries (Fig. 13.7 f). At this moment, the patient is given an injection of indigo carmine. The dye urinary clearance time is used as an indicator of

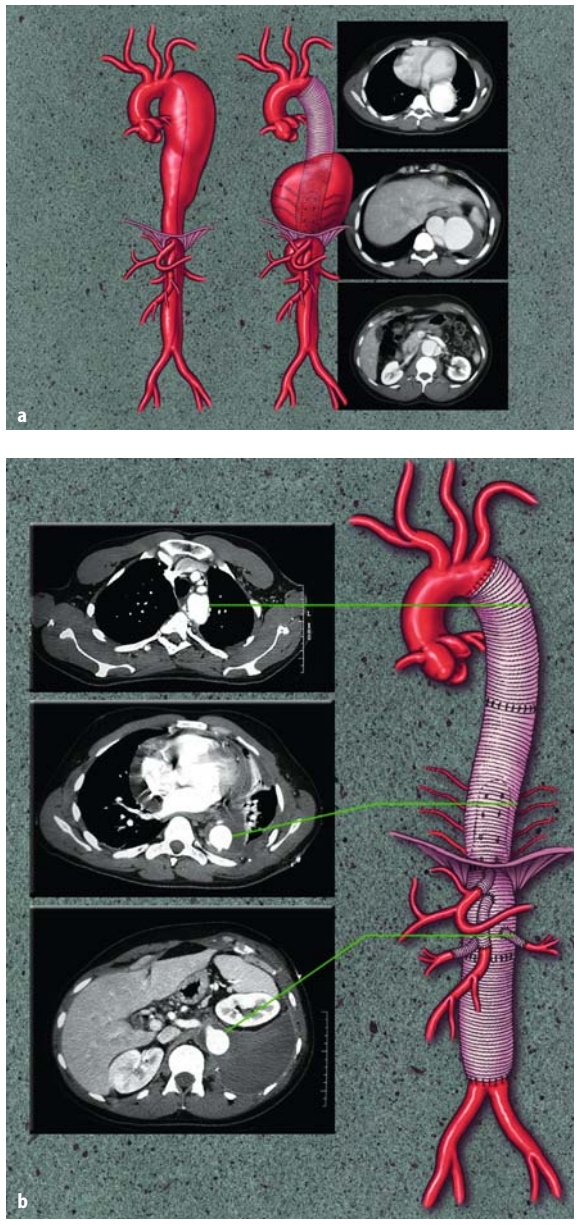


Fig. 13.8. a Example of a Marfan patient with descending thoracic aortic aneurysm (artist's illustration, *left*); this was repaired but he subsequently developed recurrent extent II thoracoabdominal aortic aneurysm (artist's illustration and preoperative computed tomography, *right*). **b** Completed repair of extent II thoracoabdominal aortic aneurysm (postoperative computed tomography and artist's illustration)

immediate postoperative renal function. The distal anastomosis is completed at the iliac bifurcation, using 3-0 or 2-0 polypropylene sutures (Fig. 13.7f). Prior to the completion of this anastomosis, we place the patient in the head-down position, and then flush the graft proximally and distally. When the anastomosis is completed, we release the clamp to restore pulsatile flow to the lower extremities.

When the distal extent of the aneurysm is below the renal arteries, the infrarenal abdominal aorta is clamped distally, if possible for the final anastomosis. Sometimes because of excessive aortic calcification or an overly large aorta, we clamp the left common iliac or external iliac artery. The reason for clamping the infrarenal or the left common or external iliac artery is that cooling of the kidneys and viscera can cause the patient's body temperature to drop precipitously, causing cardiac arrhythmias. Core body temperature is kept between 32 and 33 °C by warming the lower extremities. Alternatively, we stop the pump, open the infrarenal abdominal aorta and promptly sew the graft to the abdominal aorta above the iliac bifurcation. Once the distal anastomosis is completed, we clamp the graft and restart the pump. Pulsatile flow is promptly restored to the legs with completion of the final anastomosis, and the pump is restarted to continue warming the patient to a nasopharyngeal temperature of 36–37 °C. A representative example of an extent II thoracoabdominal aortic aneurysm repair is shown in Fig. 13.8.

13.3 Impact of Adjuncts on Outcome

Between 1991 and 2004, we performed repair of the descending thoracic and thoracoabdominal aorta in 1,106 patients [24]. Seven hundred five (64%) patients were men. The patient distribution was 215 (19.5%) for extent II and 891 (80.5%) for all others. The median age of all patients was 68 years (range, 8–92 years). Three hundred fifty-five (32%) patients were active smokers at the time of surgery. One hundred and eighteen (11%) patients suffered from cerebrovascular disease. Forty-five (4%) patients presented with acute dissection; 73 (6.6%) with rupture [25]. The adjuncts distal aortic perfusion and CSF drainage with moderate hypothermia were used in 823/1,106 (74%) patients. Four hundred thirty-six of 1,106 (39.4%) patients underwent intercostal artery reattachment. The overall 30-day mortality was 162/1,106 (14.6%) [25], and the 5-year survival rate was between 60 and 70%. Seventy percent of the patients recover from surgery without postoperative complications. Risk factors for mortality were advanced age, renal failure and paraplegia [26]. Remarkably, the use of adjunct distal aortic perfusion and CSF drainage was found to provide a beneficial effect on long-term survival (Fig. 13.9).

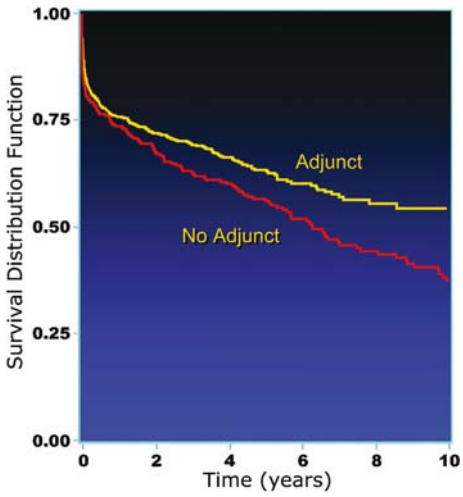
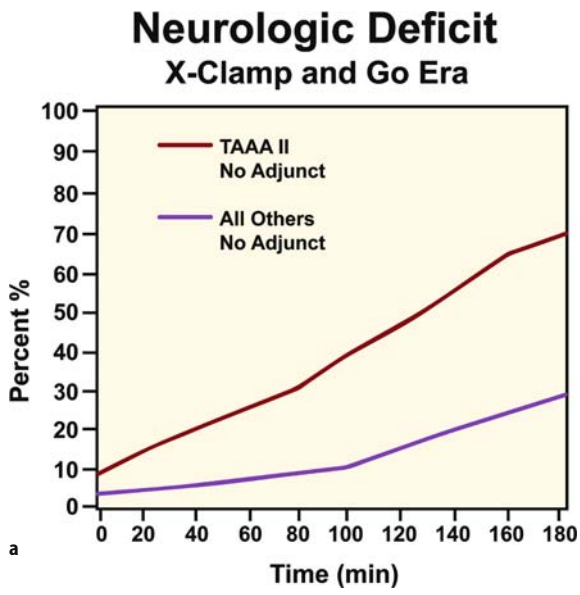


Fig. 13.9. Kaplan–Meier actuarial plot showing the beneficial 10-year survival effect of adjunct distal aortic perfusion and cerebrospinal fluid drainage (*yellow line*) compared with no adjunct (*red line*)

13.3.1 Neurological Deficit: Immediate and Delayed

In our cumulative experience, neurological deficit has been reduced by 3.7-fold with the combined adjunct distal aortic perfusion and CSF drainage [26]. The incidence of neurological deficit for all patients without the use of adjunct was 5.7%, and 2.4% with adjunct. Aortic cross-clamp times have increased significantly since 1991, yet the rate of neurologic deficit has declined in that time. Although other previously established risk factors remain significantly associated with neurologic deficit, aortic cross-clamp time is no longer associated to neurologic deficit (Fig. 13.10a, b). In the high-risk extent II, adjuncts reduced neurological deficit from 21 to 3.3% [24]. Clearly, the adoption of adjunct has impacted the overall incidence of neurological deficit, and this has led us to redefining the low versus high risk, as extent "non-II" versus extent II.

Interestingly, as improved spinal cord protection during thoracoabdominal aortic surgery has reduced the overall incidence of neurological complications, delayed-onset neurological deficit (the onset of paraplegia or paraparesis after a period of observed normal neurological function) has emerged as a significant clinical entity [2, 28]. We have observed delayed neurological deficit as early as 2 h and as late as 2 weeks following surgery. The exact mechanisms involved in the development of delayed neurological deficit remain unknown. However, we speculate that delayed neurological deficit after thoracoabdominal aortic repair may result from a "second hit" phenomenon [29]. That is, although adjuncts can protect the spinal cord intraoperatively and reduce the incidence of immediate neurological deficit, the spinal cord is still "vulnerable" during the early



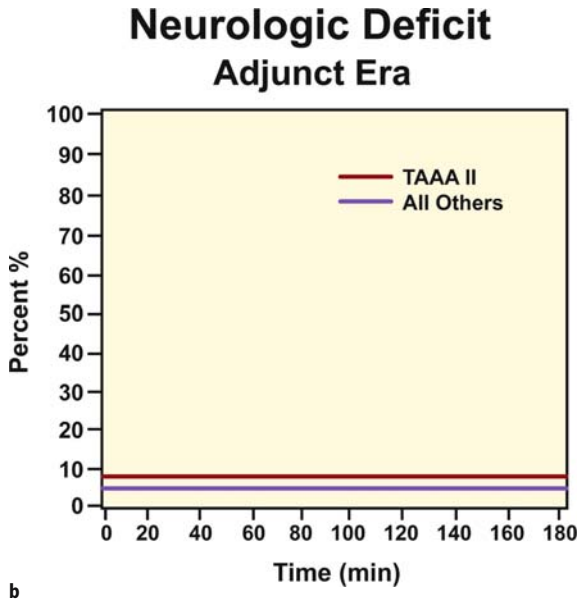


Fig. 13.10. Multiple logistic regression analyses according to risk of neurologic deficit and cross-clamp time without (**a**) and with (**b**) adjunct use

postoperative period. Additional ischemic insults, such as hemodynamic instability or malfunction of the CSF drainage catheter, may constitute a second hit, causing delayed neurological deficit. Furthermore, in the rigid unyielding spinal column, any rise in CSF pressure could lead to an increase in compartment pressure, with consequent decreased spinal cord perfusion. Hence, our reason for intermittent perioperative CSF drainage is to maintain the compartment pressure below 10 mmHg, and the same rationale applies to our approach using continuous CSF drainage in patients with delayed neurological deficits. In exploring other possible causes of delayed neurological deficit we have found no outstanding single risk factor. Using multivariable analyses, however, we have identified acute dissection, extent II and renal insufficiency as significant preoperative predictors for delayed-onset neurological deficit [30]. Postoperative clinical predictors of delayed neurological deficit include hemoglobin level less than 9 g/dL, mean arterial pressure less than 90 mmHg and CSF drain complications [31].

To optimize postoperative spinal cord perfusion and oxygen delivery, we keep the mean arterial pressure above 90–100 mmHg, hemoglobin above 10 mg/dL and cardiac index greater than 2.0 L/min. If delayed neurological deficit occurs, measures to increase spinal cord perfusion are instituted immediately. The patient is placed flat in the supine position and patency and function of the drain is ascertained at once. If the drain has been removed, the CSF catheter is reinserted immediately and CSF is drained freely until the CSF pressure drops below 10 mmHg. The systemic arterial pressure is raised, blood transfusion is liberally infused and oxygen saturation is increased, as indicated earlier. CSF drainage is continued for at least 72 h for all patients with delayed-onset neurological deficit. Using this approach, we have seen improvement in neurological function in 57% of our patients [30]. Patients who developed delayed neurological deficit but did not have CSF drainage failed to recover function.

13.3.2 Renal Failure

We have used and appraised many different forms of renal protection. including distal aortic perfusion, warm blood visceral perfusion, antegrade cold blood visceral perfusion, retrograde cold blood perfusion and the perioperative use of a renal protective pharmacologic agent, fenoldopam. None of these yielded overly promising results. Using multivariable analyses, we found preoperative renal failure (creatinine above 2.8 g/dL), left renal artery reattachment, visceral perfusion and clamp-and-go technique as predictors of acute renal failure [32]. In the past, we had used visceral perfusion without cooling and without systemic heparin, and this was likely the reason for the negative effect of visceral perfusion on renal protection. We recently reviewed the impact of various adjuncts on renal function. Distal aortic perfusion has emerged as protective, but only for aortic repair that does not directly involve the renal arteries. There is evidence, however, that patients treated with cold blood visceral perfusion have superior survival and recovery rates, and this may be related to improved liver protection. None of the adjuncts thus far evaluated have clearly prevented acute renal failure. The major predictors of postoperative renal dysfunction re-

main preoperative renal function, cross-clamp time and repair extending to the renal arteries. In our cumulative experience of descending thoracic and thoracoabdominal aortic repairs, we found that acute renal failure occurred in 17.8% of our patients overall. The incidence for descending thoracic repairs was 7.2% and 22.8% for thoracoabdominal aortic repairs. Thirty-day mortality among patients with acute renal failure was 30% compared with 10% mortality for all other patients. Although we had theorized that patients with the most extensive thoracoabdominal aortic aneurysm (extent II) would be at highest risk for the development of postoperative renal failure, multivariable analyses did not find aneurysm extent to be a significant predictor. Approximately one third of our patients who developed acute renal failure remained on hemodialysis, and long-term survival for patients on hemodialysis has been dismal.

13.3.3 Aortic Dissection

During the clamp-and-go era, aortic dissection was considered a risk factor for neurological deficit in patients undergoing surgery of the thoracoabdominal aorta [18]. With the use of distal aortic perfusion and CSF drainage, however, chronic dissection no longer poses a threat [33]. We recently showed similar low rates of paraplegia for patients who received adjuncts when undergoing thoracoabdominal aortic surgery, whether they had aortic dissection or not, 3.6% versus 4.7%, respectively. However, various surgical technical modifications are required in repairing dissected thoracoabdominal aorta, particularly in the acute phase. Identification of the true versus the false lumen is imperative. The partition/septum between the two lumens is excised (Fig. 13.11a). Before sewing the graft, we usually reinforce both proximal and distal ends of the dissected aorta with a running 4-0 polypropylene suture. Additional interrupted pledgeted polypropylene sutures are then placed in the posterior and anterior walls for further reinforcement (Fig. 13.11b). Whereas we always attempt to reattach patent lower intercostal arteries during graft replacement of the descending thoracic and thoracoabdominal aorta, we advocate ligation of all patent intercostal and lumbar arteries in the acutely dissected aorta, to avoid catastrophic bleeding associated with the friable tissues. Patent lower intercostal arteries can be safely reattached in chronic dissection using our described technique. In general, we replace all aneurysmal aortic segments, but leave the nonaneurysmal segment even if dissected.

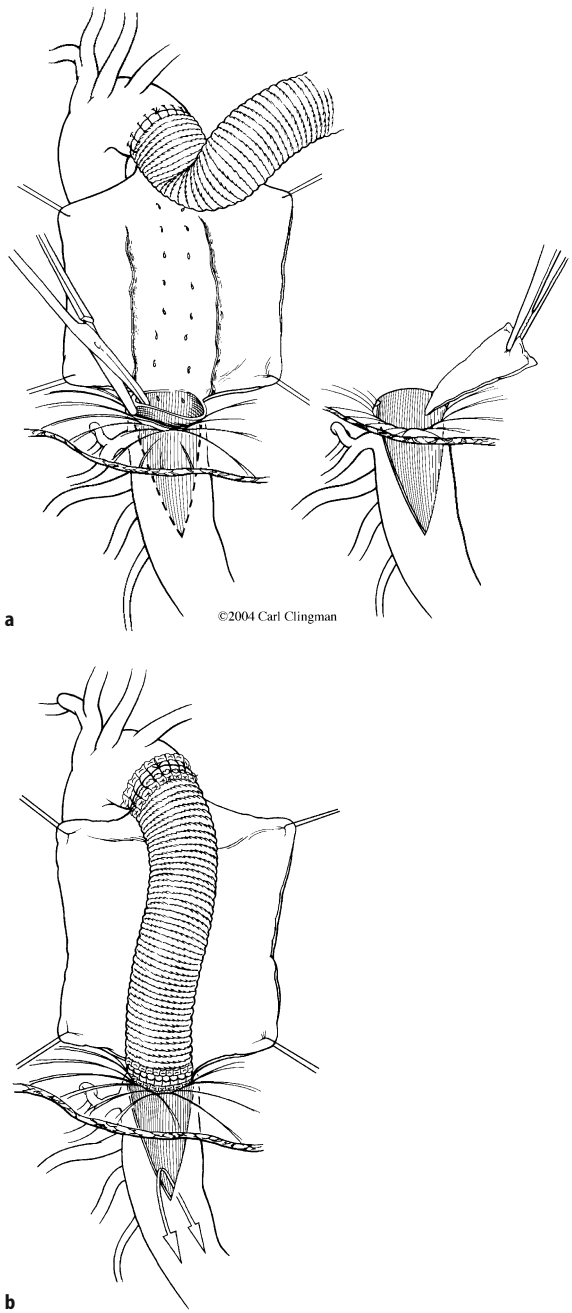


Fig. 13.11. Illustration of a thoracoabdominal aortic aneurysm repair showing excision of the distal partition/septum between the true and false lumens, and completed graft replacement with reinforced anastomoses

13.4 Summary

Incredible progress has been made in the treatment of thoracoabdominal aortic aneurysms since its inception. The various strategies of organ protection including the use of distal aortic perfusion, CSF drainage, visceral

perfusion, sequential aortic cross-clamp, intercostal artery reattachment and moderate hypothermia, as well as the evolution of surgical approach have all contributed to the decline in mortality and morbidity. Our refined surgical techniques and use of adjuncts have reduced the overall incidence of neurological deficits following thoracoabdominal aortic aneurysm repair to 2.4%, and to 6.6% for patients with extent II. Our continuing goals are to further decrease the incidence of neurological deficits and to improve renal protection, with particular focus on the extent II thoracoabdominal aortic aneurysm.

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References

1. Etheredge S, Yee J, Smith J, et al. Successful resection of a large aneurysm of the upper abdominal aorta and replacement with homograft. Surgery 1955; 138:1071–1081.
2. De Bakey ME, Creech O Jr, Morris GC Jr. Aneurysm of the thoracoabdominal aorta involving the celiac, mesenteric and renal arteries. Report of four cases treated by resection and homograft replacement. Ann Surg 1956; 179:763–772.
3. Matas R. An operation for the radical cure of aneurysm based upon arteriorrhaphy. Ann Surg 1903; 37:161–196.
4. Carrell A. Results of the transplantation of blood vessels, organs and limbs. JAMA 1908; 51:1662–1667.
5. Creech O Jr. Endo-aneurysmorrhaphy and treatment of aortic aneurysm. Ann Surg 1966; 164:935–946.
6. Connolly JE, Wakabayashi A, German JC, Stemmer EA, Serres EJ. Clinical experience with pulsatile left heart bypass without anticoagulation for thoracic aneurysms. J Thorac Cardiovasc Surg 1971; 62:568–576.
7. Korompai F, Hayward R. Preservation of visceral perfusion during resection of thoracoabdominal aortic aneurysm. Cardiovasc Dis Bull Tex Heart Inst 1975; 2:349.
8. Crawford ES. Thoraco-abdominal and abdominal aortic aneurysms involving renal, superior mesenteric, celiac arteries. Ann Surg 1974; 179:763–772.
9. Cunningham JN Jr, Laschinger JC, Merkin HA, et al. Measurement of spinal cord ischemia during operations upon the thoracic aorta: initial clinical experience. Ann Surg 1982; 196:285–296.
10. Laschinger JC, Cunningham JN J, Nathan IM, Knopp EA, Cooper MM, Spencer FC. Experimental and clinical assessment of the adequacy of partial bypass in maintenance of spinal cord blood flow during operations of the thoracic aorta. Ann Thorac Surg 1983; 36:417–426.
11. Crawford ES, Mizrahi EM, Hess KR, Coselli JS, Safi HJ, Patel VM. The impact of distal aortic perfusion and somatosensory evoked potential monitoring on prevention of paraplegia after aortic aneurysm operation. J Thorac Cardiovasc Surg 1988; 95:357–367. Erratum in: J Thorac Cardiovasc Surg 1989; 97:665.
12. McCullough J, Hollier L, Nugent M. Paraplegia after thoracic aortic occlusion: influence of cerebrospinal fluid drainage. Experimental and early clinical results. J Vasc Surg 1988; 7:153–160.
13. Crawford ES, Svensson LG, Hess KR, et al. A prospective randomized study of cerebrospinal fluid drainage to prevent paraplegia after high-risk surgery on the thoracoabdominal aorta. J Vasc Surg 1991; 13:36–45; discussion 45–46.
14. Crawford ES, Crawford JL, Safi HJ, et al. Thoracoabdominal aortic aneurysms: preoperative and intraoperative factors determining immediate and long-term results of operations in 605 patients. J Vasc Surg 1986; 3:389–404.
15. Crawford ES, Coselli JS, Safi HJ. Partial cardiopulmonary bypass, hypothermic circulatory arrest, and posterolateral exposure for thoracic aortic aneurysm operation. J Thorac Cardiovasc Surg 1987; 94:824–827.
16. Kouchoukos NT, Daily BB, Rokkas CK, Murphy SF, Bauer S, Abboud N. Hypothermic bypass and circulatory arrest for operations on the descending thoracic and thoracoabdominal aorta. Ann Thorac Surg 1995; 60:67–76; discussion 76–77.
17. Cambria R, Davison J, Zannetti S, et al. Clinical experience with epidural cooling for spinal cord protection during thoracic and thoracoabdominal aneurysm repair. J Vasc Surg 1997; 25:241–243.
18. Svensson LG, Crawford ES, Hess KR, Coselli JS, Safi HJ. Experience with 1509 patients undergoing thoracoabdominal aortic operations. J Vasc Surg 1993; 17:357–368; discussion 368–370.
19. Safi HJ, Hess KR, Randel M, et al. Cerebrospinal fluid drainage and distal aortic perfusion: reducing neurologic complications in repair of thoracoabdominal aortic aneurysm types I and II. J Vasc Surg 1996; 23:223–228; discussion 229.
20. Safi HJ, Bartoli S, Hess KR, et al. Neurologic deficit in patients at high risk with thoracoabdominal aortic aneurysms: the role of cerebral spinal fluid drainage and distal aortic perfusion. J Vasc Surg 1994; 20:434–444; discussion 442–443.
21. Engle J, Safi HJ, Miller CC 3rd, et al. The impact of diaphragm management on prolonged ventilator support after thoracoabdominal aortic repair. J Vasc Surg 1999; 29:150–156.
22. Huynh TT, Miller CC 3rd, Estrera AL, Sheinbaum R, Allen SJ, Safi HJ. Determinants of hospital length of stay after thoracoabdominal aortic aneurysm repair. J Vasc Surg 2002; 35:648–653.
23. Safi H, Miller CI, Carr C, Illiopoulos D, Dorsay D, Baldwin J. The importance of intercostal artery reattachment during thoracoabdominal aortic aneurysm repair. J Vasc Surg 1998; 27:58–68.
24. Safi HJ, Estrera AL, Miller CC 3rd, Huynh TT, Porat EE, Azizzadeh A, Meada R, Goodrick JS. Evolution of risk for neurologic deficit after descending and thoracoabdominal aortic repair. Ann Thorac Surg 2005; 80:2173–2179.
25. Huynh TT, van Eps RG, Miller CC 3rd, Villa M, Estrera AL, Azizzadeh A, Porat EE, Goodrick JS, Safi HJ. Evolution of risk for neurologic deficit after descending and thoracoabdominal aortic repair. J Vasc Surg 2005; 42:206–212.
26. Safi HJ, Miller CC 3rd, Huynh TTT, et al. Distal aortic perfusion and cerebrospinal fluid drainage for thoracoabdominal and descending thoracic aortic repair: Ten years of organ protection. Ann Surg 2003; 238:372–381.
27. Safi HJ, Miller CC 3rd, Azizzadeh A, Iliopoulos DC. Observations on delayed neurologic deficit after thoracoabdominal aortic aneurysm repair [see comments]. J Vasc Surg 1997; 26:616–622.
28. Azizzadeh A, Huynh TT, Miller CI, Safi H. Reversal of twice-delayed neurologic deficits with cerebrospinal fluid drainage after thoracoabdominal aneurysm repair: a case report and plea for a national database collection. J Vasc Surg 2000; 31:592–598.

29. Huynh TT, Miller CC 3rd, Safi HJ. Delayed onset of neurologic deficit: significance and management. Semin Vasc Surg 2000; 13:340–344.
30. Estrera AL, Miller CC 3rd, Huynh TT, Azizzadeh A, Porat EE, Vinnerkvist A, Ignacio C, Sheinbaum R, Safi HJ. Preoperative and operative predictors of delayed neurologic deficit following repair of thoracoabdominal aortic aneurysm. J Thorac Cardiovasc Surg 2003; 126:1288–1294.
31. Azizzadeh A, Huynh TTT, Miller CC 3rd, et al. Postoperative risk factors for delayed neurologic deficit after thoracic and thoracoabdominal aortic aneurysm repair: a case-control study. J Vasc Surg 2003; 37:750–754.
32. Safi HJ, Harlin SA, Miller CC, et al. Predictive factors for acute renal failure in thoracic and thoracoabdominal aortic aneurysm surgery. J Vasc Surg 1996; 24:338–344; discussion 344–345. Erratum in: J Vasc Surg 1997; 25:93.
33. Safi HJ, Miller CC 3rd, Estrera AL, et al. Chronic aortic dissection not a risk factor for neurologic deficit in thoracoabdominal aortic aneurysm repair. Eur J Vasc Endovasc Surg 2002; 23:244–250.

Femoral Bypass and Hypothermia for the Treatment of Thoracoabdominal Aneurysms

R. Scott Mitchell

14

Contents

14.1 Introduction

Aneurysms of the descending thoracic and thoracoabdominal aorta range from focal outpouchings of the thoracic aorta to extensive degenerative aneurysms encompassing the entire thoracoabdominal aorta. Similarly, treatment strategies range from simple clamp techniques, unsupported by distal perfusion, the "clamp-and-go" technique, to more complex techniques utilizing distal perfusion, separate visceral perfusion, and hypothermia as an adjunct for preservation of spinal cord function. This treatise advances our rationale for a more aggressive perfusion strategy that affords optimal protection for CNS, spinal cord, and abdominal viscera.

Although the simplicity of a clamp-and-go approach is attractive, there are severe perturbations that argue against its utility. Proximal clamping of the descending thoracic aorta or distal arch presents several major difficulties. First, in many instances with diffuse atheromatous change, clamping of the distal arch may be unsafe, with central embolization of atheromatous debris into the cerebral vasculature. Second, proximal clamping may not afford sufficient normal proximal aorta to allow a secure proximal anastomosis. Third, proximal clamping also produces severe hemodynamic disturbances, including proximal hypertension, an abrupt increase in afterload, a decrease in distal perfusion pressure, and an increase in cerebrospinal fluid (CSF) pressure [1]. In addition to a profound sympathetic stimulation, there is also requisite distal ischemia, with secondary and injurious metabolic changes, increasing the likelihood for spinal cord and visceral end-organ injury. Similarly, with the release of the aortic cross-clamp, further hemodynamic perturbations are again produced, many of which will aggravate a previous insult, including proximal hypotension, washout of ischemic metabolites, and reperfusion injury, all compounding the effects of the prior ischemic injury.

Distal aortic perfusion techniques may substantially reduce many of these ill effects, albeit at the price of introducing negative attributes essential for extracorporeal perfusion, including anticoagulation, stimulation of the inflammatory response, and alterations in coagulation.

In the absence of distal aortic perfusion, the technique of simple aortic clamping is limited to a "safe ischemic period," unpredictable, and likely highly variable for different vascular beds. Historically, spinal cord complications have been noted to rise significantly after 30–35 min of ischemia, with similar end-organ dysfunction becoming apparent after slightly longer ischemic intervals for kidneys and liver. In an effort to minimize these secondary perturbations, distal perfusion techniques have been developed to allow longer periods of ischemia and more complex reconstructions [2]. It is our contention that femoral–femoral bypass provides a stable operative environment, facilitates surgical reconstruction, provides good end-organ preservation, and affords valuable flexibility for improved surgical results, with only modest negative repercussions.

14.2 Operative Strategies

A thorough preoperative assessment, including physical examination, assessment of physiologic cardiac, pulmonary, and renal reserve, and scrutiny of available imaging modalities precedes operative intervention. Surgical as well as perfusion strategies are then decided.

The major downside of femoral–femoral bypass is the necessity for full heparinization as a membrane oxygenator is an integral part of the perfusion circuit. Usually 300 IU/kg is sufficient to maintain an activated clotting time of more than 400 s. Fully heparin coated circuitry may allow a lower systemic heparin level, usually 100 IU/kg heparin and an activated clotting

time of more than 180 s. Although expensive, fully coated circuitry may be associated with less blood loss, reduced transfusion requirements, and perhaps a decrease in the systemic inflammatory response. Similarly, the use of aprotinen (Trasolol, Bayer Pharmaceuticals) has been associated with decreased blood loss and a decreased requirement for transfusion products, but requires ascertainment of adequate heparin effect, namely a Kaolin-determined activated clotting time of more than 400 s, and a heparin concentration of more than 3.5 mg/kg.

The major advantage of femoral–femoral bypass is flexibility. For thoracic or thoracoabdominal aneurysms in which the distal arch is unsuitable for clamping (large diameter, severe calcification, intraluminal atherogenic debris, proximal extension of dissection flap), hypothermic circulatory arrest (HCA) is the method of choice for constructing a secure proximal anastomosis and avoiding cerebral atheroembolic injury. Similarly, for patients in whom sequential cross-clamping of the aorta is not possible (chronic dissection, large mural thrombus, or generalized aneurysmal enlargement without focal narrowing), HCA is an excellent method of spinal cord protection, coupled with distal aortic perfusion and CSF drainage [3–5]. The oxygenator also adds flexibility, such as with the patient with poor oxygenation who may become a ventilatory problem during single lung ventilation.

14.3 Methods

Preoperatively, an epidural catheter and a CSF drain are placed prior to operative intervention. Full intraoperative monitoring is employed, including radial and femoral artery pressure monitoring, large-bore intravenous access, and transesophageal echo (TEE). A double-lumen endotracheal tube facilitates operative exposure and minimizes operative trauma to the left lung. Both femoral arterial and venous access are attained via an oblique supra-inguinal crease incision.

Long, flexible, thin-walled venous catheters are available with tapered over-the-wire dilators that almost uniformly assure access to the right atrium. Endovascular access through the femoral vein can be ascertained by TEE visualization of the guide wire emerging from the inferior vena cava, traversing the right atrium, and entering the superior vena cava. If passage of a soft "J"-tipped guide wire is not successful, a floppy-tip Glidewire (Terumo, Tokyo, Japan) and a Benson catheter frequently assure passage.

Arterial cannulation is either via a transverse arteriotomy with a 22-F arterial catheter, or over a guide wire using a 17-F or a 19-F catheter (DLP).

Successful cannulation is assured by easy aspiration of venous blood from the venous catheter, and pulsatile flow from the arterial catheter with a pulsatile wave form in the cardiopulmonary bypass pump circuitry.

Full thoracoabdominal exposure is attained in the routine manner. Proximally, the distal arch and proximal descending thoracic aorta are circumferentially dissected, with careful sharp dissection of the phrenic, vagus, and recurrent laryngeal nerves. After careful palpation, inspection, and perhaps interrogation by transesophageal echocardiography, and/or epiaortic ultrasound, a decision is made whether the aorta can be safely clamped to allow a secure proximal anastomosis. If not, femoral–femoral bypass is used to cool the patient to 16–18 °C, and an open proximal anastomosis is constructed to the full-thickness divided aorta of normal caliber. Great care is taken to prevent any atheromatous debris from falling into the dependent aortic arch, and retrograde cerebral perfusion through the long venous cannula can be used as a partial flush of the arch vessels. Following completion of the anastomosis, the new graft is cannulated and clamped distally, and retrograde arterial perfusion of the heart and great vessels is resumed.

If retrograde perfusion from the femoral artery is thought to entail significant risk for retrograde embolization, separate antegrade cerebral perfusion can be performed from a previously placed 6-mm Dacron side limb sewn to the left common carotid artery established prior to thoracotomy.

If the aorta is focally narrowed so as to allow sequential cross-clamping, then that is done serially down the aorta, allowing retrograde femoral perfusion to provide visceral perfusion until that aortic segment is opened. Initially, a distal clamp at mid-chest allows retrograde perfusion of critical intercostal arteries. Then, clamping just above the celiac axis allows identification of large paired intercostals at the T8–T12 level which need to be attached to the graft. Decision-making about which arteries to reattach is guided by the identification of the anterior spinal artery on computed tomography or magnetic resonance imaging [6, 7], loss of either evoked sensory or motor potentials, and by their general suitability at the time of operation. It should be noted that while hypothermia is an excellent adjunct for spinal cord protection, it also effectively silences neural response, thus limiting the utility of either evoked sensory or motor potentials.

After attachment of the intercostal artery pairs, attention is directed toward the visceral vessels, which are now individually cannulated with balloon-tipped perfusion catheters and perfused with cold blood. Depending on the local anatomy, and the quality of this portion of the aorta, this reconstruction may utilize the island technique, frequently incorporating the celiac axis, superior mesenteric artery, and right renal artery as one button, and the left renal artery as a second button. Alternatively, if the quality of the aortic tissues is poor, individual grafts may be led separately to each visceral

vessel orifice. Preloading short Dacron graft segments on the balloon catheters prior to initiating perfusion greatly facilitates this reconstruction, and minimizes visceral ischemic time.

Distally, after exposure of the aorta in the retroperitoneal plane, the distal end point is determined, and the aorta is again circumferentially dissected.

Again, if this can be safely clamped, and a secure anastomosis obtained, then distal aortic perfusion is used distal to the aortic clamp. If a satisfactory length of normal aorta is not available, then distal perfusion is temporarily discontinued, and an open distal full-thickness anastomosis is constructed.

The beauty of hypothermia is that it allows the safe conduct of these multiple previous maneuvers for all patients, regardless of the extent of aortic disease, and without the risk of atheroembolization. Cardiopulmonary bypass is initiated, and the proximal and distal dissection completed while cooling proceeds to 16–18°C, with assurance of EEG silence. After equilibration of a core temperature of 16–18 °C for at least 5 min, cardiopulmonary bypass is discontinued in the head-down position, and retrograde perfusion through the venous catheter is commenced at approximately 500 ml/min to continuously flush the cerebral vasculature. The aneurysm is incised to the level of the renal arteries, and visceral artery perfusion is instigated with balloon-tipped catheters. The proximal aorta is transected to allow construction of a full-thickness anastomosis to normal aorta, after which the graft is then cannulated, clamped distally, and retrograde arterial perfusion established to cardiac and brachiocephalic vessels. Next, selective intercostal artery reimplantation is effected to large patent intercostal arteries in the critical zone. Preoperative localization of contributing intercostal pairs to the anterior spinal artery can be obtained with computed tomographic or magnetic resonance imaging. Excellent spinal cord protection is afforded during this interval by generalized hypothermia and perfusion of collaterals from the left vertebral and hypogastric systems.

The paravisceral aorta is then assessed. For good-quality aorta in the absence of connective tissue disease, aortic island reconstruction is effected, usually with the celiac axis, superior mesenteric artery, and right renal artery as one island, and the left renal artery as a separate full-thickness button. Alternatively, especially for Marfan patients in whom aneurysmal dilation of the visceral island has been noted, individual branch vessel reconstruction with 6-, 8-, or 10-mm Dacron grafts can be accomplished during continuous perfusion via balloon-tipped catheters. An open distal anastomosis is then completed, allowing restoration of femoral perfusion after clamping of the graft. Individual visceral branch vessel grafts can then be reimplanted into the central aorta graft between clamps, allowing continuous perfusion of cardiac, cerebral, and intercostal arteries, and pelvic circulation during reimplantation and warming. Visceral ischemic time is limited to the time necessary to reimplant Dacron side limbs into a central aortic graft, and its effect is minimized by the now regional hypothermia.

Although full heparinization is necessary, cardiac, central nervous system, and spinal cord protection is assured, and the hepatic contribution to postoperative coagulation is preserved by hypothermia and continuous perfusion.

Although there is a requirement for full heparinization in order to use an oxygenator, this coagulopathy may be more than offset by avoiding the use of reinfused washed red cells, with their own inherent coagulopathic tendencies. Integrity of all anastomoses can be easily assured during the period of rewarming, and the patient can then be weaned from cardiopulmonary bypass. Although a somewhat prolonged cardiopulmonary bypass run may be necessary, especially in the obese patient, good end-organ preservation is assured, and the risk of atheroembolism minimized. With more target-specific anticoagulation, coagulopathies secondary to a prolonged cardiopulmonary bypass run can be minimized, and excellent end-organ preservation can be achieved by these techniques.

References

1. Gelman S. The pathophysiology of aortic cross-clamping and unclamping. Anesthesiology 1995; 82:1026–1060.
2. Von Segesser LK, Killer I, Jenni R, et al. Improved distal circulatory support for repair of descending thoracic aortic aneurysms. Ann Thor Surg 1993; 56:1373–1380.
3. Kouchoukos NT, et al. Hypothermic cardiopulmonary bypass and circulatory arrest for operations on the descending thoracic and thoracoabdominal aorta. Ann Thorac Surg 2002; 74:S1885–1887.
4. Colon R, et al. Hypothermic regional perfusion for protection of the spinal cord during periods of ischemia. Ann Thor Surg 1987; 43:639–643.
5. Robertson CS, et al. Protection against experimental ischemic spinal cord injury. J Neurosurg 1986; 64:633–642.
6. Kawaharada N, et al. Thoracoabdominal or descending aortic aneurysm repair after preoperative demonstration of the Adamkiewicz artery by magnetic resonance angiography. Eur J Cardiothorac Surg 2002; 21:970–974.
7. Jacobs MT, et al. Spinal cord blood supply in patients with thoracoabdominal aortic aneurysms. J Vasc Surg 2002; 35:30–37.

Branch Stent-Graft Systems and Less Invasive Combined Surgical and Endovascular Treatment for Descending Thoracic Aortic Aneurysms

Krassi Ivancev, Bansi Koul

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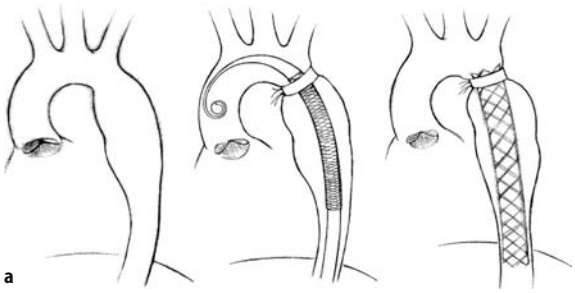
Contents

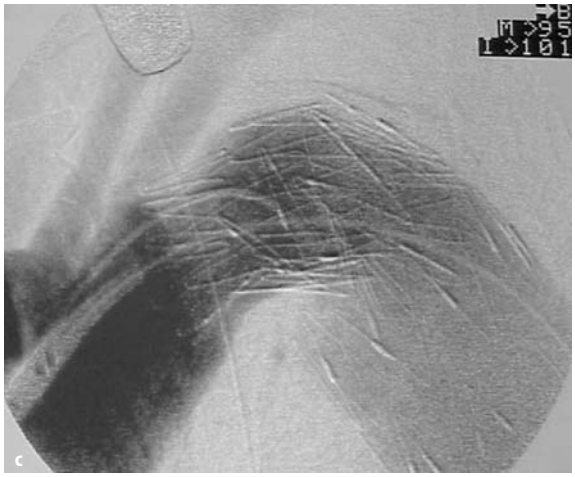
15.1 Introduction

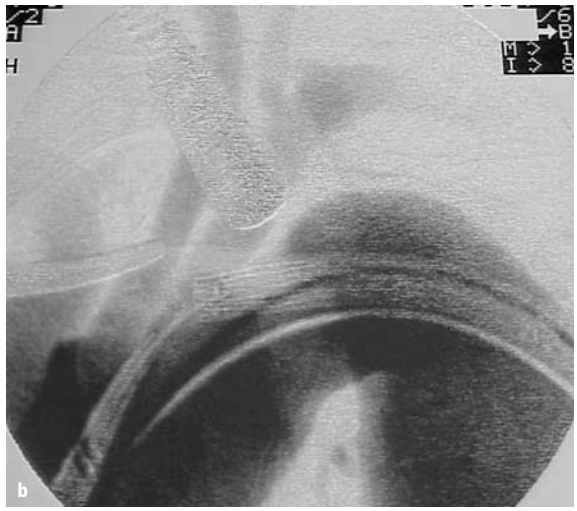
Endovascular aneurysm repair (EVAR) in the thoracic aorta has repeatedly been shown to offer advantages over open surgery thanks to its less traumatic nature. However, EVAR is limited by the absolute requirement of an adequate landing zone at least 15 mm in length in order to provide successful exclusion of an aneurysm or a dissection. In addition, the landing zone may need to be even longer when it comes to aneurysms and/or dissections in the aortic arch, where currently available stent-grafts do not provide an effective hemostatic seal owing to their relatively high rigidity [1]. For these patients, the alternative is conventional total aortic arch replacement using hypothermic extracorporeal circulation, which, in spite of recent improvements, continues to be associated with considerable mortality and the risk of cerebral complications, especially in patients with severe comorbidities. Therefore, combining the advantages of EVAR and various types of open vascular surgery may offer a valuable alternative for this category of patients.

15.2 Elongation of the Landing Zone in the Aortic Arch

In patients with symptomatic type B dissections or aneurysms in the aortic arch, it is not uncommon to cover the left subclavian artery as a means of prolonging the landing zone and thereby achieving a secure hemostatic seal for a stent-graft. However, such a maneuver may not be sufficient. The stent-graft may need to be placed further cephalad and may cover the left carotid artery as well. In order to provide continuous flow to the blocked vessels an extraanatomic bypass from the innominate artery to the left carotid and left subclavian arteries may be performed. Such a technique has been shown to be safe and efficient [2]. Occasionally, though, currently available stent-grafts may not line up along a severely angulated aortic arch with a persistent type I endoleak as a result [1]. Under these circumstances it may be advisable to place a band of Teflon felt around the aortic arch once the stent-graft is in place (Fig. 15.1). This is achieved through a minimal median sternotomy. The same access may also be used for supraaortic transposition with a bi- or trifurcated graft originating from the ascending aorta and anastomosing to the innominate artery, the left carotid artery, and the left subclavian artery [3, 4]. This is achieved without hypothermic cardiopulmonary arrest and using a side-clamp in the ascending aorta. With such an approach the trauma is kept to a minimum, avoiding total arch replacement or left thoracotomy. If a bypass is performed to the innominate artery the stent-graft may be extended across the origin of all the supraaortic vessels (Fig. 15.2).







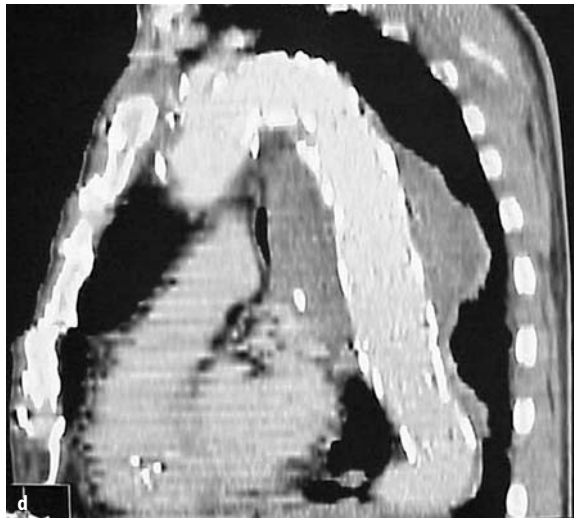


Fig. 15.1. **a** Schematic drawing representing placement of a band distal to the left subclavian artery in order to create a secure implantation site for a stent-graft. **b** Aortogram during placement of the stent-graft showing indentation from the band placed in the aortic arch. **c** Aortogram following deployment of the stent-graft showing a good hemostatic seal. **d** Computed tomography (*CT*) 6 months after stent-graft placement showing a well-excluded aneurysm

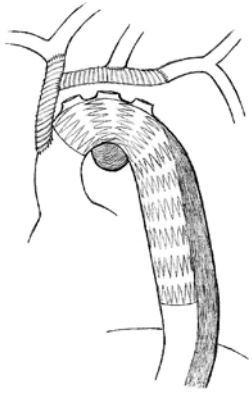


Fig. 15.2. Schematic drawing showing a supraaortic transposition using a trifurcated graft anastomosed to the ascending aorta and further to the innominate, left carotid, and left subclavian arteries. The stent-graft is placed across the aortic arch excluding an aneurysm and a type B dissection

15.3 Total Arch Replacement with Open Stent-Graft Placement

This technique is recommended when concomitant heart surgery is performed, including coronary bypass, graft replacement with or without aortic valve remodeling in the ascending aorta due to aneurysm formation or type A dissection, or when there is a type A dissection continuing into the descending thoracic aorta [5, 6, 7]. In these situations a stent-graft may be placed from the distal aortic arch under hypothermic cardiopulmonary arrest and guided either fluoroscopically or by transesophageal echography. The proximal end of the stent-graft is then sutured to the posterior wall of the aorta and possibly attached to a graft used for aortic arch replacement (Fig. 15.3). There is also a possibility to use a "stented elephant trunk" in the case of an an-

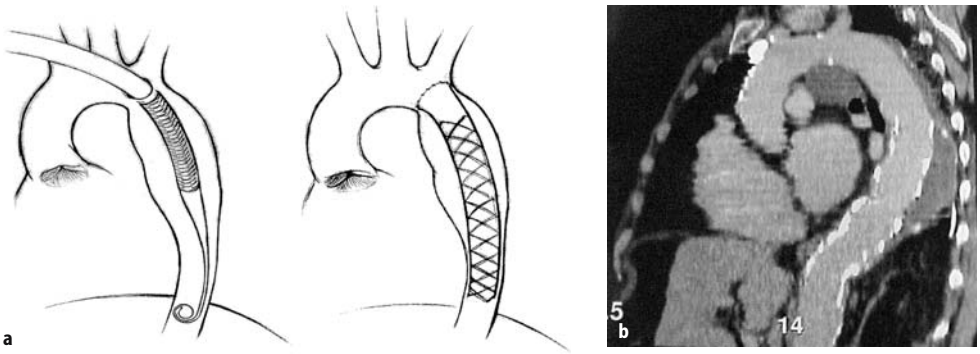


Fig. 15.3. a Schematic drawing showing an open stent-graft placement from the distal aortic arch. **b** CT showing a stent-graft anastomosed to the aortic arch, thereby excluding the aneurysm in the aortic arch and in the distal thoracic aorta

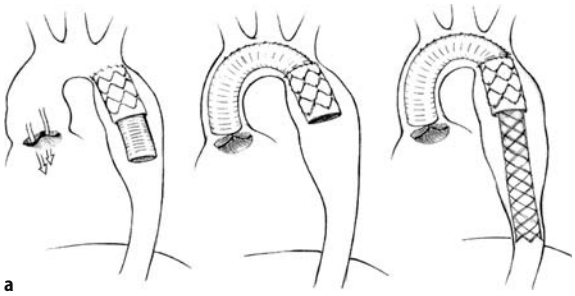
eurysm in the descending thoracic aorta [8, 9] (Fig. 15.4). The portion of the stent-graft that is free from stents is then used for the reconstruction of the aortic arch. The stented elephant trunk provides an excellent landing zone for a subsequent stent-graft placement through a femoral access. If there is no suitable landing zone in the diaphragmatic portion of the descending aorta Teflon felt may be placed as a band at this level by gaining access to the diaphragmatic portion of the descending aorta through the pericardium (Fig. 15.4). According to the results reported in the literature this open stent-graft placement under hypothermic cardiopulmonary arrest is associated with a risk, however low, of permanent spinal cord injury, i.e., paraplegia [10]. Although the causes are multifactorial, a possible way of minimizing the risk for such a complication may be to use a relatively short stented elephant trunk or stent-graft, i.e., not longer than 10–15 cm. Any subsequent persistent leaks in a setting of type B dissection or aneurysm can be treated endoluminally with a distal stent-graft extension later on (Fig. 15.4).

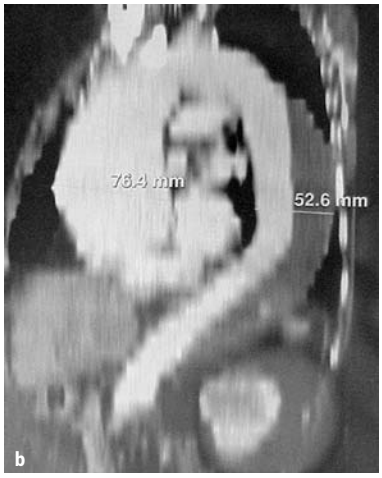
15.4 Branch Stent-Grafts for the Thoracic Aortic Arch

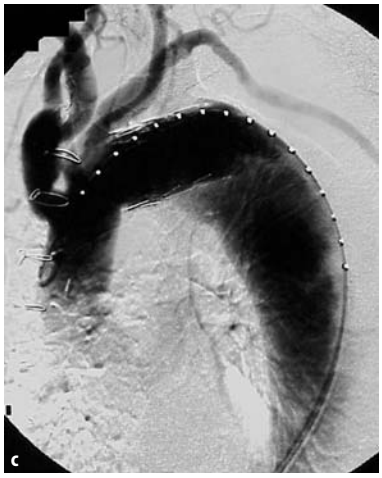
Inoue et al. [11] published their results with the use of a branch stent-graft for the thoracic aorta in 1999. Since then, little has happened in this field, most likely owing to the obvious problems associated with the deployment of branch stent-grafts in such a complex area as the aortic arch. Attempts have been made to create a modular system for the arch by using a standard stent-graft placed across the subclavian artery and then puncturing a hole from the subclavian arteries into the aortic stent-graft and placing a modular extension [12]. Chuter et al. [13] have placed a modular stent-graft from the right carotid artery into the ascending aorta and then covered the aortic arch with a stent-graft placed via a femoral approach and connected it with the main stent-graft in the ascending aorta. Extraanatomical bypasses from the right carotid artery to the left carotid artery and further to the left subclavian artery which were previously performed guaranteed preserved circulation to the supraaortic vessels [13]. All of these attempts exemplify the difficulties in achieving a safe branch stent-graft deployment in the complex area of the aortic arch [14]. The difficulties include the risk for cerebral embolization [11]. There is a risk of failed orientation and thereby failed preservation of flow to the important supraaortic vessels, with serious consequences as a result. Nevertheless, continued attempts are made to solve the inherent problems with this technique, not least because there are several advantages to be achieved. There is a large group of patients with type B dissection where the primary entry is so close to the left subclavian artery that coverage of this vessel is inevitable. Although this has been reported to be an innocuous procedure, an easily deployed branch stent-graft to the left subclavian artery may not only maintain the circulation to the left arm and left vertebral artery but may also improve the stability and fixation of the stent-graft. Similarly, the next step with a branch stent-graft further to the left carotid artery may solve the problem of extraanatomical bypasses, which today are required if the left carotid artery is blocked by a stent-graft. Further development is anticipated in this field.

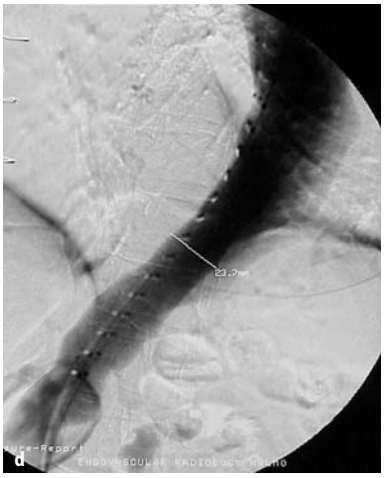
15.5 Discussion

With the advances in stent-graft technique and technology EVAR is today applied in more complex anatomy. This is particularly true for the aortic arch, where a combination of open surgical repair techniques, including either extraanatomical bypasses or bypasses from the ascending aorta to the supraaortic vessels, or a total replacement of the aortic arch, may be necessary in order to find a less traumatic solution when applying EVAR in this area. It is an evolving field and it has been









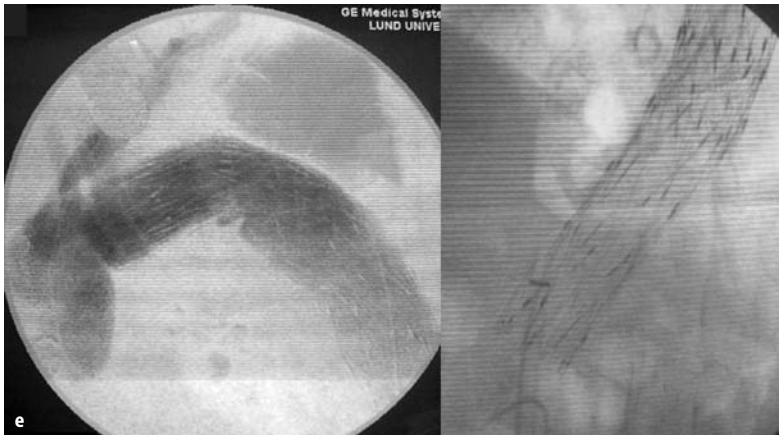


Fig. 15.4. a Schematic drawing demonstrating the various steps for deployment of a "stented elephant trunk." The elephant trunk with its stented portion and invaginated unstented graft portion is deployed in the descending aorta. The stented portion is then sutured to the aorta and the unstented graft portion is retrieved and used for reconstruction of the aortic arch. A stent-graft placed transfemorally is subsequently used for exclusion of an aneurysm in the distal thoracic aorta using the stented elephant trunk and the distal banded thoracic aorta as an implantation site. **b** CT demonstrating aneurysm in the ascending aorta and descending aorta. **c, d** Aortogram demonstrating the stented elephant trunk and banded distal thoracic aorta following open repair of the ascending aorta and the aortic arch. **e** Completion angiography following a transfemorally placed stent-graft with a good exclusion of the aneurysm

shown repeatedly to offer results superior to those from open surgery alone. Branch stent-grafts are under development and the near future will show when this new technique may replace conventional open surgical repair of the aortic arch.

References

1. Tse LW, MacKenzie KS, Montreuil B, Obrand DI, Steinmetz OK. The proximal landing zone in endovascular repair of the thoracic aorta. Ann Vasc Surg 2004; 18(2):178–185.
2. Schumacher H, Bockler D, Bardenheuer H, Hansmann J, Allenberg JR. Endovascular aortic arch reconstruction with supra-aortic transposition for symptomatic contained rupture and dissection: early experience in 8 high-risk patients. J Endovasc Ther 2003; 10(6):1066–1074.
3. Fajer S, Eyal A, Lubezky N, Karmeli R. Combined surgical and endovascular repair of type B thoracic aortic dissecting aneurysm after failed endovascular treatment. Eur J Vasc Endovasc Surg 2004; 27(5):559–562.
4. Kato N, Shimono T, Hirano T, Mizumoto T, Ishida M, Fujii H, Yada I, Takeda K. Aortic arch aneurysms: treatment with extraanatomical bypass and endovascular stent-grafting. Cardiovasc Intervent Radiol 2002; 25(5):419–422.
5. Kato M, Kuratani T, Kaneko M, Kyo S, Ohnishi K. The results of total arch graft implantation with open stent-graft placement for type A aortic dissection. J Thorac Cardiovasc Surg 2002; 124(3):531–540.
6. Sueda T, Orihashi K, Okada K, Sugawara Y, Imai K, Hamamoto M. Successful shrinkage of distal arch and proximal descending aortic aneurysm after transaortic endovascular stent-grafting. Eur J Cardiothorac Surg 2004; 25(5):716–721.
7. Fleck T, Hutschala D, Czerny M, Ehrlich MP, Kasimir MT, Cejna M, Wolner E, Grabenwoger M. Combined surgical and endovascular treatment of acute aortic dissection type A: preliminary results. Ann Thorac Surg 2002; 74(3):761–765; discussion 765–766.
8. Mizuno T, Toyama M, Tabuchi N, Wu H, Sunamori M. Stented elephant trunk procedure combined with ascending aorta and arch replacement for acute type A aortic dissection. Eur J Cardiothorac Surg 2002; 22(4):504–509.
9. Miyamoto S, Hadama T, Anai H, Sako H, Shigemitsu O. Stented elephant trunk method for multiple thoracic aneurysms. Ann Thorac Surg 2001; 71(2):705–707.
10. Usui A, Ueda Y, Watanabe T, Kawaguchi O, Ohara Y, Takagi Y, Tajima K, Nishikimi N, Ishiguchi T. Clinical results of implantation of an endovascular covered stent-graft via midsternotomy for distal aortic arch aneurysm. Cardiovasc Surg 2000; 8(7):545–549.
11. Inoue K, Hosokawa H, Iwase T, Sato M, Yoshida Y, Ueno K, Tsubokawa A, Tanaka T, Tamaki S, Suzuki T. Aortic arch reconstruction by transluminally placed endovascular branched stent graft. Circulation 1999; 100(19 Suppl): II316–321.
12. McWilliams RG, Murphy M, Hartley D, Lawrence-Brown MM, Harris PL. In situ stent-graft fenestration to preserve the left subclavian artery. J Endovasc Ther 2004; 11(2):170–174.
13. Chuter TA, Schneider DB, Reilly LM, Lobo EP, Messina LM. Modular branched stent graft for endovascular repair of aortic arch aneurysm and dissection. J Vasc Surg 2003; 38(4):859–863.
14. Chuter TA, Buck DG, Schneider DB, Reilly LM, Messina LM. Development of a branched stent-graft for endovascular repair of aortic arch aneurysms. J Endovasc Ther 2003; 10(5):940–945.

Pathophysiology of Aortic Dissection

Artur Evangelista, Teresa González-Alujas

16

Contents

16.1 Introduction

Aortic dissection is defined as the separation of the aortic media with presence of extraluminal blood within the layers of the aortic wall. In most patients one tear or one or more entries are present in the aortic intima, resulting in an abnormal communication between the true aortic lumen and the split aortic media. With primary intimal dissection the media is exposed to pulsatile aortic flow, likely to create a false aortic lumen and propagate a dissection, typically antegrade but sometimes retrograde from the site of the intimal tear. The vast majority of aortic dissections originate in one of the two sites where the greatest hydraulic stress is located in the ascending aorta, within several centimetres above the sinuses of Valsalva, and in the descending aorta, just distal to the origin of the subclavian artery at the site of the ligamentum arteriosum. Sixty-five percent of intimal tears occur in the ascending aorta, 20% in the descending aorta, 10% in the aortic arch and 5% in the abdominal aorta [17]. Most dissections have a reentry site and some communication sites throughout the descending aorta. The reentry tear is usually located in the abdominal aorta, iliac arteries or other aortic branches. These small communications, less than 2 mm in diameter, are not reentry tears but the ostia of the intercostal or lumbar arteries that have been severed by the dissecting haematoma. Reentry of the dissection is a predisposition for chronic false lumen perfusion with no tendency to thrombus formation.

16.2 Dissection Mechanism

The two mechanisms regarding the initial event in aortic dissection are primary intimal tear and initial delamination of the tunica media produced by the formation of an intramural haemorrhage. There are different lesions which can generate a primary entry tear of dissection, such as atherosclerotic lesions of the aortic intima, penetrating aortic ulcers, or iatrogenic intimal lesions [7, 21]. The second mechanism arises from bleeding of the vasa vasorum of the media (Fig. 16.1). All mechanisms weakening the aorta's media layers via microapoplexy of the vessel wall lead to higher wall stress, which can induce aortic dilatation, eventually resulting in intramural haemorrhage, aortic dissection or rupture [16]. The evolution of symptomatic intramural haematoma is to reabsorption, aneurysm formation or dissection [5]. Only 12% of intramural haematomas evolve to

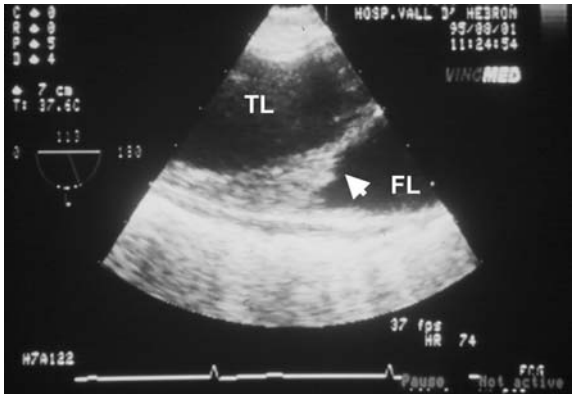


Fig. 16.1. Intimal flap (*arrow*) from an intramural haematoma which led to a classic dissection. *TL* true lumen, *FL* false lumen

classic dissection and 24% present only a localised dissection which eventually progresses to pseudoaneurysm formation [5].

Deterioration and loss of collagen and elastin in the media layer appear to be the major predisposing factors in cases of aortic dissection. Therefore, any disease process undermining the integrity of elastic and muscular components of the media predisposes to aortic dissection [9, 24].

Different processes may produce rupture of the intima:

1. Weakness of the aorta wall due to connective tissue disease such as Marfan syndrome, Edler–Danlos disease and bicuspid aorta [12, 22].
2. Mechanical stress induced from an aortic lesion secondary to jet impact as in aortic valve disease or aortic valve prosthesis [12, 22].
3. Atherosclerotic disease of the aorta wall [21].
4. Aortic intramural haematoma evolution [5, 18, 26].
5. Iatrogenic lesion by catheters or surgery. Trauma [10, 16].
6. Aortic inflammatory diseases [16].

Among the predisposing factors, untreated systemic hypertension is encountered in almost 80% of cases of aortic dissection [8]. Hypertension may not only directly weaken the aortic media, but may also initiate atherosclerosis of the vasa vasorum and thus intramural haemorrhage due to rupture of nutrient intramural vessels [26]. The causative role of systemic hypertension is further supported by the finding that coarctation of the aorta predisposes to aortic dissection [9, 26].

16.3 Pathogenesis

16.3.1 Aortic Parietal Stress

Aortic wall integrity depends mainly on two factors: contention resistance of its internal and external layers, determined by their biochemical and anatomical structure, and aortic parietal stress, which is in relation to arterial tension, luminal diameter and parietal thickness. All this can be expressed by a modified equation similar to the law of Laplace, where circumferential stress is directly related to blood pressure and aortic diameter, and inversely to parietal thickness.

As mentioned previously, aortic diameter is the main determinant of parietal stress. The aorta usually dilates before dissecting and the geometry of the dilated segment changes from cylindrical to spherical, passing through ellipsoidal. This change in aortic morphology causes a slow, progressive increase in circumferential stress and a rapid increase in longitudinal stress and accounts for the fact that the majority of intimomedial tears may be transverse. A further consideration to bear in mind regarding parietal stress is that its distribution in aorta wall thickness is not uniform. Since the pressure falls upon the internal arterial surface, parietal stress is greater on the internal than the external part. This is, in part, why the internal layers usually tear and the external layers do not [20, 23].

Arterial hypertension is considered to be a leading factor in the production of an arterial tear. However, the frequency of dissection in hypertensive patients is low and, furthermore, unpredictable. In fact, arterial pressure is only one of the components of parietal stress and, in some cases, is not even the most important. An aorta with the same pressure may dissect or not, depending on the anatomical characteristics (thickness and composition) of its walls and degree of dilatation. Therefore, the factors that may lead to dissection are as follows: (1) decrease in contention resistance of the internal layer; (2) increase in arterial pressure; (3) increase in aortic diameter; and (4) decrease in parietal thickness.

In the hypertensive type, the internal layer is normal, but there is an increase in parietal stress as a consequence of the increase in arterial pressure. This imbalance will produce a gradual increase in aortic diameter and, with time, a dissection [23].

16.3.2 Tunica Media Degeneration

Degenerative changes produced in the tunica media of patients who evolve to dissection may affect the elastic architecture, collagen and muscular component. Loss or fragmentation of any of these elements diminishes resistance of the aorta wall to haemodynamic stress. This may lead to aneurysmal dilatation of the aorta wall and subsequent dissection. In Marfan syndrome, as in other connective disorders, the dissection is due to medial degeneration. There is enhanced expression of metalloproteinases in vascular smooth muscle cells which may promote both fragmentation of medial elastic layers and elastolysis, and may lead to significant medial degeneration. In these circumstances, despite normal aortic pressure, the aorta dilates. When the aortic diameter increases, parietal stress increases and eventually a dissection ensues. In the hypertensive type, circumferential stress increases linearly with the increase in arterial pressure. In these cases, an increase of some degree of dilatation aggravates the circumferential stress even more. By contrast, in Marfan syndrome, the circumferential stress does not increase linearly, but exponentially. In these patients, a slight rise in arterial pressure accentuates the circumferential stress even more [23]. In some patients with dissection, rupture or loss of structural elements of the capa media is evident on optical microscopy; however, in other cases changes are

difficult to perceive or are even absent. These structural defects do not in themselves explain why some aortas dilate or rupture, others dissect and many remain free of any complications despite the presence of capa media degeneration. It is wrongly assumed that degeneration of the media is a lesion that diffusely affects the dissected aorta. However, as Prokop et al. [20] pointed out, once the dissection has begun, it may extend distally, affecting histologically normal segments, since propagation of the dissection depends basically on the pulse pressure wave.

According to Hirst and Gore [9], the capa media lesion in the majority of patients with dissection can be classified in two groups, depending on whether it predominantly affects the muscle or the elastic architecture. Separation and fragmentation of elastic fibres is more frequent in young patients (under 40 years) and particularly in individuals with Marfan syndrome or other hereditary defects.

Weakening of the aorta wall does not only occur as a consequence of elastic fibre fragmentation but also because of collagen and mucoid material accumulation. These changes are more prominent in ascending aorta, with the segment subjected to greater pulsatile expansion and, therefore, greater stress. As a result of the loss of elastic tissue, media cohesion is altered, muscle cells change their usual parallel orientation and cell deterioration is accelerated. Loss of muscle cells is usually focal and more frequent in hypertensive patients and those over the age of 40. Smooth muscle cells require oxygen and other nutrients to survive and consequently depend on adequate blood flow. Thickening of the intima, particularly that due to atherosclerosis, may interfere with its diffusion and permeability and affects the internal part of the capa media, whereas the external part may be threatened by atherosclerosis of the vasa vasorum.

Schlatmann and Becker [24] studied aortas of 100 patients with no known aortic disease and observed that the degree of elastic fragmentation was greater in older patients, the changes were more pronounced in the ascending aorta and the arch than in descending aorta, and the internal layer of the media was the most affected.

Larson and Edwards [12] studied 161 necropsies of patients with dissection. All patients with type A dissection had severe histologic changes. Patients with type B dissection with and without Marfan syndrome had few cystic changes in the descending aorta and many atherosclerotic lesions.

The typical histologic findings of tunica media degeneration detected in patients with dissection can also be observed in elderly patients and hypertensive patients without dissection. In this respect, many authors consider the changes in the media to result from the mixture of damage and repair lesions produced by haemodynamic aggressions repeated throughout the patients' lives [24]. The histologic difference between aortas with and without dissection may be more quantitative than qualitative and aorta wall anomalies in young patients with Marfan syndrome represented the acceleration in those that appear with ageing.

16.4 Pathophysiology

16.4.1 Mechanical Factors

Several types of mechanical forces that act on the aorta wall have been described: (1) those related to the vessel curve in certain sites; (2) those produced by the radial impact of the pulse pressure wave; and (3) the shearing longitudinal effect of blood flow.

The heart, ascending aorta and arch form a relatively mobile complex that hangs from the supraaortic trunks. In contrast, the descending aorta is more fixed on the left side of the spinal column. Flexion forces are maximum in the root and aortic isthmus. It is in these sites where the dissection entry tear is most frequently located. Tears are believed to occur in these areas since torsion movement of the aortic annulus provokes an additional downward traction of the aortic root and provokes an increase in the longitudinal stress in this segment; and in the isthmus area where the tension is due to the union of the aortic arch, which is relatively mobile, with the descending thoracic aorta, which is quite fixed [20]. Several studies have proved that the reduction in pulse pressure wave inhibits dissection progression [27]. The pulsatile nature of aortic flow is one of the principal causes of dissection progression. The aorta is quite resistant to increases in static pressure. Experimental studies show that the aorta only dissects when flow is pulsatile [20]. The longitudinal shearing forces that act on the direction of blood flow are directly related to the pressure gradient between the two aortic lumina, which is small and due to decreased pressure in the true lumen by the Bernoulli effect at high velocity. In the false lumen, there is not the same decrease in pressure during propagation of the dissection since it does not carry a net flow.

16.4.2 Morphologic Aspects

All dissections are characterised by a separation of the media layer of variable circumferential and longitudinal extension. Furthermore, a tear of the intima and media (entry tear) is observed in classic aortic dissection (Fig. 16.2). In the classic series, an entry tear could not be identified in less than 5% of necropsies. This intimomedial tear is, in general, perpendicular to the long axis of the aorta. Blood enters through this orifice, separat-

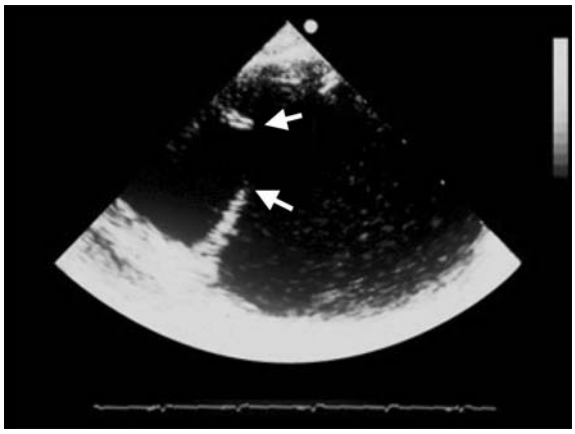


Fig. 16.2. Transoesophageal echocardiography shows a large entry tear (greater than 10 mm) localised distally to the subclavian artery in type B dissection

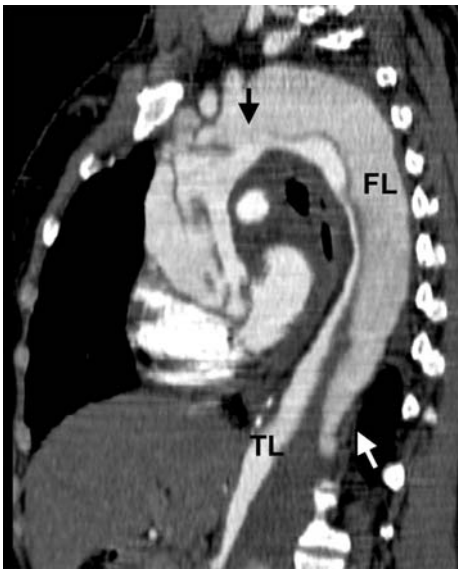


Fig. 16.3. Computed tomography study showing a type A dissection with an entry tear in the ascending aorta (*black arrow*) and a false lumen ending in a cul-de-sac due to a total thrombosis of the abdominal false lumen (*white arrow*). *TL* true lumen, *FL* false lumen

ing the media into two layers over a distance that varies in each case. The most internal two thirds of the media layer form, together with the intima, the internal wall of the false lumen. This flap is formed not only by the intima but also by the internal layer of the capa media and, consequently, should be termed intimomedial flap. The internal wall of the false lumen is thicker than the external wall which comprises the external part of the media and the adventitia.

Once the intimomedial tear has been produced, blood enters under pressure and a longitudinal dissection of the whole aorta may occur in a few seconds [21]. The dissecting haematoma can evolve to external false lumen rupture, reentry tear formation or end in a cul-de-sac. Thinness of the external wall of the false lumen is the anatomical finding related to aortic rupture. The thinner it is, the greater the probability of aortic rupture will be. It may also be assumed that the thicker it is, the thinner the intimomedial flap will be and, consequently, the greater the probability of a reentry being produced [21]. Rupture of the false lumen is the most frequent cause of death. The rupture site is usually near the entry tear and, therefore, the segment which breaks most frequently is the right anterolateral wall of the ascending aorta. Blood extravasation usually accumulates in the pericardial sac (haemopericardium), and death from cardiac tamponade is therefore frequent. If the arch ruptures, a haemomediastinum is usually produced; if it is the descending aorta, a left hemithorax; and if it is the abdominal aorta, a haemoperitoneum.

On occasions, a wide intimomedial tear may serve as an entry tear and reentry of the false canal. In this case, flow in the false canal is usually anterograde and retrograde [21]. When the dissecting canal ends in a cul-de-sac with no exterior rupture of a reentry tear, anterograde and retrograde flow may be observed (Fig. 16.3); however, in some cases, particularly if the entry tear is small, an acute total thrombosis of the false lumen might be produced. Diagnostic techniques have difficulties in distinguishing the latter from an intramural haematoma. Throughout the aorta, the portion of dissected aortic circumference is quite predictable since, albeit variable, the longitudinal course of the dissection has a determined trend. When the dissection begins in ascending aorta, the dissecting haematoma involves the larger curve of this arch and affects the right lateral region of the ascending aorta. From the isthmus, the dissection usually adopts a spiral route. The infradiaphragmatic and infrarenal aortas tend to dissect their left posterior region, leaving the right anterior vessels intact. Further down, the dissection usually affects the two iliac arteries, though more often the left one. The common femoral artery rarely dissects. For this reason, although any of the aorta branches can be affected by dissection, the right coronary artery, the supraaortic vessels, the left intercostal arteries, the left renal artery and the left common iliac artery are more frequently affected. On the other hand, the left coronary artery, the coeliac trunk, the superior mesenteric artery and the right renal artery are usually connected to the true lumen. Ambos et al. [1] qualified chronic dissection with reentry as a "healed dissection". Nevertheless, the false lumen is usually larger than the true lumen; with time, the former dilates and becomes tortuous. Aneurysmal dilatation of the false lumen is the most frequent late complication of dissection. The larger the aneurysm, the more likely rupture of its wall will be (Fig. 16.4). Some publications suggest that a reentry tear in pa-

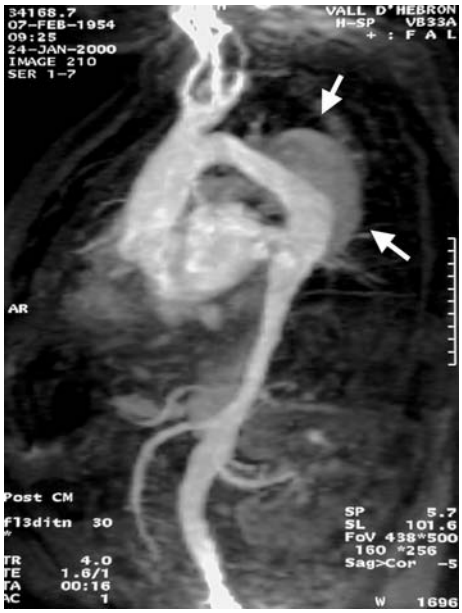


Fig. 16.4. Type B dissection by MRI. Large false lumen presenting high risk of aortic rupture due to high wall stress of the dilated false lumen (*arrows*)

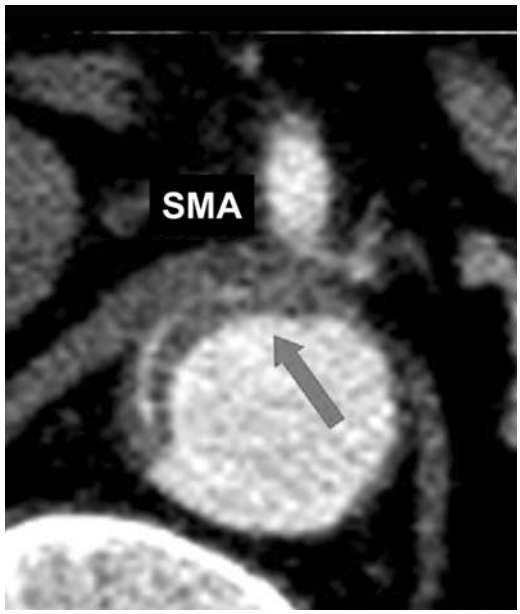


Fig. 16.5. Compression of the ostium of the superior mesenteric artery (*SMA*) by the intimal flap secondary to severe compression of the true lumen by the false lumen (*arrow*)

tients with chronic dissection does not protect against rupture of the false lumen.

16.4.3 Mechanism of Vascular Complications

The mechanism by which dissection can affect any of the branch arteries from the aorta is twofold:

1. Dynamic obstruction. In this case, the obstruction of the compromised vessel is dynamic, the true lumen is in the form of a "C" and the intimomedial flap has a concave arrangement towards the false lumen. This mechanism has been described from aortographic and computed tomography (CT) findings and, characteristically, at surgery or during necropsy, there are no data on the previous existence of arterial obstruction. Usually the true lumen is compressed by the false lumen and this generates an obstruction of the arterial ostia (Fig. 16.5).
2. Static obstruction. Here, two situations should be distinguished – arterial dissection and location of the origin of the arterial branch in the false lumen. In the first case, the intraarterial dissecting haematoma may obstruct the vessel lumen or intraarterial rupture of the haematoma may be produced, with formation of the dissection reentry tear. In some cases, the circumferential laceration of the arterial ostium may be accompanied by a circumferential dissection of the proximal segment of the artery and, thus, the intimomedial flap of the arterial branch may be distally impacted, affecting arterial flow. In many cases, obstruction of arterial branches is twofold: static and dynamic.

Ischaemia of the lower limbs as a complication of dissection has been described in up to 26% of patients with dissection and may occasionally be isolated [19], with no other clinical data of suspected dissection. Cerebral vascular accident is associated with increased early mortality in patients with dissection. The most frequently involved arteries of the supraaortic trunks are the innominate artery and the left common carotid artery. The left subclavian artery is less frequently affected than the right subclavian artery. The characteristic pattern of dissection propagation consists of involvement of the left side of the descending aorta which occurs preferably in the branches which originate on this side of the aorta. The left kidney is the organ at greatest risk of ischaemia. Kidney failure and mesenteric infarct have been identified by different groups as risk factors of early death in patients with dissection [6]. If the dissecting haematoma only affects the intercostal arteries on one side (generally the left), the arteries on the other side perfuse the spinal cord; however, if the haematoma affects the arteries on both sides, a medullary infarct will be produced.

The inexistence of a reentry tear in the distal aorta or its branches may jeopardise perfusion through the true lumen to such an extent that it collapses from the pressure or thrombosis of the false canal.

16.4.4 Aortic Dissection Evolution

Despite the significant advances in imaging techniques and therapeutic procedures in the last decade, dissection mortality in the first month of evolution continues to be very high: 25–30% for patients with type A dissections and 10–14% for patients with type B dissections [8]. Acute aortic dissection has a high risk of complications, clearly higher when the ascending aorta is affected than when it occurs distally to the innominate trunk. Risk factors for complications and mortality for patients with type A dissection are shock, hypotension and tamponade [14]. In contrast, in patients with type B dissection, mortality is related to shock and visceral ischaemia [16].

Once the acute phase has been overcome, the prognosis of dissection is clearly better, but at 10 years the survival rate averages 44% for patients with type A aortic dissection and 32% for patients with nonoperated type B dissection [16]. Mid-to-long-term mortality does not depend on aortic disease alone but also on different factors such as age, associated diseases and comorbidity.

One of the factors better related to aortic rupture evolution is aortic dilatation. Juvonen et al. [11] followed 50 type B dissections. At a mean of 3 years, 18% presented aortic rupture and 20% required elective surgery for rapid expansion of the aneurysm. Variables associated with aortic rupture were age, chronic obstructive pulmonary disease and elevated mean blood pressure. The last median descending aorta diameter before rupture in the rupture group was 54 mm. This study suggested that the continued patency of the false lumen was not an important predictor of rupture. On the other hand, two further studies showed aortic dilatation predictors to be an aorta diameter over 40 mm during the acute phase and an entry tear in the thoracic aorta or the presence of flow in the false lumen [13]. Nevertheless, the absence of flow in the false lumen in 55% of cases is surprising, and raises the suspicion that many of these cases were, in fact, intramural haematomas. Sueyoshi et al. [25] recently reported the follow-up by CT of 62 type B dissections, 75% of segments increased in size during a mean follow-up of 4 years. The presence of blood in the false lumen was the only significant risk factor, showing an increase of 3.3 mm/year, while in the group without flow in the false lumen the increase was 1.4 mm/year. In this study, total false lumen thrombosis was present in 51 of 176 cases. Another interesting finding was that the growth rate of aortic dissections in the thoracic aorta was higher than that of the abdominal aorta: 4.1 and 1.2 mm/year, respectively.

Previous studies revealed that aortic diameter was a strong predictor of enlargement and rupture. The maximum aortic diameter was considered to be between 40 and 60 mm [13]. These results can be explained by the law of Laplace, which states that the perpendicular stress on a cylinder is directly proportional to the pressure exerted by the fluid content and its radius and is inversely proportional to wall thickness. This means that the larger the diameter, the faster the growth rate will be if the pressure is constant.

Some results have shown that age is a significant risk factor for an increase in diameter in univariate analysis [11]. Anatomically, elasticity and distensibility of the aorta decline with age. Such changes occur even in normal healthy adults and, for some reasons, these changes appear earlier and are more progressive in men than in women.

Erbel et al. [3] proposed a classification based on dissection extension and the presence and location of an entry tear. Patients with aortic dissection types with absence of communication or with localised retrograde flow in the descending aorta alone had better survival. Thrombosis formation in the false lumen was a predictive factor of good prognosis. Although the results of this European multicentre study contribute very interesting data, they are limited by the single use of monoplane transoesophageal echocardiography (TEE), which limits visualisation of entry tears located in the distal ascending aorta and the proximal arch.

Some studies have shown that survival at 6 years is worse for patients with type B dissections than for patients with operated type A dissections [4]. Ergin et al. [4] reported the survival rate of patients with operated type A dissections without false lumen flow to be 85% versus 62% in the group with false lumen flow. Notably, in this series, false lumen flow was absent in 53% of cases [15]. In other studies, total obliteration of the false lumen in the descending aorta was achieved in only 10–20% of operated type A dissections [4, 15]. The better prognosis of operated type A dissections could be due to a smaller entry tear than for type B dissections.

16.4.5 Aortic Dilatation and Complications in Chronic Phase

The pathophysiology of aortic dissection in the chronic phase is essential to foresee possible complications and to select patients who are candidates for more aggressive treatment. Most complications occur in the acute phase and mortality continues to be relatively high, owing essentially to comorbidity due to associated diseases, aortic rupture due to progressive dilatation, or extension of the dissection.

Dilatation of the aorta in the long-term evolution of aortic dissection has been studied by our group. Although aortic diameters were determined by CT or MRI, haemokinetic variables of the aorta were defined

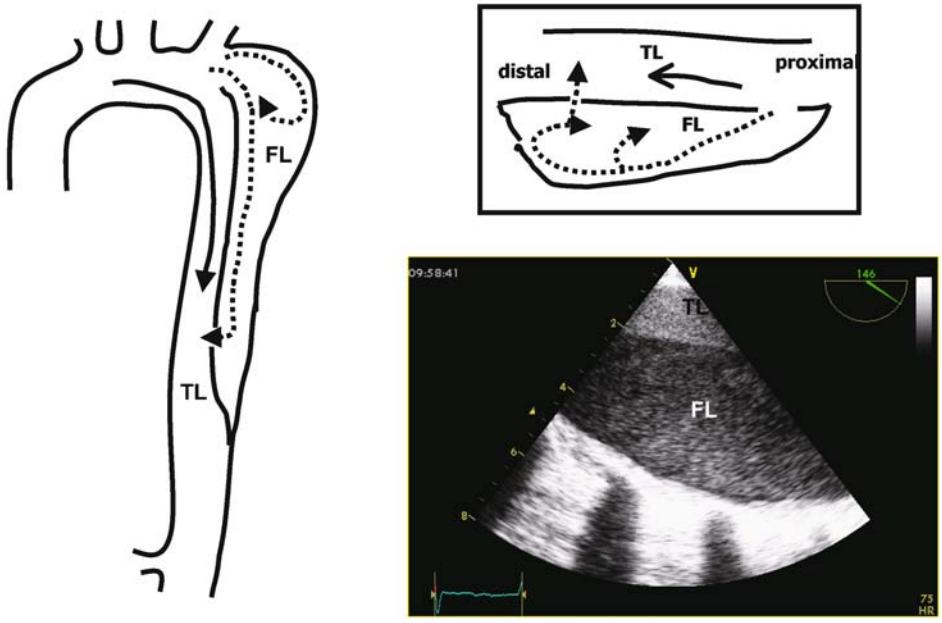


Fig. 16.6. High-pressure pattern in the false lumen owing to a large entry tear and a small distal reentry tear. Transoesophageal echocardiography shows how contrast in the false lumen has a low rate of progression compared with that in the true lumen. *TL* true lumen, *FL* false lumen

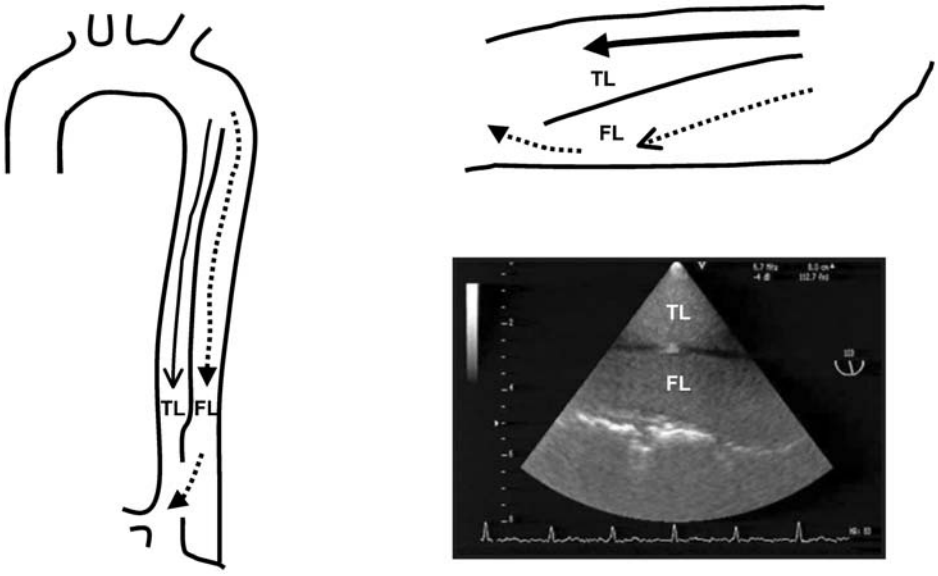


Fig. 16.7. Low-pressure pattern in the false lumen owing to similar-sized entry and reentry tears. By transoesophageal echocardiography contrast moves with similar velocity in the true lumen and the false lumen. *TL* true lumen, *FL* false lumen

by TEE performed prior to discharge. Forty-seven patients had type B dissections and 40 had operated type A dissections. The maximum aortic diameter presented dilatation between 0.2 and 6 mm/year. Dilatation of the descending aorta was greater in medically treated type B dissections than in operated type A dissections. Variables related to greater aortic dilatation were entry tear size, maximum descending aorta diameter in the subacute phase and the high-pressure pattern in the false lumen. An entry tear size over 10 mm implies higher risk of false lumen enlargement. Maximum aortic diameter in the subacute phase was a significant predictor of progressive dilatation since, according to the law of Laplace, maximum aortic diameter is the factor

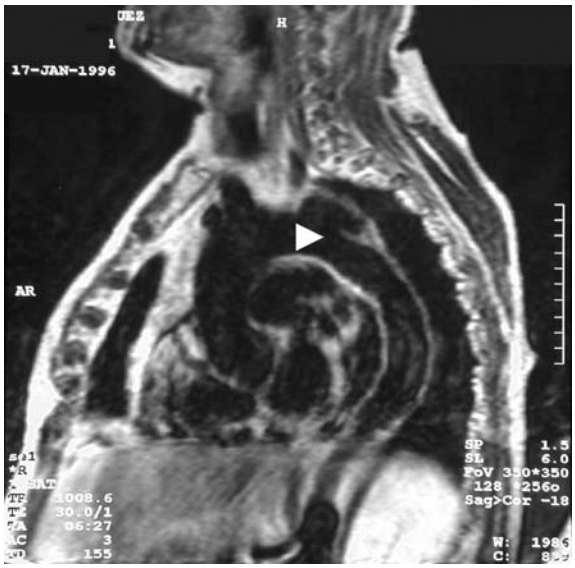


Fig. 16.8. Localised dissection secondary to an intramural haematoma (*arrow*). The majority of these dissections present progression to formation of a pseudoaneurysm

influencing increased wall stress. Finally, increased false lumen pressure was another important factor implying false lumen enlargement. The high false lumen pressure was due, in the majority of cases, to a large entry tear without distal emptying flow or a reentry site of similar size. It is often impossible to identify the reentry tears; thus, they were considered to be indirect signs of high false lumen pressure by TEE when the velocity of the echocardiographic contrast in the false lumen was slow and the contrast moved up and down for several cycles (Figs. 16.6, 16.7). MRI also permitted assessment of time and false lumen flow at different levels of the aorta, which helps to define whether the sizes of the entry and reentry tears are similar.

A suspicious, though not very specific, finding of high pressures in the false lumen is when the true lumen is compressed by the false lumen and the ratio is under 1:5. The lesser dilatation of the false lumen in operated type A dissection patients is due to the small entry tear size and the tear is often located in the distal part of the ascending aorta prosthesis. These pathophysiologic data of aortic dissection evolution may be of great interest for selecting asymptomatic patients who would benefit more from endovascular treatment in the subacute phase of aortic dissection.

On the other hand, evolution of dissection at some level of the aorta occurs in approximately 25% of haematomas [5]. The majority of dissections are localised and only are 20% classic. Extension, echolucency and thickness of the haematoma are variables related to aortic dissection evolution, most of which are asymptomatic and evident in the first 3–6 months after onset of the intramural haematoma. Small intimal tears can be identified on TEE and in a small proportion of cases trigger a dissection. Localised dissections (Fig. 16.8) evolve to pseudoaneurysm, disappearance of the intimal flap and produce an ulcerlike image. Some authors have suggested poor prognosis for haematomas presenting this evolution. In our series, two of the 17 images had disappeared at 6 months and only one case presented progressive dilatation and was treated with endovascular therapy.

Knowledge of the pathophysiology of aortic dissection is essential to understand the short- and long-term evolution, complications and most appropriate therapeutic management. Genetical or acquired structural alterations, secondary to the atherosclerotic process, are the causal substrate of most dissections. Nevertheless, the most therapeutically controllable variables are those secondary to the decrease in wall stress, both by hypertensive therapy and by surgical or endovascular treatment.

References

1. Ambos MA, Rothberg M, Lefleur RS, Weiner S, McCauley DI. Unsuspected aortic dissection: the chronic "healed" dissection. Am J Roentgenol 1979; 132:221–225.
2. Dalen JE, Pape LA, Cohn LH, Koster JK, Collins JJ. Dissection of the aorta. Pathogenesis, diagnosis and treatment. Prog Cardiovasc Dis 1980; 23:237–245.
3. Erbel R, Oelert H, Meyer J, et al. Effect of medical and surgical therapy on aortic dissection evaluated by transesophageal echocardiography. Circulation 1993; 87:1604–1615.
4. Ergin MA, Phillips RA, Galla JD, et al. Significance of distal false lumen after type A dissection repair. Ann Thorac Surg 1994; 57:820–825.
5. Evangelista A, Dominguez R, Sebastia C, et al. Long-term follow-up of aortic intramural hematoma. Circulation 2003; 108:583–589.
6. Fann JI, Sarris GE, Mitchell RS, et al. Treatment of patients with aortic dissection presenting with peripheral vascular complications. Ann Surg 1990; 212:705–713.
7. Guo D, Hasham S, Kuang S-Q, et al. Familial thoracic aortic aneurysms and dissections. Genetic heterogeneity with a major locus mapping to 5q 13-14. Circulation 2001; 103:2461–2468.
8. Hagan PG, Nienaber CA, Isselbacher EM, et al. The international registry of acute aortic dissection (IRAD): new insights into an old disease. JAMA 2000; 283:897–903.
9. Hirst AE, Gore I. Is cystic medionecrosis the cause of dissecting aortic aneurysm? Circulation 1976; 53:915–916.
10. Januzzi J, Sabatine MS, Eagle KA, et al. Iatrogenic aortic dissection. Am J Cardiol 2002; 89:623–626.
11. Junoven T, Ergin MA, Galla JD, et al. Risk factors for rupture of chronic type B dissection. J Thorac Cardiovasc Surg 1999; 117:776–786.
12. Larson EW, Edwards WD. Risk factors for aortic dissection. A necropsy study of 161 cases. Am J Cardiol 1984; 53:849–855.
13. Marui A, Mochizuki T, Mitsui N, Koyama T, Kimura F, Horibe M. Towards the best treatment for uncomplicated patients with type B acute aortic dissection. Circulation 1999; 100:II275–280.

14. Mehta RH, Suzuki T, Hagan PG, et al. Predicting death in patients with acute type A aortic dissection. Circulation 2002; 105:200–206.
15. Moore NR, Parry AJ, Trottman-Dickenson B, Pillai R, Westaby S. Fate of the native aorta after repair of acute type A dissection; a magnetic resonance imaging study. Heart 1996; 75:62–66.
16. Nienaber CA, Eagle KA. Aortic dissection: new frontiers in diagnosis and management. Circulation 2003; 108:628–635.
17. Roberts WC, Honing HS. The spectrum of cardiovascular disease in the marfan syndrome: A clinico-morphologic study of 18 necropsy patients and comparison to 151 previously reported necropsy patients. Am Heart J 1982; 104:115–135.
18. Nienaber CA, Sievers HH. Intramural hematoma in acute aortic syndrome more than one variant of dissection? Circulation 2002; 106:284–285.
19. Pacifico L, Spodick D. ILEAD-ischemia of the lower extremities due to aortic dissection: the isolated presentation. Clin Cardiol 1999; 22:353–356.
20. Prokop EK, Palmer RF, Wheat MW Jr. Hydrodynamic forces in dissecting aneurysms. In vitro studies in a tygon model and in dog aortas. Circ Res 1970; 27:121–127.
21. Roberts WC. Aortic dissection: Anatomy, consequences and causes. Am Heart J 1981; 101:195–214.
22. Roberts CS, Roberts WC. Dissection of the aorta associated with congenital malformation of the aortic valve. J Am Coll Cardiol 1991; 17:712–716.
23. Robicseck F, Thubrikar MJ. Hemodynamic considerations regarding the mechanism and prevention of aortic dissection. Ann Thorac Surg 1994; 58:1247–1253.
24. Schlatmann TJM, Becker AE. Pathogenesis of dissecting aneurysm of aorta. Comparative histopathologic study of significance of medial changes. Am J Cardiol 1977; 39:21–26.
25. Sueyoshi E, Sakamoto I, Hayashi K, Yamaguchi T, Imada T. Growth rate of aortic diameter in patients with type B aortic dissection during the chronic phase. Circulation 2004; 110:II-256–261.
26. von Kodolitsch Y, Aydin MA, Loose R, et al. Predictors of aneurysm formation after surgery of aortic coarctation. J Am Coll Cardiol 2002; 39:617–624.
27. Wheat MW. Acute dissecting aneurysms of the aorta diagnosis and treatment – 1979. Am Heart J 1980; 99:373–387.

Surgical Treatment of Acute Type B Dissection

Marc Schepens, Karl Dossche

17

Contents

17.1 Introduction

Most cases (80%) [1] of acute type B aortic dissections can be treated medically. This is also the case for acute intramural hematoma type B and for penetrating aortic ulcus. The aim of medical treatment consists of hemodynamic monitoring, lowering the blood pressure with beta-blockers and vasodilators. Beta-blockers reduce d*P*/d*t* and therefore control the ejection of blood from the heart. Prognosis treated as such is not bad: in-hospital mortality is about 11% [1] underscoring the fact that medical treatment alone is justified. Because almost all dissected aortas will dilate and become aneurysmatic over time, it is essential that patients who were initially treated medically have long-life aortic surveillance in order to detect aneurysmal dilatation in time. However, in some circumstances of acute type B aortic dissection, acute intramural hematoma type B or penetrating ulcus, medical treatment is insufficient and surgical treatment should be added.

17.2 Indications for Surgery

Surgical treatment is mandatory in patients with:

1. Rupture (Fig. 17.1): This will occur usually into the left chest and/or mediastinum, mostly from the upper portion of the descending thoracic aorta. However, it can happen all along the thoracoabdominal aorta. It is not exceptional to appreciate also a right-sided hematothorax. Moderate pleural effusion (often bilateral) is a common finding even in an uncomplicated acute type B dissection and therefore does not by itself present a surgical indication [2].
2. Uncontrollable hypertension and/or pain despite maximal medical therapy (with modern drug regimes these circumstances are rare).
3. Malperfusion: Fortunately malperfusion is a rare phenomenon because reentries occur spontaneously causing automatic relief. All side branches of the aorta, starting from the intercostal arteries and ending somewhere at the iliac arteries, are at risk for malperfusion. The mechanisms of malperfusion as classified by Beregi et al. [3] and Gaxotte et al. [4] lie in the extension of the dissecting process into the side branch, the narrowing of the side branch by the

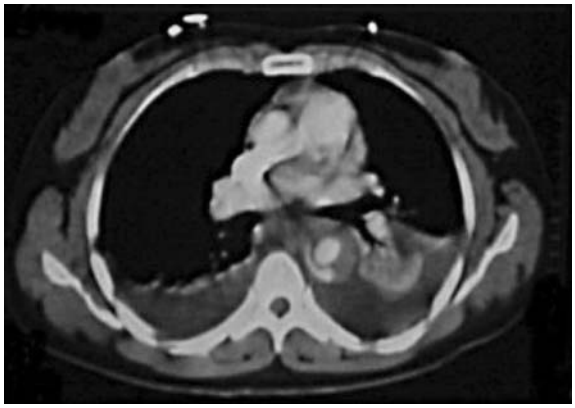


Fig. 17.1. A ruptured type B dissection on computed tomography (*CT*) scan

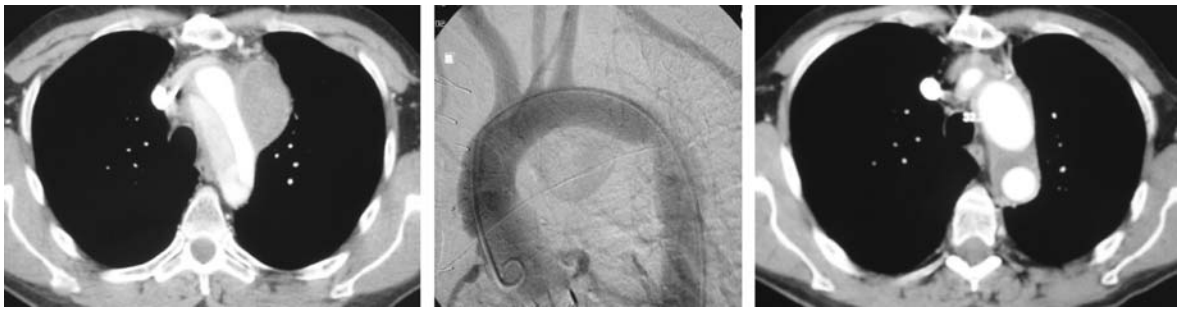


Fig. 17.2. This patient had an uneventful type B aortic dissection initially treated with antihypertensive drugs. He developed sudden hoarseness owing to the rapid expansion of the post-dissection aneurysm. The dissection extended retrogradely into the arch. The image on the *left* shows a CT scan with an acutely distended and dissected aortic arch. The image in the *middle* shows the preoperative angiography. He underwent an emergency arch and proximal descending aorta replacement using extracorporeal circulation. On the *right* is the postoperative CT scan (at 3 months)

thrombosed or expanded false lumen, intussusception of the inner layers into the side branch or combinations. This can lead to clinical pictures such as spinal cord problems (paraplegia or paraparesis), intestinal infarction, renal failure, ischemia of the lower extremities or combinations. These can occur acutely but also progressively. The main problem is that malperfusion does not always manifest itself by a clear-cut clinical sign. On the contrary, it often happens unnoticed, causing important time delay. It should be clear that the function of the end organ is at risk when malperfusion occurs; therefore, aggressive diagnostic testing (intra-arterial angiography) is mandatory. Renal failure and mesenteric infarction contribute to the high mortality in acute type B aortic dissection [1, 5–7].

4. Rapidly expanding aortic diameter might become evident on consecutive plain chest X-rays but is better appreciated on repetitive computed tomography (CT) scans.
5. Acute hoarseness: This can be an alarming sign of rapid expansion of the dissected aorta in the neighborhood of the left recurrent laryngeal nerve. If this occurs, an urgent CT scan or an MRI scan is mandatory (Fig. 17.2).

17.3 Surgical Techniques

17.3.1 General Considerations

Open surgical repair in acute type B aortic dissection should be seen as a life-saving procedure that aims at the repair by insertion of a tubular Dacron prosthesis at the proximal descending thoracic aorta and the restoration of the blood flow into the true lumen. Replacing the proximal one third of the descending thoracic aorta (Fig. 17.3) eliminates most likely the site of aortic rupture and is unlikely to interfere with the blood supply to the spinal cord. Only rarely is replacement of the distal descending or the total thoracoabdominal aorta required. In this way the risk of spinal cord problems is reduced. Mostly the dissected aorta is only moderately enlarged in the acute phase. The operation for acute distal aortic dissection should be tailored to address the specific problem necessitating the intervention. In most circumstances the distal repair can be performed in the chest.

Only if there are indications on preoperative diagnostic tests that the rupture is localized low or that the complete thoracoabdominal aorta is acutely enlarged is a complete descending thoracic aortic or thoracoabdominal aortic replacement indicated. Resecting all the

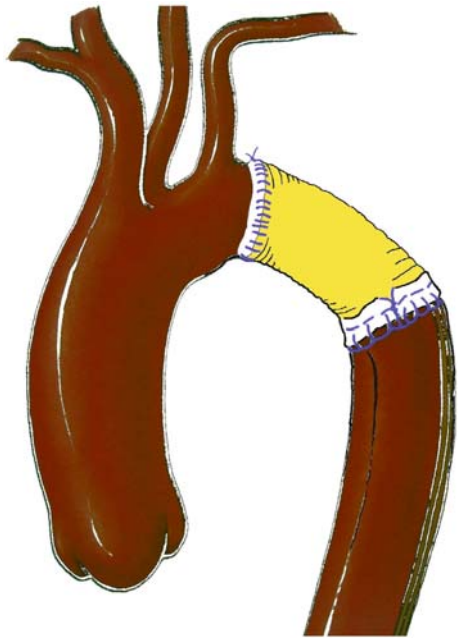


Fig. 17.3. A short interposition graft in the proximal descending thoracic aorta in a case of ruptured type B dissection

dissected aorta should not be attained in the acute settings but certainly is the goal in the case of chronic dissections.

17.3.2 Use of Soft Clamps, Teflon Felt and Glue

It is advisable not to use the regular aortic clamps on an acutely dissected aorta owing to the extreme friability. Instead, straight or angled rubber-shod Fogarty aortic clamps can be used. Owing to the fragility of the acute dissected aorta, it might be safe to use reinforcement of the suture lines with Teflon felt (either posteriorly, circumferentially, externally or internally or both) (Fig. 17.4) or to use glue, like gelatin–resorcin–formalin (Microval, Saint-Just-Malmont, France) or BioGlue (Cryolife, Kennesaw, GA, USA) [8]. When glue is used, it is important that all layers are completely dry before the application. It is much safer to transect the aorta completely circumferentially not only at the proximal suture line but also distally. This will overcome suturing the esophageal wall (reducing the risk of late aorto-esophageal fistula) and will also ensure that all layers of the dissected aortic wall are included into the anastomosis (which is not always so obvious in acute dissection).

In chronic dissections in which the intimal membrane has become fibrotic and scarred, it is advisable to resect the membrane over a short distance and to suture the graft to the outer coat of the aorta. This fenestration of the dissecting membrane is essential in chronic dissections at the distal and also at the proximal suture line. In acute aortic dissection (within 2 weeks after the onset) in contrast, all aortic layers should be sutured together and blood flow should be rerouted into the true lumen. This will allow the true lumen to expand completely, thereby also maximizing flow to compromised side branches. At the proximal aortic stump it is important to ascertain which is the true and which is the false channel: this can be done by temporarily opening the aortic cross-clamp (in the case of simple cross-clamping or left heart bypass).

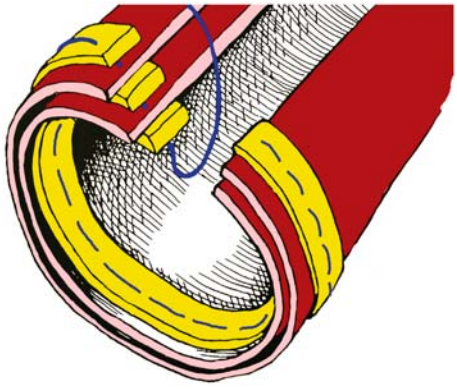


Fig. 17.4. Teflon felt is used to reinforce the aortic stumps (either externally or internally and between the layers)

17.3.3 Access

The chest of the patient is in the right lateral decubitus position with the pelvis rotated posteriorly for optimal access to the left femoral vessels. One can choose between a single thoracotomy, a double thoracotomy (through either a double or a single skin incision) or a thoracophrenolaparotomy (Fig. 17.5). It is important to choose the correct approach to achieve optimal control. Usually we prefer the fifth intercostal space (upper side of the sixth rib) for repair of the descending thoracic aorta: this approach allows for arch control and distally up to the level of the tenth thoracic level. More distal control and visibility in the area of the hiatus might become difficult or even problematic. In these circumstances one could add a second (lower) thoracotomy through the same skin incision. Therefore, the anterior aspect of the skin incision should be sloped down towards the costal arch. If the aortic arch needs to be partially or totally replaced simultaneously (which is exceptional in the case of acute type B dissection), we prefer the fourth intercostal space (upper side of the fifth rib): through this incision even the ascending aorta can be reached. Under these circumstances it will be very difficult if not impossible to reach the lower half of the descending thoracic aorta. This means that a second lower chest incision is mandatory if the planned repair extends to this region.

If a thoracoabdominal repair is anticipated, it will depend on the type of the aneurysm which approach is chosen but in general a thoracophrenolaparotomy is suitable. A low left-sided tenth- or eleventh-rib approach is useful for type IV thoracoabdominal repair and also for creating a surgical reentry in the region of the ostia of the visceral vessels.

17.3.4 Perfusion Techniques

Despite the fact that in the early experience most interventions were performed using simple cross-clamping (or clamp-and-sew technique), this technique is now no longer used because it causes difficult-to-control proximal hypertension with its detrimental effects on the heart and brain, extreme distal hypotension and ischemia of a major portion of the body including kidneys, guts and spinal cord. More important, it has been determined that 20–30 min is the safe time period of aortic occlusion (at normothermia); this time period is insufficient for performing complex repairs, which is always the case in acute type B dissection.

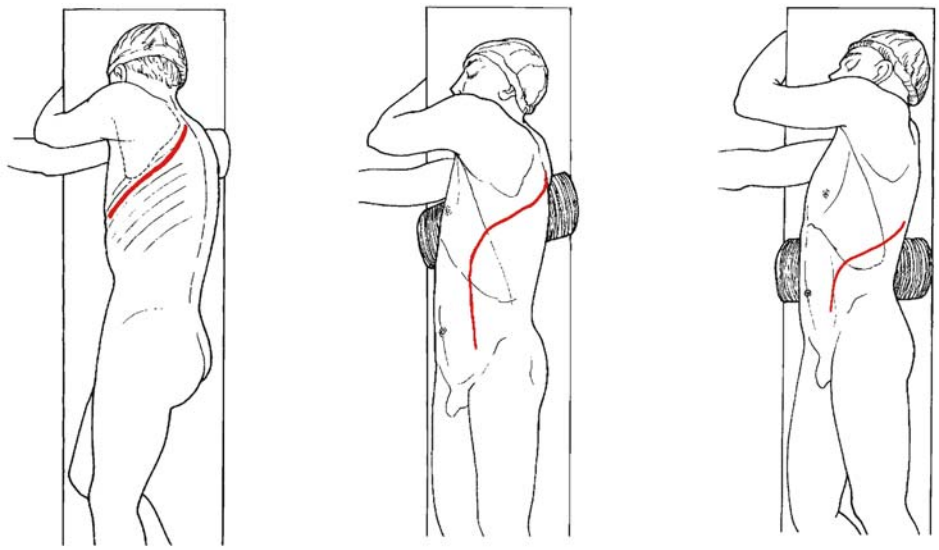


Fig. 17.5. Access possibilities: *left* posterolateral thoracotomy (for proximal repair); *middle* thoracophrenolaparotomy (for thoracoabdominal resection); *right* lumbotomy (for creating an abdominal reentry)

17.3.5 Atriofemoral Bypass (Left Heart Bypass)

Most surgeons actually use the left heart bypass. In this system, oxygenated blood is withdrawn from the left atrium (through the left atrial appendage or through the pulmonary vein) and reperfused via the left femoral artery into the lower body half, thereby reducing the ischemic time period of all distal organs, including the spinal cord. Although in chronic aneurysm one can cannulate the descending thoracic aorta, this is contraindicated in patients with acute type B dissections necessitating surgical repair. Using heparin-bonded pump circuits avoids systemic heparinization. Owing to extensive heat loss the temperature of the body will decrease to about 32 °C, which is an additional advantage; the built-in heat exchanger allows for rewarming at the end of the procedure. Maintenance of distal perfusion during clamping is the major advantage of this atriofemoral bypass: abdominal organs, including guts and kidneys, do not become ischemic. Also the ischemia of the spinal cord is limited, reducing the incidence of paraplegia/paraparesis [9, 10]. When the aortic segment containing the visceral arteries is excluded from the circulation by clamps, selective perfusion through side branches allows the visceral arteries to be perfused continuously. Proximal clamping of the aortic arch should not be a problem because theoretically the arch is not involved in the dissection (although the hematoma may spread around the arch, making identification of structures less reliable). Distally again it is important to use soft clamps so as not to damage the fragile aortic wall; an open distal anastomosis can be performed after having stopped the pump.

17.3.6 Extracorporeal Circulation (Partial or Total, Deep Hypothermic Circulatory Arrest)

Using extracorporeal circulation via the femoro-femoral (or pulmonary-femoral) route necessitates complete heparinization. Optimal organ protection can be achieved by cooling the patient. By using deep hypothermic circulatory arrest (isoelectric encephalogram, nasopharyngeal and rectal temperature at about 18 °C or lower), we can perform so-called "open" anastomoses: the application of clamps becomes unnecessary and end-to-end anastomoses can be performed in a bloodless field, on a flaccid aorta, which makes identification of all aortic layers easier. Intraoperative damage to the lung should be avoided because it will compromise the postoperative respiratory status. We think that a "no touch" technique is important: only a posterior strip of the aorta needs to be free from adherent lung tissue to allow for a longitudinal incision (this principle also applies to left heart bypass).

17.4 Surgical Steps

After having installed the bypass (e.g., left heart bypass), control over the proximal and distal aorta is established using umbilical tapes or vessel loops. Encircling an acutely dissected aorta should be performed with extreme care. In the case of replacement of the proximal part of the descending thoracic aorta, the proximal clamp should be placed on the aortic arch, between the left subclavian artery and the left carotid artery. Soft clamps are also used at the distal clamping re-

gion. The aorta is opened longitudinally, the edges retracted with stay sutures. Back-bleeding intercostal vessels can be oversewn in the higher thoracic part but it is advisable to reimplant intercostals in the lower thoracic area if major parts of the thoracic or thoracoabdominal aorta are to be replaced [8]. On the other hand, reimplantation of intercostal vessels in a very friable dissected aortic wall might be hazardous. Some authors consider reimplantation in these circumstances even contraindicated [11]. Complete transection of the proximal aorta is performed and the layers are identified and reconstructed (using Teflon or glue). It is important to have a nice cuff of aortic tissue projecting out of the clamp: this makes repair and control of bleeding easier. Finally a woven Dacron prosthesis is anastomosed in an end-to-end fashion. This anastomosis can be tested by removing the proximal clamp and occluding the vascular graft. Deairing is important to avoid air entering into the head vessels. If hemostasis is judged acceptable, the prosthesis is sized at its correct length and the distal end is anastomosed to the aorta similarly to the proximal anastomosis. Finally all clamps are removed and antegrade flow is restored. Since the acutely dissected aorta mostly is not enlarged, it is not so evident to cover the prosthesis with aortic wall; if desired one can use a poly(tetrafluoroethylene) or a bovine pericardium patch, but it is not mandatory.

17.5 Malperfusion

In the past creating a surgical reentry was the treatment of choice for malperfusion, but actually endovascular catheter-based interventions are the primary option [12]. Surgeons dealing with aortic problems should, however, keep themselves abreast of the technique of creating a surgical reentry because endovascular interventions might fail or be unsuccessful. Of course it can be performed at any aortic level; it was most frequently used at the level of the upper abdominal aorta in order to relieve malperfusion of the viscera. It was described for the first time by Shaw [13] in 1955. We prefer a low thoracophrenolaparotomy entering the chest at the level of the tenth or eleventh rib. The diaphragm can be left intact at its anterior aspect, while the posterior part can be divided circumferentially. Using this approach allows for access to and control of the lower thoracic aorta and the complete abdominal aorta up to the aortic bifurcation. The peritoneum need not be opened except for inspection of the viability of the viscera at the end of the procedure (in case of doubt). Once control over the proximal (just above the diaphragm) and distal aorta (eventually one do not need to clamp distally) is established (again using soft clamps), the dissected aorta is incised longitudinally over a short segment at the level of the compromised side branches. It is wise to avoid

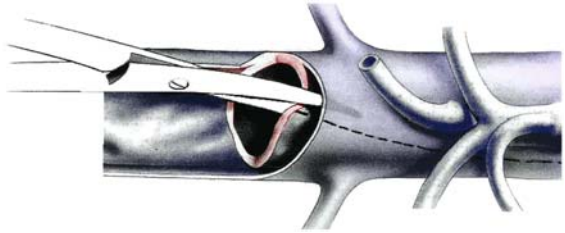


Fig. 17.6. Creating an abdominal reentry

incision in the dissected part (the "blue" part) because otherwise suturing may become problematic; the non-dissected part will have a normal color. The intimal flap is excised in both directions as far as possible (Fig. 17.6). Of course, the use of one or even two cell-savers is mandatory because back-bleeding from all side branches will obstruct clear vision. When parts of the intimal flap are no longer obstructing the ostia of the main side branches (it is very important to have clear access to all the ostia), the aorta is closed, preferably with Prolene 5×0, over two strips of Teflon. This suture line deserves utmost attention. The procedure mostly takes no longer than 20–30 min of aortic clamping, so no bypass is needed. However, if a tube graft insertion is planned, we would advise using an adjunct (left heart bypass). If at the end of the procedure the viability of the affected organs is not restored adequately (flow probes or Doppler imaging might help to assess this), extra-anatomic bypass (e.g., axillobifemoral) can be added. In the case of lower-extremity malperfusion, one can choose to insert a small abdominal tube graft into the abdominal aorta or just create an abdominal reentry as described before. Femoro-femoral cross-over or axillobifemoral bypass can be an alternative.

Because the left renal artery is often affected by the dissecting process, we completely agree with Borst et al. [2] that unilateral malperfusion of this kidney can be accepted without intervention. Acute onset paraplegia after acute type B aortic dissection without involvement of other vascular territories remains a controversial indication for creating reentry because we think that in most cases the spinal cord deficit will be irreversible.

17.6 Results

Medical treatment of acute type B aortic dissection offers a 30-day mortality of about 10% [1]. Historical series have shown in the past varying results: Masuda et al. [14] described a 6.5% hospital mortality and Appelbaum et al. [15] 32%.

Results of surgically treated acute type B dissection should be interpreted with caution. If surgery is reserved for complicated patients with malperfusion, mortality will be high, while in other series in which sur-

gery is the routine treatment of uncomplicated acute type B dissections, one might expect a low mortality rate. It has been shown that the preoperative status has a tremendous impact on surgical outcome and results: Genoni et al. [16] have shown that rupture, shock and malperfusion are significant predictors of poor survival. Nevertheless some series report zero mortality in patients treated surgically for acute type B dissection with a 5- and 10-year survival of 80 and 57%, respectively [17]. They suggest that earlier surgery for these patients might be indicated.

17.7 Conclusion

In view of recent progress in endovascular treatment of acute type B dissections with its less invasive character and excellent good initial and medium-term results, open repair becomes less and less the first option in complicated acute type B dissections. Nevertheless it must remain an important pillar in the treatment of acute complicated type B dissections. We must not forget that endovascular treatment can fail or it can be inadequate. Owing to the fact that surgery for acute type B dissections is difficult, often during the night and without optimal anesthesiological support, it should be reserved to aortic centers where a large number of acute and elective patients are treated with all treatment modalities.

References

1. Hagan PG, Nienaber CA, Isselbacher EM, et al. The International Registry of Acute Aortic Dissection (IRAD). New insights into an old disease. JAMA 2000; 283:897–903.
2. Borst HG, Heinemann MK, Stone CD. Surgical treatment of aortic dissection. New York: Churchill Livingstone; 1996.
3. Beregi JP, Cocheteux B, Koussa M, et al. Traitement endovasculaire des malperfusions au cours des dissections aortiques. In: Kieffer E, Fabiani JN, editors. Chirurgie de dissections aortiques. Paris: AERCV; 2002.
4. Gaxotte V, Cocheteux B, Haulon S. Relationship of intimal flap position to endovascular treatment of malperfusion syndromes in aortic dissection. J Endovasc Ther 2003; 10:719–727.
5. Cambria RP, Brewster DC, Gertler J, et al. Vascular complications associated with spontaneous aortic dissection. J Vasc Surg 1988; 7:199–209.
6. Fann JI, Sarris GE, Mitchell RS, et al. Treatment of patients with aortic dissection presenting with peripheral vascular complications. Ann Surg 1990; 212:705–713.
7. Borst HG, Laas J, Heinemann M. Type A aortic dissection: diagnosis and management of malperfusion phenomena. Semin Thorac Cardiovasc Surg 1991; 3:238–241.
8. Oderich GS, Panneton JM. Acute aortic dissection with side branch vessel occlusion: open surgical options. Semin Vasc Surg 2002; 15:89–96.
9. Coselli JS, LeMaire SA, Conklin LD, et al. Morbidity and mortality after extent II thoracoabdominal aortic aneurysm repair. Ann Thorac Surg 2002; 73:1107–1116.
10. Schepens MA, Vermeulen FE, Morshuis WJ, et al. Impact of left heart bypass on the results of thoracoabdominal aortic aneurysm repair. Ann Thorac Surg 1999; 67:1963–1967.
11. Huynh TT, Porat EE, Miller CC 3rd, et al. The effect of aortic dissection on outcome in descending thoracic and thoracoabdominal aortic aneurysm repair. Semin Vasc Surg 2002; 15:108–115.
12. Slonim SM, Miller DC, Mitchell RS, et al. Percutaneous balloon fenestration and stenting for life-threatening ischemic complications in patients with acute aortic dissection. J Thorac Cardiovasc Surg 1999; 117:1118–1126.
13. Shaw RS. Acute dissecting aortic aneurysm: treatment by fenestration of the internal wall of the aneurysm. N Engl J Med 1955; 253:331–333.
14. Masuda Y, Yamada Z, Morooka N, et al. Prognosis of patients with medically treated aortic dissections. Circulation 1991; 84:III7–13.
15. Appelbaum A, Karp RB, Kirklin JW. Ascending vs descending aortic dissections. Ann Surg 1976; 183:296–300.
16. Genoni M, Paul M, Tavakoli R, et al. Predictors of complications in acute type B aortic dissection. Eur J Cardiothorac Surg 2002; 22:59–63.
17. Lansman SL, Hagl C, Fink D, et al. Acute type B aortic dissection: surgical therapy. Ann Thorac Surg 2002; 74:S1833–1835.

Surgical Treatment of Chronic Descending Aortic Dissection

Michael J. Jacobs

18

Contents

18.1 Introduction

The definition of descending aortic dissection is clear, indicating a dissected descending thoracic or thoracoabdominal aorta following an acute onset of an intimal tear. More debatable is the term "chronic," which in general is used if the dissection is older than 2 weeks. It seems more appropriate to apply the term "early chronic-phase," for the first 2–4 weeks following the acute phase of 2 weeks, on the basis of the instability of the patient and the friable quality of the aorta in these weeks. In this chapter only the chronic phase is addressed, indicating more than 6 weeks after the dissection. Descending aortic dissection can be limited to the descending thoracic aorta but most often extends to the abdominal aorta and even the iliac and femoral arteries. Currently available techniques for open surgery and adjunctive protective measures will be described.

18.2 Indications for Surgery

In patients with uncomplicated chronic type B dissection there is no need for surgical intervention and adequate blood pressure management and regular anatomic assessment by means of computed tomography or magnetic resonance are performed. "Uncomplicated" basically means that the aorta is not dilated or growing in time. It rarely occurs that in chronic, not dilated dissected aortas, the patient develops acute ischemic events like intestinal ischemia, renal failure or paraplegia.

The main concern in chronic type B dissection is aortic dilatation, which will ultimately determine the indication for surgery. The initial aortic diameter at the time of the dissection and the fate of the false lumen have an important influence on the development of aneurysm formation. It has been shown that the predominant predictors for aortic enlargement in the chronic phase are the existence of a maximum aortic diameter of or greater than 40 mm during the acute phase and a patent primary entry site in the thoracic aorta [1]. Others [2] also showed that a patent false lumen and an initial diameter of 40 mm or more were independent predictors for chronic phase enlargement (larger than 60 mm) and aortic rupture.

Table 18.1 summarizes the different morphologic features at the time of the acute intimal tear. The nondilated aorta with a thrombosed false lumen will have the best prognosis, whereas the dilated aorta with a patent false lumen will likely develop an aneurysm. It is obvious that dissected aortic aneurysms carry a higher risk compared with aortic dissections.

In summary, the indication for surgical repair of chronic descending aortic dissection depends on the diameter of the aorta. Subsequently, from a surgical point of view, the dissected aorta becomes a thoracic aortic aneurysm (TAA) or a thoracoabdominal aortic

Table 18.1. Possible morphologic features of the aorta at the time of acute type B aortic dissection

Aortic dissection	Fate of lumen	Remarks
Nondilated aorta	Open true and false lumens	Most common
Nondilated aorta	Thrombosed false lumen	Best prognosis
Nondilated aorta	Thrombosed true lumen	Uncommon
Dissected aortic aneurysm	**Fate of lumen**	**Remarks**
Dilated aorta	Open true and false lumens	Most common
Dilated aorta	Thrombosed false lumen	Best prognosis
Dilated aorta	Thrombosed true lumen	Uncommon

aneurysm (TAAA). In fact, 25% of descending and TAAAs are postdissection dilatations [3].

Prosthetic replacement of a TAA or a TAAA is indicated if the diameter exceeds 6 cm. In Marfan patients the threshold is accepted at 5 cm. Additional indications for surgery comprise aorta-related symptoms like back pain and rapid, progressive aortic dilatation.

18.3 Surgical Techniques

18.3.1 Access

Surgical access is dependent on the extent of the aortic replacement. Figure 18.1 schematically depicts the different TAAs and TAAAs. Table 18.2 summarizes the surgical access for the corresponding aneurysms. Figure 18.2 depicts a giant post-type B dissection thoracic aneurysm. Figure 18.3 shows a perforation of the aortic wall and only thrombus in the false lumen prevented free rupture. Figure 18.4 illustrates the implanted polyester graft.

It is obvious that the majority of type B, C and D descending thoracic aneurysms can be treated by endovascular techniques; these modalities are described elsewhere in this book. Descending thoracic aneurysms with distal arch involvement can be treated by hybrid techniques in which an endograft covers the supraaortic arteries following bypass reconstruction of these arteries.

Table 18.2. Surgical access for the corresponding aneurysms

Extent of aneurysm	Access
Descending thoracic aorta, proximal part ± distal aortic arch (Fig. 18.1 a, b)	Left thoracotomy, fourth intercostal space
Descending thoracic aorta, mid + distal parts (Fig. 18.1 c)	Fifth intercostal space
Descending thoracic aorta, entire (Fig. 18.1 d)	Fifth intercostal space
Thoracoabdominal types I, II, III according to Crawford	Thoracolaparotomy, sixth intercostal space
Thoracoabdominal type IV	Laparotomy/left anterior thoracotomy, eighth intercostal space

18.3.2 Thoracic Approach

In open repair, type A and B descending thoracic aneurysms require a surgical approach via the fourth intercostal space. If, however, the aneurysm extends to the diaphragm, the fifth intercostal space will provide adequate exposure. In some cases it is necessary to resect the rib in order to extend the surgical working field.

The left lung is intubated with a selective bronchus blocker or double lumen tube, allowing collapse of the lung. In a substantial number of cases, the left lung is adherent to the aneurysm as a result of local fibrous reaction following dissection and dilatation. It is recommended to limit the surgical dissection of the lung as much as possible and only prepare the cross-clamp positions and the area of aortotomy.

Since the intimal tear is located at the level of the left subclavian artery in the majority of patients it is necessary to prepare a cross-clamp position proximal to the left subclavian artery. Indeed, it might be possible to clamp the aorta just distal to the subclavian artery, but often this approach does not provide enough "normal," nondissected aortic tissue to perform a secure anastomosis. During dissection of the aortic arch and left subclavian and carotid arteries, careful attention is paid to the vagus and recurrent nerve. The nerve can be dissected free from the aortic wall and secured with a vessel loop. In all cases we prefer to transect the Botalli duct, allowing more access for the proximal clamp. Safe clamping between the left carotid and the subclavian arteries requires circular dissection of the transverse aortic arch. Opening of the pericardium, posterior to the phrenic nerve, not only provides access to the left atrium or pulmonary vein, but also allows easier dissection at the inner curve of the aortic arch. After the inner and outer curves have been dissected, the final clamp position between the carotid and subclavian arteries can be prepared by two fingers encircling the aortic arch. During preparation of the distal clamp posi-

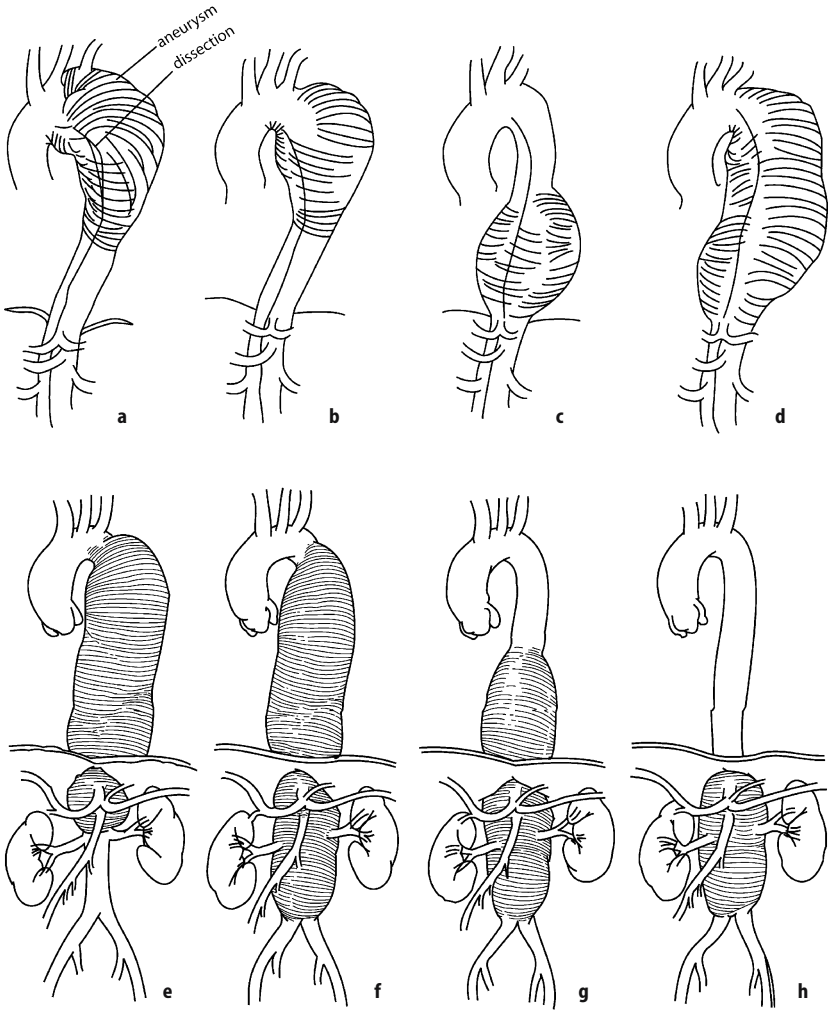


Fig. 18.1. Extent of descending thoracic aortic aneurysms (**a–d**) and thoracoabdominal aortic aneurysms (*TAAA*) (**e–h**) according to Crawford. **a** Distal arch and proximal descending thoracic aneurysm. **b** Proximal descending thoracic aneurysm. **c** Distal descending thoracic aneurysm. **d** Descending thoracic aneurysm involving the entire descending thoracic aorta. **e** TAAA from the left subclavian artery to the visceral arteries. **f** TAAA from the left subclavian artery to below the renal arteries. **g** TAAA from Th6 to below the renal arteries. **h** TAAA from the diaphragm to below the renal arteries

tion, the esophagus has to be identified and freed from the aorta. In some cases the esophagus might be adjacent to the aneurysm wall and accidental lesions caused by the clamp or anastomosis can lead to leakage in the early postoperative period or aorto-esophageal fistula in the late phase.

If the repair is performed under left heart bypass, the left atrium or pulmonary vein is used for venous cannulation. We prefer the use of the left upper or common pulmonary vein: following a double perstring with Prolene with pladgets the hooked cannula can be easily introduced. Only limited heparinization is required (0.5 mg/kg).

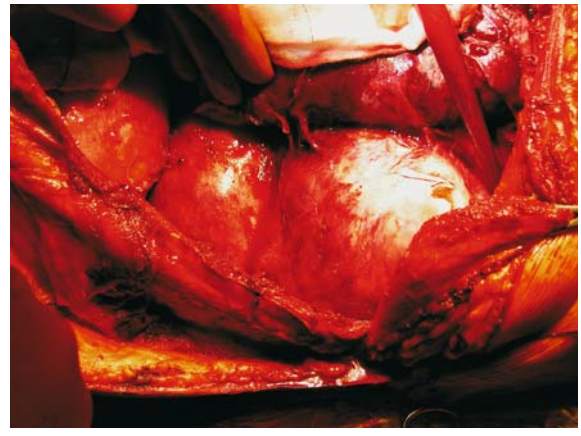


Fig. 18.2. Left thoracotomy via the fifth intercostal space and giant descending thoracic aortic aneurysm

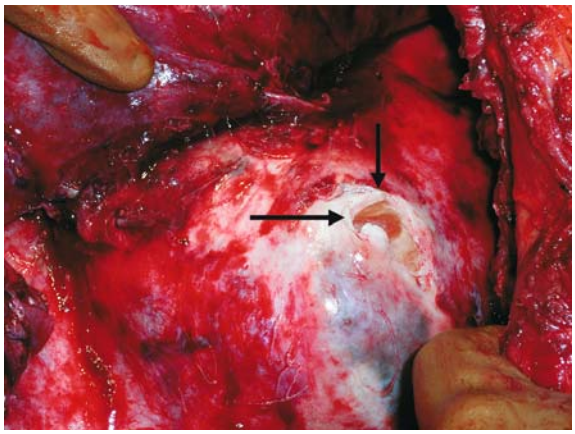


Fig. 18.3. The same aneurysm with focus on lateral aortic wall perforation. Thrombus mass in the false lumen prevents free rupture (*arrows*)

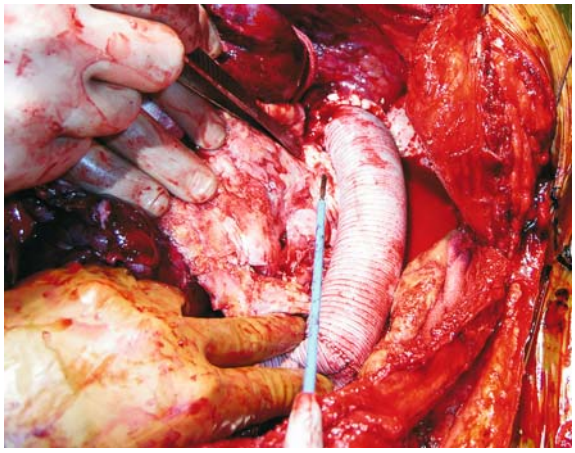


Fig. 18.4. Aortic aneurysm replacement in the same patient. Tip of electrocautery and end of forceps show the very small true lumen, whereas the rest of the giant aneurysm was dilated false lumen

18.3.3 Thoracoabdominal Approach

In type I, II and III TAAAs (according to Crawford), a left thoracolaparotomy is performed via the sixth intercostal space. The dissection of the thoracic part was described before; the abdominal part can be approached transperitoneally or retroperitoneally. We only transect the diaphragm at the anterior side (5–7 cm) and open the pillars of the crus to encircle the muscle with a loop, allowing traction and movement of the muscle. Dissection is continued laterally of the descending colon, behind the left kidney and the spleen. The left ureter has to be identified and secured with a vessel loop. The abdominal aorta is exposed following mobilization of the spleen, left kidney and colon. The soft tissue surrounding the aorta easily bleeds and adequate hemostasis is required. The large crossing veins to the hemiazygos system have to be oversewn and transected prior to aortotomy. The origin of the left renal artery is identified and the artery is secured with a vessel loop. If the aneurysm extends into the iliac arteries the surgical access has to be enlarged accordingly.

18.3.4 Abdominal Approach

Dilatation of a dissected aorta can occur in the thoracic, thoracoabdominal or abdominal aorta. If the dissected descending thoracic aorta is not or mildly dilated but the abdominal part is enlarged (more than 5–6 cm), surgical repair is limited to the abdominal aorta and the procedure is equivalent to a type IV TAAA.

Laparotomy with left subcostal extension usually provides adequate approach as described before. However, in some patients the angle at the supraceliac aorta is too narrow to perform safe dissection and repair. In these cases it is recommended to perform a limited anterior thoracotomy through the eighth or ninth intercostal space. This approach not only widens the angle but also allows clamping of the distal descending thoracic aorta.

18.4 Adjunctive Procedures

Operations on the descending and thoracoabdominal aorta have been notorious for their detrimental effects on organs supplied from these portions. Paraplegia, renal failure and visceral infarction are most feared complications of extensive aortic repair. Because of the fragile aortic quality and limited collateral networks, these complications occur even more frequently in dissected aneurysms or aneurysmatic dissections compared with degenerative aneurysmatic disease.

Spinal cord protection can be achieved by means of retrograde aortic perfusion or profound hypothermia and circulatory arrest. The latter, however, requires full heparinization with the inherent bleeding complications. We prefer left heart bypass with cannulation of the left atrium or pulmonary vein, only requiring limited heparinization. Cerebrospinal fluid drainage has extensively been evaluated and recently proven to be an important asset in the prevention of paraplegia [4].

Our surgical protocol of chronic aortic dissection with aneurysm formation is similar to our strategies in TAA and TAAA repair. Besides cerebrospinal fluid drainage (72 h) we use the technique of motor-evoked potentials. This is an accurate method for detecting cord ischemia, guiding surgical tactics to reduce neurologic deficit [5]. Unlike atherosclerotic aneurysmatic thoracoabdominal aortas, dissected aortas contain many patent intercostal and lumbar arteries. Monitoring mo-

tor-evoked potentials helps to identify those arteries which are crucial for spinal cord integrity, requiring reattachment in the aortic graft or selective grafting with small-diameter prostheses.

In descending TAA repair, distal aortic perfusion provides blood flow to the visceral organs, kidneys, lumbar arteries, pelvis and extremities. In thoracoabdominal repair, the celiac axis, superior mesenteric artery and both renal arteries are perfused by means of selective catheters which are part of the left heart bypass tubing system [6]. In patients with postdissection aneurysm, this technique allows continuous organ perfusion, offering the surgeon the opportunity to perform an optimal vascular reconstruction of the visceral and renal arteries. These arteries are always involved in the dissecting process and originate from the true or the false lumen. Dissection might even extend into the visceral and/or renal arteries. Adequate surgical repair, often including selective bypass grafts, is time-consuming. In addition, the quality of the aortic wall can require reinforcement by means of Teflon strips, adding even more time to the reconstruction. Selective organ perfusion allows these time-consuming procedures. The selective perfusion catheters contain a small-diameter channel, allowing pressure measurements. In addition, volume flow in each catheter is assessed.

In patients in whom the distal aortic arch is involved or proximal clamping is not safe, we use the selective perfusion catheters for antegrade cerebral perfusion [7]. Obviously, left heart bypass is not chosen and total extracorporeal circulation is installed. Several cannulation techniques can be applied, including femoral–femoral connection or left femoral artery and pulmonary artery. The patient is cooled to 28–30°C, the descending aorta cross-clamped, the aortic arch opened and perfusion catheters introduced in the left carotid and innominate arteries. The heart is either fibrillating with a left vent or cardioplegia is provided via a large, inflated Foley catheter in the ascending aorta. Transcranial Doppler encephalography and electroencephalography are used to assess the adequacy of antegrade perfusion. Then, the proximal anastomosis is performed and the patient rewarmed to regain normal heart activity.

18.5 General Considerations: Pitfalls During Surgery

Surgery for postdissection aneurysms differs from surgery for degenerative aneurysms. In general, blood loss in postdissection aneurysms is more profound because the majority of side branches are patent. As an example, in postdissection thoracic aneurysms, the majority of intercostal arteries are open, whereas in degenerative aneurysms the majority are occluded by plaques or thrombus [8]. A certain number of 3-French occlusion balloons should be on the sterile table to block the back-bleeding arteries. Also, a dissected aneurysm or an aneurysm of a dissected aorta is not always sufficiently cross-clamped: because of the fibrous septum and the discrepancy between tissue strength of the false and true lumens, the aortic clamp might clamp the false lumen completely and the true lumen incompletely. Therefore, it is necessary to have the aorta completely free (not necessary in a nondissected aorta), especially at the medial-posterior wall. Sometimes it is required to apply a second clamp.

In general, the diameter of the true channel is smaller than that of the false lumen. In some cases it can even be less than 5 or 10% of the total diameter. Since the true lumen is most often located at the right (medial) side, there is a potential risk that the true lumen is not identified and that repair is inadequate. Therefore, it is imperative to transect the aorta completely and open the true lumen longitudinally followed by excision of the septum. The dissected membrane is completely resected, leaving a longitudinal rim at the nondissected edges.

18.6 Additional Surgical Techniques

In addition to the techniques described in the previous sections and protective measures, some other important recommendations and variants have to be mentioned.

18.6.1 Descending Thoracic Postdissection Aortic Aneurysms

Following access and starting left heart bypass, it is technically easier to perform the distal anastomosis first. The cross-clamp has to be at least 5 cm distal to the planned area of anastomosis, because resection of the dissected membrane has to be performed, allowing distal blood flow through the true and false lumens. The quality of the aortic wall in the false lumen often requires reinforcement by means of a circumferential Teflon strip at the outer layer of the aorta. In some cases it is even necessary to apply a Teflon strip at the inner and outer layers, creating a sort of sandwiched anastomosis.

Reattachment of intercostal arteries is a challenge because in dissected, nonatherosclerotic aortas the majority are patent. Fortunately, the important intercostal arteries most often arise from the true lumen, allowing adequate anastomoses. In general, it is recommended to reattach all intercostals arteries between T8 and T12. In our experience, we rely on the information provided by motor evoked potential monitoring. In some cases it might be necessary to revascularize intercostal arteries with a separate graft, especially if the poor quality of the aorta does not allow a safe button reimplantation.

The proximal anastomosis might be hazardous, specifically if the intimal tear is located at the level of the left subclavian artery. Furthermore, in most instances this proximal part of the dissection is calcified, making a safe anastomosis even more difficult. In case of doubt we always prepare a more proximal clamp position, as described before.

18.6.2 Thoracoabdominal Aneurysms

In the majority of cases the dissection extends into the abdominal aorta and even the iliac and femoral arteries. Entries and reentries guarantee sufficient antegrade blood flow to all organs. Reversing the direction of blood flow by means of left heart bypass might cause different flow patterns and the surgeon cannot be sure about safe perfusion.

In patients with iliac dissection involvement and in whom the entire thoracoabdominal aorta has to be replaced, we prefer to reverse the direction of repair. Following exposure of the thoracoabdominal aorta, an infrarenal clamp position, if possible, is prepared. Heparin (0.5 mg/kg) is administered and the iliac arteries and infrarenal aorta are clamped. A bifurcated prosthetic graft is implanted and the body of the graft is clamped. A hooked aortic cannula is inserted in the prosthetic graft and fixated with perstrings. After cannulation of the left pulmonary vein the left heart bypass is started. The left renal artery is disconnected from the aorta and a selective perfusion catheter inserted through a 6- or 8-mm polyester graft. The end-to-end anastomosis is performed while continuous perfusion is provided. Then, the supraceliac aorta is clamped and the selective perfusion catheters positioned in the celiac axis, superior mesenteric artery and right renal artery. In general, these arteries are reattached in one aortic button. Depending on the size of the aneurysm and the possibility to cross-clamp the aorta sequentially, the descending thoracic aorta is replaced in steps. Motor-evoked potentials determine which intercostal arteries are reattached. The last step is the proximal anastomosis, according to the techniques described before.

18.7 Complications

18.7.1 Stroke

Patients with aortic dissection have a higher incidence of generalized atherosclerotic disease. Furthermore, calcification and thrombus formation at the area of the intimal tear comprise potential risks during cross-clamping, initiating turbulence and dislodging debris. No exact data on stroke rate following thoracic aortic repair are available. However, it is obvious that proximal clamping at the level of the subclavian artery or between the left carotid and subclavian arteries is prone for embolization of dislodged debris.

18.7.2 Paraplegia

Postoperative paraplegia is a dreadful event following thoracic and thoracoabdominal aortic surgery. Unlike degenerative aneurysms, in postdissection aneurysms the majority of intercostal and lumbar arteries are patent; therefore, the risk of paraplegia mainly depends on the extent of the diseased aortic segment and the adequacy of restoring blood supply to the spinal cord. In our experience of TAAA repair, approximately 25% of patients suffered from a type B dissection. Paraplegia rate is very low [8] and no differences between atherosclerotic and postdissection aneurysms existed.

If the surgical repair is limited to the descending thoracic aorta, neurologic deficit is less than 1% [9]. Obviously these excellent results are achieved by means of protective measures like left heart bypass, spinal fluid drainage and reattachment of intercostal arteries.

18.7.3 Renal Failure

The incidence of renal failure has extensively been reported in patients undergoing TAAA repair but to a much lesser extent after TAA exclusion. In patients with an initial type B dissection, one or both kidneys might have suffered from temporary or chronic renal ischemia with subsequent renal insufficiency. Furthermore, the majority of these patients suffer from severe hypertension and related renal complications.

Taking these considerations into account it is extremely important to provide adequate perfusion pressures to the kidney. If the thoracic aorta is replaced only, this can be achieved by means of left heart bypass. In TAAA surgery, pressure-guided selective perfusion can prevent renal failure in the majority of cases [6].

On the basis of the experience published in the literature, the surgical scenario mainly depends on the preoperative function of the kidneys. Furthermore, ischemic clamp times should not exceed 30 min. In patients with a normal kidney function undergoing an uncomplicated aneurysm resection, the clamp-and-sew technique without adjunctive procedures will lead to an uneventful outcome. In patients with preoperative renal insufficiency (creatinine greater than 200 µmol/l), the clamp-and-sew technique, irrespective of clamp time, will lead to temporary or permanent renal failure. In general, renal failure following extensive TAAA repair occurs in 10–18% of cases.

18.7.4 Visceral Ischemia

The incidence of gastrointestinal, biliary and hepatopancreatic ischemia following extensive TAAA repair is limited [10], but probably underestimated. Selective perfusion of the celiac axis and superior mesenteric artery has definitely improved the results; however, the immune responses of the visceral ischemia–reperfusion injury and the subsequent impact on multiple organ failure are unclear.

In thoracic aortic repair, visceral ischemia is hardly reported and therefore seems to be an irrelevant clinical problem.

18.7.5 Pulmonary Complications

Respiratory failure is the commonest complication after TAA and TAAA repair. The incidence of pulmonary complications depends on many pre-, intra- and postoperative variables. In a prospective study, Svensson et al. [11] evaluated 1,414 patients. Independent predictors for respiratory failure, defined as ventilatory support exceeding 48 h, were chronic pulmonary disease, history of smoking, and cardiac and renal complications. Pulmonary complications requiring respiratory support with tracheostomy were observed in 112 patients (8%) and 40% of these patients died. Money et al. [12] encountered 21% respiratory failure following thoracic aortic repair with a mortality rate of 42%. In patients who did not develop respiratory failure, the mortality rate was 6%. They identified age, type of aneurysm, excessive intraoperative blood transfusions, elevated creatinine and postoperative pneumonia as independent variables affecting respiratory failure. The mean number of days of intubation was 5.8. It should be emphasized that the studies of Svensson et al. and Money et al. mainly comprised patients with TAAAs. Few studies focus on respiratory failure following thoracic aneurysm repair, but it is evident that pulmonary complications occur less frequently than after thoracoabdominal aortic surgery. The main reason for this difference is transection of the diaphragm. Leaving the diaphragm intact significantly improves respiratory outcome, especially in type II aneurysms. In our own experience we reduced the incidence of respiratory failure from 61 to 45% by only transecting the first 5 cm of the diaphragm instead of complete transection, in patients with type II aneurysms.

The left lung should be handled with utmost care. Direct surgical trauma causing air leaks, subcutaneous emphysema, atelectasis or bleeding will provoke respiratory failure. For several years now we have left the left lung ventilated as much as possible, even during the thoracic part of the procedure. We feel that a continuously ventilated lung improves clinical outcome; however, not collapsing the lung increases the risk of damage (air leak, bleeding) by pushing or retracting.

18.8 Conclusion

The surgical management of chronic descending aortic dissection is actually similar to the treatment of descending and TAAAs. Stable, uncomplicated descending aortic and thoracoabdominal aortic dissections do not require surgical repair. The indication for surgical intervention is aneurysm formation, following the same criteria as in degenerative or Marfan-related TAAs and TAAAs.

Adjunctive protective measures and strategies are crucial in decreasing peri- and postoperative complications.

References

1. Akutsu K, Nejima J, Kiuchi K, Sasaki K, Ochi M, Tanaka K, Takano T. Effects of the patent false lumen on the long-term outcome of type B acute aortic dissection. Eur J Cardiothorac Surg 2004; 26:359–366.
2. Onitsuka S, Akashi H, Tayama K, Okazaki T, Ishihara K, Hiromatsu S, Aoyagi S. Long-term outcome and prognostic predictors of medically treated acute type B aortic dissections. Ann Thorac Surg 2004; 78:1268–1273.
3. Safi HJ, Miller CC, Estrera AL, Huynh TT, Porat FF, Hassoun HT, Buja LM. Chronic aortic dissection not a risk factor for neurologic deficit in thoracoabdominal aortic aneurysm repair. Eur J Vasc Endovasc Surg 2002; 23:244–250.
4. Coselli JS, Lemaire SA, Koksoy C, Schmittling ZC, Curling PF. Cerebrospinal fluid drainage reduces paraplegia after thoracoabdominal aortic aneurysm repair: results of a randomized clinical trial. J Vasc Surg 2002; 35:631–639.
5. Jacobs MJ, Elenbaas TW, Schurink GW, Mess WH, Mochtar B. Assessment of spinal cord integrity during thoracoabdominal aortic aneurysm repair. Ann Thorac Surg 2002; 74:S1864–1866.
6. Jacobs MJ, Eijsman L, Meylaerts SA, Balm R, Legemate DA, de Haan P, Kalkman CJ, de Mol BA. Reduced renal failure following thoracoabdominal aortic aneurysm repair by selective perfusion. Eur J Cardiothoracic Surg 1998; 14:201–205.
7. Jacobs MJ, de Mol BA, Veldman DJ. Aortic arch and proximal supraaortic arterial repair under continuous antegrade cerebral perfusion and moderate hypothermia. Cardiovasc Surg 2001; 9:396–402.
8. Jacobs MJ, de Mol BA, Elenbaas T, Mess WH, Kalkman CJ, Schurink GW, Mochtar B. Spinal cord blood supply in patients with thoracoabdominal aortic aneurysms. J Vasc Surg 2002; 123:531–538.
9. Safi HJ, Subramaniam MH, Miller CC, Loogan SM, Lliopoulos DC, Winnerkrist A, le Blevec D, Bahmini A. Progress in the management of type I thoraco-abdominal and descending thoracic aortic aneurysms. Ann Vasc Surg 1999; 13:457–462.
10. Svensson LG, Crawford ES, Hess KR, Coselli JS, Safi HJ. Experience with 1,509 patients undergoing thoraco-abdominal aortic operations. J Vasc Surg 1993; 17:357–370.

11. Svensson LG, Hess KR, Coselli JS, Safi HJ, Crawford ES. A prospective study of respiratory failure after high risk surgery on the thoraco-abdominal aorta. J Vasc Surg 1991; 14:271–282.

12. Money SR, Rice K, Crockett D, Becker M, Abdoh A, Wisselink W, Kazmier F, Hollier L. Risk of respiratory failure after repair of thoraco-abdominal aortic aneurysms. Am J Surg 1994; 168:152–155.

Endovascular Therapy for Aortic Dissection

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Contents

19.1 Aortic Dissection

Aortic dissection occurs when flowing blood enters the aortic wall through a disruption in the intimal lining and cleaves a longitudinal plane within the medial layer. Propagation of the delamination process can progress in variable lengths in a proximal and/or a distal direction from the entry tear (with isolated antegrade progression being the commoner pattern). As the process extends, a dissection flap or septum consisting of the cleaved lamellar layer of intima and partial thickness of media is created and partitions the original intima-lined lumen ("true" lumen) from a newly formed intramural channel ("false" lumen). This process may lead to additional disruptions in the intimal flap, producing exit or entry sites for flow between the dual lumens. Dissection propagation can also obstruct flow into aortic branch vessels, compromising downstream perfusion and causing distal ischemia (termed malperfusion syndrome). Aortic branch vessel compromise potentially involves the coronaries to iliac arteries and occurs by two mechanisms: static obstruction, where the aortic dissection flap extends directly into an aortic branch, or dynamic obstruction, where the dissection flap prolapses over the ostium of the branch vessel or collapses the true lumen of the aorta above it [1]. The eventual trajectory of flap progression results in a unique morphology for each case; thus, idiosyncratic anatomic relationships are formed between the flap, the true lumen, the false lumen, and the aortic branch vessels that are involved.

With an incidence of 2.6–3.5 per 100,000 person-years [2–4], aortic dissection is considered the commonest aortic catastrophe, occurring 2–3 times more frequently than abdominal aortic aneurysm rupture [5–7]. It tends to affect men more frequently with a male-to-female ratio ranging between 2:1 and 5:1 [8–12]. Sixty-three is the average age among 464 aortic dissection patients in the International Registry of Acute Aortic Dissection (IRAD) [9]. Patients with dissections involving the ascending aorta tend to present at a younger age (50–55 years old) than those with dissections of the descending aorta (60–70 years old) [6, 9, 13, 14].

The vast majority of aortic dissections originate in one of two locations: the lateral wall of the ascending aorta within a few centimeters of the aortic valve and in the descending aorta just distal to the site of insertion of the ligamentum arteriosum. These regions are presumably subjected to the greatest hemodynamic stress in terms of the first derivative of pressure (dP/dt) and overall pressure [15]. Anatomically, aortic dissections are classified under two systems. Under the DeBakey system, type I begins in the proximal aorta and involves both the ascending and the descending thoracic aorta, type II is confined to the ascending aorta, and type III is confined to the descending aorta [16]. Under the Stanford system, type A aortic dissection involves the ascending aorta, whereas type B dissection does not [17]. The simpler Stanford system has proven popular as the presence of ascending aortic involvement is associated with well-established prognostic implications and therapeutic considerations. Approximately 60–70% of aortic dissections are type A [5, 9]. Aortic dissections are also classified according to duration. In general, dissections present less than 2 weeks are considered acute, while those present more than 2 weeks are chronic. At 2 weeks, mortality curves of untreated aortic dissections begin to plateau [11]. A review of aortic dissection patients evaluated at the Mayo Clinic found a third to be chronic at diagnosis [13].

Although the etiology of aortic dissection is not well defined and the precise initiating event remains unclear, several predisposing factors have been identified [18]. As seen with aortic aneurysms, conditions that cause medial degeneration and in turn decrease aortic wall integrity and cohesiveness increase the risk of dissec-

tion. Patients with inherited connective tissue disorders, such as Marfan's syndrome and Ehlers-Danlos syndrome, display vascular cystic medial necrosis and are at high risk for aortic dissection. Such patients tend to present at a younger age with dissection of the ascending aorta [19–21]. In an IRAD study, Marfan's syndrome was present in half of those age 40 and under [22]. Necropsy studies have demonstrated, however, that medial degeneration is neither the predominant histological pattern of these lesions nor a prerequisite for dissection formation [23]. Other congenital predispositions to dissection include Turner's syndrome [24–26], Noonan's syndrome [27], aortic coarctation [23, 28], and bicuspid aortic valve [29, 30]. In the absence of congenital risk factors, systemic hypertension, found in 70–80% of all dissection patients, is the most important predisposing factor [9–13, 23, 31]. The incidence of coexisting hypertension is higher in patients with type B dissections (70 versus 36%) [9, 11, 23]. By placing a greater mechanical strain on the arterial wall, hypertension may accelerate the normal medial degeneration associated with aging. The potential causative role of hypertension is underlined by the near exclusive occurrence of pulmonary artery dissection in the setting of pulmonary hypertension [32]. Other less common acquired risk factors include giant cell aortitis [33, 34], cocaine use [35, 39], and deceleration and iatrogenic trauma [40–43]. There also exists a controversial association between pregnancy and dissection in young women [43–47].

The cardinal feature of acute aortic dissection is severe chest and/or back pain that is sharp, ripping, or tearing in nature and almost always abrupt in onset [9, 48, 49]. Patients with type A dissections more frequently experience anterior chest pain, whereas patients with type B dissections tend to experience back and abdominal pain [9]. Chronic dissection, in contrast, is usually painless and mostly without symptoms [13]. At least a third of acute aortic dissection patients have complications by manifestations secondary to aortic branch occlusion, proximal extension to the aortic root, and leakage to surrounding structures [50, 51]. Such complications include acute aortic regurgitation, myocardial ischemia/infarction, cardiac tamponade, stroke, syncope, pulse deficits, visceral ischemia, limb ischemia, and renal failure [9, 50].

The natural history of acute aortic dissection is particularly poor for type A dissections; the mortality rate for patients with untreated type A dissection approximates 1–2% per hour during the first 24 h after symptom onset and reaches 80% by 2 weeks [7, 11, 52]. Type B dissections, however, are less lethal and are associated with a better prognosis [9, 17, 53, 54]. Common causes of death include aortic rupture, severe aortic regurgitation, and end-organ compromise secondary to major branch vessel obstruction [4, 9, 11]. Chronic aortic dissection is also associated with a high incidence of rupture with a 5-year survival of 10–15% [52]. Progression to aneurysmal dilatation is common in chronic-phase dissections. In the 20-year follow-up of operated survivors of aortic dissection by De Bakey et al. [10], the development of and subsequent rupture of aortic aneurysms was the leading cause of late deaths.

With improvements in diagnostic imaging modalities, two radiologic and pathologic variants of aortic dissection have been recently recognized and diagnosed with increasing frequency: intramural hematoma (IMH) and penetrating atherosclerotic ulcer (PAU) [18, 55–61]. When associated with acute symptoms, these three pathologic entities are often grouped together under the general classification termed "acute aortic syndrome." It is estimated that 5–17% of diagnosed aortic dissections may actually be IMH or PAU [18, 62, 63]. IMH, considered a precursor of classic dissection, is characterized by blood in the aortic wall without an intimal disruption and is thought to originate from rupture of the vaso vasorum [18, 64]. PAU is defined by an ulceration of aortic atherosclerotic plaque that penetrates the internal elastic lamina, intima, media, and possibly the adventitia [56, 57, 65]. Compared with classic aortic dissection, both IMH and PAU tend to be found in older patients with a history of hypertension and are more likely to be located in the descending thoracic aorta (43% in IMH and 90% in PAU) [18, 57, 66, 67]. Both entities can progress to frank dissection, rupture, or aneurysm formation [56, 59, 65, 68–70]. IMH tends to behave like classic aortic dissection. Like type A dissection, type A IMH is associated with a greater risk of adverse progression [71]. In contrast, PAU rarely progresses to classic dissection and, instead, more frequently forms aneurysms (up to 50%) [57].

19.2 Conventional Treatment

A critical event in the evaluation of patients with suspected aortic dissection is the determination of whether the ascending aorta is involved. Therapeutic strategy hinges on whether type A or type B dissection is present. In general, acute type A dissections are considered surgical emergencies, while uncomplicated type B dissections are treated medically [72]. Regardless of dissection location, however, all patients in whom there is a strong suspicion of aortic dissection should be immediately placed on antihypertensive therapy to limit dissection progression [73, 74].

Given the associated high risk of sudden death due to aortic rupture, aortic regurgitation, cardiac tamponade, or myocardial infarction, type A dissection mandates expeditious diagnosis and emergent operative intervention [75, 76]. Surgical therapy involves excision of the intimal tear, removal of the most diseased segment of aorta, obliteration of the false channel, reconstitution

of the aorta directly or with the interposition of a synthetic graft, and, if necessary, restoration of aortic valve competence [75]. In a review of 547 type A dissections in the IRAD, the in-hospital mortality was 27% for patients treated surgically and 56% for those treated medically [77]. The associated survival benefit of surgical intervention remained in patients greater than 70 years old [78].

There is a small subset of type A dissections where the entry tear is in the descending aorta and propagation occurs up to the ascending aorta in a retrograde manner (retrograde type A). The incidence of this subtype ranges from 10 to 27% among De Bakey type III dissections and from 4 to 20% among Stanford type A dissections [17, 79–82]. Emergent surgical treatment is still mandated for this subtype although it is challenging and controversial [79–83]. Graft replacement of only the ascending aorta retains the primary entry tear and consequently the postoperative risk of rupture. On the other hand, excision of the entry tear and replacement of both the ascending aorta and the aortic arch is associated with high mortality and morbidity [81, 82].

Patients with acute type B dissection are at lower risk of early death from complications and tend to be older and of higher surgical risk. A large retrospective series of uncomplicated type B dissection patients from Duke University and Stanford University suggested equivalent outcome with medical and surgical treatment [84]. Consequently, the preferred treatment for most patients has therefore been medical in the form of aggressive antihypertensive treatment predominantly with beta-blockers. Surgical intervention is generally reserved for those who develop complications such as rupture, dissection progression, aneurysmal growth, refractory hypertension, intractable pain, and malperfusion syndromes from aortic branch vessel obstruction [76, 85, 86]. Underlying connective tissue disease should also prompt consideration for early operative repair [79, 87]. An IRAD study of the outcomes of this complication-specific approach revealed in-house mortality rates of 11 and 31% for medical and surgical treatment groups, respectively [9]. Surgical treatment is also associated with significant morbidity, particularly paraplegia (7–36%) [88–91]. However, it is important to note that because medical therapy alone does not stop blood flow to the false lumen, 20–50% of patients who survive the acute phase develop aneurysmal dilatation of the false lumen within 1–5 years after onset [15, 54, 92].

By definition, patients with chronic dissection have survived the acute phase of high mortality. In-hospital survival rates of such patients have approximated 90%, independent of whether they were managed surgically or medically [93]. Medical therapy, therefore, is recommended for patients with both type A and type B chronic dissection, with surgery reserved for those who develop an aneurysm or a rupture [94, 95].

Aortic dissection is complicated by malperfusion syndromes resulting from aortic branch vessel obstruction in 30–50% of patients [96, 97]. Such cases are associated with a particularly poor prognosis; those complicated by mesenteric and renal ischemia have surgical mortality rates of up to 87 and 70%, respectively [96–99]. In type A dissection, aortic branch vessel obstruction is usually corrected concomitantly with surgical management for dissection [96]. In type B dissection, complication with malperfusion syndrome is an indication for surgical intervention and treatment options include fenestration of the intimal flap, replacement of the diseased aorta, and establishment of bypasses to the ischemic vessels [99].

The treatment paradigm for IMH parallels the approach in classic aortic dissection [66, 100]. A meta-analysis review of 11 IMH studies found cumulative mortality for patients with type A IMH to be 24% for those treated surgically, 47% for those treated medically, and 34% overall; mortality for patients with type B IMH was 14% overall, with little difference between surgical (15%) and medical (13%) treatment groups [101]. At present, no consensus therapeutic strategy for PAU exists although a more aggressive surgical approach, independent of location, is being increasingly considered, especially in symptomatic patients [56, 68, 102]. The Yale Thoracic Aortic Diseases Group has identified a 40% rupture rate among PAU patients managed medically [56, 68]. At a minimum, PAU patients with complications should undergo surgical treatment [103].

19.3 Endovascular Stent-Graft Treatment

Aortic dissection is the second commonest investigational application of thoracic stent-graft technology. The concept of endovascular stent-graft repair of aortic dissection is predicated on successful placement of the device over the primary entry tear to obliterate blood flow into the false lumen. The intent is to mimic the effect of successful operative repair with isolation of the false lumen from the circulation and redirection of blood flow into the true lumen. As demonstrated in experimental models of dissection, coverage of the primary entry tear is the optimal method of relieving true lumen collapse and concomitantly promotes thrombosis of the false lumen [104]. Interestingly, dissections with naturally thrombosed false lumen are associated with improved prognosis [80, 105, 106]. False lumen patency, in contrast, contributes to progressive aortic dilatation and is a predictor of late mortality [107]. In the typical type B dissection case, progressive thrombosis proceeds distally, irrespective of the location of the primary intimal disruption [108]. The tempo of false lumen thrombosis is variable and is influenced by several factors such as the size of the false lumen and amount of resid-

ual false lumen flow via uncovered additional tears. Over time, the false lumen thrombus consolidates and the dissection lumen itself resolves. Besides such gains in aortic remodeling, this endovascular surrogate for open surgery confers additional benefits: reversal of downstream branch vessel ischemia (particularly in patients with dynamic obstruction) and protection against thoracic false lumen aneurysm formation. In acute dissection, reversal of dynamic obstruction occurs expeditiously after stent-graft placement [109].

Clinical evaluation of stent-grafts for the treatment of patients with complicated and uncomplicated acute type B dissection, a select subset of type A dissection, as well as chronic dissection with false lumen aneurysm formation are currently ongoing at a growing number of institutions around the world. Applications are limited to dissections with entry tears distal to the left subclavian artery. Initial results are encouraging. Unfortunately, as with that of thoracic aortic aneurysm, the literature for aortic dissection often mixes outcomes from applications in different clinical contexts in terms of age of dissection, extent of disease, and presence of complications. Nonetheless, valuable lessons from this early experience have served to fuel progress in our understanding of the disease process as well as its management by less invasive means. Table 19.1 summarizes the results in published studies on endovascular stent-grafting for aortic dissections. In this section, we will first review clinical experiences within specific categories of acute dissection followed by an overview of aggregate results, trends, and challenges.

Although there is general consensus that acute type B dissection should be managed medically with surgical treatment reserved for cases with complications [72], the intermediate- and long-term outcome resulting from this treatment paradigm remains unsatisfactory. The mortality rate among patients treated medically alone ranges from 11 to 20% [6, 9, 86]; furthermore, such patients are at continued long-term risk of aneurysm formation and rupture [15, 54, 92]. Mortality among type B patients treated surgically ranges from 30 to 35% and is significantly worse for those complicated by end-organ ischemia [9, 79, 93, 96].

Our group recently studied the use of thoracic stent-grafts among 15 complicated acute type B and four retrograde type A dissection patients at Stanford University and Mie University School of Medicine in Japan [109]. Eleven of these patients exhibited symptomatic branch vessel obstruction. The primary entry tear was sealed in 95% of cases with associated complete and partial thrombosis of the thoracic false lumen in 79 and 21% of patients, respectively. In all cases, true lumen expansion occurred immediately but no aneurysmal expansion or rupture was found on follow-up. More impressively, follow-up imaging found complete false lumen resolution and no residual evidence of dissection in six cases. Thirty-day mortality was 16% with no additional deaths during a mean follow-up of 13 months. Hutschala et al. [116] have also explored the use of stent-grafts in a cohort of acute type B patients who were without indications for surgery and found similar outcomes. In light of these results, the INSTEAD (Investigation of stent-grafts in patients with type B aortic dissection) trial, a prospective, multicenter, randomized, controlled clinical study, is under way to compare the 1-year outcome of type B aortic dissection treated by stent-graft placement versus conventional antihypertensive therapy [124].

There remains significant controversy over the proper treatment for patients with acute type A dissection with an entry tear in the descending aorta. Kato et al. [114, 125] treated ten retrograde type A patients without evidence of cardiac tamponade or severe aortic regurgitation using endovascular stent-grafts. Entry closure and complete thrombosis of the false lumen of both the ascending and the descending aorta was achieved in all patients. During a mean follow-up of 20 months, all patients were alive and without rupture or aneurysm formation.

Application of endoluminal stent-grafts in the setting of chronic dissection has been met with skepticism given the anatomic and hemodynamic complexity of such lesions [126]. The thick and fibrotic nature of a chronic dissection flap may limit true lumen expansion following device placement. Additionally, multiple fenestrations between the true and false lumens often exist and may hinder false lumen thrombosis. A number of groups, however, have achieved good results with stent-graft treatment of chronic dissections [117, 120, 127, 128].

Nienaber et al. [110] prospectively evaluated stent-graft treatment in 12 patients with chronic type B dissection and compared the results with 12 matched surgical controls. Proximal entry closure and complete thrombosis of the false lumen at 3 months was achieved in all patients. Stent-graft treatment resulted in no mortality or morbidity, while surgical treatment resulted in four deaths and five adverse events. At 3 months, complete thrombosis of the false lumen was achieved in all patients with clear evidence of true lumen expansion and false lumen shrinkage. A similar study by Kato et al. [113] also demonstrated favorable aortic remodeling. However, in a second study by the same group that evaluated both chronic and acute dissections, complete false lumen thrombosis was documented in all patients but complete obliteration of the false lumen was found in only 38.5% of the chronic dissection patients versus 70% of the acute dissection patients (mean follow-up of 27 months) [120].

Endovascular stent-graft treatment of aortic dissections offers the additional benefit of relieving dynamic branch vessel obstruction. In our 1999 study of acute dissection patients [109], 11 patients presented with symptomatic branch vessel obstruction involving 38 in-

Table 19.1. Summary data on studies of endovascular treatment of aortic dissections

Reference	*N*	Mean follow-up (months)	Devices	Sealing of primary entry tear (%)	Thrombosis of false lumen	30 day mortality	Long-term survival (time)	Paraplegia
Dake et al. [109]	19: 4 acute retrograde type A, 15 acute type B (11 with symptomatic compromise of branch vessels)	13	Homemade	94.7	78.9% complete, 21.1% partial	15.8%	84.2% (mean 13 months)	0%
Nienaber et al. [110]	12 chronic type B (12 matched surgical controls)	12	Talent	100	100% complete	0% stent-graft, 8.7% surgical	100% for endovascular, 66.7% for surgical (12 months)	0%
Czermak et al. [111]	7 type B: 5 acute, 2 chronic	14	Talent, Vanguard	85.7	85.7%	0%	85.7% (mean 14 months)	0%
Hausegger et al. [112]	5 acute type B uncomplicated	13.4	Talent	100	100% complete	0%	100% (mean 13.4 months)	0%
Kato et al. [113]	15 chronic: 14 type B, 1 type A	24	Homemade	100	100% complete	0%	100% (mean 24 months)	0%
Kato et al. [114]	10 type A retrograde (7 acute, 3 chronic)	20	Homemade	100	100% complete	0%	100% (mean 20 months)	0%
Sailer et al. [115]	7 acute and chronic type B, 4 PAU	8.5	Excluder, Talent, Vanguard	100	63.6% complete, 27.3% partial	0%	100% (mean 8.5 months)	0%
Hutschala et al. [116]	9 acute type B uncomplicated	3	Excluder, Talent	100	22.2% complete, 77.8% partial	0%	100% (mean 3 months)	11%
Kato et al. [117]	38: 10 acute type A, 14 acute type B, 14 chronic type B	27	Homemade	NA	NA	5.3%	92% acute, 100% chronic (1 year)	3%
Palma et al. [118]	70: 35 acute type B, 23 chronic type B, 6 IMH, 6 PAU	29	Homemade	92.9	NA	5.7%	91.4% (mean 29 months)	0%
Shim et al. [119]	15 type B	31.5	Homemade	93.3	66.7% complete	6.7%	86.7% (mean 31.5 months)	NA
Shimono et al. [120]	37: 16 acute complicated (9 type A retrograde, 7 type B), 8 acute type B uncomplicated, 13 chronic type B	24.5	Homemade	100	94.4% complete or partial	2.7% overall, 6.3% acute complicated	97.3% overall (actuarial survival 2 years), 93.8% acute complicated, 100% acute uncomplicated, 100% chronic	NA
Lonn et al. [121]	20: 14 acute type B, 4 chronic type B, 2 chronic type A	13	Excluder, Talent, Hemobahn	100	90%	15%	85% (mean 13 months)	5%
Lopera et al. [122]	10 type B complicated: 4 acute, 6 chronic	20	Homemade	90	60% complete, 30% partial	0%	90% (mean 20 months)	NA
Bell et al. [123]	115	NA	Commercial	82	NA	6.9%	NA	0.9%
Nienaber et al. [124]	105: 87 type B, 18 type A	32.4	NA	100	NA	2.9%	89.5% (mean 32.4 months)	0%

PAU penetrating atherosclerotic ulcer, *IMH* intramural hematoma, *NA* not available

fradiaphragmatic vascular beds. Of these, 22 were obstructed exclusively by a dynamic process, 15 by both dynamic and static mechanisms, and one by static obstruction alone. After stent-graft placement, all 22 of the branch vessels with exclusively dynamic obstruction and six of the 15 arteries with combined dynamic and static involvement were immediately reperfused. Adjunctive endovascular procedures were used to relieve persistent ischemia in the remaining obstructed cases.

Briefly, two endovascular techniques can be used to relieve branch obstruction. Endovascular placement of an uncovered stent in the true lumen of the obstructed branch vessel relieves static obstruction [129, 130]. Percutaneous balloon fenestration is used to mitigate dynamic obstructions by creating an artificial tear in the flap to allow communication between the true and false lumens [131]. In this procedure, the intimal flap is usually first punctured using a needle, crossed with a guide wire, and then opened using a balloon. Although the early results of these endovascular treatments appear encouraging [129–132], the long-term outcomes are unknown.

Efforts to extend application of endovascular stent-graft technology to aortic dissection variants have focused predominantly on PAU [133–136]. Because PAU is usually focal and almost always in the descending aorta, it is an ideal anatomic target for endovascular stent-graft repair [102]. To minimize the risk of paraplegia, a short device could be used to locally seal and stabilize the lesion.

In a meta-analysis of 54 patients accumulated from 13 studies, complete sealing of the ulcer was achieved in 94% of patients, neurologic complications occurred in 6% of patients, and in-hospital mortality was 5% [137]. We recently studied a cohort of 26 symptomatic type B PAU patients (half deemed inoperable) treated by endovascular repair [134]. The primary success rate was 92% and the perioperative mortality was 12% with no cases of paraplegia. At 1 and 5 years, survival estimates were 81 and 65%, respectively.

Upon review of the literature across multiple subtypes of aortic dissection, it is clear that successful entry closure was possible in 85–100% of cases. Since most primary entry tears in the descending aorta begin immediately distal to the left subclavian artery, adequate proximal anchoring of the device may be difficult. In several studies, the anatomical selection criterion for the minimum distance between the entry tear and the subclavian artery origin was set at 5 mm [110, 114, 117]. Intentional coverage of the left subclavian origin with expectant management was commonly used in these studies [112]. Alternatively, a device with a proximal segment consisting of a bare stent can be placed across the left subclavian artery to effectively maximize the length of graft contact with the aortic wall prior to the tear. However, in other settings, where there is a retrograde proximal extension of the dissection from the tear to the subclavian artery, it may be necessary to place the graft over the branch with its leading margin between the left carotid and subclavian arteries. In addition to carefully monitoring the patient after the procedure for ischemic symptoms referable to the covered left subclavian artery, it is important to carefully image the thoracic aorta to exclude persistent perfusion of the false lumen via retrograde subclavian flow around the device.

In parallel, successful entry tear coverage induced complete or partial thoracic false lumen thrombosis in 85–100% of patients, even in the settings of chronic and retrograde type A dissections. Partial thrombosis of the false lumen can still be advantageous and can protect the false lumen from enlarging over time since systemic blood pressure is no longer directly transmitted through the primary entry tear. The age of the disease process may play a role in the degree of false lumen thrombosis; it has been found to be most pronounced in those dissections treated within 6 months of presentation [108]. True lumen expansion and partial or full false lumen resolution was noted in several studies [109, 110, 119, 120].

Whereas false lumen thrombosis was consistently observed at the level of the implanted stent-graft, thrombosis distal to the device and particularly in abdominal false lumens was less common. It is thought that uncovered portions of a dissection flap oscillate with retrograde flow through distal flap disruptions, preventing false lumen thrombosis. This holds implications regarding device length. Most investigators implant stent-grafts that are clearly longer than the entry tear, usually in the range 10–15-cm long. This added length confers an appearance to the aortic morphology after implantation that is more normal anatomically, especially in the arch, than that observed following placement of a short device focally over the entry tear. In addition, the longer device promotes a more rapid tempo of thrombus formation within the proximal false lumen. Given that aortic rupture is a cause of death after device implantation [109], acceleration of false lumen thrombosis may also improve mortality outcomes. However, extension of stent-graft coverage into the distal one third of the descending thoracic aorta increases the risk of spinal cord ischemia. It has thus been suggested that distal extension with bare stents may provide the structural stability needed to promote false lumen thrombosis without sacrificing intercostal flow.

19.4 Conclusion

The recent development of endovascular stent-graft technology and its application as an alternative management strategy to medical therapy or open surgical intervention of patients with aortic dissection is an ex-

citing and potentially valuable advance. As conventional treatments for aortic dissection and its attendant complications are often associated with significant failure rates, result in substantial morbidity and mortality, and/or do little to reduce the risk of aneurysm formation as late sequelae improved treatment options are desired. Here, we have reviewed the current clinical experience with stent-graft placement for treatment of complicated and uncomplicated acute type B dissection, retrograde type A dissection, chronic dissection, and PAU. It is imperative to first appreciate the wide array of clinical, anatomic, and temporal manifestations within the umbrella pathology of aortic dissection. Evaluation of the role of endoluminal stent-graft technology must be performed within the context of each of these subgroups through rigorous, prospective controlled investigations and compared against respective standard treatment. Although this poses a much more significant challenge, the encouraging early results highlighted here underscore the potential for stent-graft therapy to supplant conventional – and often suboptimal – treatment paradigms and to provide patients with a less invasive therapeutic alternative that may concomitantly achieve gains in survival.

References

1. Williams DM, Lee DY, Hamilton BH, Marx MV, Narasimham DL, Kazanjian SN, Prince MR, Andrews JC, Cho KJ, Deeb GM. The dissected aorta: part III. Anatomy and radiologic diagnosis of branch-vessel compromise. Radiology 1997; 203:37–44.
2. Bickerstaff LK, Pairolero PC, Hollier LH, Melton LJ, Van Peenen HJ, Cherry KJ, Joyce JW, Lie JT. Thoracic aortic aneurysms: a population-based study. Surgery 1982; 92:1103–1108.
3. Clouse WD, Hallett JW Jr, Schaff HV, Spittell PC, Rowland CM, Ilstrup DM, Melton LJ 3rd. Acute aortic dissection: population-based incidence compared with degenerative aortic aneurysm rupture. Mayo Clin Proc 2004; 79:176–180.
4. Meszaros I, Morocz J, Szlavi J, Schmidt J, Tornoci L, Nagy L, Szep L. Epidemiology and clinicopathology of aortic dissection. Chest 2000; 117:1271–1278.
5. Sorensen HR, Olsen H. Ruptured and dissecting aneurysms of the aorta. Incidence and prospects of surgery. Acta Chir Scand 1964; 128:644–650.
6. Wheat MW Jr. Acute dissecting aneurysms of the aorta: diagnosis and treatment – 1979. Am Heart J 1980; 99:373–387.
7. Anagnostopoulos CE, Prabhakar MJ, Kittle CF. Aortic dissections and dissecting aneurysms. Am J Cardiol 1972; 30:263–273.
8. Coady MA, Rizzo JA, Goldstein LJ, Elefteriades JA. Natural history, pathogenesis, and etiology of thoracic aortic aneurysms and dissections. Cardiol Clin 1999; 17:615–635; vii.
9. Hagan PG, Nienaber CA, Isselbacher EM, Bruckman D, Karavite DJ, Russman PL, Evangelista A, Fattori R, Suzuki T, Oh JK, Moore AG, Malouf JF, Pape LA, Gaca C, Sechtem U, Lenferink S, Deutsch HJ, Diedrichs H, Marcos y Robles J, Llovet A, Gilon D, Das SK, Armstrong WF, Deeb GM, Eagle KA. The International Registry of Acute Aortic Dissection (IRAD): new insights into an old disease. JAMA 2000; 283:897–903.
10. De Bakey ME, McCollum CH, Crawford ES, Morris GC Jr, Howell J, Noon GP, Lawrie G. Dissection and dissecting aneurysms of the aorta: twenty-year follow-up of five hundred twenty-seven patients treated surgically. Surgery 1982; 92:1118–1134.
11. Hirst AE Jr, Johns VJ Jr, Kime SW Jr. Dissecting aneurysm of the aorta: a review of 505 cases. Medicine (Baltimore) 1958; 37:217–279.
12. Wilson SK, Hutchins GM. Aortic dissecting aneurysms: causative factors in 204 subjects. Arch Pathol Lab Med 1982; 106:175–180.
13. Spittell PC, Spittell JA Jr, Joyce JW, Tajik AJ, Edwards WD, Schaff HV, Stanson AW. Clinical features and differential diagnosis of aortic dissection: experience with 236 cases (1980 through 1990). Mayo Clin Proc 1993; 68:642–651.
14. Roberts WC. Aortic dissection: anatomy, consequences, and causes. Am Heart J 1981; 101:195–214.
15. Wheat MW Jr. Acute dissection of the aorta. Cardiovasc Clin 1987; 17:241–262.
16. De Bakey ME, Beall AC Jr, Cooley DA, Crawford ES, Morris GC Jr, Garrett HE, Howell JF. Dissecting aneurysms of the aorta. Surg Clin North Am 1966; 46:1045–1055.
17. Daily PO, Trueblood HW, Stinson EB, Wuerflein RD, Shumway NE. Management of acute aortic dissections. Ann Thorac Surg 1970; 10:237–247.
18. Coady MA, Rizzo JA, Elefteriades JA. Pathologic variants of thoracic aortic dissections. Penetrating atherosclerotic ulcers and intramural hematomas. Cardiol Clin 1999; 17:637–657.
19. Roberts WC, Honig HS. The spectrum of cardiovascular disease in the Marfan syndrome: a clinico-morphologic study of 18 necropsy patients and comparison to 151 previously reported necropsy patients. Am Heart J 1982; 104:115–135.
20. Smith JA, Fann JI, Miller DC, Moore KA, DeAnda A Jr, Mitchell RS, Stinson EB, Oyer PE, Reitz BA, Shumway NE. Surgical management of aortic dissection in patients with the Marfan syndrome. Circulation 1994; 90:II235–242.
21. Stolle CA, Pyeritz RE, Myers JC, Prockop DJ. Synthesis of an altered type III procollagen in a patient with type IV Ehlers-Danlos syndrome. A structural change in the alpha 1(III) chain which makes the protein more susceptible to proteinases. J Biol Chem 1985; 260:1937–1944.
22. Januzzi JL, Isselbacher EM, Fattori R, Cooper JV, Smith DE, Fang J, Eagle KA, Mehta RH, Nienaber CA, Pape LA. Characterizing the young patient with aortic dissection: results from the International Registry of Aortic Dissection (IRAD). J Am Coll Cardiol 2004; 43:665–669.
23. Larson EW, Edwards WD. Risk factors for aortic dissection: a necropsy study of 161 cases. Am J Cardiol 1984; 53:849–855.
24. Birdsall M, Kennedy S. The risk of aortic dissection in women with Turner syndrome. Hum Reprod 1996; 11:1587.
25. Clement CI, Brereton J, Clifton-Bligh P. Aortic dissection in Turner syndrome. Med J Aust 2004; 180:584.
26. Rubin K. Aortic dissection and rupture in Turner syndrome. J Pediatr 1993; 122:670.
27. Shachter N, Perloff JK, Mulder DG. Aortic dissection in Noonan's syndrome (46 XY turner). Am J Cardiol 1984; 54:464–465.
28. Moodie DS. Aortic dissection and coarctation. Curr Opin Cardiol 1990; 5:649–654.
29. Edwards WD, Leaf DS, Edwards JE. Dissecting aortic aneurysm associated with congenital bicuspid aortic valve. Circulation 1978; 57:1022–1025.

30. Roberts CS, Roberts WC. Dissection of the aorta associated with congenital malformation of the aortic valve. J Am Coll Cardiol 1991; 17:712–716.
31. Roberts WC. The hypertensive diseases. Evidence that systemic hypertension is a greater risk factor to the development of other cardiovascular diseases than previously suspected. Am J Med 1975; 59:523–532.
32. Steurer J, Jenni R, Medici TC, Vollrath T, Hess OM, Siegenthaler W. Dissecting aneurysm of the pulmonary artery with pulmonary hypertension. Am Rev Respir Dis 1990; 142:1219–1221.
33. Ginsburg R. Aortic aneurysm and dissection in giant cell arteritis. Ann Intern Med 1996; 124:615.
34. Liu G, Shupak R, Chiu BK. Aortic dissection in giant-cell arteritis. Semin Arthritis Rheum 1995; 25:160–171.
35. Fisher A, Holroyd BR. Cocaine-associated dissection of the thoracic aorta. J Emerg Med 1992; 10:723–727.
36. Perron AD, Gibbs M. Thoracic aortic dissection secondary to crack cocaine ingestion. Am J Emerg Med 1997; 15:507–509.
37. Hsue PY, Salinas CL, Bolger AF, Benowitz NL, Waters DD. Acute aortic dissection related to crack cocaine. Circulation 2002; 105:1592–1595.
38. Eagle KA, Isselbacher EM, DeSanctis RW. Cocaine-related aortic dissection in perspective. Circulation 2002; 105:1529–1530.
39. Rashid J, Eisenberg MJ, Topol EJ. Cocaine-induced aortic dissection. Am Heart J 1996; 132:1301–1304.
40. Januzzi JL, Sabatine MS, Eagle KA, Evangelista A, Bruckman D, Fattori R, Oh JK, Moore AG, Sechtem U, Llovet A, Gilon D, Pape L, O'Gara PT, Mehta R, Cooper JV, Hagan PG, Armstrong WF, Deeb GM, Suzuki T, Nienaber CA, Isselbacher EM. Iatrogenic aortic dissection. Am J Cardiol 2002; 89:623–626.
41. Rogers FB, Osler TM, Shackford SR. Aortic dissection after trauma: case report and review of the literature. J Trauma 1996; 41:906–908.
42. Still RJ, Hilgenberg AD, Akins CW, Daggett WM, Buckley MJ. Intraoperative aortic dissection. Ann Thorac Surg 1992; 53:374–379; discussion 380.
43. Nienaber CA, Eagle KA. Aortic dissection: new frontiers in diagnosis and management: part I: from etiology to diagnostic strategies. Circulation 2003; 108:628–635.
44. Mandel W, Evans EW, Walford RL. Dissecting aortic aneurysm during pregnancy. N Engl J Med 1954; 251:1059–1061.
45. Cavanzo FJ, Taylor HB. Effect of pregnancy on the human aorta and its relationship to dissecting aneurysms. Am J Obstet Gynecol 1969; 105:567–568.
46. Schnitker MA, Major MC, Bayer CA. Dissecting aneurysm of the aorta in young individuals, particularly in association with pregnancy: With report of a case. Ann Intern Med 1944; 20:486–511.
47. Immer FF, Bansi AG, Immer-Bansi AS, McDougall J, Zehr KJ, Schaff HV, Carrel TP. Aortic dissection in pregnancy: analysis of risk factors and outcome. Ann Thorac Surg 2003; 76:309–314.
48. Klompas M. Does this patient have an acute thoracic aortic dissection? JAMA 2002; 287:2262–2272.
49. von Kodolitsch Y, Schwartz AG, Nienaber CA. Clinical prediction of acute aortic dissection. Arch Intern Med 2000; 160:2977–2982.
50. Khan IA, Nair CK. Clinical, diagnostic, and management perspectives of aortic dissection. Chest 2002; 122:311–328.
51. Oderich GS, Panneton JM. Acute aortic dissection with side branch vessel occlusion: open surgical options. Semin Vasc Surg 2002; 15:89–96.
52. Lindsay J Jr, Hurst JW. Clinical features and prognosis in dissecting aneurysm of the aorta. A re-appraisal. Circulation 1967; 35:880–888.
53. Nienaber CA, Eagle KA. Aortic dissection: new frontiers in diagnosis and management: part II: therapeutic management and follow-up. Circulation 2003; 108:772–778.
54. Doroghazi RM, Slater EE, DeSanctis RW, Buckley MJ, Austen WG, Rosenthal S. Long-term survival of patients with treated aortic dissection. J Am Coll Cardiol 1984; 3:1026–1034.
55. Dake MD. Aortic intramural haematoma: current therapeutic strategy. Heart 2004; 90:375–378.
56. Coady MA, Rizzo JA, Hammond GL, Pierce JG, Kopf GS, Elefteriades JA. Penetrating ulcer of the thoracic aorta: what is it? How do we recognize it? How do we manage it? J Vasc Surg 1998; 27:1006–1015; discussion 1015–1006.
57. Harris JA, Bis KG, Glover JL, Bendick PJ, Shetty A, Brown OW. Penetrating atherosclerotic ulcers of the aorta. J Vasc Surg 1994; 19:90–98; discussion 98–99.
58. Lui RC, Menkis AH, McKenzie FN. Aortic dissection without intimal rupture: diagnosis and management. Ann Thorac Surg 1992; 53:886–888.
59. Nienaber CA, Richartz BM, Rehders T, Ince H, Petzsch M. Aortic intramural haematoma: natural history and predictive factors for complications. Heart 2004; 90:372–374.
60. Nienaber CA, Sievers HH. Intramural hematoma in acute aortic syndrome: more than one variant of dissection? Circulation 2002; 106:284–285.
61. Song JK, Kim HS, Kang DH, Lim TH, Song MG, Park SW, Park SJ. Different clinical features of aortic intramural hematoma versus dissection involving the ascending aorta. J Am Coll Cardiol 2001; 37:1604–1610.
62. Bolognesi R, Manca C, Tsialtas D, Vasini P, Zeppellini R, De Domenico R, Cucchini F, Visioli O. Aortic intramural hematoma: an increasingly recognized aortic disease. Cardiology 1998; 89:178–183.
63. Lansman SL, McCullough JN, Nguyen KH, Spielvogel D, Klein JJ, Galla JD, Ergin MA, Griepp RB. Subtypes of acute aortic dissection. Ann Thorac Surg 1999; 67:1975–1978; discussion 1979–1980.
64. Gore I. Pathogenesis of dissecting aneurysm of the aorta. AMA Arch Pathol 1952; 53:142–153.
65. Stanson AW, Kazmier FJ, Hollier LH, Edwards WD, Pairolero PC, Sheedy PF, Joyce JW, Johnson MC. Penetrating atherosclerotic ulcers of the thoracic aorta: natural history and clinicopathologic correlations. Ann Vasc Surg 1986; 1:15–23.
66. Nienaber CA, von Kodolitsch Y, Petersen B, Loose R, Helmchen U, Haverich A, Spielmann RP. Intramural hemorrhage of the thoracic aorta. Diagnostic and therapeutic implications. Circulation 1995; 92:1465–1472.
67. Maraj R, Rerkpattanapipat P, Jacobs LE, Makornwattana P, Kotler MN. Meta-analysis of 143 reported cases of aortic intramural hematoma. Am J Cardiol 2000; 86:664–668.
68. Tittle SL, Lynch RJ, Cole PE, Singh HS, Rizzo JA, Kopf GS, Elefteriades JA. Midterm follow-up of penetrating ulcer and intramural hematoma of the aorta. J Thorac Cardiovasc Surg 2002; 123:1051–1059.
69. Ganaha F, Miller DC, Sugimoto K, Do YS, Minamiguchi H, Saito H, Mitchell RS, Dake MD. Prognosis of aortic intramural hematoma with and without penetrating atherosclerotic ulcer: a clinical and radiological analysis. Circulation 2002; 106:342–348.
70. Sueyoshi E, Matsuoka Y, Sakamoto I, Uetani M, Hayashi K, Narimatsu M. Fate of intramural hematoma of the aorta: CT evaluation. J Comput Assist Tomogr 1997; 21:931–938.
71. von Kodolitsch Y, Csosz SK, Koschyk DH, Schalwat I, Loose R, Karck M, Dieckmann C, Fattori R, Haverich A, Berger J, Meinertz T, Nienaber CA. Intramural hematoma of the aorta: predictors of progression to dissection and rupture. Circulation 2003; 107:1158–1163.

72. Erbel R, Alfonso F, Boileau C, Dirsch O, Eber B, Haverich A, Rakowski H, Struyven J, Radegran K, Sechtem U, Taylor J, Zollikofer C, Klein WW, Mulder B, Providencia LA. Diagnosis and management of aortic dissection. Eur Heart J 2001; 22:1642–1681.
73. Wheat MW Jr, Palmer RF, Bartley TD, Seelman RC. Treatment of dissecting aneurysms of the aorta without surgery. J Thorac Cardiovasc Surg 1965; 50:364–373.
74. Wheat MW Jr. Current status of medical therapy of acute dissecting aneurysms of the aorta. World J Surg 1980; 4:563–569.
75. Miller DC, Stinson EB, Oyer PE, Rossiter SJ, Reitz BA, Griepp RB, Shumway NE. Operative treatment of aortic dissections. Experience with 125 patients over a sixteen-year period. J Thorac Cardiovasc Surg 1979; 78:365–382.
76. Masuda Y, Yamada Z, Morooka N, Watanabe S, Inagaki Y. Prognosis of patients with medically treated aortic dissections. Circulation 1991; 84:III7–13.
77. Mehta RH, Suzuki T, Hagan PG, Bossone E, Gilon D, Llovet A, Maroto LC, Cooper JV, Smith DE, Armstrong WF, Nienaber CA, Eagle KA. Predicting death in patients with acute type of aortic dissection. Circulation 2002; 105:200–206.
78. Mehta RH, O'Gara PT, Bossone E, Nienaber CA, Myrmel T, Cooper JV, Smith DE, Armstrong WF, Isselbacher EM, Pape LA, Eagle KA, Gilon D. Acute type A aortic dissection in the elderly: clinical characteristics, management, and outcomes in the current era. J Am Coll Cardiol 2002; 40:685–692.
79. Miller DC, Mitchell RS, Oyer PE, Stinson EB, Jamieson SW, Shumway NE. Independent determinants of operative mortality for patients with aortic dissections. Circulation 1984; 70:I153–164.
80. Erbel R, Oelert H, Meyer J, Puth M, Mohr-Katoly S, Hausmann D, Daniel W, Maffei S, Caruso A, Covino FE, et al. Effect of medical and surgical therapy on aortic dissection evaluated by transesophageal echocardiography. Implications for prognosis and therapy. The European Cooperative Study Group on Echocardiography. Circulation 1993; 87:1604–1615.
81. Kazui T, Tamiya Y, Tanaka T, Komatsu S. Extended aortic replacement for acute type A dissection with the tear in the descending aorta. J Thorac Cardiovasc Surg 1996; 112:973–978.
82. Lansman SL, Galla JD, Schor JS, Ergin MA, Griepp RB. Subtypes of acute aortic dissection. J Card Surg 1994; 9:729–733.
83. von Segesser LK, Killer I, Ziswiler M, Linka A, Ritter M, Jenni R, Baumann PC, Turina MI. Dissection of the descending thoracic aorta extending into the ascending aorta. A therapeutic challenge. J Thorac Cardiovasc Surg 1994; 108:755–761.
84. Glower DD, Fann JI, Speier RH, Morrison L, White WD, Smith LR, Rankin JS, Miller DC, Wolfe WG. Comparison of medical and surgical therapy for uncomplicated descending aortic dissection. Circulation 1990; 82:IV39–46.
85. Fann JI, Miller DC. Aortic dissection. Ann Vasc Surg 1995; 9:311–323.
86. Elefteriades JA, Hartleroad J, Gusberg RJ, Salazar AM, Black HR, Kopf GS, Baldwin JC, Hammond GL. Long-term experience with descending aortic dissection: the complication-specific approach. Ann Thorac Surg 1992; 53:11–20; discussion 20–11.
87. Schor JS, Yerlioglu ME, Galla JD, Lansman SL, Ergin MA, Griepp RB. Selective management of acute type B aortic dissection: long-term follow-up. Ann Thorac Surg 1996; 61:1339–1341.
88. Svensson LG, Crawford ES, Hess KR, Coselli JS, Safi HJ. Variables predictive of outcome in 832 patients undergoing repairs of the descending thoracic aorta. Chest 1993; 104:1248–1253.
89. Svensson LG, Crawford ES, Hess KR, Coselli JS, Safi HJ. Dissection of the aorta and dissecting aortic aneurysms. Improving early and long-term surgical results. Circulation 1990; 82:IV24–38.
90. Miller DC. The continuing dilemma concerning medical versus surgical management of patients with acute type B dissections. Semin Thorac Cardiovasc Surg 1993; 5:33–46.
91. Neya K, Omoto R, Kyo S, Kimura S, Yokote Y, Takamoto S, Adachi H. Outcome of Stanford type B acute aortic dissection. Circulation 1992; 86:II1–7.
92. Richter GM, Allenberg JR, Schumacher H, Hansmann J, Vahl C, Hagl S. Aortic dissection – when operative treatment, when endoluminal therapy? Radiologe 2001; 41:660–667.
93. Crawford ES, Svensson LG, Coselli JS, Safi HJ, Hess KR. Aortic dissection and dissecting aortic aneurysms. Ann Surg 1988; 208:254–273.
94. Juvonen T, Ergin MA, Galla JD, Lansman SL, McCullough JN, Nguyen K, Bodian CA, Ehrlich MP, Spielvogel D, Klein JJ, Griepp RB. Risk factors for rupture of chronic type B dissections. J Thorac Cardiovasc Surg 1999; 117:776–786.
95. Kato M, Bai H, Sato K, Kawamoto S, Kaneko M, Ueda T, Kishi D, Ohnishi K. Determining surgical indications for acute type B dissection based on enlargement of aortic diameter during the chronic phase. Circulation 1995; 92:II107–112.
96. Cambria RP, Brewster DC, Gertler J, Moncure AC, Gusberg R, Tilson MD, Darling RC, Hammond G, Mergerman J, Abbott WM. Vascular complications associated with spontaneous aortic dissection. J Vasc Surg 1988; 7:199–209.
97. Fann JI, Sarris GE, Mitchell RS, Shumway NE, Stinson EB, Oyer PE, Miller DC. Treatment of patients with aortic dissection presenting with peripheral vascular complications. Ann Surg 1990; 212:705–713.
98. Borst HG, Laas J, Heinemann M. Type A aortic dissection: diagnosis and management of malperfusion phenomena. Semin Thorac Cardiovasc Surg 1991; 3:238–241.
99. Heinemann MK, Buehner B, Schaefers HJ, Jurmann MJ, Laas J, Borst HG. Malperfusion of the thoracoabdominal vasculature in aortic dissection. J Card Surg 1994; 9:748–755; discussion 755–747.
100. Robbins RC, McManus RP, Mitchell RS, Latter DR, Moon MR, Olinger GN, Miller DC. Management of patients with intramural hematoma of the thoracic aorta. Circulation 1993; 88:II1–10.
101. Sawhney NS, DeMaria AN, Blanchard DG. Aortic intramural hematoma: an increasingly recognized and potentially fatal entity. Chest 2001; 120:1340–1346.
102. Eggebrecht H, Baumgart D, Herold U, Jakob H, Erbel R. Multiple penetrating atherosclerotic ulcers of the abdominal aorta: treatment by endovascular stent graft placement. Heart 2001; 85:526.
103. Braverman AC. Penetrating atherosclerotic ulcers of the aorta. Curr Opin Cardiol 1994; 9:591–597.
104. Chung JW, Elkins C, Sakai T, Kato N, Vestring T, Semba CP, Slonim SM, Dake MD. True-lumen collapse in aortic dissection: part II. Evaluation of treatment methods in phantoms with pulsatile flow. Radiology 2000; 214:99–106.
105. Ergin MA, Phillips RA, Galla JD, Lansman SL, Mendelson DS, Quintana CS, Griepp RB. Significance of distal false lumen after type A dissection repair. Ann Thorac Surg 1994; 57:820–824; discussion 825.
106. Williams DM, Andrews JC, Marx MV, Abrams GD. Creation of reentry tears in aortic dissection by means of percutaneous balloon fenestration: gross anatomic and histologic considerations. J Vasc Interv Radiol 1993; 4:75–83.
107. Bernard Y, Zimmermann H, Chocron S, Litzler JF, Kastler B, Etievent JP, Meneveau N, Schiele F, Bassand JP. False lumen patency as a predictor of late outcome in aortic dissection. Am J Cardiol 2001; 87:1378–1382.

108. Kato M, Matsuda T, Kaneko M, Kuratani T, Mizushima T, Seo Y, Uchida H, Kichikawa K, Maeda M, Ohnishi K. Outcomes of stent-graft treatment of false lumen in aortic dissection. Circulation 1998; 98:II305–311; discussion II311-302.
109. Dake MD, Kato N, Mitchell RS, Semba CP, Razavi MK, Shimono T, Hirano T, Takeda K, Yada I, Miller DC. Endovascular stent-graft placement for the treatment of acute aortic dissection. N Engl J Med 1999; 340:1546–1552.
110. Nienaber CA, Fattori R, Lund G, Dieckmann C, Wolf W, von Kodolitsch Y, Nicolas V, Pierangeli A. Nonsurgical reconstruction of thoracic aortic dissection by stent-graft placement. N Engl J Med 1999; 340:1539–1545.
111. Czermak BV, Waldenberger P, Fraedrich G, Dessl AH, Roberts KE, Bale RJ, Perkmann R, Jaschke WR. Treatment of Stanford type B aortic dissection with stent-grafts: preliminary results. Radiology 2000; 217:544–550.
112. Hausegger KA, Tiesenhausen K, Schedlbauer P, Oberwalder P, Tauss J, Rigler B. Treatment of acute aortic type B dissection with stent-grafts. Cardiovasc Interv Radiol 2001; 24:306–312.
113. Kato N, Hirano T, Shimono T, Ishida M, Takano K, Nishide Y, Kawaguchi T, Yada I, Takeda K. Treatment of chronic aortic dissection by transluminal endovascular stent-graft placement: preliminary results. J Vasc Interv Radiol 2001; 12:835–840.
114. Kato N, Shimono T, Hirano T, Ishida M, Yada I, Takeda K. Transluminal placement of endovascular stent-grafts for the treatment of type A aortic dissection with an entry tear in the descending thoracic aorta. J Vasc Surg 2001; 34:1023–1028.
115. Sailer J, Peloschek P, Rand T, Grabenwoger M, Thurnher S, Lammer J. Endovascular treatment of aortic type B dissection and penetrating ulcer using commercially available stent-grafts. Am J Roentgenol 2001; 177:1365–1369.
116. Hutschala D, Fleck T, Czerny M, Ehrlich M, Schoder M, Lammer J, Wolner E, Grabenwoger M. Endoluminal stent-graft placement in patients with acute aortic dissection type B. Eur J Cardiothorac Surg 2002; 21:964–969.
117. Kato N, Shimono T, Hirano T, Suzuki T, Ishida M, Sakuma H, Yada I, Takeda K. Midterm results of stent-graft repair of acute and chronic aortic dissection with descending tear: the complication-specific approach. J Thorac Cardiovasc Surg 2002; 124:306–312.
118. Palma JH, de Souza JA, Rodrigues Alves CM, Carvalho AC, Buffolo E. Self-expandable aortic stent-grafts for treatment of descending aortic dissections. Ann Thorac Surg 2002; 73:1138–1141; discussion 1141–1132.
119. Shim WH, Koo BK, Yoon YS, Choi D, Jang Y, Lee DY, Chang BC. Treatment of thoracic aortic dissection with stent-grafts: midterm results. J Endovasc Ther 2002; 9:817–821.
120. Shimono T, Kato N, Yasuda F, Suzuki T, Yuasa U, Onoda K, Hirano T, Takeda K, Yada I. Transluminal stent-graft placements for the treatments of acute onset and chronic aortic dissections. Circulation 2002; 106:I241–1247.
121. Lonn L, Delle M, Falkenberg M, Lepore V, Klingenstierna H, Radberg G, Risberg B. Endovascular treatment of type B thoracic aortic dissections. J Card Surg 2003; 18:539–544.
122. Lopera J, Patino JH, Urbina C, Garcia G, Alvarez LG, Upegui L, Jhanchai A, Qian Z, Castaneda-Zuniga W. Endovascular treatment of complicated type-B aortic dissection with stent-grafts: midterm results. J Vasc Interv Radiol 2003; 14:195–203.
123. Bell RE, Buth J, Taylor PR, Harris P, Fransen G, Thomas S, Myhre H. UK and EUROSTAR thoracic stenting registries: combined experience [abstract]. J Endovasc Ther 2004; 11:I6.
124. Nienaber CA, Rehders TK, Ince H, Petzsch M, Korber T, Weber F, Schareck W. Stent-graft intervention for type B aortic dissection: update of European trail results [abstract]. J Endovasc Ther 2004; 11:I29.
125. Shimono T, Kato N, Tokui T, Onoda K, Hirano T, Takeda K, Yuasa H, Yada I. Endovascular stent-graft repair for acute type A aortic dissection with an intimal tear in the descending aorta. J Thorac Cardiovasc Surg 1998; 116:171–173.
126. Fann JI, Miller DC. Endovascular treatment of descending thoracic aortic aneurysms and dissections. Surg Clin North Am 1999; 79:551–574.
127. Nienaber CA, Ince H, Petzsch M, Rehders T, Korber T, Schneider H, Weber F. Endovascular treatment of acute aortic syndrome. Endovasc Today 2003; Suppl:12–15.
128. Kato N, Hirano T, Shimono T, Nomura Y, Goto M, Sakuma H, Yada I, Takeda K. Treatment of chronic type B aortic dissection with endovascular stent-graft placement. Cardiovasc Intervent Radiol 2000; 23:60–62.
129. Slonim SM, Miller DC, Mitchell RS, Semba CP, Razavi MK, Dake MD. Percutaneous balloon fenestration and stenting for life-threatening ischemic complications in patients with acute aortic dissection. J Thorac Cardiovasc Surg 1999; 117:1118–1126.
130. Slonim SM, Nyman U, Semba CP, Miller DC, Mitchell RS, Dake MD. Aortic dissection: percutaneous management of ischemic complications with endovascular stents and balloon fenestration. J Vasc Surg 1996; 23:241–251; discussion 251–243.
131. Williams DM, Lee DY, Hamilton BH, Marx MV, Narasimham DL, Kazanjian SN, Prince MR, Andrews JC, Cho KJ, Deeb GM. The dissected aorta: percutaneous treatment of ischemic complications – principles and results. J Vasc Interv Radiol 1997; 8:605–625.
132. Chavan A, Hausmann D, Dresler C, Rosenthal H, Jaeger K, Haverich A, Borst HG, Galanski M. Intravascular ultrasound-guided percutaneous fenestration of the intimal flap in the dissected aorta. Circulation 1997; 96:2124–2127.
133. Brittenden J, McBride K, McInnes G, Gillespie IN, Bradbury AW. The use of endovascular stents in the treatment of penetrating ulcers of the thoracic aorta. J Vasc Surg 1999; 30:946–949.
134. Demers P, Miller DC, Mitchell RS, Kee ST, Chagonjian L, Dake MD. Stent-graft repair of penetrating atherosclerotic ulcers in the descending thoracic aorta: mid-term results. Ann Thorac Surg 2004; 77:81–86.
135. Kos X, Bouchard L, Otal P, Chabbert V, Chemla P, Soula P, Meites G, Joffre F, Rousseau H. Stent-graft treatment of penetrating thoracic aortic ulcers. J Endovasc Ther 2002; 9 Suppl 2:II25–31.
136. Murgo S, Dussaussois L, Golzarian J, Cavenaile JC, Abada HT, Ferreira J, Struyven J. Penetrating atherosclerotic ulcer of the descending thoracic aorta: treatment by endovascular stent-graft. Cardiovasc Intervent Radiol 1998; 21:454–458.
137. Eggebrecht H, Baumgart D, Schmermund A, Herold U, Hunold P, Jakob H, Erbel R. Penetrating atherosclerotic ulcer of the aorta: treatment by endovascular stent-graft placement. Curr Opin Cardiol 2003; 18:431–435.

The Use of Endografts to Treat Chronic Descending Thoracic Aortic Dissections

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Contents

20.1 Introduction

Acute type B aortic dissection is still associated with mortality as high as 10% in spite of recent sophisticated medical treatment mainly because of catastrophic complications, such as aortic rupture or aortic branch ischemia. Once the very acute phase has been overcome, the disease is well tamed and the mortality rate reduces markedly [13]. However, there are still some problems in this story. One is the patient's compliance to medical therapy. Strict control of blood pressure is mandatory in those patients for their life time to avoid aortic rupture or redissection. In addition, their quality of life is significantly impaired for the same reason. The other serious problem is development of so-called dissecting aneurysms. It has been reported that 14–20% of patients with acute type B aortic dissection treated by drug therapy alone eventually develop false aneurysms during the first 4–5 years of follow-up [1, 6, 8, 12, 17, 25, 28, 36]. Surgical aortic replacement is required in these patients to avoid rupture of the aneurysm. However, it is associated with various problems such as the need for extensive aortic replacement. Although the operative mortality rate in these patients was improved from 17–40% in the 1970s to 4–17% in the 1980s, surgical intervention is still associated with considerable invasiveness and morbidity despite advances in surgical techniques and perioperative management [6, 8, 9, 11, 12, 24, 26, 27, 34].

The purpose of this chapter is to describe the strategy and the experience of Mie University Hospital for the treatment of patients with chronic type B aortic dissection [19].

20.2 Emergence of Endografting

Endovascular repair including percutaneous fenestration and stenting had been performed mainly for the treatment of visceral or leg ischemia before endografting became clinically available. Its safety and efficacy have been reported by several investigators [30, 31, 37]. On the other hand, endografting was initiated for the treatment of abdominal aortic aneurysms and it is now a good alternative to surgical graft replacement for both abdominal and thoracic aortic aneurysms [2, 4].

Application of endografting to aortic dissection was first reported by Dake et al. [5] and Nienaber et al. [29] in 1999. Dake et al. applied endografting to acute aortic dissection, while Nienaber et al. applied it to chronic dissection. Although the number of patients and the follow-up term of both reports are extremely limited, clinicians were encouraged by their reports and started endografting for the treatment of aortic dissection all over the world.

20.3 Terminology and Classification

Terminology and classification are the same as those that used for surgical intervention. Either De Bakey classification or Stanford classification can be used to classify the diseases [23]. However, the location of the entry tear should be added when Stanford classification is adopted since endografting directly depends on it.

In terms of the age of dissection, those within 14 days since onset are referred to as acute dissection, while those beyond 14 days are referred to as chronic according to the current classification [7]. This definition comes from the fact that those patients who survive beyond the acute phase have better prognosis [24]. However, this classification could be modified when endografting is applied. Sixty-six patients with aortic dissection were treated with endografting at Mie University Hospital. Among them 37 patients were treated within 1 month after diagnosis, while the other 29 patients were treated at more than 1 month after diagnosis. Intraoperative new intimal injury caused by the edge of the endograft developed in two patients who were treated within 1 month (0 and 21 days) (Fig. 20.1). Postoperative new intimal injury developed in four patients who were treated within 1 month, too (0, 7, 9, and 21 days) (Fig. 20.2). On the other hand, no intimal injury developed in those patients who were treated after more than 1 month. From this fact that 1 month seems the turning point at which the intimal flap becomes stiff and stable enough to tolerate the force acting on the edge of the endograft, dissection within 1 month might as well be referred to as "acute", and that which is older than 1 month might as well be referred to as "chronic" when endovascular treatment of aortic dissection is discussed [19–21].

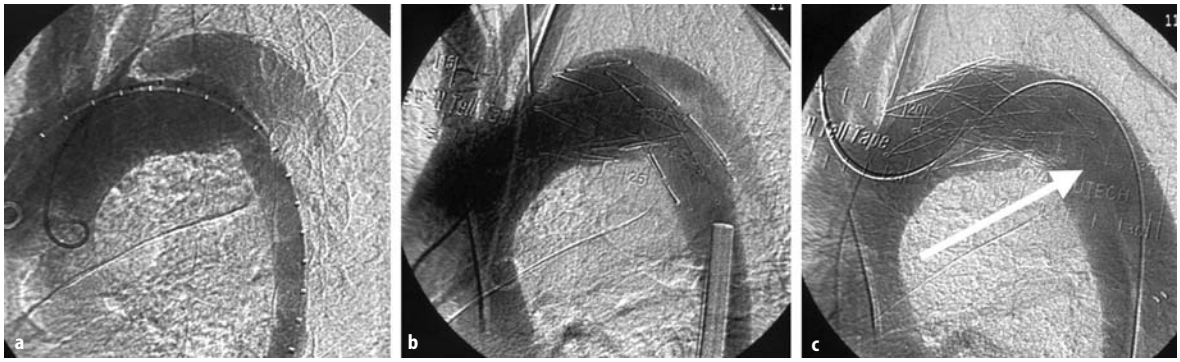

Fig. 20.1. New intimal tear caused by balloon dilatation in a patient with acute dissection. **a** Aortography obtained before endografting. **b** Aortography obtained immediately after endografting. Type I endoleak is clearly observed. Balloon dilatation was performed to obtain good apposition. **c** Aortography obtained after balloon dilatation. A new intimal tear (*arrow*) was created at the bottom end of the endograft

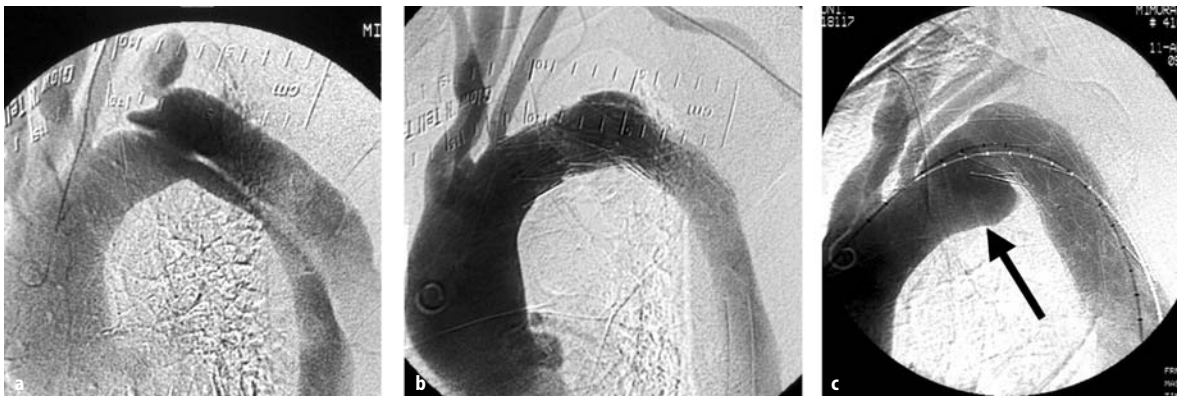

Fig. 20.2. Aneurysmal degeneration caused by the edge of the endograft in a patient with acute dissection. **a** Aortography obtained before endografting. **b** Aortography obtained immediately after endografting. The entry tear is completely closed. **c** Aortography obtained 4 months later. Aneurysmal degeneration (*arrow*) developed at the top end of the endograft. (From Kato et al. [20])

Table 20.1. Pathophysiological inclusion criteria

Aortic diameter greater than 50 mm on computed tomography
Aortic diameter greater than 40 mm on computed tomography in a dissection present for 1 month or less
Enlargement of an ulcer-like projection during follow-up
Persistent back pain despite medical therapy
Findings suggestive of aortic branch ischemia

20.4 Goals and Indications of Endografting

20.4.1 Pathophysiological Indication

The goal of the treatment of chronic aortic dissection is to avoid aortic rupture or redissection. Therefore, the same indication as that of surgical graft replacement can be applied in terms of pathophysiology.

The inclusion criteria are as follows: (1) aortic diameter greater than 50 mm on computed tomography (CT); (2) aortic diameter greater than 40 mm on CT in a dissection present for 1 month or less; (3) enlargement of an ulcer-like projection (ULP) during follow-up; (4) persistent back pain despite medical therapy; and (5) findings suggestive of aortic branch ischemia (Table 20.1). Those patients with an aortic diameter greater than 40 mm on CT in a dissection present for 1 month or less may be followed up until the aortic diameter exceeds 50 mm; however, treatment of these patients is justified, since the actuarial rate of freedom from aortic enlargement in patients with an aortic diameter greater than 40 mm is less than 30% at 5 years [18]. Growing ULP is also included in the inclusion criteria. Sueyoshi et al. [33] followed 32 patients with intramural hematomas using CT. They observed ULPs in 20 patients, and these ULPs eventually progressed to saccular aneurysms during follow-up in 60% of the patients.

20.4.2 Anatomical Indication

The rationale of endografting is to close the entry tear, induce thrombosis in the false lumen, and then prevent aortic pressure from acting on the aortic wall of the false lumen, while surgical replacement is to replace the most damaged portion, in other words, the most dilated portion of the aorta, with a graft. Therefore, there are some anatomical limitations for endografting unlike for graft replacement. They are almost similar to those applied to endografting for the treatment of thoracic aortic aneurysms.

First, one of the most important criteria is that the distance between the entry tear and the major aortic branches must be sufficiently long to allow the endograft to seal off the entry tear. The distance is 1.5–2 cm in general. When the entry tear is like a pinhole, the distance could be less than 1.5 cm; however, this limitation could be altered depending on which device is used. Use of branched or fenestrated endografts could increase candidates for endovascular treatment [15].

Second, the access route, i.e., the true lumen, must be large enough to allow a large delivery system go through it. The true lumen can be easily dilated during advancement of a delivery system in the case of acute dissection even if it is so compressed by the false lumen that the delivery sheath does not seem to advance into it. In contrast the true lumen must be large enough since the intimal flap is fibrotic in the case of chronic dissection.

Another limitation, in addition to the curve of the landing zone or tortuosity of the access route, is concerned with blood supply to aortic branches. It is not unusual that aortic branches are involved in the dissecting process. Involvement of aortic branches reportedly develops in one third to half of all patients with aortic dissection [9]. The patterns of branch involvement have already been classified in various ways [24, 32, 37]. There is one rare but ominous pattern among them in which approximation of the torn edges of the intima

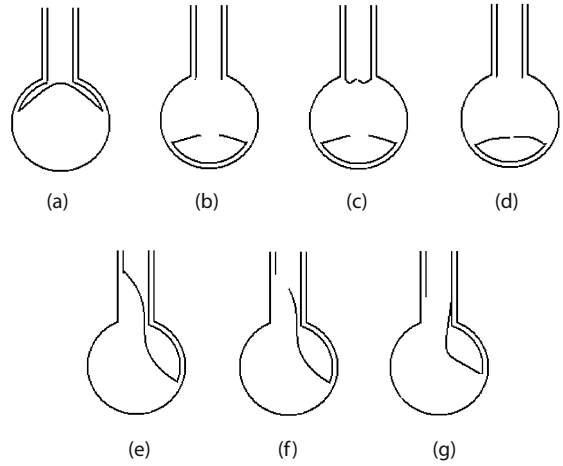

Fig. 20.3. a The aortic branch itself is not involved by dissection in this pattern. However, blood supply is compromised owing to true lumen compression by the false lumen. **b–d** The aortic branch is involved at its orifice. Ischemia does not develop in **b** since there is a large natural fenestration. The branch is occluded owing to approximation of intimal edges at the branch orifice in **c**. The fenestration may be tiny and approximate during follow-up in **d**. Ischemia could develop after endografting in such a case. **e–g** Involvement develops within the branch itself. There is no reentry within the branch in **e**. Ischemia could develop after endografting in chronic cases, while immediate recovery of blood flow in the true lumen can be expected in acute cases. Ischemia does not develop in **f** that has reentry within the branch. In **g** ischemia could develop after endografting in chronic cases because the intimal flap could become healed to the opposite wall of the branch. (Adapted from Smith et al. [32])

occurs and the blood supply to the branch is totally dependent on the false lumen (Fig. 20.3). When such cases undergo graft replacement, redirection of distal flow purposely into both the true and the false lumens is required to avoid potential risk of organ ischemia. Instead of surgical redirection of blood flow percutaneous fenestration, which can be performed simultaneously or beforehand, seems a useful adjunctive method in such cases [22].

20.5 Diagnosis

Most information necessary for endovascular entry closure, i.e., location of the entry tear, shape and size of the landing zones, and diameter and tortuosity of the access route, is obtained by CT. In addition involvement of aortic branches can be shown in most cases. Especially, multislice CT with EKG synchronization could detect and evaluate the entry tear itself even in acute cases in which the intimal flap usually moves rapidly and is sometimes hard to be identified on conventional CT. Some prefer MRI to CT because it does not need radiation exposure [29]; however, its spatial resolution is not high enough even with the latest software and hardware. In addition, it cannot be used for follow-up of patients who underwent endovascular repair with endografts made of magnetic material such as stainless steel. Therefore, MRI would be preserved only for those patients with renal insufficiency or contrast medium allergy.

Aortography is mandatory even if CT can provide almost all information because it is an important method of preoperative simulation. It is sometimes time-consuming to get the guide wire to go into the true lumen from the femoral artery when the reentry tear is large. In such a case we can advance the guide wire from the brachial artery and then into the true lumen of the aorta until the wire reaches the arteriotomy site at the time of endografting. We can determine which imaging plane is the most appropriate to depict the relation between the entry tear and major aortic branches by aortography beforehand.

In most cases the distance between the left subclavian artery and the entry tear is the most important information. To delineate it, a left anterior oblique view is mandatory. However, it is sometimes difficult to clearly point out the entry tear in cases in which the plane of the intimal flap at the level of the entry tear does not locate perpendicularly to the imaging plate. In such a case reconstructed CT images may give such essential information (Fig. 20.4).

Besides information about the entry tear, hemodynamics between true and false lumens can be appreciated thoroughly with aortography. Although the extent of the dissecting process and the location of the entry (entries), the reentry (reentries), and the fenestrations may be identified on CT in addition to involvement of aortic branches, it might be still difficult to predict what the blood supply to aortic branches would be like after endografting without true lumen aortography.

20.6 Operative Techniques

20.6.1 Device

The purpose of endografting for the treatment of aortic dissection is to close the entry tear located in the descending thoracic aorta, which usually does not have large branches contributing to type II endoleak. Therefore, the device could be simple compared with that used for the treatment of abdominal aortic aneurysms. Although some devices are already commercially available in western countries, so-called first-generation endografts,

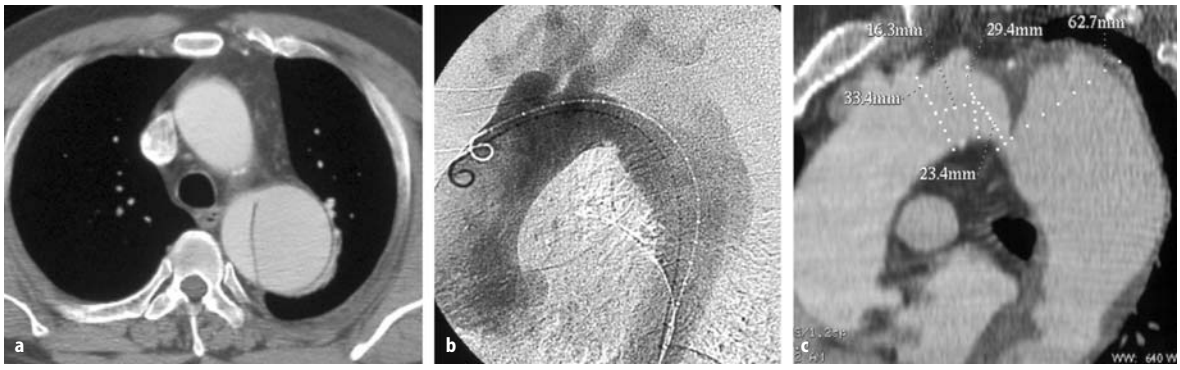

Fig. 20.4. An axial computed tomography (CT) image shows the entry tear at the lesser curvature of the proximal descending thoracic aorta (**a**). However, the relation between the entry tear and the left subclavian artery cannot be recognized from this CT image. The location of the entry tear cannot be pointed out on aortography since the entry tear locates at the lesser curvature and the intimal flap is parallel to the imaging plane (**b**). The multiplanar reconstruction image clearly shows the relation between the entry tear and the left subclavian artery (**c**)

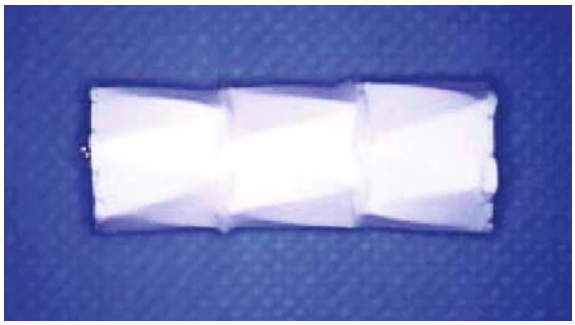

Fig. 20.5. So-called first-generation endograft which is fabricated with Z-stents and polytetrafluoroethylene

which are fabricated with Z-stents and polyester or expanded polytetrafluoroethylene (ePTFE), still work well in the treatment of aortic dissection as well as in that of thoracic aortic aneurysms [4, 16] (Fig. 20.5).

The design of the stent configuration is important when chronic dissection is treated. In the case of acute dissection the intimal flap is stretchable enough that stents can easily dilate it. Therefore, endografts can almost fully expand and become round at both the top and the bottom ends after the treatment even if the true lumen is markedly compressed by the false lumen and is paper-thin (Fig. 20.6). Thus, stents could be simply cylindrical with a round shape at both ends. In contrast, endografts do not always become round in the case of chronic dissection, especially at the distal end since the intimal flap is fibrotic and rigid (Fig. 20.7). Thus, stents have to be able to accommodate to the shape of the deformed true lumen in the case of chronic dissection. Z-stents have sufficient compressibility to fulfill this demand.

An anchoring device such as a hook is mandatory for the treatment of true aneurysms of the thoracic or the abdominal aorta to avoid migration. However, it might not be preferable in the case of dissection since it could make a new intimal tear when there is an intimal flap at the level where the hooks are supposed to be located. In addition, such an anchoring device may not be necessary because the landing zone is tapered distally in most dissection cases and such tapering of the landing zone could prevent migration of devices.

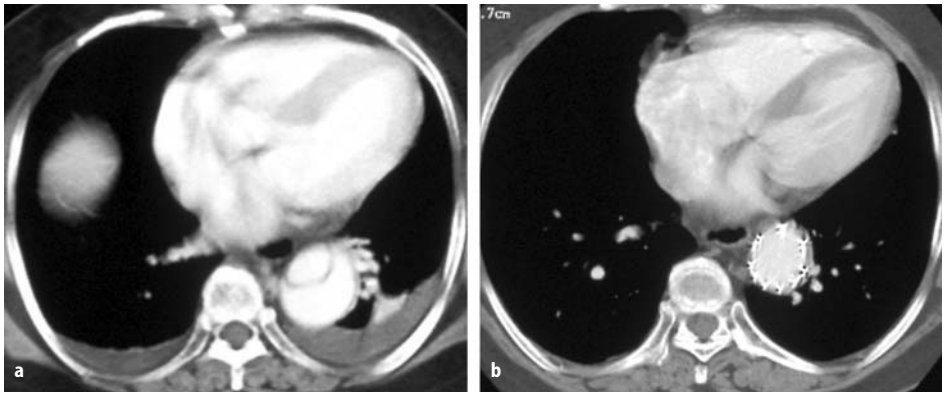

Fig. 20.6. The bottom end of the endograft, which was narrow and deformed before treatment (**a**), fully expands and is round 1 year after endografting (**b**) in the case of acute dissection

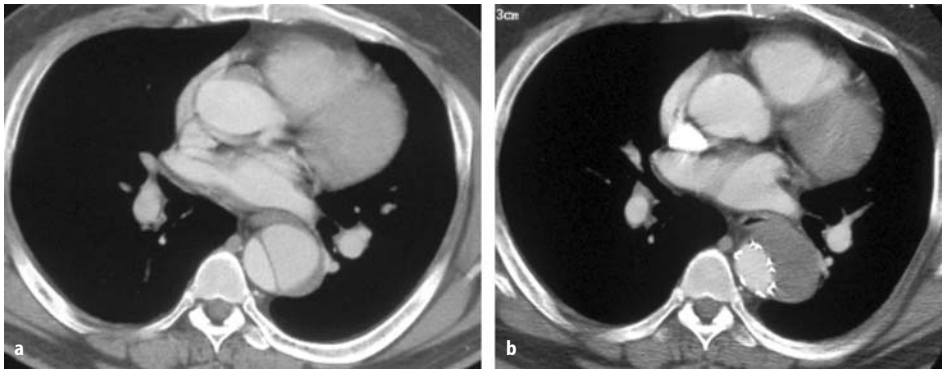

Fig. 20.7. The bottom end of the endograft seems almost the same before (**a**) and after (**b**) endografting, i.e., it does not fully expand and is still deformed 1 year after endografting

The size of the endografts is always a key to successful treatment. Endografts the diameters of which are approximately 10–15% larger than that of the landing zone are used as in the case of thoracic aortic aneurysms. The diameter of a circle which has the same circumference as the landing zone needs to be estimated since the landing zone is usually deformed in the case of aortic dissections. It can be calculated by dividing the circumference of the landing zone by π. More easily the mean of the shorter and the longer diameter of the landing zone can be substituted for it.

The other thing to be memorized is that the intimal flap does not always expand fully in the case of chronic dissection, especially when dissections older than 1 year are treated. Therefore, tapered endografts might be suitable for chronic dissections instead of straight endografts, which are usually sufficient for acute dissections, since the use of a straight one could lead to intimal injury because of too much hoop strength at the more deformed and narrower true lumen at the bottom end.

20.6.2 Procedures

Since the procedure itself is basically the same as that used for the treatment of thoracic aortic aneurysms, the details of the procedures are abbreviated in this chapter. The only difference from true aneurysms is that there are two lumens in the case of aortic dissections. A catheter and a wire inserted from the femoral artery can easily go into the false lumen when there is a large reentry tear. Thus, careful monitoring of the advancement of a catheter with occasional test injections at various levels to confirm the catheter is in the true lumen is mandatory. When it is difficult to enter the true lumen from the femoral artery, the true lumen can be obtained by advancing a catheter and a wire from the brachial artery to the femoral artery.

Completion angiography after deployment of the device must be carefully appreciated in the case of aortic dissections. The false lumen is sometimes rapidly opacified by contrast medium entering from natural fenestrations or reentry and it may resemble type I endoleak, although the false lumen is thrombosed soon or later even in such cases.

When type I endoleak is observed after deployment of an endograft, balloon dilatation can be applied. However, meticulous inflation is required to avoid making new intimal injuries although the possibility should be small compared with that in the case of acute dissection.

20.6.3 Postoperative Care

Postimplantation syndrome including high fever continuing for about 1 week is almost always observed. It can be easily controlled with antifebrile. Transient increase of C-reactive protein and white blood cells is also observed as well. However, the levels also subside together with fever [18, 28] and there is no need to treat them.

Paraplegia, which is one of the most catastrophic complications accompanying surgical graft replacement, reportedly develops in approximately 5% of patients undergoing endografting, which is comparable to or less than that of surgical intervention [4, 5]. It may develop immediately or late after endografting [14]. To avoid this challenge, cerebrospinal fluid drainage seems useful as well as in the case of graft replacement for the treatment of thoracoabdominal aortic aneurysms [3, 10, 35].

Strict control of blood pressure and close follow-up by CT even after endografting should be a must. Those patients who have suffered aortic dissection may have a higher chance of development of a new dissection at another segment of the aorta. In addition, once dissected the aorta may not be normal even if the false lumen is completely thrombosed by endografting. Fortunately, there is no patient who underwent endografting for the treatment of chronic aortic dissection and had a new dissection thereafter in our hospital; type A aortic dissection developed in one patient who underwent endografting for the treatment of acute type B dissection. Type A aortic dissection with a new intimal tear in the ascending aorta developed in another patient who underwent endografting for the treatment of acute type A dissection with the intimal tear in the descending thoracic aorta.

Follow-up CT is obtained 1 week after the treatment, 1 month, 3 months, 6 months, 1 year, and yearly thereafter in our hospital. It is not rare that only the true lumen is densely opacified in the early phase of contrast-enhanced CT since the flow into the false lumen of the descending thoracic aorta coming up from fenestrations or reentry is relatively slow. Therefore, delayed scan is mandatory to recognize the exact extent of thrombosis in the false lumen. Whenever any problem, including type I endoleak and new intimal injury, is observed, additional procedures have to be planned immediately.

The false lumen of the descending thoracic aorta sometimes remains patent because blood flow coming from fenestration or reentry is sometimes directed to such aortic branches as bronchial arteries or intercostals arteries which are supplied totally from the false lumen. However, the false lumen finally thromboses during follow-up in most cases unlike type II endoleak, which is often observed in cases of abdominal aortic aneurysms.

20.7 Results of Endografting

Nienaber et al. [29] should be credited as being first to objectively prove the efficacy of endografting for the treatment of chronic aortic dissection. They treated 24 patients with chronic aortic dissection: 12 patients with endografting and 12 patients with surgical graft replacement. Endografting was associated with no mortality or morbidity, whereas conventional surgery was associated with four deaths and five serious adverse events in their series. Although the number of the patients and the follow-up term in their series are extremely limited, their results were so impressive that those who had been hesitating to repair chronic dissection with endografts were encouraged.

From 1997 to 2004, 29 patients with chronic aortic dissection were treated with endografting in our hospital [19, 21]. "Chronic" is referred to as those dissections present for 1 month or more. The characteristics of the patients are listed in the Table 20.2. Indications for endografting are shown in Fig. 20.8. There was no death within 30 days (Table 20.3). Intraoperative complications were observed in two patients. Minor intimal injury at the external iliac artery caused by inserting the delivery system was repaired with stenting in one patient. Another patient with arterio-venous fistula for hemodialysis in the left forearm complained of left arm pain immediately after anesthesia wore off. Since the origin of the left subclavian artery was closed with an endograft, ischemia was deemed the cause of pain. The symptom disappeared after creating a bypass between both axillary arteries.

There was no major complication including cerebral infarction, spinal ischemia, and type I endoleak. The false lumen of the descending thoracic aorta was partially patent in two patients. Type II endoleak to which the bronchial artery contributed was observed in one patient. In the other patient blood entering from the natural fenestration came up the false lumen of the descending thoracic aorta and flowed into the intercostal artery. The false lumen of the descending thoracic aorta was completely thrombosed in the other 27 patients. Early postoperative complication was observed in one patient who suffered wound infection at the skin incision site.

During a mean follow-up term of 40 ± 26 months (range 1–93 months) there was no late death (Table 20.4). In addition, no device-related complications were observed. ULP developed at the descending thoracic aorta in two patients 2 and 3 years after endografting, respectively. Hemoptysis developed in one patient 3 months after endografting, although its cause was not elucidated. Complications which were not related to aortic dissection or devices were observed in two patients, lung cancer in one patient, and abdominal aortic aneurysm independent of aortic dissection in other patient.

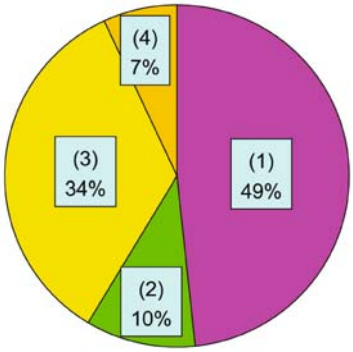

Fig. 20.8. Indications of endografting. *1* aortic diameter greater than 50 mm on CT, *2* aortic diameter greater than 40 mm on CT in a dissection present for 1 month or less, *3* enlargement of an ulcerlike projection during follow-up, *4* persistent back pain despite medical therapy

Table 20.2. Patient characteristics

Age (years)	60 ± 13
Male sex	24 (83%)
Maximal diameter of the descending thoracic aorta (cm)	47 ± 9
Dissection-related complications	0 (0%)
Dissection-unrelated complications	24 (83%)
Hypertension	18 (62%)
History of ascending aortic replacement	4 (14%)
Abdominal aortic aneurysm/thoracic aortic aneurysm	3 (10%)
Coronary arterial disease	3 (10%)
Renal failure	2 (7%)
Marfan syndrome	2 (7%)
Coagulopathy	1 (3%)

Table 20.3. Early mortality and morbidity

Mortality	0 (0%)
Complication	5 (17%)
Aorta-related	2 (7%)
Intimal injury	0 (0%)
Type I endoleak	0 (0%)
Type II endoleak	2 (7%)
Aneurysmal degeneration	0 (0%)
Aorta-unrelated	3 (10%)
Stroke	0 (0%)
Paraplegia	0 (0%)
Left arm ischemia	1 (3%)
Dissection of iliac artery	1 (3%)
Wound infection	1 (3%)

Remodeling of the aorta occurred during follow-up. The aorta and the false lumen shrank, while the true lumen expanded. However, it is not as conspicuous as in case of acute dissection, in which the false lumen often disappears and the aorta recovers its original diameter.

Table 20.4. Late mortality and morbidity

Mortality	0 (0%)
Complication	5 (17%)
Aorta-related	4 (7%)
Intimal injury	0 (0%)
Type I endoleak	0 (0%)
Type II endoleak	2 (7%)
Aneurysmal degeneration	2 (7%)
Aorta-unrelated	1 (3%)
Hemoptysis	1 (3%)

20.8 Summary

Although further follow-up is mandatory, endografting for the treatment of chronic type B aortic dissection is seemingly a superior alternative to surgical graft replacement in terms of short and midterm results, even if first-generation endografts are used. To expand indication more sophisticated devices such as branched or fenestrated endografts should be necessary.

References

1. Acute aortic dissection. Lancet 1998; 2:827–828.
2. Blum U, Voshage G, Lammer J, Beyersdorf F, Tollner D, Kretschmer G, Spillner G, Polterauer P. Endoluminal stent-grafts for infrarenal abdominal aortic aneurysms. N Engl J Med 1997; 336:13–20.
3. Coselli J, LeMaire S, Schmittling Z, Köksoy C. Cerebrospinal fluid drainage in thoracoabdominal aortic surgery. Semin Vasc Surg 2000; 13:308–314.
4. Dake MD, Miller DC, Mitchell RS, Semba CP, Moore KA, Sakai T. The "first generation" of endovascular stent-grafts for patients with aneurysms of the descending thoracic aorta. J Thorac Cardiovasc Surg 1998; 116:689–704.
5. Dake MD, Kato N, Mitchell RS, Semba CP, Razavi MK, Shimono T, Hirano T, Takeda K, Yada I, Miller DC. Endovascular stent-graft placement for the treatment of acute aortic dissection. N Engl J Med 1999; 340:1546–1552.
6. DeBakey ME, McCollum CH, Crawford ES, Morris GC, Howell J, Noon GP, Lawrie G. Dissection and dissecting aneurysms of the aorta: Twenty-year follow-up of five hundred twenty-seven patients treated surgically. Surgery 1982; 92:1118–1134.
7. DeSanctis RW, Doroghazi RM, Austen WG, Buckley ML. Aortic dissection. N Engl J Med 1987; 317:1060–1067.
8. Elefteriades JA, Hartleroad J, Gusberg RJ, Salazar AM, Black HR, Kopf GS, Baldwin JC, Hammond GL. Long-term experience with descending aortic dissection: The complication-specific approach. Ann Thorac Surg 1992; 53:11–21.
9. Fann JI, Miller DC. Aortic dissection. Ann Vasc Surg 1995; 9:311–323.
10. Fleck T, Hutschala D, Weissl M, Wolner E, Grabenwöger M. Cerebrospinal fluid drainage as a useful treatment option to relieve paraplegia after stent-graft implantation for acute aortic dissection type B. J Thorac Cardiovasc Surg 2002; 123:1003–1005.
11. Glower DD, Fann JI, Speier RH, Morrison L, White WD, Smith LR, Rankin JS, Miller DC, Wolfe WG. Comparison of medical and surgical therapy for uncomplicated descending aortic dissection. Circulation 1990; 82(Suppl IV): IV39–46.
12. Glower DD, Speier RH, White WD, Smith LR, Rankin JS, Wolfe WG. Management and long-term outcome of aortic dissection. Ann Surg 1991; 214:31–41.
13. Hagan PG, Nienaber CA, Isselbacher EM, et al. The international registry of acute aortic dissection (IRAD). JAMA 2000; 283:897–903.
14. Huynh D, Miller C, Safi H. Delayed onset of neurologic deficit: significance and management. Semin Vasc Surg 2000; 13:340–344.
15. Inoue K, Hosokawa H, Iwase T, Sato M, Yoshida Y, Ueno K, Tsubokawa A, Tanaka T, Tamaki S, Suzuki T. Aortic arch reconstruction by transluminally placed endovascular branched stent graft. Circulation 1999; 100(Suppl II): II316–321.
16. Ishida M, Kato N, Hirano T, Shimono T, Takeda K. Endovascular stent-graft treatment for thoracic aortic aneurysms: short- to midterm results. J Vasc Interv Radiol 2004; 15:361–367.
17. Juvonen T, Ergin MA, Galla JD, Lansman SL, McCullough JN, Nguyen K, Bodian CA, Ehrlich MP, Spielvogel D, Klein JJ, Griepp RB. Risk factors for rupture of chronic type B dissections. J Thorac Cardiovasc Surg 1999; 117:776–786.
18. Kato M, Bai H, Sato K, Kawamoto S, Kaneko M, Ueda T, Kishi D, Ohnishi K. Determining surgical indications for acute type B dissection based on enlargement of aortic diameter during the chronic phase. Circulation 1995; 92 (Suppl II):II107–112.
19. Kato N, Hirano T, Shimono T, Ishida M, Takano K, Nishide Y, Kawaguchi T, Yada I, Takeda K. Treatment of chronic aortic dissection by transluminal endovascular stent-graft placement: preliminary results. J Vasc Intervent Radiol 2001; 12:835–840.
20. Kato N, Hirano T, Kawaguchi T, Ishida M, Shimono T, Yada I, Takeda K. Aneurysmal degeneration of the aorta after stent-graft repair of acute aortic dissection. J Vasc Surg 2001; 34:513–518.
21. Kato N, Shimono T, Hirano T, Suzuki T, Ishida M, Sakuma H, Yada I, Takeda K. Mid-term results of stent-graft repair of aortic dissection: comparison between acute and chronic dissection – the complication-specific approach-. J Thorac Cardiovasc Surg 2002; 124:306–312.
22. Kato N, Hirano T, Ishida M, Cheng SH, Shimono T, Takeda K. Stent-graft placement combined with percutaneous fenestration for the treatment of aortic dissection with a risk of renal ischemia. Ann Thorac Surg 2004; 78:1072–5.
23. Kouchoukos NT, Dougenis D. Surgery of the thoracic aorta. N Engl J Med 1997; 336:1876–1888.
24. Miller DC. Surgical management of aortic dissections: indications, perioperative management, and long-term results. In: Doroghazi RM, Slater EE, editors. Aortic dissection. McGraw-Hill, New York, 1983. pp. 193–243.
25. Miller DC. The continuing dilemma concerning medical versus surgical management of patients with acute type B dissections. Sem Thorac Cardiovasc Surg 1993; 5:33–46.
26. Miller DC, Stinson EB, Oyer PE, Rossiter SJ, Reitz BA, Griepp RB, Shumway NE. Operative management of aortic dissections. Experience with 125 patients over a sixteen-year period. J Thorac Cardiovasc Surg 1979; 78:365–382.
27. Miller DC, Mitchell RS, Oyer PE, Stinson EB, Jamieson SW, Shumway NE. Independent determinants of operative mortality for patients with aortic dissections. Circulation 1984; 70(Suppl I):I153–164.
28. Neya K, Omoto R, Kyo S, Kimura S, Yokote Y, Takamoto S, Adachi H. Outcome of Stanford type B acute aortic dissection. Circulation 1992; 86(Suppl II): II1–7.
29. Nienaber CA, Fattori R, Lund G, Dieckmann C, Wolf W, von Kodolitsch Y, Nicolas V, Pierangeli A. Nonsurgical re-

construction of thoracic aortic dissection by stent-graft placement. N Engl J Med 1999; 340:1539–1545.
30. Slonim SM, Nyman URO, Semba CO, Miller DC, Mitchell RS, Dake MD. Aortic dissection: percutaneous management of ischemic complications with endovascular stents and fenestration. J Vasc Surg 1996; 23:241–253.
31. Slonim SM, Nyman URO, Semba CP, Miller DC, Mitchell RS, Dake MD. True lumen obliteration in complicated aortic dissection: endovascular treatment. Radiology 1996; 201:161–166.
32. Smith DC, Jang GC. Radiological diagnosis of aortic dissection. In: Doroghazi RM, Slater EE, editors. Aortic dissection. McGraw-Hill, New York, 1983. pp. 193–243.
33. Sueyoshi E, Matsuoka Y, Sakamoto I, Uetani M, Hayashi K, Narimatsu M. Fate of intramural hematoma of the aorta: CT evaluation. J Comput Assist Tomogr 1997; 21:931–938.
34. Svensson LG, Crawford ES, Hess KR, Coselli JS, Safi HJ. Dissection of the aorta and dissecting aortic aneurysms. Circulation 1990; 82(Suppl IV):IV24–38.
35. Tefera G, Acher C, Wynn M. Clamp and sew techniques in thoracoabdominal aortic surgery using naloxane and CSF drainage. Semin Vasc Surg 2000; 13:325–330.
36. Wheat MW. Current status of medical therapy of acute dissecting aneurysms of the aorta. World J Surg 1980; 4:563–569.
37. Williams DM, Lee DY, Hamilton BH, Marx MV, Narasimham DL, Kazanjian SN, Prince MR, Andrews JC, Cho KJ, Deeb GM. The dissected aorta: percutaneous treatment of ischemic complications – principles and results. J Vasc Interv Radiol 1997; 8:605–625.

Problems Encountered During and After Stent-Graft Treatment of Aortic Dissection

Jong Yun Won, Do Yun Lee

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Contents

21.1 Introduction

Aortic dissection is one of the life-threatening diseases involving the aorta whether it is acute or chronic [7, 23]. The conventional treatment strategy depends on the extension of the dissecting process: surgical repair of the aortic replacement with prosthetic graft when it involves the ascending aorta (Stanford type A), and medical treatment when it involves the descending thoracic aorta (DTA) (Stanford type B). However, more than 20% of patients with Stanford type B aortic dissection need surgical intervention for the various indications: an expanding false lumen of dissection, branch vessel and leg ischemia, recurrent pain, or impending rupture [8, 31]. Because of high surgical morbidity and a mortality rate around 20–60% [9, 34], endovascular stent-graft placement has emerged as a new treatment modality as a substitute for open surgery in aortic dissection with a descending aortic intimal tear and many authors have reported their encouraging results of more than 60% of complete thrombosis or resolution rate [1, 3, 5, 21, 37].

However, because of the very limited number of patient populations and the duration of follow-up, many questions are still controversial. Especially, only a few reports have concerned the various problems which can be encountered in stent-graft treatment of the aortic dissection [15, 16]. In this article, we present our experiences and review other authors' reports about these problems encountered during the procedure of stent-graft placement and the follow-up period in patients with aortic dissections.

21.2 Materials and Methods

21.2.1 Patients

Between July 1994 and December 2003, 60 patients with aortic dissections who underwent stent-graft placement in the DTA were included in this study. The protocol was approved by the Institutional Review Board, and informed consent was obtained from all patients. The 39 men and 21 women ranged in age from 37 to 88 years (mean 59 years). The inclusion criteria for the stent-graft were type A with retrograde dissection and an intimal tear located in the DTA, type B dissection with dynamic obstruction of abdominal aortic branch vessels, persistent or recurrent pain, aortic rupture, and an aortic diameter greater than 40 mm in the acute phase of dissection or greater than 60 mm in the chronic phase [22]. Five of nine patients with type A dissections had retrograde dissection with a primary entry tear located distal to the left subclavian artery (SCA). Therefore, a stent-graft was available for the treatment of this rare type of dissection. The other four

patients, including two with Marfan syndrome, with type A dissection had previously undergone surgical replacement of the ascending thoracic aorta and the aortic arch, leaving a large reentry tear in the DTA. Ten patients presented acute (less than 2 weeks) symptoms; 50 patients had chronic (2 weeks or more) symptoms [24]. The location of the primary entry tears were at the proximal DTA in 38 patients and at the mid to distal DTA in 22 patients. All aortic dissections simultaneously involved the abdominal aorta below the level of the diaphragm, with contiguous extension. The distal extents of the dissections were variable from the suprarenal abdominal aorta to both iliac arteries. All patients showed patent false lumen flows from the proximal primary entry tear to the distal several reentries in the abdominal aorta or the iliac artery.

21.2.2 Imaging

Before the procedures, all patients underwent contrast-enhanced spiral computed tomography (CT) scans and digital subtraction aortograms in order to measure the dimension of the aorta and to evaluate entry and reentry tears. Conventional spiral CT scans of the aorta were evaluated using the following parameters: collimation of 7 mm with a table feed of 7 mm/s, 2-mm reconstruction, 120 kV, and 220 mA s. The patients received 120–150 ml of contrast medium at a rate of 3.0 ml/s. Recently, we used a 16-channel multidetector row CT scan (Somatom Sensation 16, Siemens, Forchheim, Germany) with the following parameter: table feed of 15 mm, gantry rotation time of 0.5 s, tube voltage of 120 kV, amperage of 150 mA m, 2-mm reconstruction. Between 10 and 15 s after the end of the arterial phase acquisition, a second acquisition was performed. The aortography was performed with the use of a calibrated marker catheter (Cordis, Roden, The Netherlands). We injected 25–30 ml of contrast medium at a rate of 15 ml/s and obtained six to ten images per second for the thoracic aorta and two to six images per second for the abdominal aorta. Angiographies of the femoral, external iliac, and common iliac arteries allowed accurate sizing of these arteries and evaluation of tortuosity for the adequate vascular access.

21.2.3 Stent-Graft

We used two different kinds of stent-graft. Until the end of 1999, we implanted a homemade Z-shaped stent covered with balloon-dilated poly(tetrafluoroethylene) (Impra, Tempe, AZ, USA) material in 20 patients. Since then, we have implanted our self-designed percutaneous separated stent-graft that can be deployed percutaneously through a 12-French low-profile introducer. The new device consists of two separate bodies: the main body with two anchoring stents at both ends connected by a Dacron graft and the second body of an inner nitinol bare stent. This unique structure enables percutaneous deployment and less resistance against blood flow during deployment, so we could implant the stent-graft without any blood pressure, lowering medication [14]. Each stent-graft was individually constructed and manufactured to be 10–15% larger than the diameter of the unaffected aorta proximal to the entry tear of dissection. The mean diameter and the mean length of the stent-graft were 33 ± 4 mm (24–40 mm) and 9.6 ± 2.0 cm (6.0–15.0 cm).

21.2.4 Procedures

The method of Z-shaped stent-graft placement was almost the same as those described in a previous report [20]. All procedures were performed in angiography units under local or epidural anesthesia and full hemodynamic monitoring while placing the patients in the supine position. Vascular access was obtained through the femoral artery following surgical cut-down. After inserting an exchange (260-cm) 0.035-in.-diameter Amplatz superstiff guidewire (Boston Scientific, Watertown, MA, USA), we advanced the 20- or 22-French stent-graft delivery sheath (Keller-Timmerman Sheath, Cook, Bloomington, IN, USA) over the guidewire. The patient was anticoagulated with intravenous heparin (5,000 IU) before the insertion of the stent-graft delivery sheath. After that, we deployed the stent-graft by rapidly withdrawing the introducer sheath. Aortography via a contralateral percutaneous femoral artery approach with a 5-French multisidehole catheter (Cook, Bloomington, IN, USA) was performed before and after the stent-graft deployment in order to confirm the exact location of the stent-graft, the absence of perigraft leakage, and the patency of adjacent branch vessels.

Deployment of the percutaneous separated stent-graft needs slightly different steps from conventional Z-shaped stent-graft. First, the main body of the stent-graft is deployed and subsequently the bare stent is deployed inside the main body. In addition, deployment of a percutaneous separated stent-graft was performed through a 12-French low-profile introducer under local anesthesia without surgical cut-down. Recently the puncture site has been closed using a Perclose device (Abbott Vascular Devices, Redwood City, CA, USA).

21.2.5 Follow-Up

Follow-up spiral CT scans were performed within 1 month of the procedures, then at 3–6-month intervals for 2 years, and annually thereafter. Each patient was

Table 21.1. List of problems encountered in stent-graft placement for aortic dissection

Problems during the procedure
Stent-graft migration
Stent-graft torsion
Complication related to the size of the stent-graft
Appearance of a hidden intimal tear in the descending thoracic aorta
Type I endoleak
Problems during follow-up
Postimplantation syndrome
Neurologic complication
Persistent type I endoleak
Type II endoleak
Progressive abdominal aortic aneurysm
New intimal tear
Mechanical failure of the stent-graft

followed for 9–103 months and the mean follow-up was 31 months. Technical success was defined as the completion of the stent-graft deployment at the target area without stent-graft failure. Clinical success was defined as complete exclusion of the primary entry tear from the circulation without a significant adverse cardiovascular event by serial CT. We assessed all technical problems during the procedure and complications which occurred during the follow-up period (Table 21.1).

21.3 Problems During the Procedure

21.3.1 Stent-Graft Migration

Migration of the stent-graft caused by the "wind sock" effect of ventricular ejection results predominantly in technical failure, particularly when proximal fixation is at or near the aortic arch [2]. To avoid this serious technical problem, lowering the blood pressure with a vasodilator or beta-blocker drugs has been done [16, 25]. Despite this effort, stent-graft migration has reported to occur with an incidence of 2–20% by many authors [29].

In our experience, we observed two cases (3%) of stent-graft migration, which occurred in two patients in our early period when we used a single stent-graft system and nitroprusside to lower the blood pressure during deployment of the stent-graft. Primary entry tears of those two patients were located at the proximal DTA, 3 and 5 cm from the left SCA. We attempted to correct the location of the stent-graft with a balloon, but failed. We deployed an additional stent-graft and successfully excluded the primary entry tear in one patient. However, in the other patient, an additional stent-graft of adequate size was not readily available. Later, the patient refused further intervention and his false lumen remained patent without demonstrable interval changes on the follow-up CT scan. The patient is under close observation for 16 months. Since changing the device to a separated stent-graft, the migration problem has no longer happened. Many investigators are known to design their own devices which enable a better proximal fixation, using stent appendages such as hooks or barbs and a rapid deployment system using a pull-string to avoid this unfavorable complication [12, 35].

21.3.2 Complications Related to the Size of the Stent-Graft

The method of measuring the adequate size of the stent-graft in aortic disease seems to be an subject that needs general consensus, especially in aortic dissection. Investigators determine the diameter of a stent-graft in many different ways. We use the diameter of the proximal unaffected aorta as a base line and manufacture the

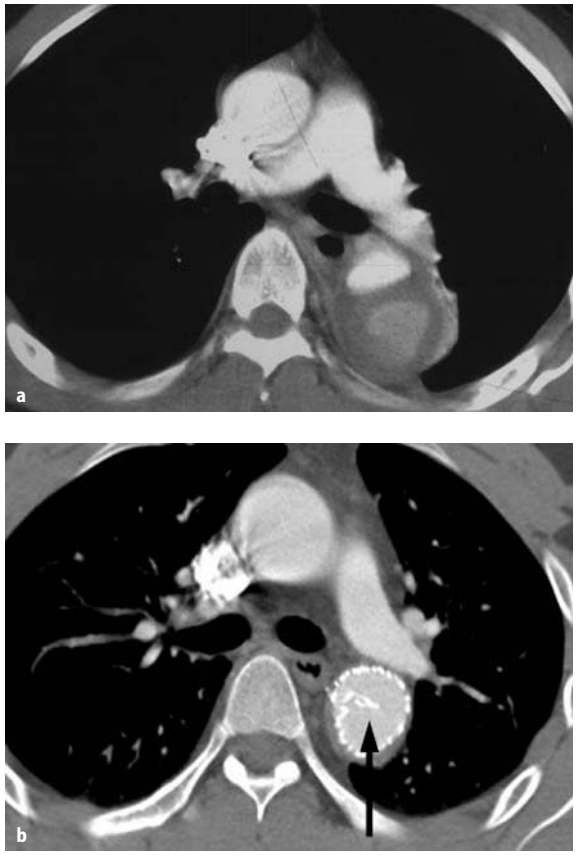


Fig. 21.1. Stent-graft folding. A 56-year-old man with De Bakey type III chronic aortic dissection. **a** Preoperative computed tomography (*CT*) scan shows the true lumen and the false lumen of the descending thoracic aorta. **b** Fifty-two-month follow-up CT scan after the stent-graft treatment. Despite inward folding of the stent-graft strut (*arrow*), complete resolution of the thoracic false lumen is achieved

stent-graft 10–15% larger. Shimono et al. [33] use a stent-graft 10% larger than the average of the maximum and minimum diameters of the thoracic true lumen in acute dissection and 20% in chronic dissection. Choosing a stent-graft diameter that is too small can cause an endoleak or migration, whereas oversizing of the prosthesis may lead to infolding of the graft. In the experimental report of Schurink et al. [32], oversizing and folding of the stent-graft were significantly related to the grade of the endoleak, and balloon expansion can not help to reduce the endoleak.

Among 60 patients of our study, two stent-grafts (3%) were infolded during deployment, which was caused by overestimation of the stent-graft size. On the follow-up CT scan, those stent-grafts were not expanded even after the aortic true lumens had been fully expanded. Fortunately, primary entry tears of these two patients were completely excluded and there was no thrombus formation around the deformed stent-graft on follow-up CT scans taken 46 and 55 months after the procedure (Fig. 21.1). We keep following these patients closely because of the possibility of blood flow disturbance inside the aorta by the protruding stent strut.

21.3.3 Appearance of a Hidden Intimal Tear in the DTA

Many authors mentioned the importance of verifying every intimal tear of the thoracic aorta on preoperative imaging. Especially in long-standing chronic dissections, it is more important owing to the possibility of multiple fenestrations in the DTA and the abdominal aorta. In chronic dissections, along with fibrosis, contraction of the myointima, and dilated outer layers, even a small intimal tear could disturb reattachment of the intima to the outer media and adventitia [17, 20]. According to our experience, every thoracic false lumen of acute dissection was decreased in size only with the exclusion of the primary entry tear. However, in chronic dissection, the size of the thoracic false lumen did not decrease until every intimal tear including the primary entry tear was excluded. In addition, the time required for complete thrombosis of the thoracic aortic false lumen was longer in the chronic dissections, as was the resolution time. Those differences might be related to the formation of the multiple thoracic reentry tears, the status of endothelialization in the false lumen, and the endotension caused by reentry tears.

In three patients (5%) with primary entry tear in the distal DTA of our series, initially undetected hidden intimal tears appeared within 2 cm of the proximal (n=1) and the distal (n=2) margins of the stent-graft which had been successfully deployed upon the primary entry tear. All of their dissections were acute. One of them underwent additional stent-graft deployment upon the hidden intimal tear. The other two patients could not have further intervention because a suitably sized device was not readily available. Despite persistent contrast enhancement of the thoracic false lumen in these two patients, gradual decrease of the aortic diameter was seen on serial follow-up CT scans at 6 and 27 months each (Fig. 21.2).

In our institute, very thin sections of spiral CT scans of less than 2-mm slice thickness and a three-dimensional reconstruction image combined to aortograms with a high frame rate of more than 6 frame/s and oblique views perpendicular to the aortic intimal flap are obligatory for the preoperative evaluation for the aortic dissection. Recently, the multidetector CT scan became available and enables more accurate evaluation of aortic dissection by its greater spatial resolution, thinner slice thickness, and faster scan time [17]. Despite careful evaluation of the preoperative images, we lost three cases of proximal and distal hidden intimal tears which were relatively small compared with the adjacent primary entry tear. Pamler et al. [26] suggested obtaining many preoperative aortograms with the catheter tip at different levels. They also propose covering every intimal tear in the thoracic aorta with a stent-graft to prevent distal reperfusion of the false lumen.

21.3.4 Type I Endoleak

Twelve endoleaks (20%) were detected immediately after the successful deployment of the stent-graft and all of them were type I endoleaks (attachment site endoleak) at the proximal margin of the stent-graft. Ten of the twelve patients with endoleaks had a primary entry tear in the aortic arch and the proximal DTA and one of them was located in the lesser curvature side.

21.4 Problems During the Follow-Up

21.4.1 Postimplantation Syndrome

Postimplantation syndrome can be manifested in various symptoms and signs, such as fever, leukocytosis, elevated C-reactive protein level, pleural effusion, and decreased platelet count.

Fever, leukocytosis, and elevated C-reactive protein level, of which the incidence is known to be 20–60%, are suggested to be a nonspecific systemic inflammatory reaction rather than true infection. However, it has been reported to result in little prolonged complication by many authors [20, 36]. In our early experiences, we routinely medicated prophylactic antibiotics; however, this did not help to lower the incidence of postimplantation syndrome. All the patients recovered with conservative treatments in 2–10 days. Many institutes manage these

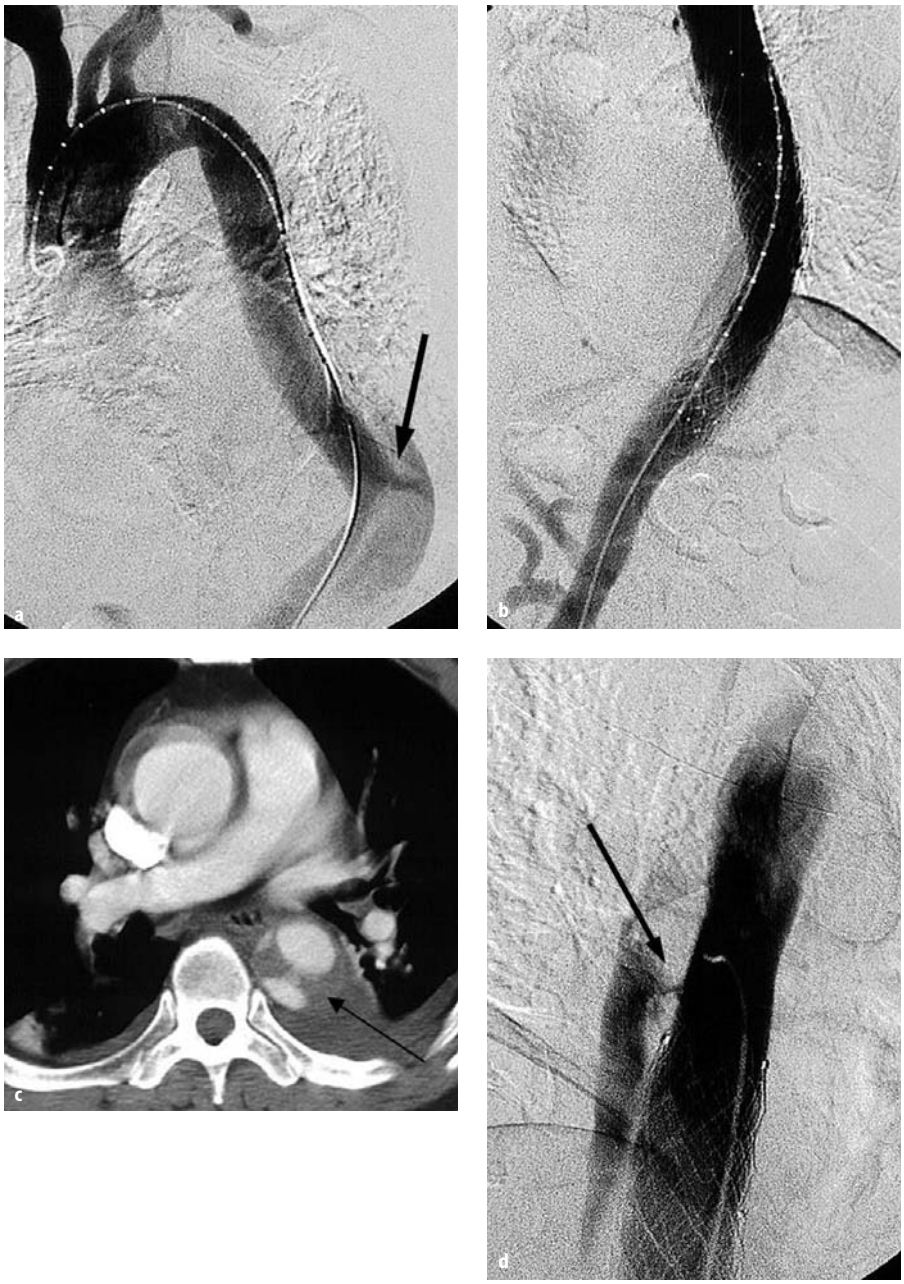


Fig. 21.2. Emergence of hidden intimal tear. A 66-year-old man with De Bakey type III acute aortic dissection. **a** Preoperative aortogram demonstrates a large entry tear located at the distal descending thoracic aorta near the diaphragm (*arrow*). No other entry tear is defined in the descending thoracic aorta. **b** Immediately after the stent-graft deployment, the completion aortogram shows exclusion of the entry tear and nonvisualization of the false lumen. **c, d** One week after the stent-graft treatment, emergence of a hidden entry tear (*arrow*) is depicted just above the stent-graft on CT (**c**) and aortograms of 50° right anterior oblique view (**d**). Contrast enhancement of the thoracic false lumen is still noted

complications only with anti-inflammatory agents or even without any medication and recommend judicious use of antibiotics [12, 25, 30].

Pleural effusion and decreased platelet count are not well-known complications of stent-grafts in aortic dissection. In our series, 34 patients (57%) with pleural effusion and 22 patients (37%) with decreased platelet count to more than 50% of the base line were observed during the follow-up. All patients with pleural effusion, which we suggest to originate from foreign-body irritation to the adjacent pleura, showed complete resolution on 1-month ($n=25$) or 3-month ($n=9$) follow-up CT

scans without any specific treatment. In 22 of our patients, the platelet count decreased until 1–3 days after the stent-graft placement and it recovered to the initial base line in 3–13 days (mean 5.2 days) without transfusion or any other treatment. Because all cases of platelet count drop occurred in patients whose former patent false lumens had been obliterated by thrombus formation, consumptive coagulopathy is suggested to be the cause of this transient complication.

21.4.2 Neurologic Complication

Cerebral ischemic complication is reported to occur in 3–10% of stent-grafts in aortic dissection [16, 25]. A possible embolic event might be responsible for this uncommon complication. Gentle maneuver of the guidewire and the introducer could be the only way to lower the incidence of cerebral embolic complication. In our series, transient ischemic attack developed immediately after the stent-graft treatment in one patient (2%); this patient spontaneously recovered without any sequelae.

Our own device of separated stent-grafts was deployed upon the orifice of the carotid artery and the left SCA with the bare stent portion in 13 patients. Pannus formation did not disturb the cerebral or extremity circulation during follow-up and our cases of surgical conversion proved a wide-open carotid and SCA owing to the large cell size (1×1 cm) of the bare stent portion which had covered the branch vessels of the aortic arch. Czemark et al. [3] and Quinn et al. [28] also reported that they placed the uncovered part of the stent-graft over the ostium of the left SCA without any neurologic complication.

We have not experienced any other neurologic complications such as paraparesis or paraplegia. Although spinal ischemia has been reported by some authors [18, 19], many different authors' experiences to date permit the conclusion that the usual surgical paradigm relative to intercostal artery sacrifice and aortic clamping during open repair and its resultant incidence of spinal cord ischemic complication as much as 7–35% does not pertain to stent-graft repair [27]. Furthermore, in the case of aneurysms with partial thrombosis, many intercostal branches are already occluded and the spinal cord is perfused by collaterals. The sudden deployment of the stent-graft followed by the occlusion of the intercostal branches does not produce steal syndrome in the perfusion of the spinal cord [11]. Cambria et al. [2] observed no spinal cord complication in 28 cases of thoracic aortic stent-graft treatment. Seventy patients of Palma et al. [25] were free from paraplegia with thoracic stent-grafts. Kato et al. [16] reported one case of paraplegia developed after a surgical conversion to fix an endoleak out of 38 thoracic stent-grafts.

21.4.3 Persistent Type I Endoleak

Type I endoleak (attachment site endoleak) is known to be the most frequent complication in the stent-graft treatment of aortic dissection, which could be a potential clinical failure during follow-up [10, 18]. The percentage of type I endoleak reported in the literature ranges from 0 to 44 [4]. A proximal neck less than 2 cm from the left SCA and the existence of an entry tear located at the lesser curvature of aortic arch are known as risk factor of an endoleak [26, 33].

In our series, 12 cases (20%) of endoleaks were depicted on immediate aortograms out of 60 cases. Ten of 38 patients (26%) whose entry tears were located at the aortic arch and the proximal DTA showed an endoleak, whereas two of 22 patients (9%) with entry tears at the mid and distal thoracic aorta showed an endoleak. The distance between the left SCA and the primary entry tear was 1.5–8 cm (mean 4.1 cm) in patients with an endoleak, which was significantly shorter than in patients without an endoleak (mean 12.7 cm) ($p<0.05$).

In terms of the fate of type I endoleaks, there is still some debate between authors. However, many authors reported their experiences of the spontaneous healing of type I endoleaks. Lepore et al. [18] reported seven patients (16%) with type I endoleaks among 43 thoracic aortic stent-grafts. They treated three of them with additional stent-graft deployment and the others resolved spontaneously within 1 month. Shimono et al. [33] reported 80% spontaneous resolution of type I endoleaks in 37 stent-grafts for aortic dissection.

Also in our study, six (50%) of 12 patients who had demonstrated type I endoleaks on immediate angiograms after the deployment of stent-grafts showed spontaneous thrombosis of the thoracic false lumen without any further treatment (Fig. 21.3). The duration of self-resolution was 1 week to 8 months. The other six endoleaks remained persistent on follow-up CT scans. Among them, two patients showed progressive aneurysmal dilatation of the false lumen (Fig. 21.4). One of them underwent surgical graft replacement and the other one refused further treatment and are under close follow-up for 4 years. Four other patients did not show any remarkable changes in the size and the shape of the thoracic false lumen for 8–89 months (mean 45). In case of type I endoleaks, we suggest following the patients with repeated imaging to see if there is any change in the dissected false lumen. Surgical management could be avoided unless overt enlargement of the false lumen is detected.

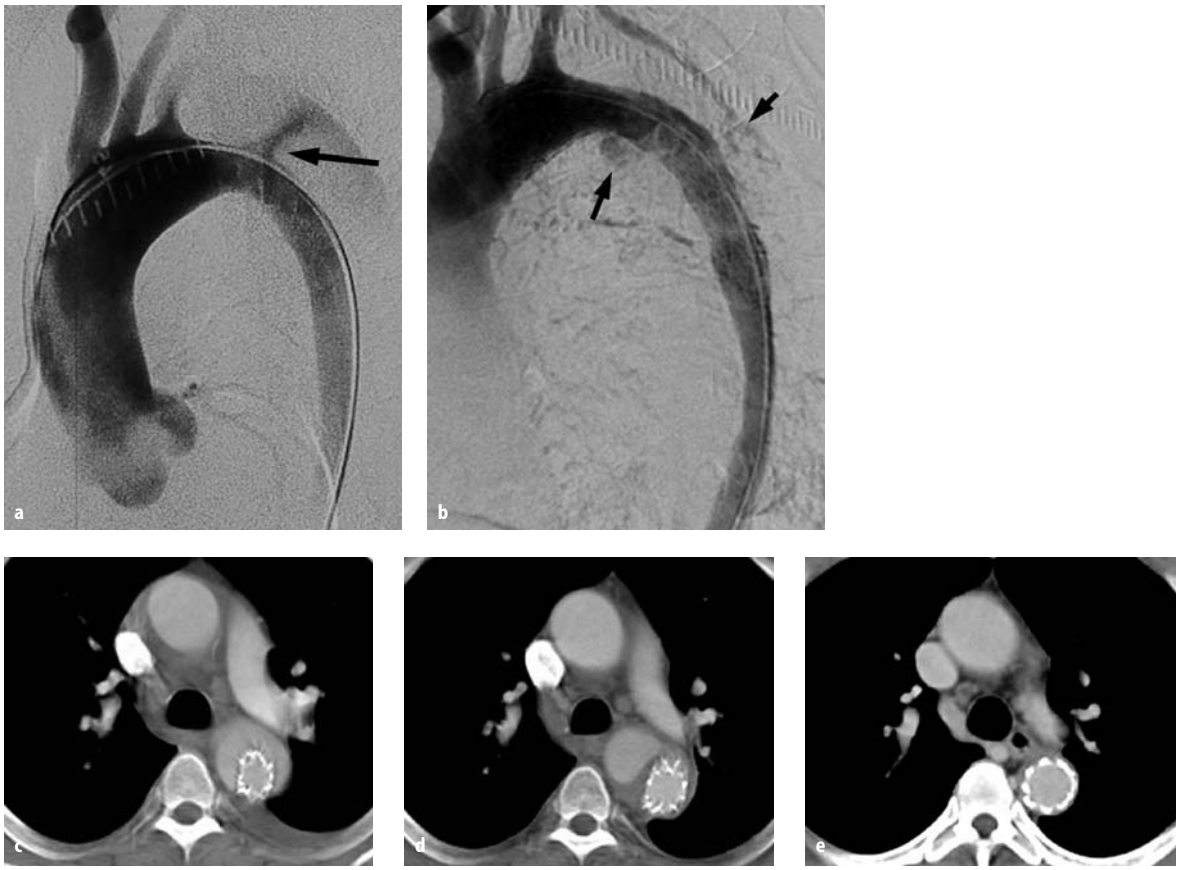


Fig. 21.3. Spontaneous resolution of a type I endoleak. A 44-year-old man with De Bakey type III aortic dissection. **a** The aortogram demonstrates De Bakey type III aortic dissection. A primary entry tear is located on the greater carvature side 4 cm from the left subclavian artery. **b** After the deployment and balloon apposition of the stent-graft, contrast leakage into the false lumen at the proximal end of the stent-graft (type I endoleak) is seen (*arrows*). **c** The 1-month follow-up CT scan shows persistent contrast enhancement of the thoracic false lumen around the stent-graft. **d** With the further expansion of the true lumen, remodeling of the thoracic aorta is shown on the 4-month follow-up CT scan. **e** On the 8-month follow-up CT scan, complete resolution of the previous endoleak is demonstrated. Furthermore, the thoracic false lumen disappeared completely

21.4.4 Type II Endoleak

A type II endoleak after the stent-graft treatment is not as much a concern in aortic dissection as it is in abdominal aortic aneurysm. Sometimes, type II endoleaks through the intercostal artery can occur in aortic dissection and make contrast enhancements around the intercostal attachment sites of the false lumen. Bortone et al. [1] also reported two cases of type II endoleaks among 43 stent-grafts for type B dissection, associated with a complete thrombosis of the thoracic false lumen and an insignificant retrograde flow. Palmer et al. [26] found open and retrogradely perfused intercostal arteries in the region of the stent-graft in a patient whose thoracic false lumen was completely thrombosed. They assumed that collateral perfusion through the intercostal artery enables good residual blood flow to the spinal cord rather than a harmful effect such as endotension.

In our series, two cases of type II endoleaks (3%) through the intercostal arteries were demonstrated by follow-up CT scans taken 1 month after the stent-graft treatment. Those endoleaks did not affect the remodeling and the thrombosis in the thoracic false lumen. They resolved spontaneously after 5 and 6 months (Fig. 21.5).

21.4.5 Progressive Abdominal Aortic Aneurysm

Despite an adequate sealing of the primary entry tears in the DTA after stent-graft placement, the lack of remodeling of the abdominal aorta has been a constant problem observed by many authors. The preliminary results of Kato et al. [15] dealing with 15 chronic type B dissections showed there was no significant difference in the size of the abdominal true and false lumens even after the successful remodeling of thoracic dissection.

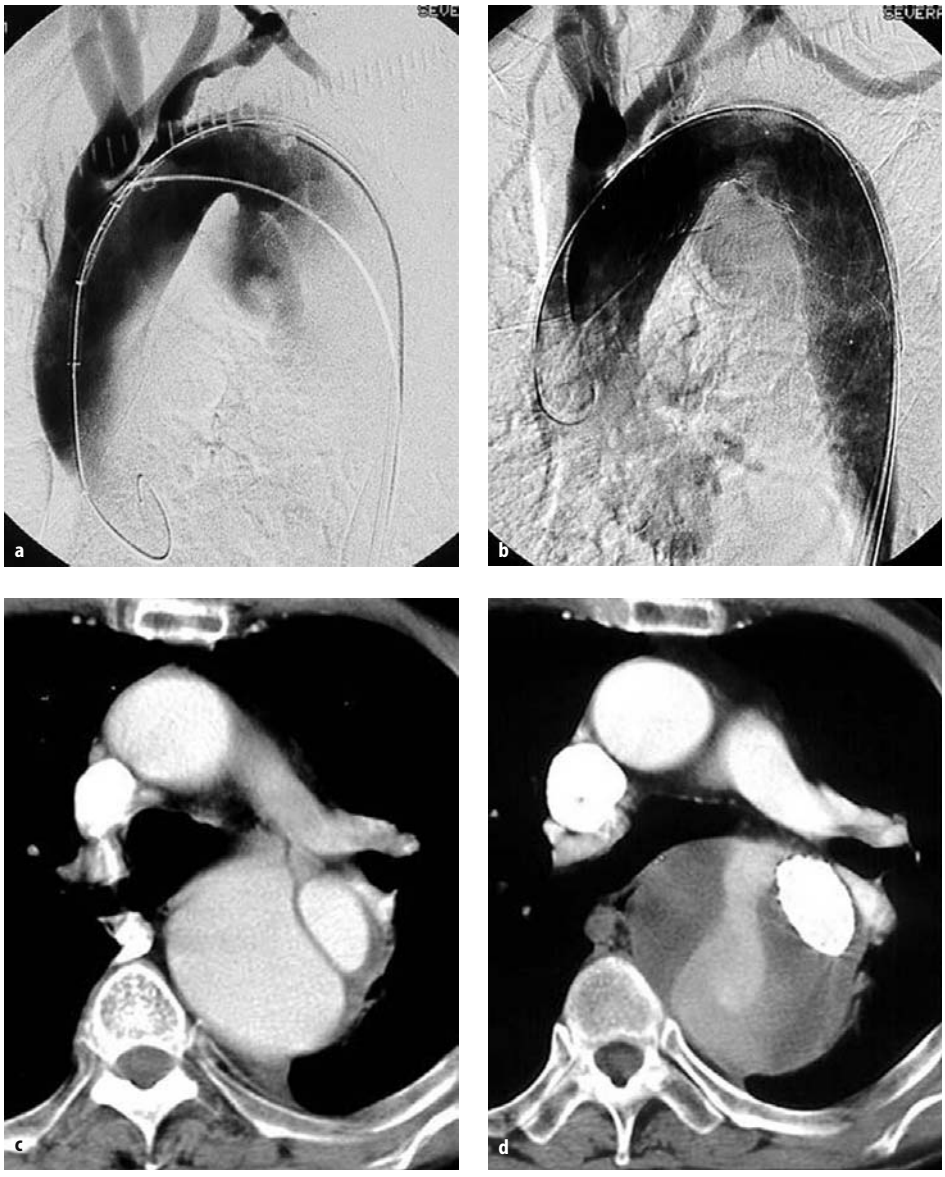


Fig. 21.4. Progression of the endoleak. A 70-year-old man with De Bakey type III aortic dissection. **a** The aortogram shows an entry tear located at the lesser curvature distal from the left subclavian artery. **b** After the placement of the stent-graft, an endoleak of contrast material at the proximal end of the stent-graft is detected. Balloon apposition turned out to be a failure. **c,d** Comparison of CT scans before stent-graft treatment (**c**) and at 1-year follow-up (**d**), enlargement of the descending thoracic aorta from 6.3 to 8.0 cm can be seen. This patient refused any further treatment and is under close observation for 46 months

Quinn et al. [28] reported a case of progressive aneurysmal dilatation of the infrarenal abdominal aorta after placing a stent-graft in the DTA; the aneurysms were treated by surgical repair. Lopera et al. [20] placed stent-grafts in four acute and six chronic type B dissections. Among them, two cases of abdominal false lumen rupture occurred 9 and 13 months after the procedure and all of their dissections were chronic.

Although 47 of 60 patients (78.3%) in our study achieved complete thrombosis or resolution of the thoracic aortic false lumen, complete thrombosis or resolution of dissected abdominal aortic false lumens was achieved in only five patients. During the follow-up, four patients (7%) with technical success showed progressive dilatation of the abdominal false lumen in our study and all of their dissections were chronic. The maximal diameter of their abdominal aorta was increased after the procedure from 3.9 to 4.8 cm during the mean follow-up period of 35 months. We could not find any predicting factors for this problem except the

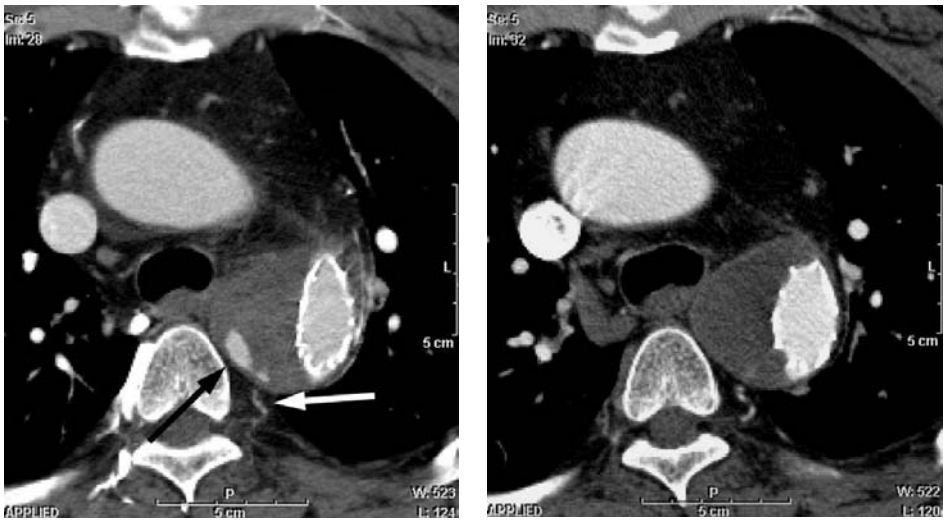


Fig. 21.5. Type II endoleak. A 55-year-old man with De Bakey type III chronic aortic dissection. **a** Follow-up CT scan taken 1 week after the complete exclusion of the entry tear with a stent-graft shows focal contrast enhancement in the false lumen representing a type II endoleak (*black arrow*) through the nearby intercostal artery (*white arrow*). **b** Five-month follow-up CT scan shows resolution of the endoleak despite the persistent enhancement of the intercostal artery

chronicity of the dissection that might be related to the number of reentry tears in abdominal aorta. A patent abdominal false lumen originated from the persistent false lumen flow through multiple reentry tears of the abdominal aorta. Because reentry tears in the abdominal aorta tend to be located near the exit sites of branch vessels, it is mostly impossible to exclude those reentry tears [25]. Fortunately, because of the favorable location of the reentry site, two patients were eligible for further intervention in our study; one with three more stent-graft placements upon the reentry tears in the proximal abdominal aorta, the infrarenal abdominal aorta, and the common iliac artery 53 months after the initial stent-graft treatment (Fig. 21.6); the other one with coil embolization of reentry in the renal artery and the stent-graft over the reentry in the common iliac artery.

21.4.6 New Intimal Tear

Recently, many authors reported the formation of a new intimal tear resulting in pseudoaneurysm or dissection at the margin of the stent-graft from intimal injury as one of the most frequent complications in aortic stent-graft treatment [15, 20, 26].

In our study, we identified six cases (10%) with a new intimal tear complicating saccular aneurysms (n=3) (Fig. 21.7) or new dissections (n=3) developed on both ends (n=1) or either end (n=5) of the stent-graft. Two patients had acute dissection and four had chronic dissection. The delay between the stent-graft implantation and identification of a complicating intimal tear was 1–5 months (mean 3.2 months). Three of six patients (50%) underwent surgical conversion: one with newly developed pseudoaneurysms at both ends of the stent-graft, another with dissection due to the new intimal tear at the distal end of the stent-graft, and the other with retrograde type A dissection due to the intimal tear 6 cm above the proximal end of the stent-graft in a patient with Marfan syndrome; these were confirmed on open repair. In one patient whose previous entry tear had been located at the mid-DTA, a new intimal tear developed at the distal margin of the stent-graft at the level of the diaphragm. He presented acute collapse of the abdominal aortic true lumen and mesenteric ischemia from dynamic occlusion. We deployed another stent-graft upon the new intimal tear (Fig. 21.8). The other two patients have been under close observation for 24 and 41 months.

One case of complicating type A dissection in a patient with Marfan syndrome is suggested to be related not to irritation from the stent-graft itself but to guidewire manipulation according to the retrospective review of intraprocedural films and the surgical findings. Care should be taken in stent-graft treatment for Marfan syndrome because of its well-known instability of the aortic wall [6].

Lopera et al. [20] also reported two cases (20%) of aneurysm formation at the ends of the stent-graft in ten patients with type B aortic dissection. Both cases were successfully managed with placement of additional stent-grafts. Lepore et al. [18] reported two cases of sudden death from aortic rupture 34 and 139 days after stent-graft treatment for acute aortic dissection. Autopsy revealed perforation of the aortic wall by the

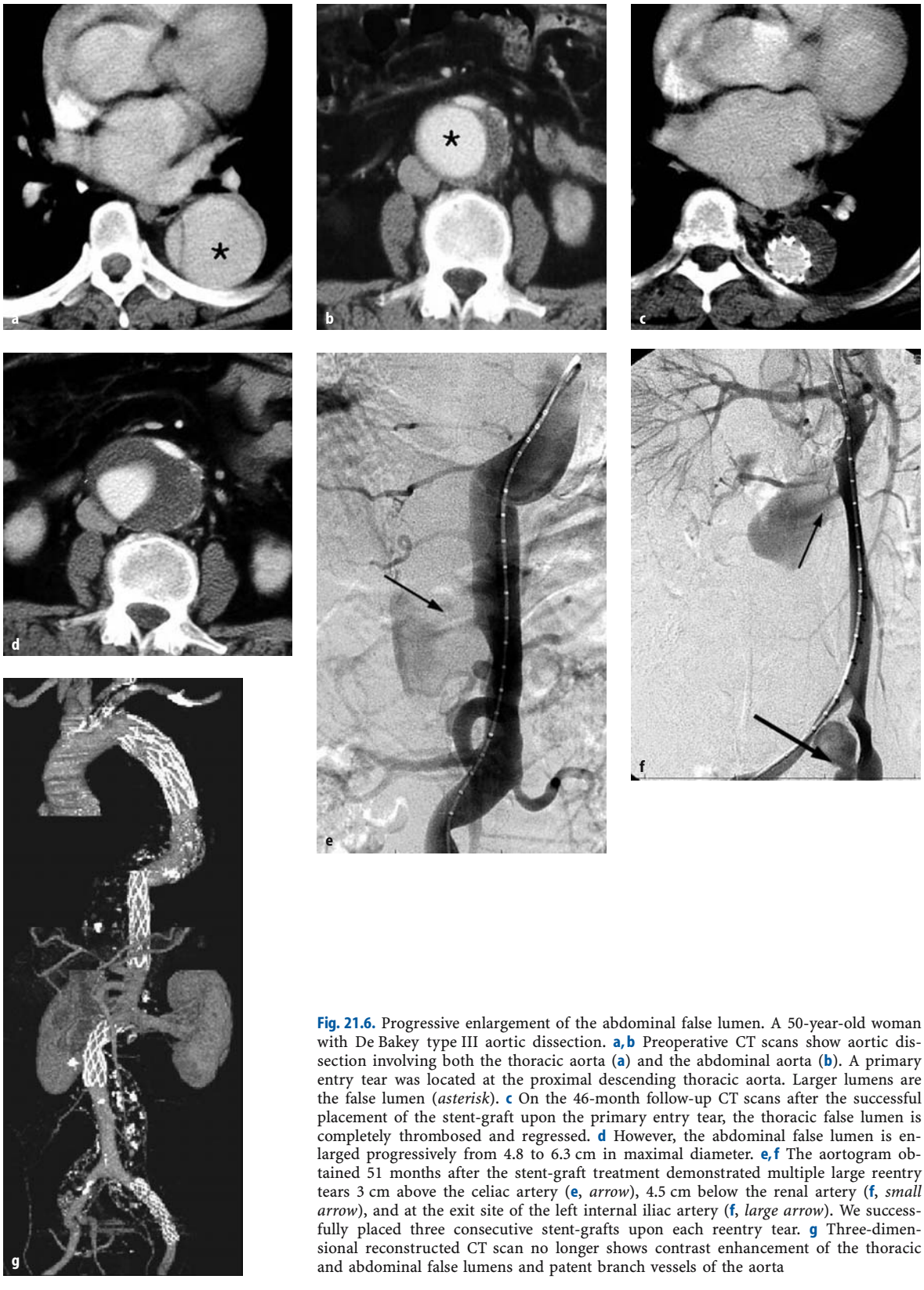


Fig. 21.6. Progressive enlargement of the abdominal false lumen. A 50-year-old woman with De Bakey type III aortic dissection. **a,b** Preoperative CT scans show aortic dissection involving both the thoracic aorta (**a**) and the abdominal aorta (**b**). A primary entry tear was located at the proximal descending thoracic aorta. Larger lumens are the false lumen (*asterisk*). **c** On the 46-month follow-up CT scans after the successful placement of the stent-graft upon the primary entry tear, the thoracic false lumen is completely thrombosed and regressed. **d** However, the abdominal false lumen is enlarged progressively from 4.8 to 6.3 cm in maximal diameter. **e,f** The aortogram obtained 51 months after the stent-graft treatment demonstrated multiple large reentry tears 3 cm above the celiac artery (**e**, *arrow*), 4.5 cm below the renal artery (**f**, *small arrow*), and at the exit site of the left internal iliac artery (**f**, *large arrow*). We successfully placed three consecutive stent-grafts upon each reentry tear. **g** Three-dimensional reconstructed CT scan no longer shows contrast enhancement of the thoracic and abdominal false lumens and patent branch vessels of the aorta

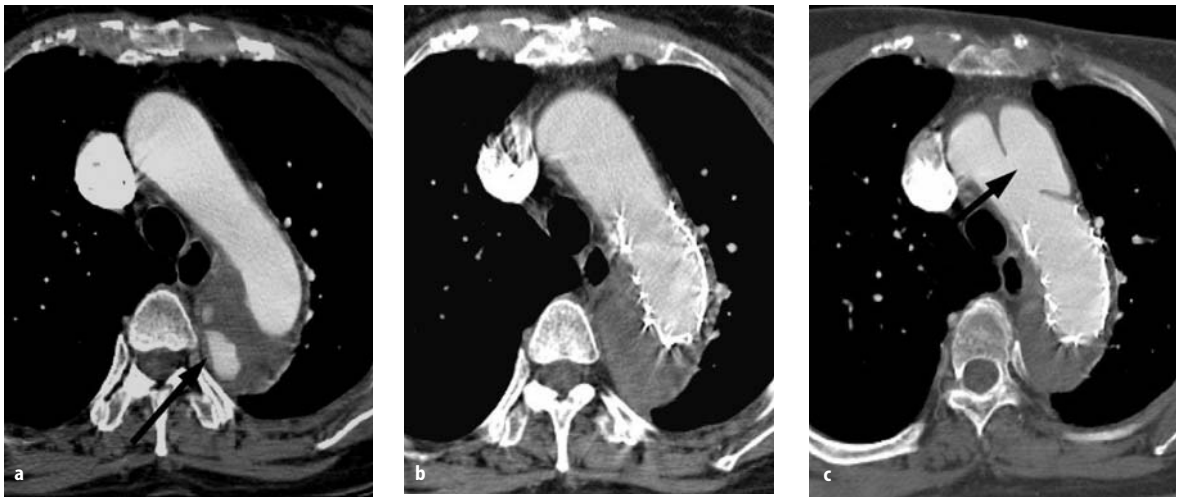
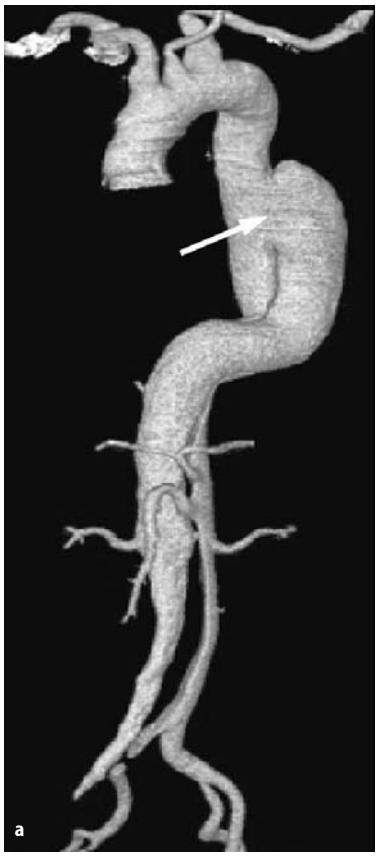


Fig. 21.7. Complicating saccular aneurysm at the proximal end of the stent-graft. A 56-year-old woman with De Bakey type III chronic aortic dissection. **a** The initial CT scan taken 3 months after the onset of the patient's symptom shows aortic dissection involving the descending thoracic aorta. Partial thrombosis of the false lumen is noted (*arrow*). Five days after the stent-graft treatment, the false lumen is excluded. **c** On the 2-month follow-up CT scan, a saccular aneurysm is newly developed near the proximal end of the stent-graft (*arrow*). This saccular aneurysm shows no demonstrable interval change on the 15-month follow-up CT scan

proximal end of the stent-graft. Also in our three surgical converted cases, intimal tears were clearly depicted. Kato et al. [16] reported five cases (13.2%) of new aneurysm formation after the stent-graft repair for 38 aortic dissections. The intervals between the diagnosis and notification of the aneurysms ranged from 17 to 99 days (mean 63 days). Additional stent-graft placement and surgical graft replacement were performed for the management of these patients. All of their five patients were admitted owing to acute dissection and all of the newly developed aneurysms were located at the curved portion of the DTA that attached the stent-graft at an angle. Similarly, five of our six intimal tears developed at the curved portion of aorta where the stent-graft and the intima meet at an angle. Many articles dealing with stent-graft treatment suggest that the causes of the development of intimal tears are mechanical intimal injury, stent-graft migration, and weakened aortic wall. They also suggest several methods to avoid these complications; first, the stent-graft should cover longer portions of the descending aorta until it fits the parallel portion of the aortic wall or intima; second, development of stent-grafts with smoother edges and more flexible bodies [16]. During our early phase of study, we assumed that acute dissection should be more vulnerable in the formation of complicating pseudoaneurysm rather than chronic dissection because of the unstable and fragile intima. However, four of six patients with this complication were managed from chronic dissection and there was no relationship between the duration of the aortic dissection and the development of complicating pseudoaneurysm or dissection. We consider the mechanical stress by the sharp stent tip, the inflexibility of the stent-graft, and the pulsatile force of the aorta have as much adverse effect as the instability of acutely dissected intima. Another possible reason we assume is diaphragmatic motion in the fixed aorta because two of these six intimal tears were located near the diaphragmatic portion of the descending aorta. We also consider ballooning for the purpose of stent-graft apposition as one of the possible etiologic factors of the complicating intimal tear and we do not routinely perform the balloon apposition in stent-graft treatment of aortic dissection. As demonstrated, it is imperative to be aware of the possibility of an intimal tear on both ends of the stent-graft during follow-up.

21.4.7 Mechanical Failure of the Stent-Graft

Since the first stent-graft was placed for the treatment of aortic disease, this technique has improved remarkably with growing understanding of metallurgic and fabric sciences. However, mechanical failure from stent-graft materials of metal and graft continues to be a potential problem in aortic stent-graft treatment. The inherent properties of the resistance of the materials (strength and corrosion) combined with extrinsic forces contribute significantly to the risk of device fatigue. Before deployment, the metallic stent may experience increased risk for failure as a result of damage during loading and subsequent confinement in the delivery catheter. Once implanted, the device is then subjected to additional extrinsic forces imposed by the geometry of the tortuous aorta and the impact of continuous,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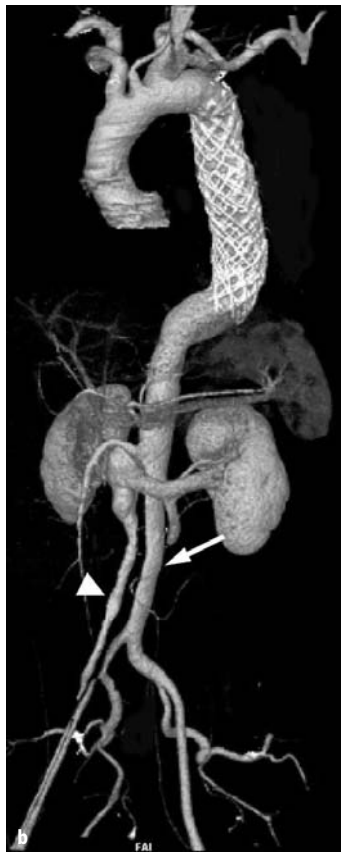
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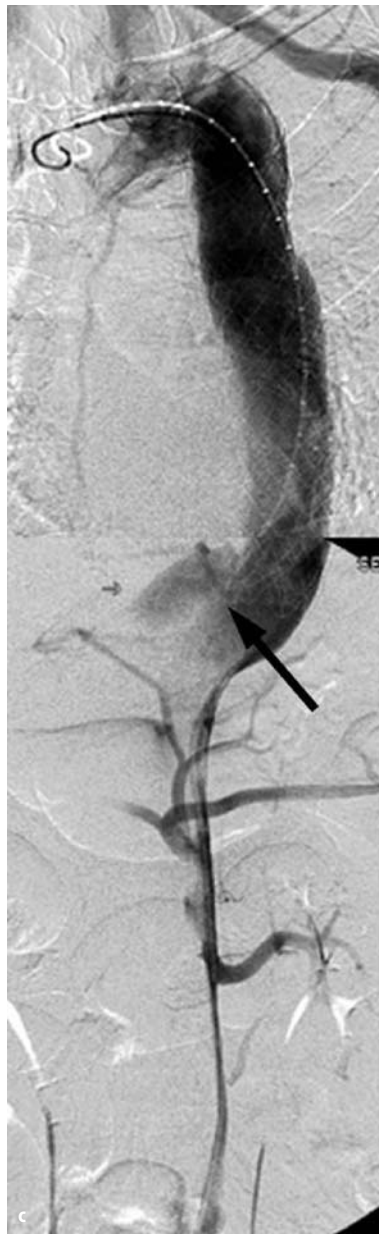
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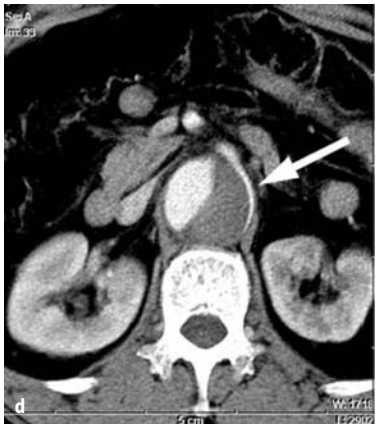
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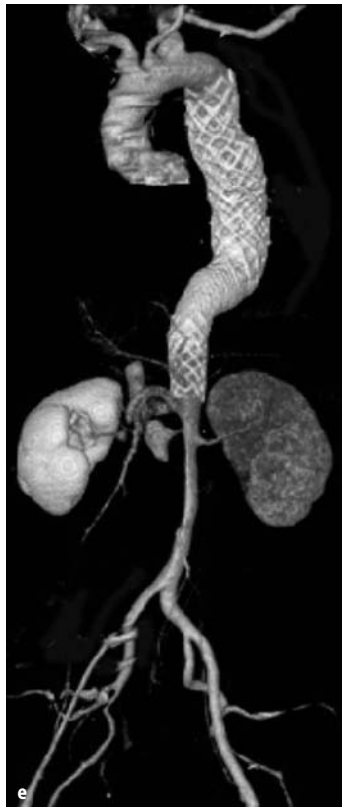
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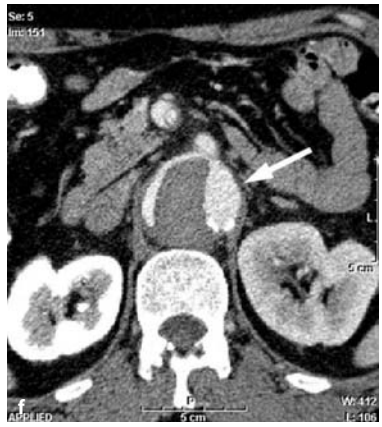
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high-pressure blood flow. Mechanical failure of the stent-graft can occur in the form of metallic fracture, fabric wear, and suture breakage. Recent large series by Jacobs et al. [13] identified 60 patients (9%) with mechanical failure of the stent-graft out of 618 patients who underwent aortic stent-graft placement. Forty-three of them had metallic stent fracture, 14 suture disruption, and three graft wear. The average time to the recognition of mechanical failure of the prosthesis was 19 months. Six of them resulted in surgical conversion and the other ones have been asymptomatic and have not needed interventions for device fatigue. They recommend that if a patient is asymptomatic and there is no evidence of disease progress or a type I or type III endoleak, observation of the stent graft fatigue is acceptable in the setting of increased graft surveillance.

In our series, two cases (3%) with mechanical failure were identified: one with metallic fracture and the other with fabric wear. Metallic fracture was found 36 months after the initial stent-graft placement. Fabric wear occurred at the proximal portion of the graft and made an endoleak around the tear site. However, they have had further complications such as false lumen enlargement or rupture for 56 and 69 months.

21.5 Conclusion

In conclusion, a stent-graft is a more efficient and safer modality for the treatment of aortic dissection than any other current treatment modality, having 87% success rate and 0% mortality. However, various problems and complications could occur during the procedure and the follow-up period. Careful design of the stent-graft, the procedure itself and close follow-up are mandatory for the avoidance and prompt management of such problems.

References

1. Bortone AS, Cillis ED, D'Agostino D, Schinosa LL (2004) Endovascular treatment of thoracic aortic disease four years of experience. Circulation 110(Suppl):II262–II267.
2. Cambria RP, Brewster DC, Lautebach SR, Kaufman JL, Geller S, Fan CM, Greenfield A, Hilgenberg A, Clouse WD (2002) Evolving experience with thoracic aortic stent graft repair. J Vasc Surg 35:1129–1136.
3. Czermak BV, Waldenberger P, Fraedrich G, Dessl AH, Roberts KE, Bale RJ, Perkmann R, Jaschke WR (2000) Treatment of Stanford type B aortic dissection with stent-grafts: preliminary results. Radiology 217:544–550.
4. Czermak BV, Waldenberger P, Perkmann R, Rieger M, Steingruber IE, Mallouhi A, Fraedrich G, Jaschke WR (2002) Placement of endovascular stent-grafts for emergency treatment of acute disease of the descending thoracic aorta. Am J Roentgenol 179:337–345.
5. Dake MD, Kato N, Mitchell RS, Semba CP (1999) Endovascular stent-graft placement for the treatment of acute aortic dissection. N Engl J Med 340:1546–1552.
6. DeSanctis RW, Doroghazi RM, Austen WG, Buckley MJ (1987) Aortic dissection. N Engl J Med 317:1060–1067.
7. Dinis da Gama A (1991) The surgical management of aortic dissection: from uniformity to diversity, a continuous challenge. J Cardiovasc Surg 32:141–153.
8. Dinsmore RE, Willerson JT, Buckley MJ (1972) Dissecting aneurysm of the aorta: aortographic features affecting prognosis. Radiology 105:567–572.
9. Fann JI, Miller DC (1995) Aortic dissection. Ann Vasc Surg 9:311–323.
10. Gorich J, Asquan Y, Seifarth H (2002) Initial experience with intentional stent-graft coverage of the subclavian artery during endovascular thoracic aortic repairs. J Endovasc Ther 9(Suppl):II39–II43.
11. Grabenwoeger M, Hutschala D, Marek PE, Cartes-Zumelzu F, Thurnher S, Lammer J, Wolner E, Havel M (2000) Thoracic aortic aneurysms: treatment with endovascular self-expandable stent grafts. Ann Thorac Surg 69:441–445.
12. Hutschala D, Fleck T, Czerny M, Ehrlich M, Schoder M, Lammer J, Wolner E, Grabenwoger M (2002) Endoluminal stent-graft placement in patients with acute aortic dissection type B. Eur J Cardiothorac Surg 21:964–969.
13. Jacobs TS, Won J, Gravereaux EC, Faries PL, Morrissey N, Teodorescu VJ, Hollier LH, Marin ML (2003) Mechanical failure of prosthetic human implants: a 10-year experience with aortic stent graft devices. J Vasc Surg 37:16–26.
14. Kang SG, Lee DY, Maeda M, Kim ES, Choi DH, K BO, Yoon HK, Sung KB, Song HY (2001) Aortic dissection: percutaneous management with a separating stent-graft – preliminary results. Radiology 220:533–539.
15. Kato N, Hirano T, Kawaguchi T, Ishida M, Shimono T, Yada I, Takeda K (2001) Aneurysmal degeneration of the aorta after stentgraft repair of acute aortic dissection. J Vasc Surg 34:513–518.
16. Kato N, Shimono T, Hirano T, Suzuki T, Ishida M, Sakuma H, Yada I, Takeda K (2002) Midterm results of stent-graft repair of acute and chronic aortic dissection with descending tear: The complication-specific approach. J Thorac Cardiovasc Surg 124:306–312.
17. Lawler LP, Fishman EK (2003) Multidetector row computed tomography of the aorta and peripheral arteries (review). Cardiol Clin 21:607–629.

Fig. 21.8. Complicating new intimal tear at the distal end of the stent-graft. A 46-year-old man with De Bakey type III chronic aortic dissection. **a** Three-dimensional reconstructed CT angiography shows aortic dissection with a large intimal tear in the distal descending thoracic aorta (*arrow*). Simultaneous involvement of the abdominal aorta and the right iliac artery is seen. **b** After placement of the stent-graft upon the primary entry tear, complete exclusion of the thoracic false lumen is demonstrated. Expansion of the abdominal true lumen (*arrow*) and decreased size of the false lumen (*arrowhead*) is seen. **c** Four months after the stent-graft placement, the patient complained of abdominal and leg pain. The aortogram shows a new intimal tear at the distal margin of the stent-graft (*arrow*). **d** Collapse of the abdominal true lumen (*arrow*) from the dynamic obstruction is seen on the contrast-enhanced CT scan. **e** After consecutive deployment of a bare stent in the collapsed true lumen and another stent-graft upon the new intimal tear, dynamic obstruction subsided. **f** The abdominal true lumen restores its blood flow (*arrow*). The patient's symptoms were improved

18. Lepore V, Lonn L, Delle M, Bugge M, Jeppsson A, Kjellman U, Radberg G, Risberg B (2002) Endograft therapy for diseases of the descending thoracic aorta: results in 43 high-risk patients. J Endovasc Ther 9:829–837.
19. Lonn L, Delle M, Falkenberg, Lepore V, Klingenstierna H, Radberg G, Risberg B (2003) Endovascular Treatment of Type B Thoracic Aortic Dissections. J Card Surg 18:539–544.
20. Lopera J, Patiño JH, Urbina C, Garcia G, Alvarez LG, Upegui L, Jhanchai A, Qian Z, Castaneda-Zuniga W (2003) Endovascular treatment of complicated type-B aortic dissection with stent-grafts: midterm results. J Vasc Interv Radiol 14:195–203.
21. Mackenzie KS, LeGuillan M, Steinmetz OK, Montreuil B (2004) Management trends and early mortality rates for acute type B aortic dissection: a 10-year single-institution experience. Ann Vasc Surg 18:158–166.
22. Marui A, Mochizuki T, Mitsui N (1999) Toward the best treatment for uncomplicated patients with type B acute aortic dissection: a consideration for sound surgical indication. Circulation 100(Suppl):II275–II280.
23. Mitchell RS, Dake MD, Semba CP, Fogarty TJ, Zarins CK, Liddell BA, Miller C (1996) Endovascular stent-graft repair of thoracic aortic aneurysms. J Thorac Cardiovasc Surg 111:1054–1062.
24. Nienaber CA, Eagle KA (2003) Aortic dissection: new frontiers in diagnosis and management. Circulation 108: 628–635.
25. Palma JH, Souza JAM, Alves CMR, Carvalho AC, Buffolo E (2002) Self-expandable aortic stent-grafts for treatment of descending aortic dissections. Ann Thorac Surg 73:1138–1142.
26. Pamler RS, Kotsis T, Görich J, Kapfer X, Orend KH, Plassmann LS (2002) Complications after endovascular repair of type B aortic dissection. J Endovasc Ther 9:822–828.
27. Prendergast BD, Boon NA, Buckenham T (2002) Aortic dissection: advances in imaging and endoluminal repair. Cardiovasc Interv Radiol 25:85–97.
28. Quinn SF, Duke DJ, Baldwin SS, Bascom TH, Ruff SJ, Swangard RJ, DeHaas DR, Padgett RC, Bergin PJ, Lau S (2002) Percutaneous placement of a low-profile stent-graft device for aortic dissections. J Vasc Interv Radiol 13:791–798.
29. Resch T, Ivancev K, Brunkwall J, Nyman U, Malina M, Lindblad B (1999) Distal migration of stent-grafts after endovascular repair of abdominal aortic aneurysms. J Vasc Interv Radiol 10:257–264.
30. Ryan JM, Ryan BM, Smith TP (2004) Antibiotic prophylaxis in interventional radiology. J Vasc Interv Radiol 15:547–556.
31. Schor JS, Yerlioglu ME, Galla JD, Lansman SL, Ergin MA, Griepp RB (1996) Selective management of acute type B aortic dissection: longterm follow-up. Ann Thorac Surg 61:1339–1341.
32. Schurink GW, Aarts NJ, van Baalen JM, Kool LJS, van Bockel JH (1999) Stent attachment site-related endoleakage after stent graft treatment: An in vitro study of the effects of graft size, stent type, and atherosclerotic wall changes. J Vasc Surg 30:658–667.
33. Shimono T, Kato N, Yasuda F, Suzuki T, Yuasa U, Onoda K, Hirano T, Takeda K, Yada I (2002) Transluminal Stent-Graft Placements for the Treatments of Acute Onset and Chronic Aortic Dissections. Circulation 106(Suppl):I241–I247.
34. Svensson LG, Crawford ES, Hess KR, Coselli JS, Safi HJ (1993) Variables predictive of outcome in 832 patients undergoing repairs of the descending thoracic aorta. Chest 104:1248–1253.
35. Veerapen R, Dorandeu A, Serre I, Berthet JP, Marty-Ane CH, Mary H, Alric P (2003) Improvement in proximal aortic endograft fixation: an experimental study using different stent-grafts in human cadaveric aortas. J Endovasc Ther 10:1101–1109.
36. Velazquez OC, Carpenter JP, Baum RA, Barker CF, Golden M, Criado F, Pyeron A, Fairman RM (1999) Perigraft air, fever and leukocytosis after endovascular repair of abdominal aortic aneurysms. Am J Surg 178:185–189.
37. Won JY, Lee DY, Shim WH, Chang BC, Park SI, Yoon CS, Kwon HM, Park BH, Jung GS (2001) Elective endovascular treatment of descending thoracic aortic aneurysms and chronic dissections with stent-grafts. J Vasc Interv Radiol 12:575–582.

Medical Treatment or Endovascular Stent-Graft Treatment for Acute Aortic Syndrome

Christoph A. Nienaber

22

Contents

22.1 Introduction

Cardiovascular disease is the leading cause of death in most western societies, and is increasing steadily in many developed countries. Aortic diseases constitute an emerging share of the burden. New diagnostic imaging modalities, longer life expectancy in general, longer exposure to elevated blood pressure and the proliferation of modern noninvasive imaging modalities have all contributed to the growing awareness of acute and chronic aortic syndromes.

All mechanisms weakening the aorta's media layers via microapoplexy of the vessel wall lead to higher wall stress, which can induce aortic dilatation and aneurysm formation, eventually resulting in intramural hemorrhage, aortic dissection or rupture. Especially chronic hypertension chronically affects the arterial wall composition, causing intimal thickening, fibrosis and calcification, and extracellular fatty acid deposition. In parallel, the extracellular matrix undergoes accelerated degradation, apoptosis and elastolysis with hyalinization of collagen eventually leading to intimal disruption, aortic wall ulceration, intramural hematoma and eventually classic dissection of the aortic layers; the clinical picture of these pathologies is today coined acute aortic syndrome.

22.2 Pathogenesis of Aortic Dissection

Chronic hypertension affects the arterial wall composition, causing intimal thickening, fibrosis and calcification, and extracellular fatty acid deposition. Moreover, adventitial fibrosis may obstruct nutrient vessels feeding the arterial wall as well as small intramural vasa vasorum, which may result in necrosis of smooth muscle cells and fibrosis of elastic structures rendering the vessel wall vulnerable to pulsatile forces and creating a substrate for aneurysms and dissections [1–11]. In addition to chronic hypertension, smoking and dyslipidemia and potentially the use of crack cocaine are modulating risk factors. On rare occasions, inflammatory diseases destroy the media layers and cause weakening, expansion and dissection of the aortic wall. Iatrogenic aortic dissection may occur in association with invasive retrograde catheter interventions, or during or after valve or aortic surgery [12–14]. Given the morbidity and mortality of iatrogenic aortic dissection careful assessment is strongly encouraged in patients with unexplained hemodynamic instability or malperfusion syn-

Table 22.1. Etiology of iatrogenic aortic dissection in the International Registry of Aortic Dissection

Cause	Type A	Type B
Cardiac surgery	18 (69%)	1 (12%)
Coronarography/ intervention	7 (27%)	7 (87%)
Renal angioplasty	1 (4%)	–
Complication	Iatrogenic (%)	Spontaneous (%)
Myocardial ischemia	36*	5
Myocardial infarction	15*	3
Limb ischemia	14	8
Mortality (30 days)	35	24

* $p \leq 0.001$

dromes following invasive vascular procedures or aortic surgery (Table 22.1).

Finally, pregnancy-related dissection although a dramatic scenario is a rare event as long as the patient is not affected by any form of connective tissue disease. The putative association of pregnancy in otherwise healthy women and acute dissection may largely be an artifact of selective reporting. Pregnancy is a common condition and may coincidentally occur only with concomitant existence of other risk factors such as long-standing or pregnancy-associated hypertension, or Marfan's syndrome. Preliminary data from the International Registry of Aortic Dissection (IRAD) show that pregnancy in Marfan's syndrome is not associated with aortic tears, unless root size exceeds 40 mm.

22.2.1 Marfan's Syndrome

Among hereditary diseases, Marfan's syndrome is the most prevalent connective tissue disorder with an estimated incidence of 1/7,000 and an autosomal dominant inheritance with variable penetrance. More than 150 mutations on the fibrillin-1 (FBN-1) gene have been identified encoding for a defective fibrillin in the extracellular matrix, which may affect the ocular, cardiovascular, skeletal and pulmonary systems, as well as skin and dura mater. The diagnosis of Marfan's syndrome is currently based on revised clinical criteria of the Gent nosology [15]. The Gent criteria pay particular attention to genetic information like Marfan's syndrome in kindred of an unequivocally affected individual. Moreover, both skeletal and cardiovascular features are major (e.g., diagnostic) criteria if four or more of eight typical manifestations are present. Considering, however, borderline manifestations such as the MASS phenotype (mitral valve, aorta, skeleton, and skin), or subtle phenotypic features ("forme fruste"), the molecular analysis of suspected Marfan's syndrome and the delineation of criteria for differentiating other inherited conditions (genotypes) from a Marfan phenotype are attracting interest [16–20]. The clinical variety of Marfan's syndrome is only partially explained by the number of mutations on the FBN-1 gene. Genetic heterogeneity and the involvement of a second gene (Marfan syndrome type 2, MFS2) may further add to the broad spectrum of symptoms [21].

A common denominator of all phenotypic forms of aortic wall disease is the dedifferentiation of vascular smooth muscle cells not only with classic aneurysm formation, but also from enhanced elastolysis of aortic wall components [22], as shown in a fibrillin-q-deficient animal model [23]. Moreover, enhanced expression of metalloproteinases in vascular smooth muscle cells of the aorta of Marfan patients may promote both fragmentation of medial elastic layers and elastolysis, thus initiating an activated phenotype of smooth muscle cells [24]. In parallel, expression of peroxisome proliferator-activated receptor-γ (PPAR-γ) is upregulated in smooth muscle cells of the aorta of Marfan patients and with cystic medial degeneration, and correlates with clinical severity, while vascular smooth muscle cell apoptosis is likely to be related to progression of aortic dilatation. Thus, PPAR-γ expression might reflect the pathogenesis of cystic medial degeneration and disease progression in the aorta of Marfan and non-Marfan patients without any vascular inflammatory response [25].

22.2.2 Ehlers-Danlos Syndrome

Ehlers-Danlos syndrome (EDS) is a heterogeneous group of hereditable connective tissue disorders characterized by articular hypermobility, skin hyperextensibility and tissue fragility. Eleven types of EDS have been characterized; the true prevalence of EDS is unknown. An aggregate incidence of 1/5,000 births is often cited with no racial or ethnic predisposition. Aortic involvement is seen primarily in autosomal dominant EDS type IV [26].

22.2.3 Annuloaortic Ectasia and Familial Aortic Dissection

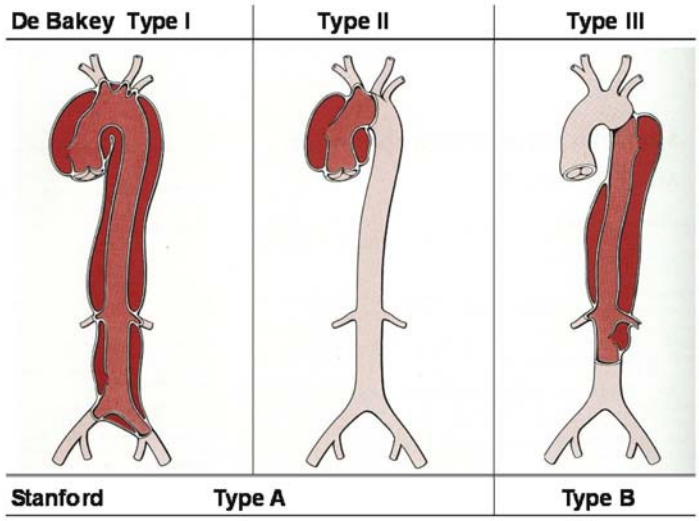
More than five mutations in the FBN-1 gene have now been identified in patients presenting with either sporadic or familial forms of thoracic aortic aneurysms and dissection [27, 28]. Histological examination of the aortic wall reveals elastolysis or loss of elastic fibers, deposits of mucopolysaccharide-like materials and cystic medial degeneration similar to Marfan's syndrome. However, no abnormalities of types I and III collagen or any specific fibrillopathy were found in fibroblast cultures.

22.2.4 Abdominal Aortic Aneurysms and Dissection

Careful examination of family pedigrees often reveals involvement of both the abdominal aorta and disease in proximal aortic segments, or other features suggestive of Marfan's or EDS syndrome. Differentiation of familial forms of abdominal aortic aneurysm/dissection from thoracic aortic aneurysms/dissection with an abdominal component is difficult considering that only one mutation within the COL3A1 gene is known [29]. In fact, many candidate genes encoding for collagens, fibrillins, fibrullins, microfibril-associated glycoproteins, matrix metalloproteinases and their inhibitors have been investigated, but no mutation has been identified. Similar pathogenetic processes have been described with coarctation [1] and with the bicuspid aortic valve architecture [2].

22.3 Definition and Classification

The Stanford classification of aortic dissection distinguishes between type A and type B (Fig. 22.1) [29, 30]. Type A involves the ascending aorta; a type B dissection does not involve the ascending aorta. The De Bakey classification subdivides the dissection process into type I dissection involving the entire aorta, type II dissection involving only the ascending aorta and a type III dissection sparing the ascending aorta and the arch. Various attempts to further subdivide both classification systems have not been established in the medical community [31, 32], although the arch region deserves integration into a modern classification system. Recent observations highlight the importance of precursors of typical aortic dissection such as intramural hematoma,



De Bakey

Type I	Originates in the ascending aorta, propagates at least to the aortic arch and often beyond it distally
Type II	Originates in and is confined to the ascending aorta
Type III	Originates in the descending aorta and extends distally down the aorta or, rarely, retrograde into the aortic arch and ascending aorta

Stanford

Type A	All dissections involving the ascending aorta, regardless of the site of origin
Type B	All dissections not involving the ascending aorta

Fig. 22.1. The commonest classification systems of thoracic aortic dissection

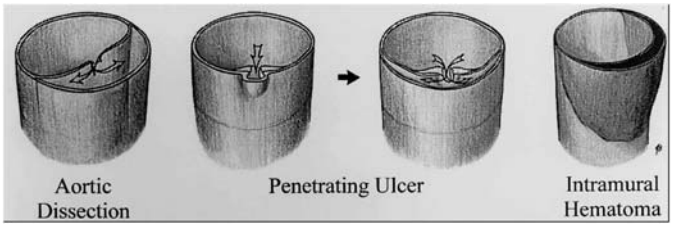


Fig. 22.2. Schematic representation of aortic dissection, penetrating ulcer and intramural hematoma (*IMH*)

penetrating aortic ulcers or a localized intimal tears as variants of a wall-dissecting process [33, 34] (Fig. 22.2).

22.3.1 Classic Aortic Dissection

Acute aortic dissection is characterized by the rapid development of an intimal flap separating the true and the false lumen [35, 36]. In the majority of cases (approximately 90%) intimal tears are identified as sites of communication between the true and the false lumen. The dissection can spread in an antegrade or retrograde fashion, involving side branches and causing complications such as malperfusion syndrome by dynamic or static side branch obstruction, tamponade or aortic insufficiency. The arbitrary classification of acute, subacute or chronic dissection appears helpful neither for didactic nor for differential therapeutic considerations, but may rather be used to describe the individual situation and time span of survival of a given patient. From a pathophysiological point of view progression of dissection is difficult to predict once a patient with dissection has survived the initial 2 weeks after its inception, although false lumen expansion is likely to develop over time. Several clinical features may be used to roughly estimate late risk, including evidence of persistent communication and patent false channel [32, 35, 36].

22.3.2 Intramural Hematoma

Aortic intramural hematoma is considered a precursor of classic dissection, and originates from ruptured vasa vasorum in medial wall layers, eventually provoking a secondary communication with the aortic lumen [34, 37, 38]; this process may be initiated by an "aortic wall infarction." Similar to classic dissection, intramural hematoma may extend along the aorta, may progress, regress or reabsorb. The prevalence of intramural hemorrhage is in the range 10–30% [38–40]. Intramural hematoma can lead to acute aortic dissection in 21–47% of patients or to regression in about 10%. Involvement of the ascending aorta is considered an indication for expeditious surgery owing to the inherent risk of rupture, tamponade or compression of coronary ostia. Distal intramural hematoma may warrant watchful waiting and potentially stent-graft placement [41–43] (Fig. 22.3). Studies in Asian patients from Japan and Korea have argued that wall hematoma reflects a more benign condition, in which aggressive medical therapy and serial imaging allow a watchful waiting strategy [41, 42]. The reasons for this disparity may relate either to a different gene pool of Asian and white patients or to semantic differences. However, at present the cardiological and surgical communities have generally concluded that acute intramural hematoma involving the ascending aorta should be managed surgically similar to type A dissection.

Take home message for therapy: intramural hematoma

1. Surgery is advocated in patients with acute intramural hematoma involving the ascending aorta
2. Aggressive medical therapy is advocated in patients with acute intramural hematoma involving the descending aorta and regular follow-up imaging; in case of progression to dissection endovascular therapy may be considered.

22.3.3 Plaque Rupture/Ulceration

Ulceration of atherosclerotic aortic plaques can lead to aortic dissection or perforation [44–46]. Noninvasive imaging of aortic ulceration has been improved by tomographic scanning and has shed light on pathophysiology and etiology. Aortic ulcers occur predominantly in the descending thoracic and abdominal aorta, penetrate intimal borders and appear in nipplelike projection with an adjacent hematoma [46, 47]; symptomatic ulcers and/or with signs of deep erosion are more likely to rupture than others.

22.4 Clinical Symptoms

The challenge in managing acute aortic syndrome – and especially dissection – is appropriate clinical suspicion and action in pursuing diagnosis and therapy [48,

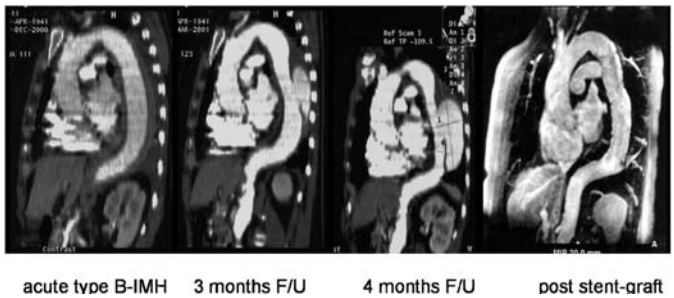


Fig. 22.3. Evolutions of acute IMH of the descending aorta (*left*) to growing local dissection and formation of an aneurysm on spiral contrast-enhanced computed tomography scans within 4 months; reconstruction of the dissected aorta and exclusion of aneurysm after interventional stent-graft placement. *F/U* follow-up

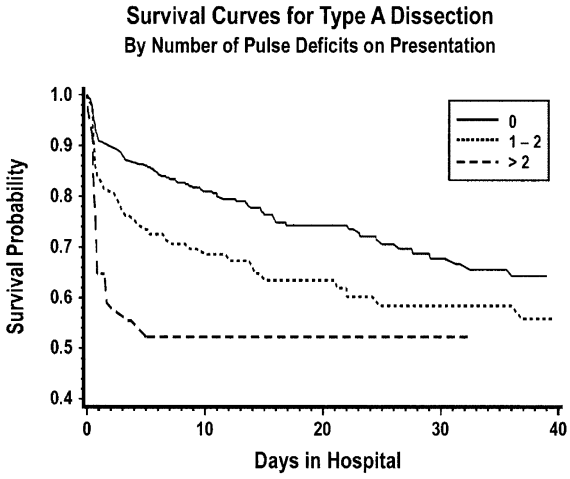


Fig. 22.4. Kaplan–Meier survival curves from patients with and without pulse deficits; log-rank for curves of patients with one, two or three or more pulse deficits differ from patients with no pulse deficits ($P = 0.03$ and 0.004)

49]. Typical features of dissection are the acute onset of chest and/or back pain of blunt, radiating and migrating nature. Chronic hypertension is common if obvious signs of connective tissue disorders are absent. Clinical manifestations of acute aortic dissection are often explained by specific malperfusion syndrome from dissection-related side branch obstruction. Every fifth patient with acute aortic dissection may present with syncope from tamponade, severe hypotension or carotid obstruction [6–8, 50, 51]. Emerging heart failure is usually related to severe aortic regurgitation or coronary obstruction. Cerebrovascular manifestations, limb ischemia or pulse deficits are caused by involvement of a side branch orifice in the dissection or obliteration of the true lumen by an expanding false lumen [9, 52]. Paraplegia may emerge if too many pairs of intercostal arteries are separated from the aortic lumen.

Recurrent abdominal pain, elevation of acute-phase proteins and increase of lactate dehydrogenase are indicators of involvement of either the celiac trunk (observed in approximately 8% of patients) or the superior mesenteric artery (in 8–13% of patients). Involvement of renal arteries may result in oliguria or anuria and propagation of dissection is heralded by repetitive bouts of pain, or a deteriorating clinical picture [16, 17].

Pulse deficits on physical examination occur in approximately 20% of patients and are important clues heralding complications and bad outcome (Fig. 22.4). A diastolic murmur indicative of aortic regurgitation is seen in approximately 50% of patients with proximal dissection. Signs of pericardial effusion, jugular venous distension or a paradoxical pulse should confirm the diagnosis. Shock may be a presenting sign, resulting from tamponade, coronary compression, acute aortic valve incompetence or loss of blood and imminent exsanguinations [6, 9, 11, 49].

Table 22.2. Life-threatening causes of acute chest pain

Acute coronary syndromes
Aortic dissection
Pulmonary embolus
Tension pneumothorax
Esophageal rupture

Consequently, the differential diagnosis of acute aortic dissection should always be considered in patients presenting with chest pain, back pain, unexplained syncope, abdominal pain, stroke, acute onset of congestive heart failure, pulse differentials or malperfusion syndrome of extremities or viscera (Table 22.2). In the present absence of useful specific biomarkers for aortic dissection, interpretation of positive cardiac markers may be even more complex in a scenario of the aortic dissection compromising coronary ostia.

22.5 Diagnostic Procedures

Considering the differential diagnosis of acute aortic dissection, its etiology and the wide spectrum of symptoms, it is not surprising that 70% of ECG findings were pathological [11]. ECG findings are nonspecific, with misleading normal results in type B dissection or acute ischemic changes with involvement of the coronary arteries in type A dissection.

Moreover, a routine chest X-ray is abnormal in 56% of cases of suspected aortic dissection. Transthoracic echocardiography (TTE) has a sensitivity of 60% and a specificity of 83% for type A dissection and also shows aortic regurgitation, pleural effusion and pericardial effusion/tamponade. Transesophageal echocardiography (TEE) with color Doppler interrogation overcomes the limitations of TTE with a sensitivity of 94–100% for identifying an intimal flap and 77–87% for identifying the site of entry; specificity ranges from 77–97% [7, 11 53].

Multislice computed tomography (MCT) scanning is available in many hospitals and is usually offered on an emergency basis [54]. MCT provides complete anatomical information of the aorta, including branch vessel involvement, and enables visualization of the ostium and the proximal part of both coronary arteries. CT scanning has a sensitivity of 83–100% and a specificity of 90–100% for aortic dissection [6, 7, 51]. In randomized trials, cardiac magnetic resonance was more precise than TEE and CT and had a precision of nearly 100% for aortic dissection. For identifying the site of entry, sensitivity was 85% and specificity 100% [8]. Aortography, an invasive procedure, is no longer required for diagnosing aortic dissection. Coronary angiography adds

little to the decision-making process and should generally be avoided in type A dissection [7].

22.6 Medical Management

Acute aortic dissection of the ascending aorta is highly lethal, with a mortality rate of 1–2% per hour early after symptom onset [6, 55]. Acute type A dissection is a surgical emergency. Medical management alone is associated with a mortality rate of nearly 20% by 24 h after presentation, 30% by 48 h, 40% by 1 week and 50% by 1 month. Even with surgical repair, the mortality rates are 10% by 24 h, 13% by 7 days and nearly 20% by 30 days, as recently documented in the largest registry of aortic dissection, although randomized data are not available [9, 11, 56].

Acute aortic dissection affecting the descending aorta is less lethal than type A dissection. Patients with uncomplicated type B dissection have a 30-day mortality rate of 10% [6]. Conversely, those who develop an ischemic leg, renal failure, visceral ischemia or contained rupture often require urgent aortic repair; their mortality rate is 20% by day 2 and 25% by day 30. Not surprisingly, advanced age, rupture, shock and malperfusion are the most important independent predictors of early mortality [7, 50, 57].

Patients with suspected acute aortic dissection should be admitted to an intensive care or monitoring unit and undergo diagnostic evaluation immediately. Pain and blood pressure control to a target systolic pressure of 110 mmHg can be achieved using morphine sulfate and intravenous beta-blockers (metoprolol, esmolol or labetalol) or in combination with vasodilating drugs such as sodium nitroprusside or angiotensin-converting enzyme inhibitors. Intravenous verapamil or diltiazem may also be used, if beta-blockers are contraindicated. Monotherapy with beta-blocking agents may be adequate to control mild hypertension, and in concert with sodium nitroprusside at an initial dosage of 0.3 μg/kg/min, is often effective in a severe hypertensive state (Table 22.3). In normotensive or hypotensive patients, careful evaluation for loss of blood, pericardial effusion or heart failure (by cardiac ultrasound) is mandatory before administering fluids. Patients with profound hemodynamic instability often require intubation, mechanical ventilation and urgent bedside TEE or rapid CT for confirmatory imaging. In rare cases, the external ultrasound diagnosis of cardiac tamponade may justify immediate sternotomy and surgical access to the ascending aorta to prevent circulatory arrest, shock and ischemic brain damage. Percutaneous pericardiocentesis as a temporizing step has often failed, and can accelerate bleeding and shock [58].

Table 22.3. Management of patients with suspected aortic dissection

Recommendation [a]	Class I, IIa, IIb, III
ECG: documentation of ischemia	I
Heart rate and blood pressure monitoring	I
Pain relief (morphine sulfate)	I
Reduction of systolic blood pressure using beta-blockers (intravenous metoprolol, esmolol or labetolol)	I
In patients with severe hypertension despite beta-blockers, additional vasodilator (intravenous sodium nitroprusside to titrate blood pressure to 100–120 mmHg)	I
In patients with obstructive pulmonary disease, blood pressure lowering with calcium channel blockers	II
Imaging in patients with ECG signs of ischemia before thrombolysis if aortic pathology is suspected	II
Chest X-ray	III
Diagnostic imaging (noninvasive)	I

[a] All recommendations are level of evidence C

22.7 Surgical Management

The aim of surgical therapy in proximal type A (types I and II) aortic dissection is prevention of rupture or development of pericardial effusion which may lead to cardiac tamponade and death. Similarly, sudden onset of aortic regurgitation and coronary flow obstruction requires urgent surgical intervention with the aim to resect the region of intimal tear in dissection limited to the ascending aorta and replacement by a composite or interposition graft (if the aortic valves are intact or resuspendable). When the dissection extends to the aortic arch or the descending aorta, resection of the entire in-

Table 22.4. Surgical therapy of acute type A (types I and II) aortic dissection

Recommendation [a]	Class I, IIa, IIb, III
Emergency surgery to avoid tamponade/aortic rupture	I
Valve-preserving surgery – tubular graft if normal size aortic root and no pathological changes of valve cusps	I
Replacement of aorta and aortic valve (composite graft) if ecstatic proximal aorta and/or pathological changes of valve/aortic wall	I
Valve-sparing operations with aortic root remodeling for abnormal valves	IIa
Valve preservation and aortic root remodeling in Marfan patients	IIa

[a] All recommendations are level of evidence C

timal flap may not be possible or the patient may require partial or total arch replacement [59]. A recent report highlights the problem of either resecting or leaving unrecognized intimal tears in the arch or descending thoracic aorta, which is seen in 20–30% of patients and predisposes to later distal aortic reoperation [60]. Considering an operative mortality between 15 and 35% even in centers of excellence, adjunctive measures such as profound hypothermic circulatory arrest and selective retrograde perfusion of head vessels have been used in the surgical management of arch repair or an open distal anastomosis [61]. Whereas the later recently gained growing acceptance for improved outcome with a 5-year survival of 73 ± 6%, profound hypothermic circulatory arrest failed to improve early complications, survival and distal reoperation rates in patients with acute type A dissection; 30-day, 1-year and 5-year survival estimates were 81 ± 2, 74 ± 3 and 63 ± 3%, and thus were not different from those of other techniques using propensity-matched retrospective analysis [4]. The key to success is rapid surgery prior to any hemodynamic instability or deterioration (Table 22.4).

Once the patient is on extracorporal circulation and preferably antegrade cerebral perfusion, which is usually established after cannulation of one femoral artery and the right atrium, the aorta is mobilized to visualize the innominate artery and the aortic root. If the valve leaflets are intact, aortic valve reconstruction using David's or Yacoub's resuspension technique is gaining growing acceptance over valve replacement [62, 63].

The approach to an acute type A (types I and II) dissection (Fig. 22.1) in a previously ectatic proximal aorta must be different. In such instances, mostly in patients with Marfan's syndrome, a composite graft (aortic tube graft with integrated valve) is preferred with coronary reimplantation [64–66]. Surgical allografts and xenografts are experimental since late postoperative degeneration may require reoperation on the aortic root. Valve-sparing operations are delicate endeavors in an emergency and require great surgical competence in centers with expertise in elective cases. If the dissection compromises the left or the right ostium without disrupting the coronary vessel, the ostium can usually be preserved. An ostium completely surrounded by dissected aortic wall may be excised in button form. The dissected layers around the ostium are conjoined using tissue adhesive and over-and-over suturing before the anastomosis to a tube graft is accomplished. Bypass grafting of coronary arteries using saphenous vein segments is limited to those instances where a small torn ostium precludes reconstruction.

22.7.1 The Aortic Arch in Acute Type A (Types I and II) Dissection

Treatment of the acutely dissected aortic arch remains an unresolved issue. At present there is growing consensus that any dissected arch should be explored during hypothermic circulatory arrest. In the absence of an arch tear, an open distal anastomosis of the graft and the conjoined aortic wall layers at the junction of the ascending and arch portions is justified. Arch tears occur in up to 30% of patients with acute dissection [67, 68]. Whenever extensive tears are found, which continue beyond the junction of the transverse and descending aortic segments, or with an acute dissection of a previously aneurysmatic arch, subtotal or total arch replacement may be required with reconnection of some or all supraaortic vessels to the graft during hypothermic circulatory arrest and antegrade head perfusion [69].

In dissecting and nondissecting aneurysms extending to the downstream aorta an elephant trunk extension of the arch graft is an option described by Borst et al. [70]. This technique greatly facilitates later procedures on the downstream aorta. Instead of performing a conventional anastomosis between the end of the graft and the descending aorta, the graft is allowed to float freely in the aortic lumen. In a later procedure, the elephant trunk section of the graft may either be connected surgically to the distal descending aorta directly

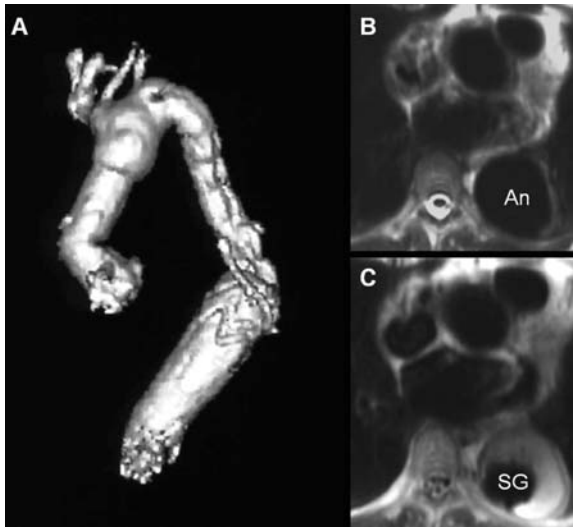


Fig. 22.5. a Reconstructed 3D MRI after percutaneous use of a customized stent-graft to connect a surgically inserted elephant trunk with the upper abdominal aorta in order to exclude an aneurysm that had formed at the distal end of the elephant trunk (**b**); after placement of the customized stent-graft, the thoracic aneurysm was successfully excluded from circulation with thrombus formation around the stent-graft protheses (**c**). *An* aneurysm, *SG* stent-graft

or be extended with another tubular prosthesis, or it may be connected interventionally by a customized endovascular stent-graft which may then be anastomosed at any desired downstream level of the aorta (Fig. 22.5).

In summary, surgery is advised without delay in acute type A (types I and II) dissection both to prevent aortic rupture, pericardial tamponade and death and to relieve aortic regurgitation.

Take home message for treatment of type A dissection

1. Surgery provides definitive treatment for patients with type A acute aortic dissection
2. The aim of surgery is to prevent aortic rupture, pericardial tamponade, and to relieve aortic regurgitation
3. In general, implantation of a composite graft in the ascending aorta with or without reimplantation of coronary arteries is performed
4. A large variety of surgical approaches exist.

22.7.2 Surgery in Type B (Type III) Aortic Dissection

In the current era, indications for operative treatment in patients with acute type B (type III) dissection are limited to the prevention or relief of life-threatening complications such as intractable pain, a rapidly expanding aortic diameter or signs of imminent aortic rupture and can also be managed by interventional stent-graft placement. The onset of complications such as malperfusion of vital aortic side branches warrants interventional therapy by stent-grafting to improve distal true lumen flow or in rare instances catheter-guided fenestration of an occlusive lamella. When this approach does not lead to prompt relief of symptoms, surgical intervention may still be required. At present uncomplicated type B (type III) aortic dissections are usually treated conservatively, since surgical repair has no proven superiority over medical or interventional treatment in stable patients. In complicated cases the concept of interventional stent-graft placement is currently being explored [71–73].

22.7.3 Interventional Endovascular Stent-Graft Treatment

Conventional treatment of Stanford type A (De Bakey types I and II) dissection consists of surgical reconstruction of the ascending aorta with complete or partial resection of the dissected aortic segment; endovascular strategies have no clinical application except to relieve critical malperfusion prior to surgery of the ascending aorta by distal fenestration in cases of thoracoabdominal extension (De Bakey type I) and peripheral ischemic complications. Endovascular stent-graft placement was recently introduced to treat type B dissection, however, it has potential to reconstruct the aorta by sealing one or multiple proximal entry tears with a Dacron-covered scaffold, thus initiating thrombosis of the false lumen [71–74]. Reconstruction of a collapsed true lumen might result in reestablishment of side branch flow (Fig. 22.6). Most scenarios of malperfusion syndrome are amenable to endovascular management considering that surgical mortality rates in patients with acute peripheral vascular ischemic complications are similar to those with mesenteric ischemia, and reach 89% in-hospital mortality [75, 76].

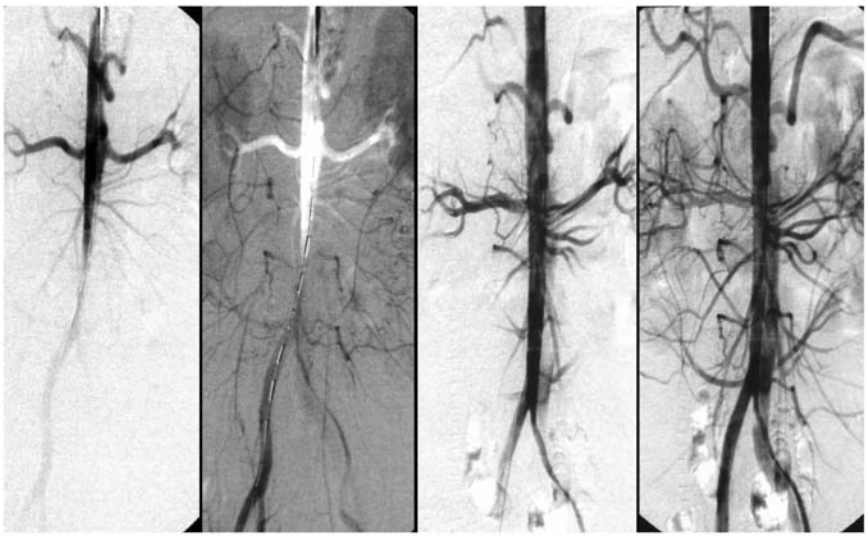


Fig. 22.6. Malperfusion of the distal aorta by occlusive type B dissection. Stent-graft placement in the true lumen of the proximal descending aorta reestablished flow to the abdomen and legs

The interventional management of Stanford type B (De Bakey type III) dissection and the use of stent-grafts evolved to avoid of the risk of paraplegia from spinal artery occlusion as seen in up to 18% of patients after open surgery. In the near future combined surgical and interventional procedures even for proximal dissection are likely to evolve [77, 78].

22.7.4 Indications for Stent-Graft Placement

There appears to be a role for interventional concepts in the treatment of static or dynamic obstruction of aortic branch arteries; static obstruction of a branch can be overcome by placing endovascular stents in the ostium of the compromised side branch, and dynamic obstruction may benefit from stents in the aortic true lumen. In classic aortic dissection, successful fenestration leaves false lumen pressure unchanged. Sometimes bare stents deployed from the true lumen into side branches are useful to buttress the flap in a stable position [79]. Conversely, fenestration may increase the long-term risk of aortic rupture because a large reentry tear promotes flow in the false lumen and provides the basis for aneurysmal expansion of the false lumen; moreover, there is risk of peripheral embolism from a perfused, but partially thrombosed false lumen.

The most effective method to exclude an enlarging and aneurysmal dilated false lumen is the sealing of proximal entry tears with a customized stent-graft; the absence of a distal reentry tear is desirable for optimal results but is not a prerequisite. Adjunctive treatment by fenestration and/or ostial bare stents may help establish flow to compromised aortic branches. Compression of the true aortic lumen cranial to the main abdominal branches with distal malperfusion (so called pseudocoarctation) may also be corrected by stent-grafts that enlarge the compressed true lumen and improve distal aortic blood flow [71–73, 76]. Depressurization and shrinking of the false lumen is the most beneficial result to be gained, ideally followed by complete thrombosis of the false lumen and remodeling of the entire dissected aorta, and in rare occasions even in retrograde type A dissection. Similar to previously accepted indications for surgical intervention in type B dissection, scenarios such as intractable pain with descending dissection, rapidly expanding false lumen diameter and extraaortic blood collection as a sign of imminent rupture or distal malperfusion syndrome are accepted indications for emergent stent-graft placement [73, 79–81]. Moreover, late onset of complications such as malperfusion of vital aortic side branches may justify endovascular stent-grafting as a first option (Table 22.5).

Table 22.5. Interventional therapy in aortic dissection

Recommendation [a]	Class I, IIa, IIb, III
Stenting of obstructed branch origin for static obstruction of branch artery	IIa
Balloon fenestration of dissecting membrane plus stenting of aortic true lumen for dynamic obstruction	IIa
Stenting to keep fenestration open	IIa
Fenestration to provide reentry tear for dead-end false lumen	IIa
Stenting of true lumen	
+ to seal entry (covered stent)	IIb
+ enlarge compressed true lumen	IIa

[a] All recommendations are level of evidence C

22.7.5 Interventional Therapy in an Elective Setting

With both bare stents in side branches and sometimes fenestrating maneuvers compromised flow can be restored in more than 90% (range, 92–100%) of vessels obstructed from aortic dissection. The average 30-day mortality rate is 10% (range, 0–25%) and additional surgical revascularization is rarely needed. Most patients remain asymptomatic over a mean follow-up time of about 1 year. Fatalities related to the interventional procedure may occur as a result of irreversible ischemic complications, progression of the dissection or complications of additional reconstructive surgical procedures on the thoracic aorta. Potential problems may arise from unpredictable hemodynamic alterations in the true and the false lumen after fenestration and side branch stenting. These alterations can result in loss of previously well-perfused arteries or initially salvaged side branches.

Recent reports suggest that percutaneous stent-graft placement in the dissected aorta is safer and produces better results than surgery for type B dissection [72, 73]. Paraplegia may occur after use of multiple stent-grafts but still appears to be a rare phenomenon, especially with a stented segment of less than 16 cm. The results of short-term follow-up are an excellent 1-year survival rate of more than 90%; tears can be readapted and aortic diameters generally decrease with complete thrombosis of the false lumen. This suggests that stent placement may facilitate healing of the dissection, sometimes of the entire aorta, including abdominal segments (Fig. 22.7). However, late reperfusion of the false lumen has been observed occasionally, underlining the need for stringent follow-up imaging.

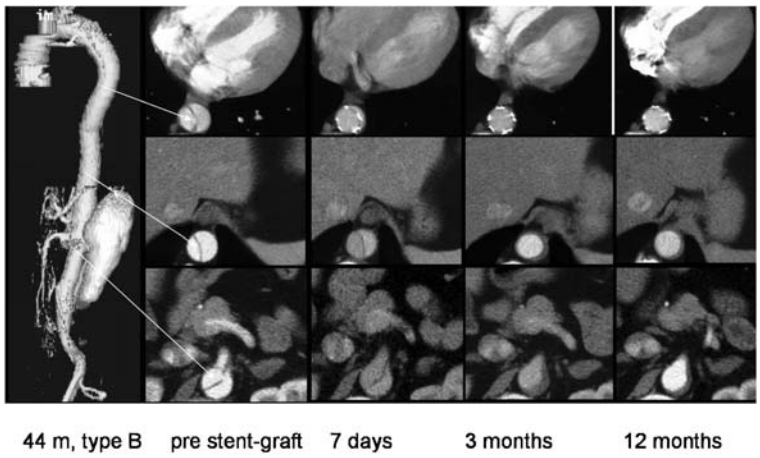


Fig. 22.7. Acute type B aortic dissection in a 44-year-old man; note the communications between the true and the false lumen at the thoracic and abdominal level. After stent-graft placement across the proximal thoracic entry, the entire aorta including the abdominal segment is reconstructed with time, with complete "healing" of the dissected aortic wall and closure of distal communication

22.7.6 Interventional Stent-Graft Therapy as an Emergency

The concept of emergent stent-graft placement for urgent endovascular aortic repair of dissection is attractive, and a growing number of acute type B aortic dissections are subjected to endovascular repair with little evidence of periprocedural morbidity with the result of aborted malperfusion or sealed leakage, and eventually reconstruction of the dissected aorta; stent-graft placement in complicated distal aortic dissection is an emerging concept not associated with excessive peripheral or neurological complications in experienced hands [80–82] and yields better short-term and midterm outcome than surgical or medical treatment in high risk groups of type B dissection.

In conclusion, current advances with stent-graft thoracic intervention must be viewed as exciting new developments that offer hope to many patients with type B dissection. Technical strategies and devices continue to evolve and it is likely that these techniques will soon become first-line therapy for most patients presenting with anatomically suitable thoracic and thoraco-abdominal aortic lesions.

22.7.7 Role of Endovascular Therapy

The exact role of percutaneous fenestration and stent placement in aortic dissection is still evolving. Patients with acute aortic dissection may have life-threatening complications manifested by end-organ ischemia. The mortality rate of patients with renal ischemia is 50–70% and as high as 87% in patients with mesenteric ischemia. Although the surgical success rate at reversing peripheral pulse deficits is high, the surgical in-hospital mortality rates in the setting of end-organ ischemia remain as high as 89%. As such, percutaneous management of this complication has emerged as a viable therapy before or after definitive surgical management if needed.

In 384 patients with acute type B aortic dissections in the IRAD registry, 46 (12%) were managed with endovascular stent-grafting, which was similar to the number of patients treated with surgery (56, 15%) [11]. Only three (6.5%) died during the initial hospitalization. Nienaber et al. [72] compared the outcome of stent-grafting with surgery in a nonrandomized evaluation of 24 patients with chronic type B aortic dissection with at least one indication for surgery. Stent-graft placement resulted in no morbidity or mortality, whereas surgery for type B dissection was associated with four deaths (33%) and five serious adverse events within 12 months. Dake et al. [73] studied the placement of endovascular stent-grafts across the primary entry tear in 19 patients with acute aortic dissection (four patients with type A and 15 with type B). Dissections involved aortic branches in 14 of the 19 patients (74%) and symptomatic compromise of multiple branch vessels was observed in seven patients (37%). Placement of a stent-graft across the primary tear was technically successful in all 19 patients. Complete thrombosis of the false lumen was achieved in 15 patients (79%). Revascularization of ischemic branch vessel was successful in 76% of the obstructed branches. Three of 19 (16%) patients died at 30 days without further death during the subsequent average follow-up of 13 months.

The European Society of Cardiology Task Force on acute aortic dissection released its recommendations for the indications for stent-graft placement and/or fenestration [83]. Additionally, in high-risk patients not suitable for surgery because of age, comorbid conditions or personal preference, endovascular repair offers palliative treatment to those who otherwise would have been left to follow the natural course of the disease.

Take home message for endovascular therapy

1. Endovascular stent grafts have been successfully utilized as a less invasive procedure for patients with surgical indications for chronic type B aortic dissections
2. Endovascular therapies continue to evolve in the treatment of malperfusion syndromes in type A and type B aortic dissections and serve to complement or sometimes replace the need for open surgical procedures.

22.7.8 Descending (Type B) Aortic Dissection

In the current era, endovascular stent-graft intervention for acute descending (type B) aortic dissection is reserved for complications of the disease because surgical repair has no proven superiority over medical or interventional treatment in stable patients. Patients with uncomplicated aortic dissections confined to the descending thoracic aorta (Stanford type B or De Bakey type - III) are best treated with medical therapy. Medical treatment consists of invasive hemodynamic monitoring, beta-blockade and arterial vasodilators if needed to keep systolic blood pressure less than 120 mmHg. Pain control with morphine sulfate is also important to attenuate the sympathetic release of catecholamines to pain with resultant tachycardia and hypertension. Once the patient is stable, oral beta-blockers and other antihypertensive medications if necessary are substituted and the patient is discharged with very close follow-up.

In a series of 384 patients with type B dissections from the IRAD registry, 73% were managed medically. In-hospital mortality for these patients was 10% [11]. The reported long-term survival rate with medical therapy is approximately 60–80% at 4–5 years and approximately 40–45% at 10 years [84–86]. Survival is best in patients with noncommunicating and retrograde dissections.

Indications for endovascular operation in patients with acute type B aortic dissections are generally limited to prevention or relief of life-threatening complications. These complications include aortic rupture, ischemia of limbs and organ systems, renal hypertension, persistent or recurrent intractable pain, progression of dissection and aneurysm expansion, all more likely with a patent false lumen and enlarging aortic diameter (Fig. 22.8), and uncontrolled hypertension. In most series, classic open operations for acute type B aortic dissections carry a higher mortality that historically ranges between 35 and 75%. Furthermore, patients with a complicated course may preferentially undergo endovascular procedures rather than surgery, which may lower the short-term mortality for such patients (Fig. 22.9) [11].

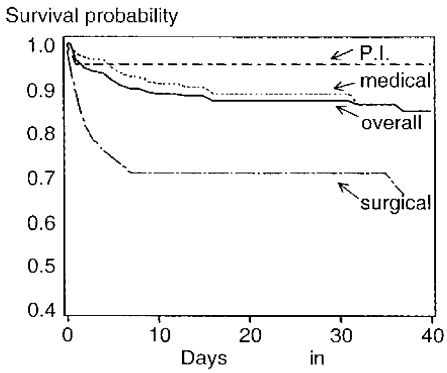


Fig. 22.9. Survival curves due to acute type B aortic dissection for all patients and by management group based on Kaplan-Meier analysis of 40-day mortality. *P.I.* percutaneous intervention. (Taken from Ref. [11])

Take home message for therapy: type B aortic dissection

1. Patients with uncomplicated aortic dissections confined to the descending aorta are best treated with medical therapy
2. Medical therapy includes beta-blockers, other antihypertensives and adequate analgesia to keeps systolic blood pressure below 120 mmHg

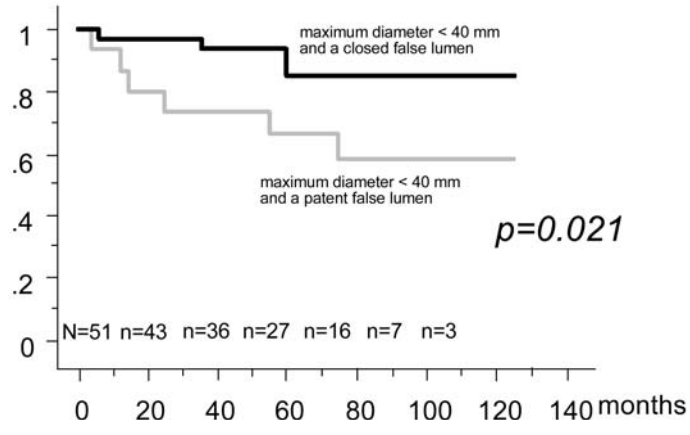


Fig. 22.8 Actuarial survival curves for patients classified by thrombosis of the false lumen and total aortic diameter. (Taken from Ref. [93])

3. The indications for stent-graft placement in type B dissection are limited to persistent or recurrent chest pain, aortic expansion, dissection progression, and end-organ malperfusion syndromes.

22.7.9 Long-Term Therapy and Follow-Up

The long-term approach to patients with successful initial treatment of acute aortic dissection begins with the appreciation of a systemic illness. Systemic hypertension, advanced age, aortic size and the presence of a patent false lumen are all factors which identify higher risk, as does the entire spectrum of Marfan's syndrome [87–89]. All patients merit aggressive medical therapy, follow-up visits and serial imaging. It has been estimated that nearly a third of patients surviving initial treatment for acute dissection will experience extension of dissection, aortic rupture or require surgery for aortic aneurysm formation within 5 years of presentation. Treatment with effective beta-blockade is the cornerstone of medical therapy. By lowering both blood pressure and d*P*/d*t*, beta-blockers have been shown to retard aortic expansion in Marfan's syndrome [90] and that associated with chronic abdominal aortic aneurysms. Blood pressure should be titrated below 135/80 in usual patients and below 130/80 in those with Marfan's syndrome [83, 90–92].

Serial imaging of the aorta is an essential component of long-term management (before and after surgery or stent-graft placement) in Marfan's disease and in all cases of chronic dissection. The choice of imaging modality is dependent on institutional availability and expertise. Previous recommendations suggest follow-up imaging at 1, 3, 6, 9, and 12 months following discharge, and annually thereafter [83]; this aggressive strategy underlines the observation that both hypertension and aortic expansion/dissection are common and not easily predicted in the first months following hospital discharge. Imaging should not be confined to the region of initial involvement since both dissection and aneurysm formation may occur anywhere along the entire length of the aorta.

Development of an ascending aortic diameter of 4.5–5.0 cm is an indication for surgical repair in patients with Marfan's syndrome. In non-Marfan patients an ascending aortic diameter of 5.5–6 cm warrants repair, as does distal aortic expansion to 6.0 cm or more in all types of patients. As with nondissecting aneurysms, the rate of growth and the size of the aorta are both important factors to consider when it comes to prophylactic vascular surgery. An ascending aortic aneurysm of 5.0 cm may merit urgent repair in a young patient with Marfan's syndrome [91]. Conversely, an aneurysm of 5.0 cm for 3 years in an elderly person with well-controlled blood pressure is unlikely to rupture. Patients who have been treated with surgery and/or endovascular stent-grafting warrant similar follow-up to those whose initial treatment was limited to medical treatment.

Considering both the aging patient population in Western societies with prolonged survival despite hypertension and the better diagnostic strategies available to more patients, the cardiovascular community faces an increasing incidence of acute and chronic aortic problems, such as dissection, aneurysm, intramural hematoma, ulcerations and traumatic lesions, that desperately need to be stratified using both early biomarkers of an inflammatory and dissecting process and functional imaging of the aortic wall. At this pivotal point in time, an elevated level of awareness in clinical cardiology and the availability of modern imaging technology should trigger interest in diagnosing and treating the complex of acute aortic syndromes similar to previous efforts in acute coronary syndromes. Cardiologists should improve diagnostic pathways and vascular staging in acute and chronic aortic diseases, form regional referral networks and allocation systems, and utilize uniform follow-up programs. Moreover precise definitions of pathology using clear semantics should be integrated into prospective registries of aortic diseases by a multidisciplinary team of physicians in an attempt to validate previous retrospective observations and to make the best use of evolving diagnostic and endovascular treatment strategies. Finally, cardiologists are in need of credible prognostic models that can support decisions for individual patient care independent of investigators, at different times, and in worldwide locations.

Take home message for follow-up

1. Close follow-up by a specialized team includes the assessment of signs of aortic expansion, aneurysm formation, signs of leakages at anastomoses/stent sites, and malperfusion
2. Excellent blood pressure control below 135/80 mmHg is paramount to prevent complications
3. After hospital discharge, regular outpatient visits and imaging should be performed at 1, 3, 6, 9, and 12 months and at least yearly thereafter.

References

1. von Kodolitsch Y, Aydin MA, Loose R, et al. Predictors of aneurysm formation after surgery of aortic coarctation. J Am Coll Cardiol 2002; 39:617–624.
2. Ward C. Clinical significance of the bicuspid aortic valve. Heart 2000; 83:81–85.
3. Reed D, Reed C, Stemmermann G, Hayashi T. Are aortic aneurysms caused by atherosclerosis? Circulation 1992; 85:205–211.
4. Stefanadis CI, Karayannacos PE, Boudoulas HK, et al. Medial necrosis and acute alterations in aortic distensibil-

ity following removal of the vasa vasorum of canine ascending aorta, Cardiovasc Res 1993; 27:951–956.
5. Larson EW, Edwards WD. Risk factors for aortic dissection: a necropsy study of 161 cases, Am J Cardiol 1984; 53:849–855.
6. Hagan PG, Nienaber CA, Isselbacher EM, et al. The international registry of acute aortic dissection (IRAD): new insights into an old disease. JAMA 2000; 283:897–903.
7. Nienaber CA, von Kodolitsch Y, Nicolas V, et al. The diagnosis of thoracic aortic dissection by noninvasive imaging procedures. N Engl J Med 1993; 328:1–9.
8. von Kodolitsch Y, Schwartz AG, Nienaber CA. Clinical prediction of acute aortic dissection. Arch Intern Med 2000; 160:2977–2982.
9. Mehta RH, O'Gara PT, Bossone E, et al. Acute type A aortic dissection in the elderly: clinical characteristics, management, and outcomes in the current era. J Am Coll Cardiol 2002; 40:685–692.
10. Januzzi JL, Isselbacher EM, Fattori R, et al. Characterizing the young patient with aortic dissection: results from the International Registry of Aortic Dissection (IRAD). J Am Coll Cardiol 2004; 43:665–669.
11. Suzuki T, Mehta RH, Ince H, et al. Clinical profiles and outcomes of acute type B aortic dissection in the current era. Lessons learned from the International Registry of Aortic Dissection (IRAD). Circulation 2003; 108(Suppl 1): II312–317.
12. Januzzi J, Sabatine MS, Eagle KA, et al. Iatrogenic aortic dissection. Am J Cardiol 2002; 89:623–626.
13. von Kodolitsch Y, Simic O, Schwartz A, et al. Predictors of proximal aortic dissection at the time of aortic valve replacement. Circulation 1999; 100(19 Suppl):II287–294.
14. Pieters FAA, Widdershoven JW, Gerardy AC, et al. Risk of aortic dissection after aortic valve replacement. Am J Cardiol 1997; 72:1043–1047.
15. De Paepe A, Devereux R, Dietz H, et al. Revised diagnostic criteria for the Marfan syndrome. Am J Med Genet 1996; 62:417–426.
16. Sakai L, Keene D, Engvall E. Fibrillin, a new 350 kD glycoprotein is a compound of extracellular microfibrills. J Cell Biol 1986; 103:2499–2509.
17. Collod G, Babron MC, Jondeau G, et al. A second locus for Marfan syndrome maps to chromosome 3p24.2-p25. Nat Genet 1994; 8:264–268.
18. Milewicz DM, Pyeritz RE, Crawford ES, et al. Marfan syndrome: defective synthesis, secretion and extracellular matrix formation of fibrillin by cultured dermal fibroblasts. J Clin Invest 1992; 89:79–86.
19. Ramirez F. Fibrillin mutations in Marfan syndrome and related phenotypes. Curr Opin Genet Dev 1996; 6:309–315.
20. Aoyama T, Francke U, Dietz H, et al. Quantitative differences in biosynthesis and extracellular deposition of fibrillin in cultured fibroblasts distinguish five groups of Marfan syndrome patients and suggest distinct pathogenetic mechanisms. J Clin Invest 1994; 94:130–137.
21. Boileau D, Jondeau G, Babron MC, et al. Autosomal dominant Marfan-like connective-tissue disorder with aortic dilatation and skeletal anomalies not linked to the fibrillin genes. Am J Hum Genet 1993; 53:46–54.
22. Lesauskaite V, Tanganelli P, Sassi C, et al. Smooth muscle cells of the media in the dilatative pathology of ascending thoracic aorta: morphology, immunoreactivity for osteopontin, matrix metalloproteinases, and their inhibitors. Hum Pathol 2001; 32:1003–1011.
23. Bunton TE, Biery NJ, Myers L, et al. Phenotypic alteration of vascular smooth muscle cells precedes elastolysis in a mouse model of Marfan syndrome. Circ Res 2001; 88:37–43.
24. Segura AM, Luna RE, Horiba K, et al. Immunohistochemistry of matrix metalloproteinases and their inhibitors in thoracic aortic aneurysms and aortic valves of patients with Marfan's syndrome. Circulation 1998; 98:II331–337; discussion II337–338.
25. Sakomura Y, Nagashima H, Aoka Y, et al. Expression of peroxisome proliferator-activated receptor-γ in vascular smooth muscle cells is upregulated in cystic medial degeneration of annuloaortic ectasia in Marfan Syndrome, Circulation 2002; 106(Suppl I):I259–263.
26. Steinmann B, Royce P, Superti-Furga A. The Ehlers-Danlos syndrome. In: Royce PM, Steinmann B, editors. Connective tissue and its heritable disorders. New York: Wiley-Liss; 1993. p. 351–407.
27. Glesby M, Pyeritz R. Association of mitral valve prolapse and systemic abnormalities of connective tissue. A phenotypic continuum. JAMA 1989; 262:523–528.
28. Furthmayr H, Francke U. Jascending aortic aneurysm with or without features of Marfan syndrome and other fibrillinopathies: new insights. Semin Thorac Cardiovasc Surg 1997; 9:191–205.
29. De Bakey ME, Beall AC, Cooley DA, et al. Dissecting aneurysms of the aorta. Surg Clin North Am 1966; 46:1045–1055.
30. Daily PO, Trueblood HW, Stinson EB, et al. Management of acute aortic dissection. Am Thorac Surg 1970; 10:237–247.
31. Lansmann SL, McCullough JN, Nguyen KH, et al. Subtypes of acute aortic dissection. Ann Thorac Surg 1999; 67:1975–1978.
32. Erbel R, Oelert H, Meyer J, et al. Effect of medical and surgical therapy on aortic dissection evaluated by transesophageal echocardiography. Implication for prognosis and therapy (The European Cooperative Study Group on Echocardiography). Circulation 1993; 83:1604–1615.
33. Nienaber CA, von Kodolitsch Y, Petersen B, et al. Intramural hemorrhage of the thoracic aorta. Diagnostic and therapeutic implications. Circulation 1995; 92:1465–1472.
34. Vilacosta I, San Roman JA, Ferreiros J, et al. Natural history and serial morphology of aortic intramural haematoma: a novel variant of aortic dissection. Am Heart J 1997; 134:495–507.
35. Pretre R, von Segesser LK. Aortic dissection. Lancet 1997; 349:1461–1464.
36. Meszaros I, Moroez J, Szlavi J, et al. Epidemiology and clinicopathology of aortic dissection. Chest 2000; 117:1271–1278.
37. Nienaber CA, Eagle KA. Aortic dissection: new frontiers in diagnosis and management: Part I: from etiology to diagnostic strategies. Circulation 2003; 108:628–635.
38. von Kodolitsch Y, Csösz S, Koschyk DH, et al. Intramural hematoma of the aorta: Predictors of progression to dissection and rupture. Circulation 2003; 107:1158–1163.
39. Evangelista A, Mukherjee D, Mehta RH, et al. Acute intramural hematoma of the aorta – a mystery in evolution. Circulation 2005; 111:1063–1070.
40. Die K, Uchida H, Otsuji H, et al. Acute aortic dissection with intramural hematoma: possibility of transition to classic dissection or aneurysm. J Throac Imaging 1996; 11:46–52.
41. Kaji S, Akasaka T, Horibata Y, et al. Long-term prognosis of patients with type A aortic intramural hematoma. Circulation 2002; 106(Suppl I):I248–252.
42. Song JK, Kim HS, Kang DH, et al. Different clinical features of aortic intramural hematoma versus dissection involving the ascending aorta. J Am Coll Cardiol 2001; 37:1604–1610.
43. Neri E, Capannini G, Carone E, et al. Evolution toward dissection of an intramural hematoma of the ascending aorta. Ann Thorac Surg 1999; 68:1855–1866.

44. von Kodolitsch Y, Nienaber CA. Penetrating ulcer of the thoracic aorta: Natural history, diagnostic and prognostic profiles. Z Kardiol 1998; 87:917–927.
45. Movsowitz HD, Lampert C, Jacobs LE, et al. Penetrating atherosclerotic aortic ulcers. Am Heart J 1994; 128:1210–1217.
46. Ganaha F, Miller DC, Sugimoto K, et al. The prognosis of aortic intramural hematoma with and without penetrating atherosclerose ulcer: a clinical and radiological analysis. Circulation 2002; 106:342–348.
47. Marcu CB, Ghantous AE, Donahue TJ. Intramural hematoma of the descending thoracic aorta. Conn Med 2005; 69:457–459.
48. DeSanctis RW, Doroghazi RM, Austen WG, et al. Aortic dissection. N Engl J Med 1987; 317:1060–1067.
49. Fuster V, Halperin JL. Aortic dissection: a medical perspective. J Card Surg 1994; 9:713–728.
50. Cigarroa JE, Isselbacher FM, De Sanetis RW, et al. Diagnostic imaging in the evaluation of suspected aortic dissection. Old standards and new directions. N Engl J Med 1993; 328:35–43.
51. Svensson LG, Crawford ES. Aortic dissection and aortic aneurysm surgery: clinical observations, experimental investigations and statistical analyses. Part II. Curr Probl Surg 1992; 29:913–1057.
52. Miller DC. The continuing dilemma concerning medical versus surgical management of patients with acute type B dissection. Semin Thorac Cardiovasc Surg 1993; 5:33–46.
53. Erbel R, Engberding R, Daniel W, et al. Echocardiography in diagnosis of aortic dissection. Lancet 1989; 1:457–461.
54. Moore AG, Eagle KA, Bruckman D, et al. Choice of computed tomography, transesophageal echocardiography, magnetic resonance imaging, and aortography in acute aortic dissection: International Registry of Acute Aortic Dissection (IRAD). Am J Cardiol 2002; 89:1235–1238.
55. Hirst AE Jr, Johns VJ Jr, Kime SW Jr. Dissecting aneurysm of the aorta: a review of 505 cases. Medicine 1958; 37:217–279.
56. Mehta RH, Suzuki T, Hagan PG, Bossone E, et al. Predicting death in patients with acute type A aortic dissection. Circulation 2002; 105:200–206.
57. Eagle KA, Quertermous T, Kritzer GA, et al. Spectrum of conditions initially suggesting acute aortic dissection but with negative aortograms. Am J Cardiol 1986, 57:322–326.
58. Isselbacher EM, Cigarroa JE, Eagle KA. Cardiac tamponade complicating proximal aortic dissection: is pericardiocentesis harmful? Circulation 1994; 90:2375–2379.
59. Lai DT, Robbins RC, Mitchell SC, et al. Does profound hypothermic circulatory arrest improve survival in patients with acute type A aortic dissection? Circulation 2002; 106:I218–228.
60. Schor JS, Yerlioglu ME, Galla JD, et al. Selective management of acute type B aortic dissection: long-term follow-up. Ann Thorac Surg 1996; 61:1339–1341.
61. Kazui T, Washiyama N, Muhammad BA, et al. Extended total arch replacement for acute type A aortic dissection: experience with seventy patients. J Thorac Cadiovasc Surg 2000; 119:558–565.
62. David TE, Feindel CM. An aortic valve-sparing operation for patients with aortic incompetence and aneurysm of the ascending aorta. J Thorac Cardiovasc Surg 1992; 103:617–621; discussion 622.
63. Yacoub MH, Gehle P, Candrasekaran V, et al. Late results of a valve preserving operation in patients with aneurysms of the ascending aorta and root. J Thorac Cardiovasc Surg 1998; 115:1080–1090.
64. Kouchoukos NT, Wareing TH, Murphy SF, et al. Sixteen-year experience with aortic root replacement. Results in 172 operations. Ann Surg 1991; 214:308–318; discussion 318–330.
65. Gott VL, Greene PS, Alejo DE, et al. Replacement of the aortic root in patients with Marfan's syndrome. N Engl J Med 1999; 340:1307–1317.
66. Bentall H, De Bono A. A technique for complete replacement of the ascending aorta. Thorax 1968; 23:338–339.
67. Ergin MA, O'Connor J, Guinto R, et al. Experience with profound hypothermia and circulatory arrest in the treatment of aneurysms of the aortic arch. Aortic arch replacement for acute aortic arch dissections. J Thorac Cardiovasc Surg 1982; 84:649–655.
68. Nguyen B, Muller M, Kipfer B, et al. Different techniques of distal aortic repair in acute type A dissection: impact on late aortic morphology and reoperation. Eur J Cardiothorac Surg 1999; 15:496–500.
69. Griepp RB, Ergin MA, Lansman SL, et al. The physiology of hypothermic circulatory arrest. Semin Thorac Cardiovasc Surg 1991; 3:188–193.
70. Borst HG, Walterbusch G, Schaps D. Extensive aortic replacement using 'elephant trunk' prosthesis. Thorac Cardiovasc Surg 1983; 31:37–40.
71. Ince H, Nienaber CA. The concept of interventional therapy in acute aortic syndrome. J Card Surg 2002; 17:135–142.
72. Nienaber CA, Fattori R, Lund G, et al. Nonsurgical reconstruction of thoracic aortic dissection by stent-graft placement. N Engl J Med 1999; 340:1539–1545.
73. Dake M, Kato N, Mitchell RS. Endovascular stent-graft placement for the treatment of acute aortic dissection. N Engl J Med 1999; 340:1524–1531.
74. Walkers PJ, Miller DC. Aneurysmal and ischemic complications of type B (type III) aortic dissections. Semin Vasc Surg 1992; 5:198–214.
75. Walkers PJ, Dake MD, Mitchell RS, et al. The use of endovascular techniques for the treatment of complications of aortic dissection. J Vasc Surg 1993; 18:1042–1051.
76. Fann JI, Sarris GE, Mitchell RS, et al. Treatment of patients with aortic dissection presenting with peripheral vascular complications. Ann Surg 1990; 212:705–713.
77. Yano H, Ishimaru S, Kawaguchi S, et al. Endovascular stent-grafting of the descending thoracic aorta after arch repair in acute type A dissection. Ann Thorac Surg 2002; 73:288–291.
78. Iannelli G, Piscione F, Di Tommaso L, et al. Thoracic aortic emergencies: impact of endovascular surgery. Ann Thorac Surg 2004; 77:591–596.
79. Kato N, Shimono T, Hirano T, et al. Transluminal placement of endovascular stent-grafts for the treatment of type A aortic dissection with an entry tear in the descending thoracic aorta. J Vasc Surg 2001; 34:1023–1028.
80. Nienaber CA, Ince H, Weber F, et al. Emergency stent-graft placement in thoracic aortic dissection and evolving rupture. J Card Surg 2003; 18:464–470.
81. Beregi JP, Haulon S, Otal P, et al. Endovascular treatment of acute complications associated with aortic dissection: midterm results from a multicenter study. J Endovasc Ther 2003; 10:486–493.
82. Pansini S, Gagliardotto PV, Pompei E, et al. Early and late risk factors in surgical treatment of acute type A aortic dissection. Ann Thorac Surg 1998;66:779–784.
83. Erbel R, Alfonso F, Boileau C, et al. Diagnosis and management of aortic dissection. Task force report of the European Society of Cardiology. Eur Heart J 2001; 22:1642–1681.
84. Doroghazi RM, Slater EE, DeSanctis RW, Buckley MJ, Austen WG, Rosenthal S. Long-term survival of patients with treated aortic dissection. J Am Coll Cardiol 1984; 3:1026–1034.
85. Umana JP, Lai DT, Mitchell RS, Moore KA, Rodriguez F, Robbins RC, Oyer PE, Dake MD, Shumway NE, Reitz BA, Miller DC. Is medical therapy still the optimal treatment

strategy for patients with acute type B aortic dissections? J Thorac Cardiovasc Surg 2002; 124:896–910.
86. Bernard Y, Zimmermann H, Chocron S, Litzler JF, Kastler B, Etievent JP, Meneveau N, Schiele F, Bassand JP. False lumen patency as a predictor of late outcome in aortic dissection. Am J Cardiol 2001; 87:1378–1382.
87. Shores J, Berger KR, Murphy ER, et al. Progression of aortic dilatation and the benefit of long-term beta adrenergic blockade in Marfan's-syndrome, N Engl J Med 1994; 330:1335–1341.
88. Nienaber CA, von Kodolitsch Y. Therapeutic management of patients with Marfan syndrome – focus on cardiovascular involvement. Cardiol Review 1999; 7:332–341.
89. Pereira L, Levran O, Ramirez F, et al. A molecular approach to the stratification of cardiovascular risk in families with Marfan's syndrome. N Engl J Med 1994; 331:148–153.
90. Deeb GM, Williams DM, Bolling SF, et al. Surgical delay for acute type A dissection with malperfusion. Ann Thorac Surg 1997; 64:1669–75; discussion 1675–1677.
91. Finkbohner R, Johnston D, Crawford ES, et al. Marfan syndrome. Long-term survival and complications after aortic aneurysm repair. Circulation 1995; 91:728–733.
92. Silverman DI, Burton KJ, Gray J, et al. Life expectancy in the Marfan syndrome. Am J Cardiol 1995; 75:157–160.
93. Marui A, Mochizuki T, Mitsui N, et al. Toward the best treatment for uncomplicated patients With type B acute aorticdissection – a consideration for sound surgical indication. Circulation 1999; 100(Suppl II):II275–280.

Physiopathology of Ischemic Complications of Aortic Dissections

David M. Williams, Bora Peynircioglu

23

Contents

23.1 Introduction

Acute aortic dissection typically kills by tamponade or exsanguination owing to false-lumen rupture or by organ ischemia owing to the malperfusion syndromes [4, 8, 9, 12, 13]. Until recently, the purview of angiography was treating the malperfusion syndromes, with the goal of restoring flow to obstructed arteries and treating medically the ensuing reperfusion injury as best we could. This treatment consisted of fenestration and deployment of uncovered stents on the basis of complete evaluation of the aorta and critical branch arteries, as directed by the clinical examination of the patient, intravascular ultrasound survey of the aorta, and branch arteriography and manometry. The availability of endografts initiated the opportunity of treating the malperfusion syndromes more expeditiously and, in addition, preventing rupture by inducing thrombosis of the false lumen [3, 5, 10, 11]. As in any medical endeavor, errors in diagnosis lead to errors in treatment. The goals of this chapter are to survey the mechanisms by which aortic dissection leads to organ or limb malperfusion and to consider a few of the pitfalls in establishing the diagnosis. In particular, the discussion of malperfusion in the setting of aortic dissection will be divided into these topics:

- Identification of the true and false lumens
- Importance of *abdominal* aortic dissection
- Classification of branch artery obstruction
- Clinical diagnosis of malperfusion
- Setting priorities and avoiding pitfalls.

23.2 Identification of the True and False Lumens

Identification of the true and false lumens is crucial in the endovascular treatment of aortic dissection. The true and false lumens behave differently. In most acute aortic dissection, the false lumen is prone to ectasia and is at risk of rupture, and the true lumen is prone to collapse and is at risk of compromise of its branch arteries. Numerous steps in the endovascular treatment of dissection require real-time knowledge of which lumen the guidewire, the diagnostic catheter, and treatment devices lie within. These steps include:

- Deploying an endograft across the entry tear within the true lumen
- Stenting a branch artery to the aortic true lumen
- Stenting the aortic true lumen after fenestration, to reduce a prolapsing flap
- Aligning both iliac arteries with the aortic true lumen during aortoiliac stenting
- Avoiding complicating future transfemoral catheter procedures, retrograde aortic perfusion, or endograft treatment because of injudicious placement of aortic or branch artery stents.

In chronic dissections, the distinction between the true and false lumens is usually straightforward. For most of these patients, the interventionalist will have the benefit of a chest, abdomen, and pelvis computed tomography (CT) scan. In acute dissections, a complete CT examination may not be available. Features identifying the false lumen include aortic cobwebs and the "beak" sign [6, 7, 14]. Aortic cobwebs are remnants of media stretching (like cobwebs) between the dissection flap and the outer wall of the false lumen (Fig. 23.1). The beak sign is the acute angle by which the dissection flap meets the outer wall of the aorta (Fig. 23.1). As

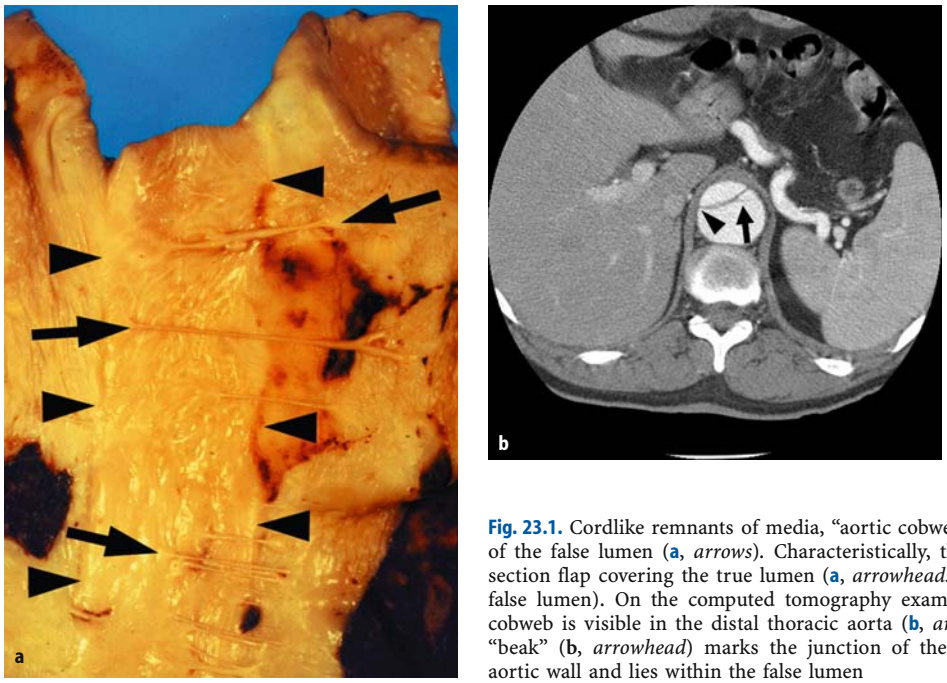


Fig. 23.1. Cordlike remnants of media, "aortic cobwebs," are a reliable marker of the false lumen (**a**, *arrows*). Characteristically, they stretch from the dissection flap covering the true lumen (**a**, *arrowheads*) to the outer wall of the false lumen). On the computed tomography examination of this patient, a cobweb is visible in the distal thoracic aorta (**b**, *arrow*). The acute angle or "beak" (**b**, *arrowhead*) marks the junction of the dissection flap with the aortic wall and lies within the false lumen

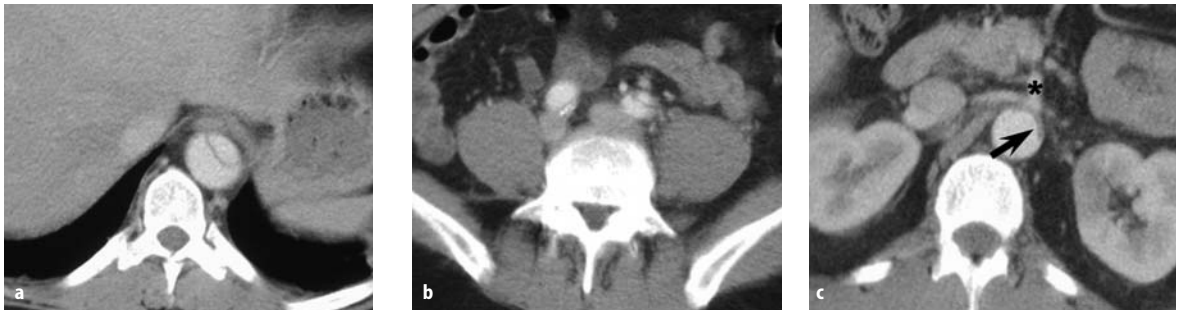


Fig. 23.2. Two distinct lumens are present in the thoracic aorta (**a**) and in the common iliac arteries (**b**). In the intervening abdominal aorta, the second lumen has nearly disappeared (**c**). Here, the true lumen has collapsed completely and is visible as a curvilinear filling defect along the anterior margin on the aorta (**c**, *arrow*), where it lies across the origin of the superior mesenteric artery (*asterisk*)

such, this angle (or beak) is the imaging correlate of the cleaving wedge of hematoma which splits the medial layers to form the false lumen. These signs are highly reliable identifiers of the false lumen. Generally reliable characteristics of the true lumen are continuity with the aortic root, which remains the source of the majority of the large-diameter aortic branches, and continuity with the femoral arteries.

Once the lumens have been identified, they should be traced from root to groin. A reliable anatomical rule to use while drawing a mental path within the aorta from slice to slice on a CT examination is that every time the path crosses the flap it changes the lumen. A second reliable anatomical rule is that, in acute dissections, the lumens are continuous. If two lumens are observed in the chest and two are observed in the pelvis, then two are present in the abdomen, although one of them may be difficult to identify (Fig. 23.2). Sources of branch artery perfusion are identified as exclusively true lumen, exclusively false lumen, or shared true and false lumens. Branches with shared perfusion are further characterized as with or without reentry tears.

23.3 Importance of Abdominal Aortic Dissection

Renal, mesenteric, or spinal cord malperfusion approximately doubles the mortality of patients with acute aortic dissection [2]. Most of these malperfusion syndromes arise as complications of the dissection path through

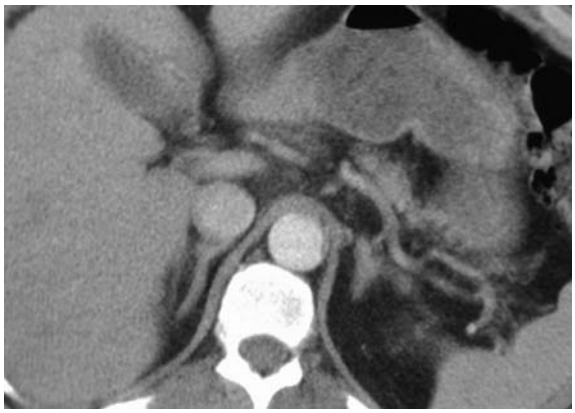


Fig. 23.3. A single lumen is prominent at the level of the aortic crura near the diaphragm in the same patient as in Fig. 23.2. Careful tracing of this lumen back to the heart shows that it is the false lumen, and that the true lumen is completely collapsed and nearly invisible. Until proven otherwise, the bowel must be considered at risk. The true lumen has collapsed against the anterior wall of the aorta, scalloping the anterior margin of the false lumen

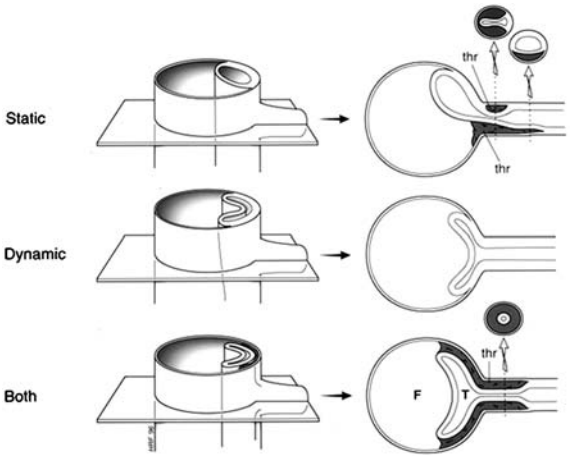


Fig. 23.4. Anatomical drawing, static vs dynamic obstruction. Reprinted with permission [19]

the abdominal aorta, the source of the critical branch arteries. Because of its crucial prognostic role, separate discussion of the abdominal aorta is worthwhile. The false lumen which tapers and disappears at the diaphragm may be of little consequence; however, the true lumen which tapers and disappears at this location represents a lethal, if not mortal, injury (Fig. 23.3), because every true lumen branch distal to the disappearing flap is at risk of obstruction and end-organ infarction. In some cases, the true lumen is so completely collapsed that it is visible only as a scalloping of the anterior aortic lumen (Fig. 23.3). If a lumen "ends" at the diaphragm, make sure it is the false lumen, not the true lumen.

23.4 Classification of Branch Artery Obstruction

The Michigan classification of branch artery obstruction [15] is based on the anatomical relationship of the dissection flap to the branch artery in question (Fig. 23.4). It is an intuitively appealing classification because this anatomic distinction forms the basis of distinct treatment strategies. The causes of obstruction may be distinguished as follows:

- Static obstruction
- Dynamic obstruction
- Mixed static and dynamic obstruction
- Miscellaneous
  - Related to dissection: thrombosis, embolism
  - Unrelated to dissection: atherosclerosis, fibromuscular dysplasia.

In static obstruction, the dissection flap intersects the origin of a branch and potentially encroaches on the lumen. If the dissection enters the vessel origin but does not reenter, the true lumen of the vessel is narrowed, and a pressure gradient may be measured across the stenosis between the aorta and the arterial trunk. If the false lumen reenters through a large enough tear, it can completely compensate for a narrowed true lumen, and no pressure gradient may be present. Treatment is aimed at relieving the branch artery stenosis.

In dynamic obstruction, the dissection flap spares the vessel origin, but prolapses across it like a curtain. This obstruction is dynamic in two senses. It is observed only during cross-sectional imaging with the aorta pressurized and conducting flow; it disappears when the aorta is observed at aortotomy or at necropsy (Fig. 23.5). Furthermore, it may disappear during medical treatment with antihypertensives and beta-blockers, and recur when medications are discontinued (Fig. 23.6). Treatment must be directed at the dissection flap in the aorta.

Static and dynamic obstruction can simultaneously contribute to branch artery obstruction. In addition, complete occlusion of a vessel by either mechanism can lead to thrombosis of the true lumen distally. In the kidney, which has no effective collateral supply, this can lead to diffuse renal branch artery thrombosis, an unsalvageable condition. In the pelvis, iliac artery thrombosis is often arrested at the iliac bifurcation, where collateral supply from lumbar arteries or the contralateral internal iliac artery reconstitutes the obstructed internal and external iliac arteries.

A false lumen which thromboses without a reentry tear can completely fill an artery (or even the aorta), effectively obliterating the true lumen. Furthermore, retrograde thrombosis beginning distally in the vessel can proceed to complete occlusion of that vessel. We have observed this in the iliac, renal, and superior mesenter-

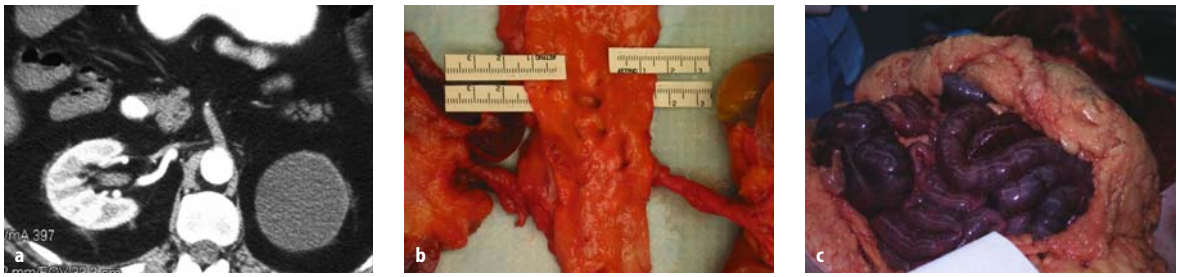


Fig. 23.5. a Computed tomography shows collapse of the true lumen against the anterior wall of the abdominal aorta, occluding the superior mesenteric artery (*SMA*). Small rulers were inserted medially into the false lumen on the autopsy specimen (**b**) up to the anterior margins of the dissection. These confirm that the dissection flap spared the SMA origin, despite diffuse bowel infarction (**c**)

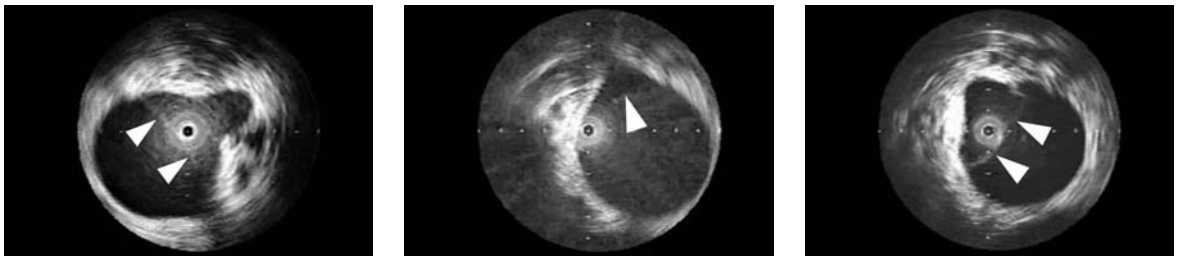


Fig. 23.6. A patient with acute type B dissection was being evaluated for renal artery involvement. Intravascular ultrasound when the patient was at her well-treated normotensive state (**a**) of 90/50 showed a capacious true lumen with unimpeded SMA perfusion. During treatment for impending sedation-induced respiratory arrest, her pressure was driven up to 159/83, resulting in collapse of the true lumen and obstruction of the SMA (**b**). When her pressure returned to the baseline, the true lumen also returned to its baseline state, reopening the SMA (**c**). The dissection flap is marked by *arrowheads*

ic arteries. When it occurs in the aorta, the patient may present with symptoms of spinal cord ischemia. A true lumen may thrombose distal to a dissection flap which covers yet does not enter the vessel origin. This occurs most often in the common iliac artery, when the dissection spares one common iliac origin but enters the other. Complete stasis is present on the nondissected side, and thrombosis ensues. Cross-pelvic collaterals from the contralateral dissected side generally arrest this thrombosis at the iliac artery bifurcation. When the iliac artery is completely thrombosed, it may be difficult to tell whether the thrombosis is within the true or the false lumen, but the distinction is crucial. When thrombosis is present in the false lumen, the obstruction may be treated by means of a stent in the true lumen. When the thrombosis is in the true lumen, the thrombosis must be cleared by mechanical or other thrombolysis before flow in the true lumen is restored by endograft or fenestration.

Embolic occlusion of false and true lumen branches is unusual. Embolism to false lumen branches usually originates from thrombus poorly adhering to the dissection flap. Embolism to true lumen branches usually originates from thrombus forming in regions of stasis, as outlined in the previous paragraph. Other sources include thrombus on the true lumen side of the dissection flap forming at sites of spontaneous reentry tears, or from thrombus within a false lumen extruded into the true lumen through an iatrogenic reentry tear during an angioplasty or stent delivery.

Special situations are beyond the scope of this chapter. These include presentation of dissection and malperfusion in patients with a prior aortic endograft or interposition graft, causes of malperfusion in patients with aortic dissection unrelated to the dissection flap, and causes of malperfusion in patients with previous negative angiographic workup.

23.5 Diagnosis of Branch Artery Obstruction

Cross-sectional imaging is useful to ruling out "ischemic anatomy." If the true lumen is of reasonable caliber from entry tear to termination, and if the dissection flap spares every major branch artery, branch artery obstruction is unlikely. However, if the flap crosses a vessel origin, or the true lumen is collapsed, malperfusion may be present, and should be evaluated by angiography. Evaluation begins with inspection of the flap in relation to branch artery origins. This can be done most expeditiously using intravascular ultrasound. Pressure measurements are made simultaneously in the aor-

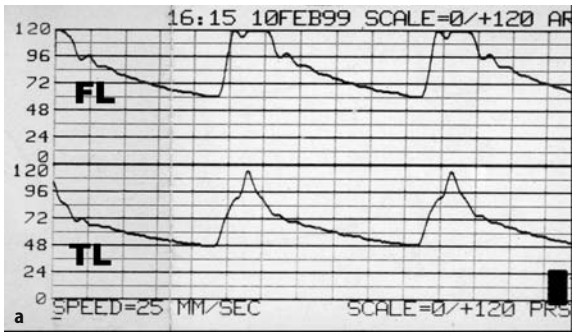


Fig. 23.7. Pressure tracings at the level of the SMA from the patient in Fig. 23.3. True and false lumen pressures are nearly equal (**a**), despite nearly total collapse of the true lumen. In contrast, a profound pressure deficit is present in the SMA, which arises exclusively from the true lumen (**b**). *TL* true lumen, *FL* false lumen

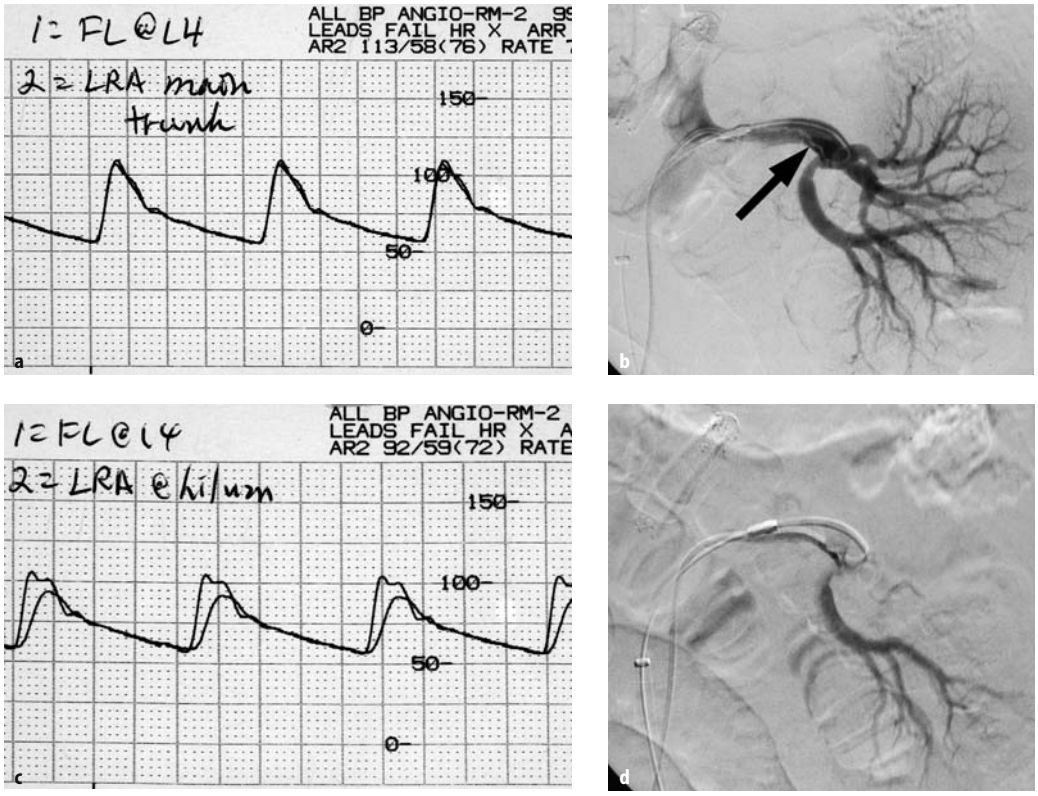


Fig. 23.8. Pressures. No aortorenal gradient is present in the proximal renal artery (**a**). However, the renal artery injection shows that the dissection flap (*arrow*) extends to the renal hilum (**b**), and so the proximal renal artery pressure may not reflect renal perfusion pressure. A catheter in the true lumen distal to the dissection (**c**) documents a small aortorenal pressure gradient (**d**). Other renal branches may be subject to different deficits in perfusion pressure

tic root and abdominal aortic true and false lumens. If these are equal, subsequent pressure measurements can be made using the abdominal aortic pressure as a surrogate for root pressure. If they are unequal, then a search for a pressure drop across a coarctation-like obstruction within the aorta should be made.

Aortic pressures should be compared with arterial trunk pressures in the organ of clinical concern as well as in those branches suspected of being compromised on the basis of imaging. Equal pressures in a false lumen and a collapsed true lumen do not mean that the branch artery pressures are also equal (Fig. 23.7). Pressure measurements should be made within the branch artery of interest. Furthermore, branch artery manometry should be followed by selective arteriography, to make sure that measurements are representative of per-

fusion pressure at the organ level. This precaution is necessary in instances of static obstruction, wherein the reentry tear may be several centimeters deep in the trunk; unless the measurement is distal to the reentry tear, it may underestimate the branch artery deficit in perfusion pressure (Fig. 23.8).

As already noted, dynamic obstruction may be demonstrably pressure-dependent (Fig. 23.6). An occasional scenario is the patient who arrives in the emergency department with tearing chest pain, loss of leg pulses, and refractory hypertension, is aggressively treated with antihypertensives and beta-blockers, and finally arrives, chatty and serene, in the angiography suite to rule out malperfusion. In cases such as this, especially when the clinical history suggests the patient is noncompliant with medications or clinical follow-up, a negative workup for malperfusion is followed by reassessment after tapering down the dose of the beta-blocker. For this reason, we request patients with subacute dissection and a history suggesting sporadic episodes of malperfusion be converted to short-acting beta-blockers, antihypertensives, and sedation. Patients with acute dissection are, ordinarily, already being treated with short-acting drugs.

23.6 Setting Priorities and Avoiding Pitfalls

The leaking false lumen (which heralds impending rupture or tamponade) and florid aortic insufficiency take precedence over malperfusion, and are indications for immediate open repair in patients with reasonable operative risk. The De Bakey and Stanford classifications provide straightforward anatomical criteria for stratifying patients into immediate surgical or medical management. Patients with prolonged malperfusion of gut or lower extremity may be unsuitable for immediate repair even with type A dissection, and in such cases immediate therapy is directed at restoring flow to critical vessels. The mechanism of arterial obstruction determines the appropriate treatment in a given case, and so the first principle of treatment is to define arterial anatomy and assess visceral perfusion. In particular, assuring the integrity of the superior mesenteric artery, or restoring perfusion to the compromised superior mesenteric artery, has the highest priority of any endovascular goal in this group of patients. Even when resection of dead bowel is necessary, preoperative endovascular restoration of superior mesenteric artery perfusion will give the general surgeon reliable margins between uncompromised and unsalvageable bowel.

While correcting life-threatening malperfusion is the goal of these procedures, nevertheless the endovascular physician should bear in mind that additional endovascular procedures may be necessary in the future. This is especially important when treating patients with type A dissections complicated by malperfusion, in whom aortic root reconstruction may be delayed. For example, deploying a Wallstent through a fenestration tear, from the false lumen above to the true lumen below, may effectively treat the malperfusion. However, by compressing the true lumen adjacent to the false lumen component of the Wallstent, this procedure greatly complicates future transfemoral access to the brachiocephalic vessels and may preclude future cardiac bypass using retrograde transfemoral perfusion. Instead, the stent should be deployed entirely within the aortic true lumen. A similar consideration in patients with acute type A dissection complicated by malperfusion is pertinent to creation of the circumferential tear in the flap during the so-called scissor technique [1].

23.7 Conclusion

The malperfusion syndromes greatly increase the mortality of acute aortic dissection. Endovascular techniques, if timely and if carried out with clear and complete understanding of the vascular pathoanatomy of the individual patients, are highly successful in correcting malperfusion.

References

1. Beregi J-P, Prat A et al (2000) Endovascular treatment for dissection of the descending aorta. Lancet 356:482–483.
2. Cambria RP, Brewster DC et al (1988) Vascular complications associated with spontaneous aortic dissection. J Vasc Surg 7:199–209.
3. Dake MD, Kato N et al (1999) Endovascular stent-graft placement for the treatment of acute aortic dissection. N Engl J Med 340:1546–1552.
4. Hirst AE, Johns VJ et al (1958) Dissecting aneurysm of the aorta: a review of 505 cases. Medicine (Baltimore) 37:217–279.
5. Kato K, Matsuda T et al (1998) Outcomes of stent-graft treatment of false lumen in aortic dissection. Circulation 98:II305–312.
6. Lee DY, Williams DM et al (1997) The dissected aorta. II. Differentiation of the true from the false lumen with intravascular US. Radiology 203:32–36.
7. LePage MA, Quint LE et al (2001) Aortic dissection: CT features that distinguish true lumen from false lumen. Am J Roentgenol 77:207–211.
8. Mehta RH, Suzuki T et al (2002) Predicting death in patients with acute type A aortic dissection. Circulation 105:200–206.
9. Miller DC, Mitchell RS et al (1984) Independent determinants of operative mortality for patients with aortic dissections. Circulation 70(3 Pt 2):I153–164.
10. Nienaber CA, Fattori R et al (1999) Nonsurgical reconstruction of thoracic aortic dissection by stent-graft placement. N Engl J Med 340:1539–1545.
11. Palma JH, Marcondes de Souza JA et al (2002) Self-expandable aortic stent-grafts for treatment of descending aortic dissections. Ann Thorac Surg 73:1138–1142.
12. Roberts WC (1981) Aortic dissection: Anatomy, consequences, and causes. Am Heart J 101:195–214.

13. Suzuki T, Mehta RH et al (2003) Clinical profiles and outcomes of acute type B aortic dissection in the current era: lessons from the International Registry of Aortic Dissection (IRAD). Circulation 108(Suppl 1):II312–317.
14. Williams DM, Joshi A et al (1994) Aortic cobwebs: an anatomic marker identifying the false lumen in aortic dissection-imaging and pathologic correlation. Radiology 190:167–174.
15. Williams DM, Lee DY et al (1997) The dissected aorta. III. Anatomy and radiologic diagnosis of branch-vessel compromise. Radiology 203:37–44.

Endovascular Treatment of the Complications of Aortic Dissection: Fenestration and Stenting

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24

Contents

24.1 Introduction

Acute aortic dissection is a medical, radiological and surgical emergency that rapidly compromises the patient's chances of survival [1, 2]. Dissection of the ascending aorta almost invariably requires emergency surgical replacement; when the ascending aorta is not involved, dissection is primarily treated medically, except in the event of complications [3]. The traditional management, based on Stanford classification, is discussed because of emergent endovascular treatment for aorta and malperfusion syndrome.

Malperfusion is defined in this context by the ischemia of an organ during aortic dissection. Malperfusions can concern the heart, brain and spinal cord, and in the case of extension of the dissection to the abdominal aorta and the iliac axes, the digestive tract, kidneys and lower limbs. This type of complication aggravates the already high morbidity and mortality linked to the thoracic complications of dissection [4, 5]. Several mechanisms may be responsible for this malperfusion, and the necessity for endovascular treatment is dependent on these mechanisms.

The purpose of this chapter is to describe the mechanisms behind the malperfusions and to propose the indications and endovascular treatment techniques. In this publication, we only cover renal, digestive and lower-limb malperfusions.

24.2 Malperfusion Symptomatology

In accordance with the Stanford classification, type A dissection concerns the ascending aorta, regardless of the entry site; type B dissection concerns the descending aorta, the entry site being generally situated on the descending aorta, sometimes on the aortic branch. Malperfusion of the visceral branches of the abdominal aorta or the iliac axes can occur in cases of extension of the dissection to the abdominal aorta, whether or not the ascending aorta is concerned with the dissection.

In the case of an aortic dissection with acute symptoms of malperfusion (Table 24.1), diagnosis must be done quickly in order for emergency treatment to be administered.

An aneurysm and/or renal insufficiency should make the practitioner suspect renal ischemia. It is particularly important to check the condition of the renal vascular system rapidly, as soon as dissection is diagnosed. In-

Table 24.1. Symptoms due to malperfusion syndrome in the case of aortic dissection with involvement of the abdominal aorta

Organs	Acute symptoms	Chronic symptoms
Kidneys	Renal failure, anuria	Refractory hypertension
Digestive	Abdominal pain, biological signs (hepatic enzymes)	Digestive angina
Lower limb	Acute ischemia with white and painful leg	Claudication

deed, secondarily, the onset of renal insufficiency in the recovery period or postoperatively (replacement of the ascending aorta) can depend on multiple factors. Early diagnosis of renal malperfusion allows the appropriate endovascular treatment to be initiated without delay.

In the context of aortic dissection extending to the abdominal aorta, spontaneous pain or palpation-induced pain must lead to the rapid diagnosis of intestinal ischemia. This ischemia is difficult to confirm with para-clinical examinations but, if untreated in the hours following the onset of the symptoms, will prove fatal.

Lastly, ischemia of the lower limbs is easily detected using the usual symptomatology (coldness and pain in the limbs and lack of pulse).

The symptoms observed in the acute phase of an aortic dissection must lead to the rapid administration of treatment. Such treatment must sometimes be carried out before the ascending thoracic aorta can be repaired, as in the case of a type A aortic dissection [6, 7].

At the chronic stage, whether a medically treated type B dissection or a type A surgical dissection is involved, the symptoms of malperfusion can appear during follow-up. This can consist of refractory arterial hypertension, digestive angina or intermittent claudication of a lower limb. A morphological analysis of the dissection must be conducted in order to plan the appropriate treatment according to the mechanism of the malperfusion.

24.3 Mechanisms

Malperfusions can currently be treated by endovascular means: implantation of arterial stents in the visceral branches of the abdominal aorta, in the iliac axes, in the abdominal aorta, fenestration of the intimal flap, implantation of a thoracic aortic stent-graft and a combination of these different techniques. These forms of treatment seem to yield better results than surgery in cases of malperfusion-related complications. In order to choose the appropriate treatment, it is essential to know the morphology of the aortic dissection and the extension into vascular branches to understand the mechanisms responsible for the malperfusion(s).

These mechanisms of visceral malperfusion were studied in 1997 by Williams et al. [8]. These authors proposed a system of classification that separates the so-called static mechanisms from those considered dynamic. The static character is described by analogy to classic athermatous lesions that narrow the diameter of the artery like ostial or proximal stenosis. Dynamic lesions are described as resulting from compression of the true arterial lumen by a false lumen secondary to extremely high pressure in the latter. However, this classification system does not describe all possible cases

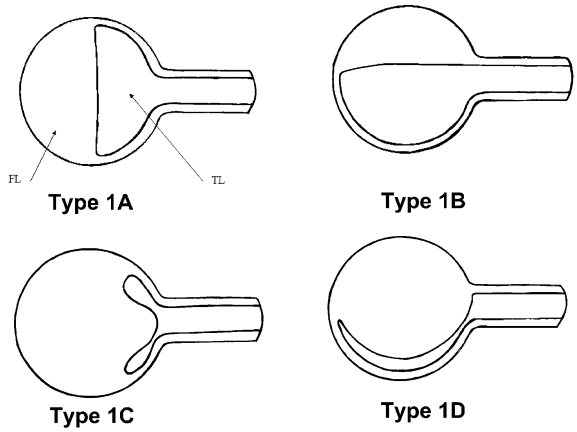

Fig. 24.1. Type 1A, 1B, 1C and 1D lesions. *FL* false lumen, *TL* true lumen

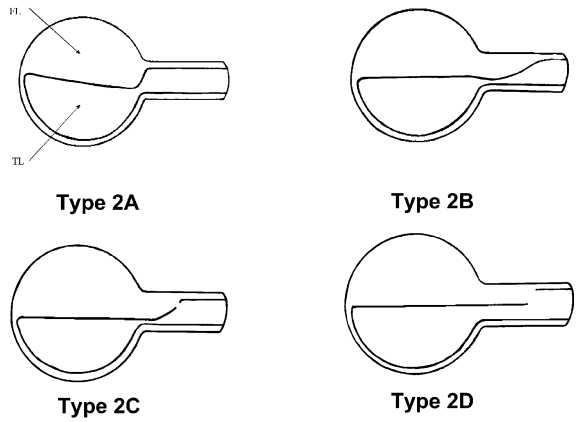

Fig. 24.2. Type 2A, 2B, 2C and 2D lesions. *FL* false lumen, *TL* true lumen

and it is often difficult to link the symptoms with the mechanisms, thus resulting in treatment problems. In fact, all lesions are dynamic. The lesion defined as static is an extension of the dissection into a dead-end visceral artery. This extension leads to a reduction in the true channel by compression of the false channel where the blood enters but cannot exit. Given the blind aspect of the lesion, it tends to thrombose, giving rise to the erroneous diagnosis of a static lesion.

We propose an analysis of lesions in relation to the position of the dissection flap in the aorta followed by examination of the visceral arteries to investigate a possible dissection or an ostial tear (Fig. 24.1). This approach, in a study of 61 patients [9], demonstrated that type 1c and 1d lesions with malperfusion lead to fenestration (Fig. 24.2), whereas type 2a, 2b, 2c and 3c lesions lead to the implantation of a stent in the artery affected by the dissection with downstream ischemia (Fig. 24.3).

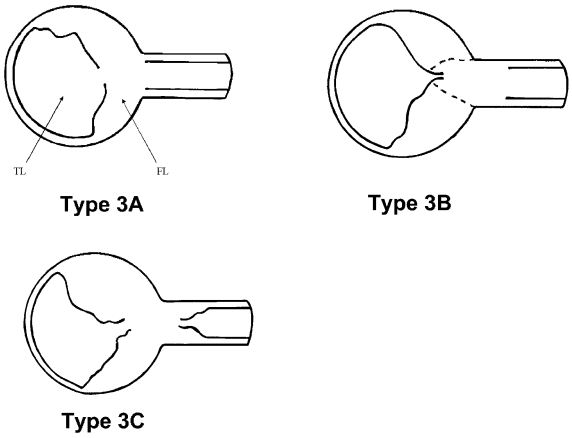

Fig. 24.3. Type 3A, 3B and 3C lesions. *FL* false lumen, *TL* true lumen

Table 24.2. Objectives of imaging techniques when aortic dissection is suspected

To perform the diagnosis of aortic dissection or hematoma
To determine the level of the extension into the aorta (ascending, cross, descending)
To analyse the trajectory of the true and false lumens throughout the total aorta and to evaluate the position of the intimal flap (compression or not of the true lumen)
To detect entry tears: numbers and location
To diagnose thoracic complications of the aortic dissection
To analyse possible extension into branches of the aorta and disconnection of the origin; to look for ischemic signs in the organs: Supra-aortic vessels (brain ischemia) Visceral arteries (kidneys and bowel ischemia) Iliac arteries (lower limb ischemia)
To evaluate tortuosity, calcification and the diameter of the iliac and common femoral arteries for a possible endovascular treatment such as a thoracic stent-graft

24.4 Para-clinical Examinations

The objectives of imaging techniques in cases where aortic dissection is clinically suspected are given in Table 24.2. The diagnostic imaging techniques at our disposal are transthoracic echocardiography, transoesophageal echocardiography (TOE), computed tomography (CT) angiography, MRI and arteriography. TOE, CT angiography and MRI display high, identical levels of sensitivity (greater than 90%) in the diagnosis of aortic dissection [2, 10–12]. TEE responds partially to the objectives mentioned; it does not facilitate complete diagnosis of the dissection, as it is limited to the study of the thoracic aorta. However, this technique can be used in the intensive care unit with no displacement of the patient.

There is less access to MRI in France and we have few machines dedicated to emergencies and to the treatment of haemodynamically unstable patients.

A CT angiogram acquires a large volume of data (thoracic–abdominal–pelvic), allowing thorough investigation of the dissected aorta. Its performance in the exploration of the aorta has been well established [13–15]. The technological contribution of helicoidal data acquisition in the diagnosis of aortic dissection has improved its sensitivity, which now varies between 88 and 100%. The essential objectives mentioned can be achieved using this technique. Exploration is conducted without and then with the injection of a contrast medium. The data acquisition techniques for axial sections are variable and depend on the performance of the equipment used. This technology has allowed more extensive investigation and thorough comprehension of malperfusions. It is also the preferred technique for detecting and analysing malperfusions on a practical level.

Although the technique has been in use for a long time, arteriography is no longer used to diagnose dissection but is employed only as a complementary technique (e.g. before implantation of a thoracic stent-graft) or for an endovascular procedure.

24.5 Endovascular Treatments

Besides surgical treatments such as bypasses, surgical fenestration [16] or closure of the entry points, endovascular techniques have developed as they are better tolerated in the context of aortic dissection with malperfusion [11].

Endovascular fenestration is specific to the treatment of aortic dissections. This technique is carried out whenever malperfusion is suspected in association with a dynamic mechanism or with types 1c and 1d. The principle consists in creating a wide orifice of communication between the true and false channels or in increasing the passage of blood between these two channels [17]. The former technique involves creating an exit site by perforating the intimal flap, from the true channel towards the false channel, using a trans-septal needle. This technique is currently made safer by the use of an endovascular ultrasound probe; this enables surgeons to better locate the position of the intimal flap and to guide movements on perforation [18]. Once the aperture has been made in the flap, it is enlarged by angioplasty with a balloon measuring over 12 mm in diameter. The second possibility for carrying out fenestration, termed the scissor technique [19], involves the introduction of a rigid guide wire into the true channel and another into the false channel, both using the same sheathed introducers (8-F minimum, 45 cm long) installed by the femoral route. A fixed point on the guide wires and graduated, clear-cut advance of the introducer allow a tear to be made in the flap. A tear is observed either in the centre of the flap or at the ex-

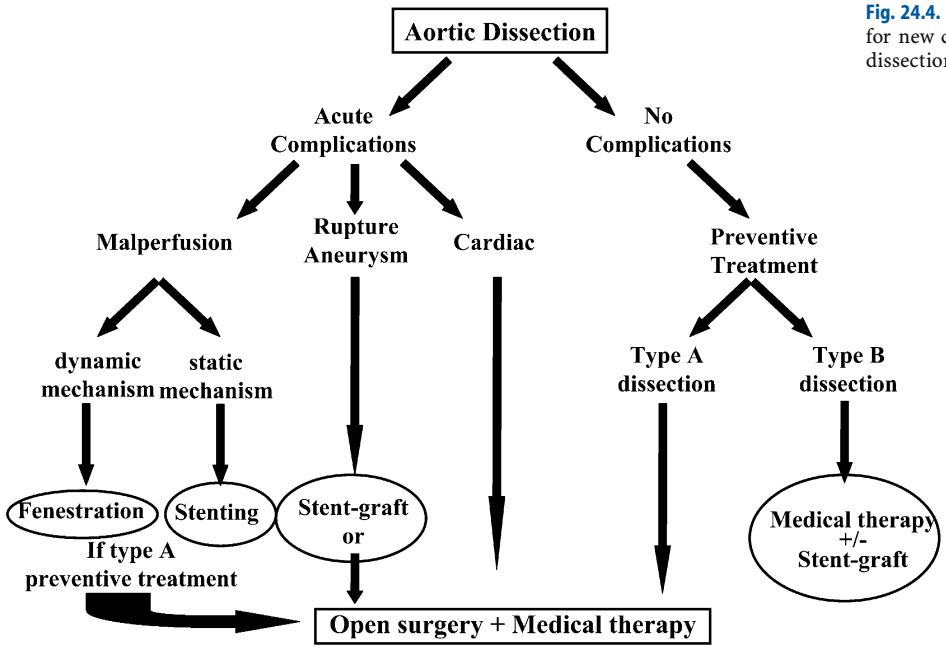

Fig. 24.4. Schematic proposition for new clinical practices in aortic dissection

tremities of the flap, or else the dissection is continued around the remainder of the circumference, extending the height of the fenestrated aorta. This latter mechanism is the most frequent. It can then be useful to unfold the flap by inflating a large-diameter balloon (over 12 mm) inside the thoracic aorta and retracting it as far as the iliac junction, with the balloon inflated. The risk of a torn flap folding back on itself must be taken into account as this can turn and trigger ischemia in the lower limbs [20]. The insertion of a complementary stent will then become necessary. It is also important to carry out stenting of the flap beneath the fenestration site if the false channel is perfused without an exit; there is a risk of aortic rupture linked to the very high pressure in the false channel. Lastly, the scissor fenestration technique does not need to be extensively long; fenestration of 3–5 cm seems sufficient. This generally lowers the pressure in the false channel, relieves compression of the true channel, relieves the ischemia linked to the dynamic mechanism, inhibits complications and gives the surgeon the option of returning at the end of the acute episode with a view to closing all the entry sites. However, in certain cases, fenestration of the intimal flap at the subrenal level is not sufficient to relieve dynamic compression on the renal and digestive arteries; this can be explained by blood flowing predominantly in the true channel, to the low-resistance organs, provoking an attraction of the intimal flap, which remains pressed against the ostium. It then becomes necessary also to install an aortic stent in the true lumen, above the visceral branches. The technique of fenestration is reserved for emergency cases with severe intestinal ischemia (Fig. 24.2). This technique, which is carried out in less than 1 h in the angiography room, provides immediate relief from the symptoms. In the event of renal lesion and delayed treatment, an acute tubular necrosis can also arise with recovery of renal functions in 3 weeks. In patients presenting with chronic symptoms, it is rare to have to carry out a fenestration.

Implantation of bare stents in the abdominal aorta or in the arteries of the organs affected by the malperfusion is carried out using classic endoprostheses. The use of a strong radial action stent is preferable in cases where the true channel is compressed by the false channel. This is why we currently prefer to use balloon-mounted stents. The positioning of a stent at the root of a visceral branch can sometimes prove tricky; this stent must, in effect, push back the false channel that is compressing the true channel in the artery but also at the root. The stent must therefore overlap into the aorta and apply pressure on the false channel (Fig. 24.3), but the latter does not provide stable support; a sufficiently long stent is required in the artery to maintain the whole system. Negotiation of the bend between the aorta and the malperfused artery can be difficult if the balloon-mounted stent, with strong radial action, exceeds 3 cm in length. Account should also be taken of the lack of atheroma, which normally maintains the stent after expansion, and therefore of the risk, after retraction of the balloon, of the stent falling into the aorta, carried away by the balloon. The implantation diameter of the stent must be equal to or greater than that of the treated artery to prevent any secondary movement. The ostial tears, with malperfusion (type 3 c) (Fig. 24.1), also necessitate implantation of a stent (Fig. 24.3).

The mechanisms of malperfusion of the visceral branches of the abdominal aorta and the iliac axes can

be related. When fenestration is necessary, it is this treatment that is carried out first; it is often necessary to complement fenestration with the implantation of a stent on one or several branches. However, the full extent of the remaining lesions is not always easy to ascertain by postfenestration angiography. This highlights the importance of preoperative contrast angiography for a better understanding of the mechanisms of malperfusion, before carrying out arteriography. It is sometimes useful to carry out the procedure in two phases with a new clinical evaluation and diagnostic imaging (echo-Doppler or contrast angiography).

In cases of type B dissection, the implantation of a stent-graft to close the entry site at thoracic level is a therapeutic possibility [21]; it is rarely carried out in the emergency treatment of malperfusion. The availability of stent-grafts, the necessity for a full examination beforehand and the slow regression of the symptoms after implantation are the principal reasons. Emergency implantation of a thoracic stent-graft is indicated in cases of rupture of the false channel. In cases of subacute or chronic symptoms, treatment with a stent-graft can be proposed after anatomical evaluation. The symptoms can take several weeks to disappear owing to thrombosis in the false channel and the slow regression of the latter.

We systematically combine endovascular treatment with medical treatment and observation in recovery or in the cardiac intensive care unit [2]. Blood pressure must be controlled, even if this requires the intravenous administration of several antihypertensive drugs. We start an anticoagulant treatment with intravenous heparin in cases of malperfusion in order to combat organ ischemia. Aortic dissection is no longer a contraindication to the use of heparin in cases of associated malperfusion. The dose administered must ensure efficient anticoagulation. After fenestration, regardless of whether a stent was installed in the visceral branches or a stent graft was used, anticoagulant treatment is continued until malperfusion is relieved and the symptoms disappear. No antiaggregation treatment is used.

24.6 Conclusion – Therapeutic Guidelines

To conclude, visceral malperfusions must be systematically investigated (preferably by thoracic, abdominal and pelvic CT angiography) during the course of aortic dissections as their presence leads to high mortality. Yet visceral malperfusions can be treated using effective endovascular therapies. Their presence leads to a change in the treatment guidelines and lends too much credence to the overly classic dogma: a type A dissection must be surgically corrected and a type B dissection must be treated medically. Modern treatment guidelines are based on the presence or absence of complications. The dissection complications must be treated immediately before considering prophylactic treatment. Type B dissections, just like type A ones, can become complicated owing to malperfusion. It is therefore important to hospitalise the patients, in order to carry out essential diagnostics and design an appropriate course of treatment. Relying on a multidisciplinary treatment protocol, we propose that the organisation chart in Fig. 24.4 should reduce the mortality and morbidity of patients with this condition.

References

1. Wolf JE, Eicher JC, Rezaizadeh-Bourdariat K. Dissection aortique. Rev Prat 2002; 52:1084–1088.
2. Erbel R, Alfonso F, Boileau C, Dirsch O, Eber B, Haverich A, Rakowski H, Struyven J, Radegran K, Sechtem U. Diagnosis and management of aortic dissection: Task Force on Aortic Dissection, European Society of Cardiology. Eur Heart J 2001; 22:1642–1681.
3. Kouchoukos NT, Dougenis D. Surgery of the thoracic aorta. N Engl J Med 1997; 336:1876–1888.
4. Cambria RP, Brewster DC, Gertler J, Moncure AC, Gusberg R, Tilson MD, Darling RC, Hammond G, Mergerman J, Abbott WM. Vascular complications associated with spontaneous aortic dissection. J Vasc Surg 1988; 7:199–209.
5. Mehta RH, Suzuki T, Hagan PG, Bossone E, Gilon D, Llovet A, Maroto LC, Cooper JV, Smith DE, Armstrong WF, Nienaber CA, Eagle KA. Predicting death in patients with acute type A aortic dissection. Circulation 2002; 105:200–206.
6. Fabre O, Vincentelli A, Willoteaux S, Beregi JP, Prat A. Preoperative fenestration for type A acute aortic dissection with mesenteric malperfusion. Ann Thorac Surg 2002; 73:950–951.
7. Deeb GM, Williams DM, Bolling SF, Quint LE, Monaghan H, Sievers J, Karavite D, Shea M. Surgical delay for acute type A dissection with malperfusion. Ann Thorac Surg 1997; 64:1669–1675.
8. Williams DM, Lee DY, Hamilton BH, Marx MV, Narasimham DL, Kazanjian SN, Prince MR, Andrews JC, Cho KJ, Deeb GM. The dissected aorta: part III. Anatomy and radiologic diagnosis of branch-vessel compromise. Radiology 1997; 203:37–44.
9. Gaxotte V; Cocheteux B, Haulon S, et al. Relationship of intimal flap position to endovascular treatment of malperfusion syndromes in aortic dissection. J Endovasc Ther 2003; 10:719–727.
10. Chemla P, Rousseau H, Otal P, Chabbert V, Joffre F. Imagerie de l'aorte. Rev Prat 2002; 52:1066–1072.
11. Rousseau H, Otal P, Soula P, Colombier D, Joffre F. Diagnostic et traitement endovasculaire de la pathologie aortique thoracique. J Radiol 1999; 80:1064–1079.
12. Sommer T, Fehske W, Holzknecht N, Smekal AV, Keller E, Lutterbey G, Kreft B, Kuhl C, Gieseke J, Abu-Ramadan D, Schild H. Aortic dissection: a comparative study of diagnosis with spiral CT, multiplanar transesophageal echocardiography, and MR imaging. Radiology 1996; 199:347–352.
13. Ledbetter S, Stuk JL, Kaufman JA. Helical (spiral) CT in the evaluation of emergent thoracic aortic syndromes. Traumatic aortic rupture, aortic aneurysm, aortic dissection, intramural hematoma, and penetrating atherosclerotic ulcer. Radiol Clin North Am 1999; 37:575–589.

14. Sebastia C, Pallisa E, Quiroga S, Alvarez-Castells A, Dominguez R, Evangelista A. Aortic dissection: diagnosis and follow-up with helical CT. Radiographics 1999; 19:45–60.
15. Rubin GD, Shiau MC, Schmidt AJ, Fleischmann D, Logan L, Leung AN, Jeffrey RB, Napel S. Computed tomographic angiography: historical perspective and new state-of-the-art using multi detector-row helical computed tomography. J Comput Assist Tomogr 1999; 23(Suppl 1):S83–90.
16. Elefteriades JA, Hammond GL, Gusberg RJ, Kopf GS, Baldwin JC. Fenestration revisited. A safe and effective procedure for descending aortic dissection. Arch Surg 1990; 125:786–790.
17. Slonim SM, Miller DC, Mitchell RS, Semba CP, Razavi MK, Dake MD. Percutaneous balloon fenestration and stenting for life-threatening ischemic complications in patients with acute aortic dissection. J Thorac Cardiovasc Surg 1999; 117:1118–1126.
18. Chavan A, Hausmann D, Dresler C, Rosenthal H, Jaeger K, Haverich A, Borst HG, Galanski M. Intravascular ultrasound-guided percutaneous fenestration of the intimal flap in the dissected aorta. Circulation 1997; 96:2124–2127.
19. Beregi JP, Prat A, Gaxotte V, Delomez M, McFadden EP. Endovascular treatment for dissection of the descending aorta. Lancet 2000; 356:482–483.
20. Lookstein RA, Mitty H, Falk A, Guller J, Nowakowski FS. Aortic intimal dehiscence: a complication of percutaneous balloon fenestration for aortic dissection. J Vasc Interv Radiol 2001; 12:1347–1350.
21. Dake MD, Kato N, Mitchell RS, Semba CP, Razavi MK, Shimono T, Hirano T, Takeda K, Yada I, Miller DC. Endovascular stent-graft placement for the treatment of acute aortic dissection. N Engl J Med 1999; 340:1546–1552.

Thoracic Infectious Aortitis

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Contents

25.1 Introduction

The infectious attacks of the thoracic aorta remain a rare disease. They are characterized by an endarteritis of infectious origin generally followed by the formation of an aneurysm commonly called mycotic aneurysm. The adjective "mycotic" can be a source of confusion. It could suggest a fungal nature of the aneurysm, whereas bacteria represent the majority of the causes of these infections. This term was introduced by Osler [1] in 1885 to describe an infectious vascular aneurysm taking the aspect of a "fresh mushroom" in a patient suffering from an infectious endocarditis. It should be understood as indicating any vascular aneurysmal formation of infectious origin.

Before the era of antibiotics, the diagnosis was generally made by autopsy and 86% of the cases were secondary to an infectious endocarditis [2], syphilis excluded. Currently the causes are varied. Each aetiology has particular characteristics with physiopathological, clinical and therapeutic aspects. It is thus currently difficult to regard the infectious attack of the thoracic aorta as a single pathology. It should rather be seen like a collection of different diseases having the same anatomical tropism. Certain causes have a very particular importance, like syphilis, salmonellosis or tuberculosis in addition to the traditional pathogenic bacteria like *Staphylococcus aureus* or *Streptococcus*, and will thus be studied separately.

25.2 General Case

25.2.1 Epidemiology

These infections are currently rare. In an autopsic series reporting 22,000 cases realized in Boston between 1902 and 1951, mycotic aneurysms (thoracic and abdominal) accounted for 2.6% of all thoracic aneurysms, themselves being rare (1.5% of the patients) [3]. In another study (20,000 autopsies) of the Mayo Clinic conducted between 1925 and 1954 [4], only six of 178 aortic aneurysms found were of infectious origin. The analysis of four more recent series (between 1946 and 1975) [5–8] found 78 cases of mycotic aortic aneurysms. Lastly, a retrospective study of the Mayo Clinic found between 1976 and 1999 [9] 29 cases of aortic infectious aneurysms, nine of them involving the thoracic aorta and 20 the abdominal aorta. There is a male prevalence in these affections with a sex ratio of 3:1. This must undoubtedly be linked to the significant role that atherosclerosis plays in the genesis of these infections. Athero-

sclerosis is indeed more frequent in men than in women [10]. The average age of occurrence is 65 years old [11–13]. In the particular context of infectious endocarditis, the average age is lower (40 years old) and there is no prevalence of gender [14].

25.2.2 Physiopathology

Four principal mechanisms are found [15]:

1. Secondary aneurysm with the embolism of the vasa vasorum by the germ in question
2. Arterial infection of the intima injured at the time of a bacteremia
3. Traumatism of the arterial wall with direct contamination
4. Infection of the vascular wall by extension of a contiguous infectious site.

The infectious attack of the arterial wall leads to an endarteritis, generally followed by the formation of an aneurysm or a false aneurysm. These aneurysms will generally have a saccular aspect but can also appear fusiform or cupular. The first mechanism of contamination of the arterial wall occurs in particular in the case of infectious endocarditis. The contaminant source is then the valvular vegetation. The germ disseminates in a haematogenous way, embolizes the vasa vasorum and is fixed in the arterial media [14]. An infection appears right inside the arterial wall, which extends in a centrifugal way. The result is major vascular brittleness and the development of an aneurysm with a considerable risk of rupture. It is the same physiopathological mechanism in tuberculosis and especially in syphilis.

The second mechanism involves directly the previously injured arterial wall. The normal intima of the aorta is very resistant to infection, but when it is damaged, infection is likely to develop there. The risk factors of this type of attack are primarily represented by the atherosclerosis with or without an aneurysm, and the intraluminal thrombi. Secondary infections of a preexisting aneurysm are most commonly found in the abdominal aorta (70%), but 30% of them concern aneurysms of the thoracic aorta (15% for the ascending aorta and 15% for the thoracic descending aorta) [14]. Thus, the intima is the first arterial zone involved in the development of the infection of the interior towards the depth of the vascular wall leading to a thinning of this wall and thus to weakness. The germs in question are classically represented by the germs responsible for infectious endocarditis, the physiopathology of these two infections being very similar. Moreover, salmonellas too are very often found in this type of attack.

In infectious endocarditis, one can see these two mechanisms of aortic attack. More than 70% of mycotic aneurysms found within this pathology concern the proximal part of the thoracic aorta [14]. They are caused by the embolism of the vasa vasorum but can also develop while profiting from an injured zone of the aortic intimae and in particular on the supravalvular level where the arterial wall can be deteriorated by the infective flow of blood [16]. These aneurysms are then of small volume and cupular. In parallel, the physiopathology of infectious endocarditis, with an increased susceptibility in the event of preexisting valvular lesions, is very close to the superinfection of atherosclerotic aneurysms and it is easily understood that a germ which was fixed at the level of an injured cardiac valve can also be fixed at an atherosclerotic aneurysm. Lastly, another mechanism of the aortic attack within the framework of this pathology is the attack of the proximal aorta by the extension of the valvular infection.

The acquired lesions of the aorta are thus a factor of risk of superinfection. Certain congenital lesions can also be to blame. Coarctation of the aorta can indeed be the seat of an endarteritis with a mycotic aneurysm developing just above the stenosis [17]. This aneurysm is then of small volume, of saccular aspect and generally develops on the left edge of the aorta [14].

Traumatisms of the thoracic aortic wall leading to an infection are rare. They generally occur in an iatrogenic context (arterial catheterization, surgery) and can in this case involve nosocomial germs. Injuries caused by knives and firearms can also be involved but they remain an exceptional cause of aortitis.

Attacks of the aortic wall by a neighbouring infectious site are more frequent. The causes are mainly thoracic osteomyelitis, pulmonary infections and mediastinitis. The aortic wall is then eroded with an infection developing from outside the artery towards the luminal canal and a major risk of arterial rupture.

Apart from these four large physiopathological mechanisms, two other contexts are to be mentioned.

Firstly, cases of prosthetic superinfection of material of the thoracic aorta. These cases are outside the field of infectious aortitis and will not be treated here.

Secondly, real immunological attacks of arteries following an infectious episode are possible, in particular on the level of small arteries. In the thoracic aorta, these postinfectious arteritis remain controversial. However, this type of attack can be found in poststreptococcic acute rheumatoid arthritis. In this pathology, one can indeed in rare cases see an endarteritis of the thoracic aorta resulting in an arterial attack of the media, with oedema and leucocytic infiltrate, also able to affect the adventitia and the vasa vasorum. Aneurysm is, in this context, exceptional. The arterial attack is here of immunological origin with a certain antigenic proximity between the *Streptococcus* and the arterial media. It is followed by an immune reaction directed against the components of the arterial wall leading to endarteritis [16].

25.2.3 Risk Factors

The risk factors are mainly marked by those of atherosclerosis: male sex, age, tobacco smokers, hypertension, diabetes mellitus, dyslipidemia [9, 11, 12]. Congenital anomalies of the aorta (coarctation of the aorta, ductus arteriosus) also represent risky situations [14]. The immune statute of the patient also seems to play a role with probably an increased risk in the event of immune system depression mainly caused by diabetes mellitus, treatments (corticosteroids, immunosuppressive treatments) or haematological malignancies. Infection by the human immunodeficiency virus (HIV) does not seem to represent a risk of infectious aortitis. In fact, the major risk factor is atherosclerosis and therefore concerns patients over 45 years old. Patients suffering from HIV are frequently younger, without any atherosclerotic arteries. However, the HIV infection and the therapeutic treatment necessary for its control are probably responsible for vascular attacks of atherosclerotic origin [18]. This coupled with the lengthening of lifespan in the event of HIV seropositivity could, in the future, favour the emergence of infectious aortitis in this context.

25.2.4 Microbiology

Before the era of antibiotics, the most common germs were *Streptococcus* and syphilis [19]. Since the introduction of antibiotics and their significant use, the nature of responsive germs has changed. Currently, the commonest bacteria in the thoracic aortitis are the gram-positive cocci which occur in 60% of cases (Table 25.1). Among them, *Staphylococcus aureus* represents, according to studies, between 30 and 50% of all aortitis cases. *Streptococcus* is the second commonest bacterium found. It is frequently associated with infective endocarditis. In such a situation, the proximal aorta is frequently involved. Then come *Enterococcus* and *Streptococcus pneumoniae* [20–22]. Gram-negative bacilli are also frequent (between 20 and 40% of the cases according to the studies) [9, 11–14, 23–26]. Among the gram-negative bacilli, salmonellas are the commonest kind in the aorta in general. They often affect the abdominal aorta and less frequently the thoracic aorta (12%) [9]. In the same way, some cases (nine) of infection by *Campylobacter fetus* have been reported but they concern mainly the abdominal aorta [27–31]. With this germ we notice a fast increase in the size of the aneurysm. These infections generally occur on immunodepressed grounds, and associations with neoplasia and especially with digestive neoplasia are often noted [32, 33]. Infection by mycobacteria can also occur and will be detailed in Sect. 25.5.

Table 25.1. Clinical and microbiological characteristics of thoracic aortitis

Data	Results
Sex ratio men/women	
General case	3:1
Infectious endocarditis	1:1
Mean age	
General case	65 years old
Infective endocarditis	40 years old
Risk factor	Atherosclerosis Smoking Diabetes mellitus Hypertension Hyperlipidemia Immunodepression Diabetes mellitus Corticoids Malignancy
Symptoms	Fever (70%) Pains Dorsal and thoracic (60%) Abdominal (20%) Chills Compressive signs: dyspnea, dysphagia, changing voice, vena cava superior syndrome
Microorganisms	Gram-positive (60%) *Staphylococcus aureus* (30–50%) *Streptococcus* *Streptococcus pneumoniae* *Enterococcus* Gram-negative (20–40%)

Many other germs were occasionally described in isolated case reports (*Listeria monocytogenes* [34], *Clostridium septicum* [35], *Pasteurella multicoda* [36], *Haemophilus influenzae* [37], *Brucella melitensis* [38], *Nocardia asterodes* [39], *Burkholderia pseudomallei* [40]).

Finally, fungal aortic attack is seldom due to *Candida*, *Aspergillus*, *Cryptococcus* and paracoccidioidomycosis. It occurs in a context of disseminated fungal infection associated, in the cases of aspergillosis or paracoccidioidomycosis, with a preexisting pulmonary fungal infection [11, 14, 41].

25.2.5 Clinical Presentation

The clinical signs are not very specific. Diagnoses are therefore often delayed. Fever is the most constant sign (70%). Shoulder, dorsal or thoracic pains are often present (60%). Abdominal pains may also be noticed (20%). Shivering can be the sign of a persistent bacteraemia and secondary infectious locations are possible by septical embolisms [9, 11, 12]. Compressive signs are present in the event of large aneurysms and their character depends on the location of this aneurysm: dyspha-

gia, dyspnea, cough, voice alteration by a compression of the left recurrent laryngeal nerve, oedema of facial and upper extremities by a compression of the superior vena cava. In the event of aneurysmal rupture in the trachea or the oesophagus, massive haemoptysis or gastrointestinal bleeding [11, 14, 42, 43] will occur.

25.2.6 Diagnosis

The infectious attack of the aorta can be visualized thanks to the imaging examinations. Standard chest X-rays find aortic aneurysms, shown by opacities of different size in the mediastinum. These opacities are the same density as the rest of the aorta. X-rays at different angles will show the topography of the aneurysm [44].

A computed tomographic scan with contrast injection is the most useful examination to define the precise location of the arterial attack. It initially shows an inhomogeneous enhancement of the vascular wall with rupture of a ring of preexisting calcifications. The aortic wall thins and an inflammation appears around the aorta. Then the aortic diameter increases to form an aneurysm or a false aneurysm. The presence of air in the vascular wall has sometimes been considered as specific indicator of an infectious injury. Indirect signs can suggest the infectious origin of the aortitis, such as the presence of perivascular fluid collection, periaortic lymph nodes or adjacent infectious focus [45].

Echography is sometimes useful. Transoesophageal echocardiography can measure the exact size of the aneurysm or the thickness of the aortic wall [46, 47]. It is also interesting in the event of suspicion of associated aortic dissection.

There is little interest in magnetic resonance imaging compared with computed tomographic scans. Some teams use positron emission tomography in suspicions of mycotic aneurysms of the aorta in order to prove the inflammatory character of this aneurysm, but this technique has still to be assessed [21]. Leukocyte scintigraphy is not used anymore but can be of interest in the case of doubtful diagnosis by showing a signal at the level of the infected aorta [48, 49]. Aortography is carried out in preoperative treatment.

Blood cultures have cardinal importance in the assumption of responsibility of these infections. They are indeed the only means of microbiological diagnosis before surgery and they help to find the best adapted antibiotherapy. Unfortunately, blood cultures are not systematically positive. An analysis of the literature on this subject finds a rate of positivity varying from 50 to 90%. This poor rate is probably partly related to the frequency of antibiotic prescription before realization of blood cultures. Indeed, clinical presentations, often not very specific, involve prescription of a presumptive antibiotherapy before a diagnosis of infectious aortitis has been made. However, even in preliminary absence of antibiotics, the blood cultures are not always positive [9, 11, 13, 14]. Their positivity depends on the type of germ concerned (positive blood cultures are rare in the event of anaerobic germs) and on the mechanism of the attack of the arterial wall. Infections which first concern the arterial intimae (superinfection of atherosclerotic aneurysm, endovascular traumatism) often have positive blood cultures, whereas infections without initial contact with the aortic lumen (embolization of the vasa vasorum, except for the case of infectious endocarditis, and extension of a contiguous infectious centre), probably have a lower frequency of positive blood cultures.

Lastly, a high leukocyte count with polynuclear neutrophils (higher than 10,000/mm^3) is found in 65–83% of cases [9, 14].

25.2.7 Histological Findings

Until 2004, series interested in histological data of infectious aortitis were autopsic series. Recently, a team analysed the results of a histological study of 29 operational parts among patients having undergone a surgical operation for infectious aortitis [9]. Six different types of anomaly were found in the arterial wall:

1. Type 1: transmural acute inflammation with focal abscesses of the previously affected aortic wall with calcifications and thinning of the media. This aspect was found in 55% of the cases. Blood cultures were positive in 81% of the cases and there was a positive culture of the aortic wall in 67% of the cases.
2. Type 2: chronic inflammation of the wall (lymphocytes and histiocytes infiltrate) on a wall deteriorated by atherosclerosis. This type was found in 20% of the cases; blood cultures were positive in 17% of the cases as was the culture of the aortic wall.
3. Type 3: transmural acute inflammation and subjacent abscess without atherosclerosis were found in 4% of the cases (positive blood cultures, 50%; positive culture of the wall, 100%).
4. Type 4: granulomatous inflammation of the media without attack of the intima. This type was connected to infections by mycobacteria (4% of the cases in this study).
5. Type 5: pseudoaneurysm with adjacent rupture of the media at the zone of insertion of the aneurysm of which the wall is made up of only a new intimae and adventitia without media. That relates to 7% of the cases with blood cultures and a culture of the arterial wall always being negative in this study.
6. Type 6: 7% of the cases: nongranulomatous chronic inflammation of the adventitia. The blood cultures were negative and the culture of the arterial wall was positive in 100% of the cases.

25.2.8 Outcome and Treatment

The prognosis is related to the infectious attack and the specific complications which it can involve (severe sepsis, septic shock, embolisms with secondary infectious locations). But the severity of this disease is particularly related to the risk of rupture of the aneurysm [7, 50–53].

Without any treatment, the aneurysm will progressively increase, leading to a fatal rupture without emergency surgery. Mortality during surgery in the event of a rupture of the aorta is very high. The principal mortality factor is delay of diagnosis. Other factors exist, like underlying immunodepressive conditions or the type of germ. Infections by gram-negative bacilli have a worse prognosis than those by gram-positive bacteria, with a 72% risk of a rupture of aneurysms caused by gram-negative bacteria, against 25% for gram-positive bacteria, after diagnosis has been made [12, 15].

Treatment must include a surgical treatment and a medical treatment. Except in rare cases, with a medical or surgical treatment alone, the mortality rate remains close to 100%. Administration of antibiotics should be started at best 10 week before the surgical operation and will be adapted according to the data from the blood cultures. They must be bactericidal. Treatment with antibiotics should be continued for at least 4–6 weeks after the surgical operation with close monitoring of the patients and repeated realization of blood cultures. The follow-up of the patients after stopping the antibiotics treatment will be prolonged [9, 11, 13, 14].

After the beginning of antibiotics treatment, surgery is carried out using extracorporal circulation, generally by excision of all infected tissues and installation of a vascular prosthesis [43, 54]. Many surgical samples, including the excised aortic wall, must be sent to the microbiology laboratory.

Thanks to the treatment, the prognosis is good, with a rate of survival according to studies and especially according to diagnostic and therapeutic conditions varying from 75 to 100% [9, 14].

We must insist on the importance of a prolonged follow-up of these patients.

25.3 Syphilitic Aortitis

25.3.1 Epidemiology

Before the use of antibiotics, syphilis was a one of the most frequent aetiologies of thoracic aortitis [55]. Today this disease has become very uncommon. Nevertheless, its diagnosis often remains ignored and can be mentioned in the case of a thoracic aortic aneurysm. The aortic attack appears 10–40 years after the first infection [56, 57] and corresponds to the tertiary phase of the disease. It represents the most frequent vascular attack in this pathology. Its frequency varies according to syphilis frequency. It is believed that 30% of untreated patients may contract aortitis, 10–15% of them [56] showing clinical signs. It represents one of the major causes of death together with diseases of the central nervous system.

25.3.2 Physiopathology

Very early at the course of infection by *Treponema pallidum*, the spirochetes reach the adventitious aorta [55, 58]. Then, they penetrate inside the arterial wall following the lymphatic vessels and the vasa vasorum to reach the media. An inflammatory infiltrate, with lymphocytes, plasmocytes and sometimes with giant cells, appears around the vasa vasorum, causing an obliterating endarteritis leading to the formation of necroses points inside the aortic media. The elastic tissue is then destroyed showing the “tree-bark” traditional aspect [56] and is replaced by fibrosis accompanied by thinning of the media. The wall is weakened and a syphilitic aneurysm can appear [56, 57]. Parietal calcifications can be present especially in the ascending aorta in the case of chronic evolution.

Four types of syphilitic aortic attacks are described, classified by order of frequency [55]:

1. Asymptomatic syphilitic aortitis
2. Aneurysm of the ascending aorta (40%)
3. Aortic insufficiency (29%)
4. Coronary ostial stenosis (26%).

Thus, syphilitic aneurysm generally involves the ascending thoracic aorta and the aortic arch, areas where the lymphatic vessels are most numerous inside the arterial wall. The ascending aorta is concerned in 50% of all the cases, the aortic arch in 30–40% and the descending aorta in 10–20% [56]. It almost never involves the abdominal aorta because of the low number of lymphatic vessels on this level. Generally, there is only one aneurysm but in 7% of cases they may be multiple [55]. They are generally saccular and sometimes fusiform [59–62]. The aneurysm is frequently surrounded by inflammatory arterial tissue, which can worsen the possible compressive signs.

Aortic insufficiency is caused by dilation of the overlying thoracic aorta. Coronary ostial stenosis [57, 63, 64] are almost constantly associated with aortic insufficiency (87%) [64, 65]. They can nevertheless represent the only manifestation of a syphilitic vascular attack in 11% of cases [55]. Ischemia, and even myocardial necrosis, can be the consequences of that coronary attack [66, 67].

25.3.3 Clinical Presentation

The evolution of syphilitic aortitis is insidious with often delayed diagnosis. Clinical examination is often of poor interest; the diagnosis is quite frequently made accidentally, when a radiological examination is made. Infectious signs are missing: no fever or high leukocyte count.

The historical presentation of syphilitic aneurysm is represented by the "exteriorized aneurysm". It is characterized by a beating mass located at the flat rim of the sternum, between the first and second intercostal spaces or at the cervical level. The skin in front of this mass is of normal aspect. An inflammatory aspect usually means that the aneurysm has found its way through the plan of the chest wall. In this context the risk of a rupture is imminent. Nowadays, this form has nearly disappeared [16].

According to the exact location of the aneurysm, the compressive signs seen in the case of huge thoracic aneurysms are dysphagia, stridor, inspiratory dyspnoea, cough and left vocal cord paralysis by left recurrent laryngeal nerve compression. A superior vena cava syndrome is possible [68].

Aortic insufficiency and coronary ostial stenosis have their own nonspecific symptoms, with a cardiac insufficiency, a diastolic aortic bruit and signs of angina pectoris.

When a syphilitic vascular attack of this type is found, the clinical examination must attempt to seek signs revealing a neurological attack, and an Argyll Robertson sign, a tabes, disorders of the cognitive functions and a Claude Bernard-Horner syndrome (by involvement of the cervical sympathetic nerve) must be looked for as well as syphilitic gums.

25.3.4 Diagnosis

Plain chest films are not very specific. They find a widening of the upper mediastinum in the chest radiography. Linear calcifications in the ascending aorta are frequent. This X ray can also show a left ventricular enlargement in the case of aortic regurgitation. A computed tomographic scan and aortography define the topography and the anatomy of the aneurysm. Computed tomography will especially find a thinning of the arterial wall and sometimes a double-ring aspect of the wall with a hypodense internal ring and a hyperdense peripheral ring [59, 69]. Electrocardiogram findings are signs of left ventricular hypertrophy or myocardial ischemia.

The most important laboratory examination is syphilitic serology. Unfortunately, the tests currently used are not always positive. Nonspecific tests (Venereal Disease Research Laboratory, VDRL) are positive only in 40% of cases and specific tests like fluorescent treponemal antibody absorption (FTA-ABS) and *T. pallidum* haemaglutination assay (TPHA) are positive in 90% of cases. In addition, the rate of false negatives to these specific tests is more significant among elderly people. In this context, the Nelson test can be useful [57].

Some teams [70] use PCR assay to detect the presence of *T. pallidum* DNA inside the aortic wall when a surgical operation has been performed. This technique seems to be interesting but must still be evaluated.

Lastly, let us point out the importance of the tracking of an unperceived neurosyphilis. Lumbar puncture with realization of the nonspecific and specific reactions in the CSF must thus be systematic.

25.3.5 Complications and Prognosis

An aneurysm rupture is obviously the most serious complication. This rupture can occur in the oesophagus, the trachea or the left pleural cavity, and also in the mediastinum.

The risk of dissection with a syphilitic aneurysm is limited because of the importance of fibrosis of the media [71, 72].

Syphilitic aneurysm is distinguished from the other aetiologies of aortic aneurysms by a long asymptomatic evolution. This aneurysm develops silently and can reach significant size and brittleness without any clinical demonstrations. At the time of diagnosis, the situation is often very advanced with a reserved prognosis without treatment. The mortality rate is 80% after 2 years following the diagnosis with an average of survival estimated at 6–9 months following the emergence of the first symptoms [56]. Death classically occurs at the time of the aneurysm rupture. Some observations report the death of the patients within 1 week following the diagnosis [56]. Thus, the prognosis will be all the better if the diagnosis is established early.

Aortic insufficiency without significant aortic aneurysm has a particular evolutive profile. The total survival rate is 10 years for 30–40% of cases. This survival is correlated to the presence or absence of a cardiac insufficiency. Without a cardiac insufficiency, the 5-, 10- and 15-year survival rates are 75, 67 and 56%, respectively. In the event of a cardiac failure, the prognosis is darker, with survival rates of 5 and 10 years [56] of 15 and 5%, respectively.

25.3.6 Treatment

The treatment involves a medical and a surgical treatment. The antibiotic treatment is carried out by administration of 2.4×10^6 units of benzathine penicillin in an intramuscular injection per week for 3 weeks. In the event

of neurosyphilis, the treatment consists of 14×10^6 units of penicillin G per day intravenously for 15 days [73].

In the event of an allergy, penicillin is replaced by 500 mg of tetracyclin four times a day or 100 mg of doxycycline twice a day for 30 days [56].

Jarisch-Herxheimer reactions can occur at the beginning of treatment.

Signs of cardiac failure and a myocardial ischemia require an usual treatment with coronary revascularization if required.

Surgery is generally necessary to treat an aortic aneurysm with replacement by a vascular prosthesis [74]. Aortic insufficiency could be treated at the same time by valvular replacement.

Thanks to that treatment, prognosis is good. Antibiotics will cure the syphilis and the risk of rupture will be eliminated by surgery. The risk of death during the operation is estimated at 15%. In the event of an emergency intervention for aortic rupture, the risk of death is very high.

25.4 Aortitis due to *Salmonella*

25.4.1 Epidemiology

Endovascular infection is the most serious complication of an infection with nontyphoid salmonellas [75]. The aortic attack is much more frequent than the attack of peripheral arteries. It especially involves the abdominal aorta (83%), but also the thoracic aorta in 17% of cases [76–78].

It is estimated that bacteremia occurs in 5% of the cases of gastroenteritis caused by nontyphoid salmonellas. Among these bacteremia, the rate of endovascular infection ranges from 10 to 40%. This endovascular infection risk is especially present after 50 years of age. Before this age, this risk is almost nil [76–78].

The mean age of the patients with nontyphoid salmonellas aortitis is 61 years (range 32–86). These infections occur more in men than in women, with a sex ratio of 3:1 [76, 79].

25.4.2 Physiopathology and Risk Factors

The principal risk factor of *Salmonella* aortitis is atherosclerosis. Diabetes mellitus, hypertension and dyslipidemia are thus associated with a risk of endovascular infection in the event of *Salmonella* bacteremia. Diabetes mellitus has particular importance in the occurrence of these infections. Indeed, it seems to be the most frequently underlying pathology involved (in 25% of cases) [76–78, 80]. Other elements seem to represent risk factors of bacteremia if gastroenteritis from salmonella occurs, but they are not directly risk factors of endovascular infection such as aortitis. They are immunodeficiency, hypoacidity and gastric atrophy, long course antacid treatment, deterioration of endogenous digestive flora, extreme age, underlying malignancy, rheumatologic inflammatory diseases and lupus erythematosus HIV infection with AIDS [76, 81]. In the new-born babies and in patients suffering from AIDS, which are two situations with risk of nontyphoid *Salmonella* bacteremia, endovascular infection never occurs because of the lack of the primordial risk factor of vascular attack, which is atherosclerosis.

Thus, *Salmonella* aortitis occurs in an exceptional way on a healthy artery, but develops after fixation of bacteria on an injured intima by atherosclerosis.

The most frequently found serogroups are *Salmonella typhimurium* (31%), *Salmonella enteritidis* (16%) and *Salmonella cholerasuis* (16%) [76, 79]. Other serogroups can be found in a more anecdotic way and are listed in Table 25.2.

Table 25.2. Distribution of *Salmonella*'s serogroups involved in aortitis according to Soravia-Dunand et al. [79]

Microorganisms	Cases (%)
S. typhimurium	31
S. enteritidis	16
S. cholerasuis	16
Salmonella group D other than *S. enteritidis*	16
Salmonella group B other than *S. typhimurium*	3
S. dublin	3
Salmonella group C other than *S. cholerasuis*	3
Salmonella group E	1
Salmonella sp.	6

25.4.3 Clinical Features

The mean time between diagnosis and the first symptom is 38 days (range 1–240). The only symptom present is often fever. It is found in 75% of cases. The other signs are chills (16%), sweats (5%) and back (21%), thoracic (17%) and abdominal (21%) pains [76, 79].

Other signs are found in the event of complications. The most frequent complications apart from aortic rupture are the aorto-bronchial fistulas occurring in 17% cases and revealed by a massive haemoptysis. Then, pulmonary infections (4%) and osteomyelitis (4%) can occur [76]. Signs of gastroenteritis are not very frequent even if *Salmonella* is found in stool culture.

25.4.4 Diagnosis

Leucocytosis is usual. Blood cultures must be systematic. They are positive in 85% of cases. In the event of surgical operation, culture of the vascular wall finds the

causal germ only in 65% of cases. This relatively low rate is undoubtedly partly explained because antibiotics treatment is frequently begun before surgery [76, 79].

It is interesting to perform stool cultures. These can indeed find *Salmonella* even if blood cultures are negative.

The most efficient imaging technique is the computed tomographic scan with contrast injection. The first sign found is an inhomogeneous enhancement of the aortic wall. Then, the aortic wall becomes thin and more irregular and sometimes a haematoma is present. Fragmentation of parietal calcifications is often a sign of imminent rupture of an aneurysm. The presence of an adjacent infectious focus (osteomyelitis) is an indirect sign of the infectious character of the aneurysm [76, 79, 82].

Aortography is a less powerful technique to detect the early modifications of the wall but is useful in the preoperative period.

25.4.5 Prognosis and Treatment

Salmonella aortitis is always fatal without any treatment [83, 84]. With treatment, the mortality rate is 60%. It is much higher if medical treatment is performed alone (96%) [76, 79] but some teams have reported therapeutic success through long-term suppressive antibiotherapy without surgery [85, 86][8].

The optimal management of this disease relies on combined surgical and medical treatment. The surgery consists of an excision of all infected tissues and sending them to the laboratory for microbiologic culture, and replacement by a vascular prosthesis [87].

Antibiotics treatment must be begun as soon as possible, if possible before the surgical assumption. β-Lactamines are the antibiotics of choice in induction treatment. Amoxicillin is frequently used in high dosages (200 mg/kg/day) with very good results, but one notes an increase in the incidence of resistance of the salmonellas to this antibiotic. Although no comparative study has been carried out, cephalosporines of the third generation seem to be the antibiotics of choice in this indication: ceftriaxone (75 mg/kg/day) or cefotaxime (200 mg/kg/day). Association with an aminoglycoside (gentamicin) is frequently reported. The results of this regimen do not seem to be better than those with β-lactamine alone but its use is often justified by the gravity of the clinical situation in order to increase the bactericidy speed. Induction treatment must be continued for 6 weeks postoperatively. Then, it is better to continue with long-term suppressive antibiotics treatment. Fluoroquinolones are then the antibiotics of choice [76, 79].

Thanks to this treatment, the mortality rate is 36% mainly by deaths during surgical intervention in the event of surgery in emergencies and of early postoperative complications. The recurrence rate on a prosthesis is currently low, about 10%, and decreases further with the use of long-term suppressive antibiotherapy [76, 79].

25.5 Tuberculous Aortitis

25.5.1 Epidemiology

Tuberculous aortitis is a very unusual form of tuberculosis [88]. The abdominal aorta is the most frequent location of aortitis, being the location in 66% of cases. The thoracic aorta is involved in 33% cases [89].

The mean age of occurrence is 50 years old (range 20–80). There is no prevalence of gender. This attack occurs in a context of disseminated tuberculosis in 46% of cases, but sometimes it represents the only manifestation of tuberculosis (38%) [90, 91].

25.5.2 Physiopathology

Three mechanisms are involved. The most frequent one (75%) is the attack of the aorta by extension of an adjacent tuberculous hearth (lymph nodes, Pott disease, pulmonary hearth). Sometimes, attack of the aorta is caused by haematogenous dissemination of the tuberculous bacillus. The bacterium fixes itself on the arterial wall in a pre-existing atherosclerotic area. Lastly, in an exceptional way, the aortic infection occurs by embolization of vasa vasorum [91].

25.5.3 Presentation

In 63% of cases, tuberculosis is already evident when diagnosis of aortitis is made [90].

Clinical signs are classic with frequent deterioration of general state, fever and night sweats [92, 93]. Thoracic or dorsal pains are present in 44% of cases. Sometimes the clinical situation is dramatic with massive haemoptysis or gastrointestinal bleeding at the time of an aorto-bronchial or aorto-oesophagal fistula [90, 94, 95]. Aneurysmal rupture is possible [96–98].

On the anatomical plan, aortitis is presented in an aneurysm form (99% of cases), which is usually saccular (88% of cases) [91]. Radiological examinations are not very specific but are interesting to carry out for the complete assessment of tuberculosis [99].

Histology findings are giganto-epithelio-cellular granuloma with necroses. Direct examination and culture are not always positive and PCR assay can then be useful.

25.5.4 Prognosis and Treatment

Without any treatment, the mortality rate is 100%. The aneurysm's size is not in this context a factor of bad outcome. On the other hand, the symptomatic character of the aneurysm is a factor of bad outcome with a high risk of rupture and prompt surgery is recommended.

Treatment includes surgery and antibiotherapy. A medical or surgical treatment alone never allowed recovery (mortality rate 100%). By associating both treatments, the survival rate is estimated as 75–100% according to studies [90, 91].

Unlike other infectious aortitis aetiologies, it is not necessary to begin the medical treatment before surgery. There is no consensus regarding the necessary duration of antibiotherapy. It must probably be prolonged, from 12–18 months. The follow-up must be close during and after the antibiotic treatment in order not to ignore a recurrence on a vascular prosthesis.

References

1. Osler W. The Gustonian lectures on malignant endocarditis. Br Med J 1885; 1:467–470.
2. Stengel A, Wolferth C. Mycotic (bacterial) aneurysms of intravascular origin. Arch Intern Med 1923; 123:527–535.
3. Parkhurst GF, Decker JP. Bacterial aortitis and mycotic aneurysm of the aorta; a report of twelve cases. Am J Pathol 1955; 31:821–835.
4. Sommerville R, Allen E, Edwards J. Bland and infected arteriosclerotic abdominal aortic aneurysms. A clinicopathologic study. Medicine (Baltimore) 1959; 38:207.
5. Anderson C, Butcher H, Ballinger W. Mycotic aneurysms. Arch Surg 1974; 109:712.
6. Bennett DE, Cherry JK. Bacterial infection of aortic aneurysms. A clinicopathologic study. Am J Surg 1967; 113:321–326.
7. Cliff M, Soulen R, Firestone A. Mycotic aneurysms: a challenge and a clue. Arch Intern Med 1970; 126:977.
8. Jarrett F, Darling C, Mundth ED, et al. Experience with infected aneurysms of the abdominal aorta. Arch Surg 1975; 110:1281.
9. Miller DV, Oderich GS, Aubry MC, Panneton JM, Edwards WD. Surgical pathology of infected aneurysms of the descending thoracic and abdominal aorta: clinicopathologic correlations in 29 cases (1976 to 1999). Hum Pathol 2004; 35:1112–1120.
10. Bickerstaff LK, Pairolero PC, Hollier LH, et al. Thoracic aortic aneurysms: a population-based study. Surgery 1982; 92:1103–1108.
11. Kearney RA, Eisen HJ, Wolf JE. Nonvalvular infections of the cardiovascular system. Ann Intern Med 1994; 121:219–230.
12. Gomes MN, Choyke PL, Wallace RB. Infected aortic aneurysms. A changing entity. Ann Surg 1992; 215:435–442.
13. Oz MC, Brener BJ, Buda JA, et al. A ten-year experience with bacterial aortitis. J Vasc Surg 1989; 10:439–449.
14. Scheld W, Sande M. Endocarditis and intravascular infections. In: Mandell GL, Bennett JE, Dolin R, editors. Principles and practice of infectious diseases, 4th ed. Churchill Livingstone, New York. 1995. p. 740–783.
15. Jarrett F, Darling RC, Mundth ED, Austen WG. The management of infected arterial aneurysms. J Cardiovasc Surg (Torino) 1977; 18:361–366.
16. Vacheron A, Le Feuvre C, Di Matteo J. Pathologie de l'aorte. In: Vacheron A, Le Feuvre C, Di Matteo J, editors. Cardiologie, 3rd ed. Expansion Scientifique, Paris. 1999. p. 693–720.
17. Schneider JA, Rheuban KS, Crosby IK. Rupture of postcoarctation mycotic aneurysms of the aorta. Ann Thorac Surg 1979; 27:185–190.
18. Grinspoon S, Carr A. Cardiovascular risk and body-fat abnormalities in HIV-infected adults. N Engl J Med 2005; 352:48–62.
19. Bennett DE. Primary mycotic aneurysms of the aorta. Report of case and review of the literature. Arch Surg 1967; 94:758–765.
20. Maclennan AC, Doyle DL, Sacks SL. Infectious aortitis due to penicillin-resistant Streptococcus pneumoniae. Ann Vasc Surg 1997; 11:533–535.
21. Hoogendoorn EH, Oyen WJ, van Dijk AP, van der Meer JW. Pneumococcal aortitis, report of a case with emphasis on the contribution to diagnosis of positron emission tomography using fluorinated deoxyglucose. Clin Microbiol Infect 2003; 9:73–76.
22. Bronze MS, Shirwany A, Corbett C, Schaberg DR. Infectious aortitis: an uncommon manifestation of infection with Streptococcus pneumoniae. Am J Med 1999; 107:627–630.
23. Sebesta P, Klika T, Mach T, et al. [Bacterial aortitis]. Rozhl Chir 2004; 83:209–216.
24. Fiessinger JN, Paul JF. [Inflammatory and infectious aortitis]. Rev Prat 2002; 52:1094–1099.
25. Johansen K, Devin J. Mycotic aortic aneurysms. A reappraisal. Arch Surg 1983; 118:583–588.
26. Johnson JR, Ledgerwood AM, Lucas CE. Mycotic aneurysm. New concepts in therapy. Arch Surg 1983; 118:577–582.
27. Abassade P, Cremieux O, Korach JM, et al. [Campylobacter fetus subspecies fetus endoaortitis on a Bentall tube prosthesis. Apropos of a case]. Arch Mal Coeur Vaiss 1994; 87:1483–1487.
28. Morrison VA, Lloyd BK, Chia JK, Tuazon CU. Cardiovascular and bacteremic manifestations of Campylobacter fetus infection: case report and review. Rev Infect Dis 1990; 12:387–392.
29. Blabey RG Jr, Parry MF, Bull SM, Weed CB. Mycotic aneurysm of the abdominal aorta: successful management of Campylobacter fetus aortitis. Conn Med 1983; 47:129–130.
30. Anolik JR, Mildvan D, Winter JW, Puttlitz D, Rubenstein S, Lozman H. Mycotic aortic aneurysm. A complication of Campylobacter fetus septicemia. Arch Intern Med 1983; 143:609–610.
31. File TM Jr, Barnishan J, Fass RJ. Campylobacter fetus sepsis with mycotic aortic aneurysm. Arch Pathol Lab Med 1979; 103:143–145.
32. Baty V, Hoen B, Selton-Suty C, et al. [Campylobacter fetus endocarditis manifested by a popliteal mycotic aneurysm]. Presse Med 1998; 27:357–358.
33. Rucker CM, Menias CO, Bhalla S, Geraghty P, Heiken JP. Clostridium septicum infrarenal aortitis secondary to occult cecal adenocarcinoma. Am J Roentgenol 2004; 183: 1316–1318.
34. Navarro-Martinez A, Gomez-Merino E, Gomez-Garrido M, Fernandez-Funez A. [Listeria monocytogenes aortitis]. Rev Clin Esp 2001; 201:490.
35. Zenati MA, Bonanomi G, Kostov D, Lee R. Images in cardiovascular medicine. Fulminant Clostridium septicum aortitis. Circulation 2002; 105:1871.
36. Balestra B. Mycotic aneurysms of the aorta caused by infection with Pasteurella multocida. Clin Infect Dis 2000; 31:E1–2.

37. Byrne G, Barber P, Farrington M. Aortitis caused by beta-lactamase producing Haemophilus influenzae type b. J Clin Pathol 1989; 42:438–439.
38. Aguado JM, Barros C, Gomez Garces JL, Fernandez-Guerrero ML. Infective aortitis due to Brucella melitensis. Scand J Infect Dis 1987; 19:483–484.
39. Allevato PA, Eisses JF, Mezger E, Fisher EJ, Romig DA, Morales AR. Nocardia asteroides aortitis with perforation of the aorta. Hum Pathol 1985; 16:743–746.
40. Tanyaowalak W, Sunthornyothin S, Luengtaviboon K, Suankratay C, Kulwichit W. Mycotic aneurysm caused by Burkholderia pseudomallei with negative blood cultures. Scand J Infect Dis 2004; 36:68–70.
41. Manns BJ, Baylis BW, Urbanski SJ, Gibb AP, Rabin HR. Paracoccidioidomycosis: case report and review. Clin Infect Dis 1996; 23:1026–1032.
42. Tozzi FL, da Silva ES, Campos F, Fagundes Neto HO, Lucon M, Lupinacci RM. Primary aortoenteric fistula related to septic aortitis. Sao Paulo Med J 2001; 119:150–153.
43. Barth H, Moosdorf R, Bauer J, Schranz D, Akinturk H. Mycotic pseudoaneurysm of the aorta in children. Pediatr Cardiol 2000; 21:263–266.
44. Jaffe RB, Condon VR. Mycotic aneurysms of the pulmonary artery and aorta. Radiology 1975; 116:291–298.
45. Gomes MN, Choyke PL. Infected aortic aneurysms: CT diagnosis. J Cardiovasc Surg (Torino) 1992; 33:684–689.
46. Wein M, Bartel T, Kabatnik M, Sadony V, Dirsch O, Erbel R. Rapid progression of bacterial aortitis to an ascending aortic mycotic aneurysm documented by transesophageal echocardiography. J Am Soc Echocardiogr 2001; 14:646–649.
47. Bansal RC, Ashmeik K, Razzouk AJ. An unusual case of vegetative aortitis diagnosed by transesophageal echocardiography. J Am Soc Echocardiogr 2001; 14:237–239.
48. Ben-Haim S, Seabold JE, Hawes DR, Rooholamini SA. Leukocyte scintigraphy in the diagnosis of mycotic aneurysm. J Nucl Med 1992; 33:1486–1493.
49. Seabold JE, Binet EF, Schaefer RF. Mycotic aortic aneurysm diagnosed by In-111 leukocyte scintigraphy and computed tomography. Clin Nucl Med 1983; 8:486–487.
50. Knipping L, Mangold G. [Bacterial infections of the abdominal aorta]. Chirurg 1995; 66:887–889.
51. Huang JJ, Chen JS, Shu GH, Chuang YC, Wu JS, Yang YJ. Mycotic aneurysm rupture: report of four cases. J Formos Med Assoc 1992; 91:209–213.
52. Singh H, Parkhurst GF. Bacterial aortitis. NY State J Med 1972; 72:2779–2781.
53. Mundth ED, Darling RC, Alvarado RH, Buckley MJ, Linton RR, Austen WG. Surgical management of mycotic aneurysms and the complications of infection in vascular reconstructive surgery. Am J Surg 1969; 117:460–470.
54. Luo CY, Ko WC, Kan CD, Lin PY, Yang YJ. In situ reconstruction of septic aortic pseudoaneurysm due to Salmonella or Streptococcus microbial aortitis: long-term follow-up. J Vasc Surg 2003; 38:975–982.
55. Heggtveit HA. Syphilitic Aortitis. A clinicopathologic autopsy study of 100 cases, 1950 to 1960. Circulation 1964; 29:346–355.
56. Jackman JD Jr, Radolf JD. Cardiovascular syphilis. Am J Med 1989; 87:425–433.
57. Case records of the Massachusetts General Hospital. Weekly clinicopathological exercises. Case 10-1998. A 46-year-old man with chest pain and coronary ostial stenosis. N Engl J Med 1998; 338:897–903.
58. Shibata H, Matsuzaki T, Shichida K, Hiraoka K, Sugiura M. Syphilis and its cardiovascular complications in the elderly. Jpn Heart J 1976; 17:452–458.
59. Kimura F, Satoh H, Sakai F, et al. Computed tomographic findings of syphilitic aortitis. Cardiovasc Intervent Radiol 2004; 27:179–181.
60. Samson L, Chalaoui J, Paradis B. Case of the day. General. Syphilitic aortitis, with saccular aneurysm of the descending aorta and fusiform aneurysm of the ascending aorta. Radiographics 1990; 10:508–510.
61. du Toit DF, McCormich M, Laker L. Syphilitic aortitis. A case report. S Afr Med J 1985; 67:778–779.
62. Tadavarthy SM, Castaneda-Zuniga WR, Klugman J, Ben Shachar J, Amplatz K. Syphilitic aneurysms of the innominate artery. Radiology 1981; 139:31–34.
63. Cohen MG, Anderson RD, Navia D, Belloso W, Gallo A, Grinfeld LR. Syphilitic aortitis. Catheter Cardiovasc Interv 2001; 52:237–239.
64. Bruenn HG. Syphilitic disease of the coronary arteries. Am Heart J 1934; 9:421–436.
65. Aizawa H, Hasegawa A, Arai M, et al. Bilateral coronary ostial stenosis and aortic regurgitation due to syphilitic aortitis. Intern Med 1998; 37:56–59.
66. Frank MW, Mehlman DJ, Tsai F, Lomasney JW, Joob AW. Syphilitic aortitis. Circulation 1999; 100:1582–1583.
67. Hajji L, Alami M, Ghannam R, et al. [Syphilitic aortitis and "accelerated" atherosclerosis]. Arch Mal Coeur Vaiss 1998; 91:1183–1186.
68. Phillips PL, Amberson JB, Libby DM. Syphilitic aortic aneurysm presenting with the superior vena cava syndrome. Am J Med 1981; 71:171–173.
69. Pugh PJ, Grech ED. Images in clinical medicine. Syphilitic aortitis. N Engl J Med 2002; 346:676.
70. O'Regan AW, Castro C, Lukehart SA, Kasznica JM, Rice PA, Joyce-Brady MF. Barking up the wrong tree? Use of polymerase chain reaction to diagnose syphilitic aortitis. Thorax 2002; 57:917–918.
71. Chauvel C, Cohen A, Albo C, Ziol M, Valty J. Aortic dissection and cardiovascular syphilis: report of an observation with transesophageal echocardiography and anatomopathologic findings. J Am Soc Echocardiogr 1994; 7:419–421.
72. Tai YT, Mok CK, Chow WH, Chan FL, So KF. Ascending aortic dissection complicating syphilitic aortitis, late after aortic valve replacement. Clin Cardiol 1990; 13:227–229.
73. Hook EW 3rd, Marra CM. Acquired syphilis in adults. N Engl J Med 1992; 326:1060–1069.
74. Duncan JM, Cooley DA. Surgical considerations in aortitis: part III: syphilitic and other forms of aortitis. Tex Heart Inst J 1983; 10:337–341.
75. Donabedian H. Salmonella aortitis. Clin Infect Dis 1996; 22:739–740.
76. Fernandez Guerrero ML, Aguado JM, Arribas A, Lumbreras C, de Gorgolas M. The spectrum of cardiovascular infections due to Salmonella enterica: a review of clinical features and factors determining outcome. Medicine (Baltimore) 2004; 83:123–138.
77. Hsu RB, Tsay YG, Chen RJ, Chu SH. Risk factors for primary bacteremia and endovascular infection in patients without acquired immunodeficiency syndrome who have nontyphoid salmonellosis. Clin Infect Dis 2003; 36:829–834.
78. Benenson S, Raveh D, Schlesinger Y, et al. The risk of vascular infection in adult patients with nontyphi Salmonella bacteremia. Am J Med 2001; 110:60–63.
79. Soravia-Dunand VA, Loo VG, Salit IE. Aortitis due to Salmonella: report of 10 cases and comprehensive review of the literature. Clin Infect Dis 1999; 29:862–868.
80. Chiu CH, Ou JT. Risk factors for endovascular infection due to nontyphoid salmonellae. Clin Infect Dis 2003; 36:835–836.
81. Sleiman I, Pelizzari G, Favret M, Balestrieri GP. Recurrent Salmonella sepsis and aortitis in a patient with hepatocellular carcinoma. Recenti Prog Med 1998; 89:304–305.
82. Steiger MJ, Johnston ID. Thoracic aortitis due to Salmonella. J Clin Pathol 1990; 43:877–878.

83. Choi JB, Yang HW, Oh SK, Yun KJ. Rupture of ascending aorta secondary to tuberculous aortitis. Ann Thorac Surg 2003; 75:1965–1967.
84. Salzberger LA, Cavuoti D, Barnard J. Fatal salmonella aortitis with mycotic aneurysm rupture. Am J Forensic Med Pathol 2002; 23:382–385.
85. Schoevaerdts D, Hanon F, Vanpee D, et al. Prolonged survival of an elderly woman with Salmonella dublin aortitis and conservative treatment. J Am Geriatr Soc 2003; 51:1326–1328.
86. Balestra B, Sepic A, Noseda G. Successful treatment of Salmonella aortitis with ciprofloxacin. Clin Microbiol Infect 1998; 4:230–231.
87. Cicconi V, Mannino S, Caminiti G, et al. Salmonella aortic aneurysm: suggestions for diagnosis and therapy based on personal experience – a case report. Angiology 2004; 55:701–705.
88. Munyer TP, Margulis AR. Tuberculous aortitis. Am J Roentgenol 1981; 136:1024–1026.
89. Silbergleit A, Arbulu A. Tuberculous mycotic aneurysms. Chest 1999; 116:1142.
90. Long R, Guzman R, Greenberg H, Safneck J, Hershfield E. Tuberculous mycotic aneurysm of the aorta: review of published medical and surgical experience. Chest 1999; 115:522–531.
91. Allins AD, Wagner WH, Cossman DV, Gold RN, Hiatt JR. Tuberculous infection of the descending thoracic and abdominal aorta: case report and literature review. Ann Vasc Surg 1999; 13:439–444.
92. Mally A, D'Souza C, Dwivedi S, Shatapathi P. Pulmonary tuberculosis with multiple saccular aneurysms of the aorta – a case report. Angiology 1990; 41:333–336.
93. Umerah BC. Unfolding of the aorta (aortitis) associated with pulmonary tuberculosis. Br J Radiol 1982; 55:201–203.
94. de Kruijf EJ, van Rijn AB, Koelma IA, Kuijpers TJ, van't Wout JW. Tuberculous aortitis with an aortoduodenal fistula presenting as recurrent gastrointestinal bleeding. Clin Infect Dis 2000; 31:841–842.
95. Goldbaum TS, Lindsay J Jr, Levy C, Silva CA. Tuberculous aortitis presenting with an aortoduodenal fistula: a case report. Angiology 1986; 37:519–523.
96. Matsumoto A, Noguchi Y, Ishiwa N, Yamamoto Y, Yoshida S. Tuberculous aortitis, ruptured 48 years after therapeutic implantation of synthetic balls. J Cardiovasc Surg (Torino) 2002; 43:129–132.
97. Cargile JS 3rd, Fisher DF Jr, Burns DK, Fry WJ. Tuberculous aortitis with associated necrosis and perforation: treatment and options. J Vasc Surg 1986; 4:612–615.
98. Silbergleit A, Arbulu A, Defever BA, Nedwicki EG. Tuberculous aortitis: surgical resection of ruptured abdominal false aneurysm. JAMA 1965; 193:333–335.
99. Gajaraj A, Victor S. Tuberculous aortoarteritis. Clin Radiol 1981; 32:461–466.

26

Is There a Place for Endovascular Treatment in Thoracic or Thoraco-abdominal Mycotic Aneurysms?

Louis Labrousse, Oliver Pellerin, Doron Carmi, Marc Sapoval

Contents

26.1 Introduction

First described in 1885 by Osler [1], mycotic aneurysms are usually painful, rapidly growing, often ruptured at the time of the procedure and usually with a history of fever, leukocytosis and positive blood cultures. The term mycotic aneurysm is inappropriate as they are related to a secondary abscess secondary to a remote bacterial infection. Although rare, they are frequently associated with a life-threatening condition with significant morbidity and mortality; their management remains one of the most challenging clinical problems facing vascular physicians.

The traditional approach in this setting is surgery with intensive antibiotic administration, extensive excision and debridement of the infected field associated with extra-anatomic or in situ prosthetic bypass grafting. However, results from the literature suggest that optimal results are not achieved with this traditional open-chest treatment, especially in terms of mortality and morbidity. And as for other high-risk patients, endoluminal treatment appeared to be an attractive alternative with an increasing number of cases reported in the literature; however, its use is still a matter of debate mainly because the lack of debridement which is associated with endovascular repair goes against surgical teaching [2].

In this chapter, we report the published results of the surgical and endoluminal management of thoracic mycotic aneurysms in order to determine the exact place of the endovascular treatment.

26.2 Surgical Strategy

To begin with, two specific points need to be highlighted:

1. As mycotic aneurysms are unusual, the number of articles specifically related to thoracic localization is low. Moreover, most series contain a small number of patients with limited follow-up.
2. Moreover, in these articles mycotic aneurysm and infected aortic grafts are often mixed.

So as infectious problems facing surgeons are similar, we will also take into account in this discussion series including abdominal mycotic aneurysms or infected aortic grafts.

From the 1960 to the 1980s, with the usual extensive excision and debridement of the infected field, the recommended treatment included ligation of the aorta associated with extra-anatomical bypass graft (from the ascending aorta) [3, 4]. Theoretically, the main advantage of extra-anatomical revascularization in a noncontamined field is the reduction of the risk of secondary graft infection. The first step of the surgical procedure includes median sternotomy and midline laparotomy, which allow distal revascularization, and is followed in a second step by left thoracotomy for aortic ligation. In some specific cases, axillo-femoral grafting can alternatively be performed, even if retrograde blood supply of the entire abdominal cavity seems in this case generally not reliable.

However, as for the aortic arch, in descending or thoraco-abdominal (paravisceral) aortic localizations, extra-anatomical bypass is in a large majority of cases impossible owing to the proximity of major aortic branches [5] and in situ grafting is unavoidable. At the beginning of the 1990s, with increasing experience and the improvement of thoraco-abdominal surgery results, the first series with in situ revascularization and good results were published [5–8]. Moreover, this technique is potentially associated with a less aggressive surgery

(one step) and better long-term patency (and obviously avoid aortic stump blowout [6]).

Initially, the prosthetic repair was performed with a Dacron prosthesis [5–8]. But, in order to decrease the risk of recurrence of the infection, and because of good results obtained in cardiac surgery with a homograft valve in the setting of endocarditis, a similar therapeutic concept has been introduced by using arterial allografts [9–11]. They have provided superior resistance to infection which could be related to their viability which is associated with a higher antibiotic concentration level and immunocompetent cell density into the wall and the perigraft space [12]. Basically, the aortic homograft is harvested on a brain-dead patient and stored in a tissue bank; and during the implantation, the graft is inserted as a Dacron prosthesis. Although experiences with "fresh" or "refrigerated" allografts have been associated with early rupture and late aneurismal degeneration [13, 14], the use of cryopreserved homografts and technical modifications have allowed these complications to be dealt with successfully [12–16] and so it appears to be the management of choice. Alternatively, if a homograft is not available, include the use of a graft soaked with rifampicin [17, 19, 20], local application of antibiotic-impregnated fibrin glue or gauze [12, 18, 19] and in all cases, the reconstruction should be covered with an omental flap if it is technically possible [5]. It is noteworthy that in an in vitro experimental model poly(tetrafluoroethylene)-expanded grafts appeared to be more resistant to infections than Dacron grafts [21]; up to now, clinical data are insufficient to draw conclusions.

Lastly, if the lesion is well circumscribed, a simple excision and repair with a patch can be performed (Dacron, pericardial, arterial allograft or the more recently described venous patch from the superficial femoral vein [22]).

The operative survival rates of the main recent series reported in the literature are summarized in Table 26.1. Overall perioperative mortality was between 5 and 75%. Note that the series from Cinà et al. includes a literature review of mycotic thoraco-abdominal aortic aneurysm from 1966 to 1999.

Regarding operative morbidity, and compared with atherosclerotic disease of the thoraco-abdominal aorta, surgeons are facing the same problems, which especially include postoperative respiratory and renal failure and neurological deficit. Moreover, in this specific clinical setting, the morbidity is increased by septic complications and probably reflects the combination of an aggressive surgery with a difficult localization (especially for thoracic and paravisceral localization) in patients with comorbidities such as diabetes, immunocompromised state, renal failure, age of more than 70 and pulmonary disease [5, 15–20, 23]. Concerning the high rate of aneurysmal rupture in these patients, the recent review by Cinà et al. [20] found similar early results compared with the results from elective surgery; probably because most of the ruptures were contained and the patients had a stable hemodynamic state.

The midterm and long-term follow-up of these patient depends on the recurrence of the infectious disease. In modern series, recurrence has been reported in 5–15% of patients [5, 8], and is especially related to periaortic extension infection and to aggressive germs like *Staphylococcus aureus* [5, 8, 17, 23]. There is no consensus on the duration of antibiotic therapy. Usually the recommended length is at least 6 weeks [15, 16], but for some patients a longer length can be recommended [12], or even lifelong prophylactic antibiotherapy [5, 18, 19], especially if *Salmonella* is involved or if the infection is active at the time of the surgery. Indeed, in some patients the infectious etiology of the aneurysm is determined incidentally from the history of the disease with all cultures (blood or aortic wall) negative [17, 24]. And in this situation the risk of recurrence seems obviously lower compared with that for patients with frank purulent effusion or adjacent infected focus (osteomyelitis). Lastly, the classically poor survival rate in patients with aortic infection due to *Salmonella* was

Table 26.1. Operative results in recent surgical series with thoracic mycotic aneurysms and/or aortic graft infections

	Number of patients	Operative mortality	Graft use
Chan et al. [4]	22	14% (3/22)	Dacron
Cinà et al. [20]	73 (thoraco-abdominal review)	Extraanat graft: 66% (2/6) In situ graft: 75% Emergent repair: 74% Elective repair: 75%	Dacron + poly(tetrafluoroethylene)
Muller et al. [17]	33	36%	Dacron
Oderich et al. [19]	43	21%	Dacron
Hsu et al. [18]	19 (9 supra renal)	5%	Dacron
Vogt et al. [10]	49 (mycotic and infected graft)	6%	Arterial allograft
Kieffer et al. [16]	179 (infrarenal aortic infected graft)	20%	Arterial allograft
Teebken et al. [15]	42 (39 infected graft)	14%	Arterial allograft

not confirmed by the last series from Hsu et al. [18], with no death among 14 consecutive patients.

Long-term biological monitoring usually involves measurement of the white cell count, erythrocyte sedimentation rate and C-reactive protein level as these are regarded as sensitive indicators for the presence of infection. Our own method as well as that of others [20] is to stop the antibiotherapy after at least three consecutive months with strictly normal biological monitoring.

To conclude, clinical, biological and imaging follow-up lifelong seems reasonable and should include at least quarterly biological examinations, and an imaging examination yearly. MRI or a computed tomography (CT) scan is usually advocated [16, 19], but one can also use a labeled white blood cell scan with gallium-67 isotope, which seems to distinguish reliably between seroma/hematoma and adjacent infection, and so excludes recurrence of the infection [25].

26.3 Endovascular Strategy

The development of the endovascular treatment of thoracic aneurysm, which has shown, since the middle of the 1990s, good results even in challenging situations [26], explains that the endoluminal technique appears to be very attractive in this clinical setting. Moreover, results of open-chest surgical series (Table 26.1) are not yet satisfactory in term of morbidity and mortality. Lastly, these series are from teams known to be "leaders" in the thoracic surgery field. In other places, these patients are basically either contraindicated for surgery, or results are not good enough to be published.

The main problem facing the endovascular approach is that extensive excision and debridement of the infected field, which are part of the surgical strategy, are impossible to perform. So, the potential benefit due to this minimally invasive approach has to be compared with the obvious higher risk of recurrence of the infection. However, there are an increasing number of cases

Table 26.2. Results of endovascular stent-graft placement for thoracic mycotic aneurysms

	Number of patients	Organism	Follow-up
Semba et al. [27]	3	*Proteus mirabilis* *Clostridium septicum* Unknown	25 months died (NR*) 24 months alive 4 months alive
Madhavan et al. [28]	1	*Staphylococcus*	12 months alive
Kinney et al. [29]	1	*Escherichia coli*	10 months died (NR*)
Krämer et al. [30]	4	*Escherichia coli* *Staphylococcus epidermitis* *Staphylococcus aureus* *Staphylococcus aureus*	34 months alive 3 months alive 12 months alive 7 months alive
Lepore et al. [31]	3	*Staphylococcus aureus*	Alive. Follow-up <3years
Ishida et al. [32]	1	*Staphylococcus aureus*	2 days died (R**)
Stanley et al. [33]	4	*Streptococcus* *Staphylococcus aureus* *Enterococcus* *Streptococcus pneumoniae*	12 months alive 15 months alive 10 months alive 1 month died (R**)
Bell et al. [34]	1	*Staphylococcus aureus*	15 months alive
Lamme et al. [35]	2	*Clostridium/Salmonella*	27 months alive
Stoica et al. [36]	1	*Salmonella*	24 months alive
Krohg-Sorensen et al. [37]	3	*Staphylococcus aureus* *Streptococcus empyema* *Streptococcus*	15 months alive 18 months alive 11 days died (NR)
Ting et al. [38]	1	*Salmonella*	12 months alive
Nishimoto et al. [39]	1	*Salmonella*	12 months alive
Kotzampassakis et al. [40]	1	*Salmonella*	6 months alive
Jones et al. [2]	9	*Salmonella* ($n=2$) *Strptococcus pneumoniae* Unknown ($n=6$)	2 deaths (R) at 5 and 62 months
Total	36		4 deaths (R) 2 deaths (NR) Follow-up: 11 months (1–62)

NR death not related to the aneurysm or to the endoprosthesis, *R* death related to failed endovascular treatment

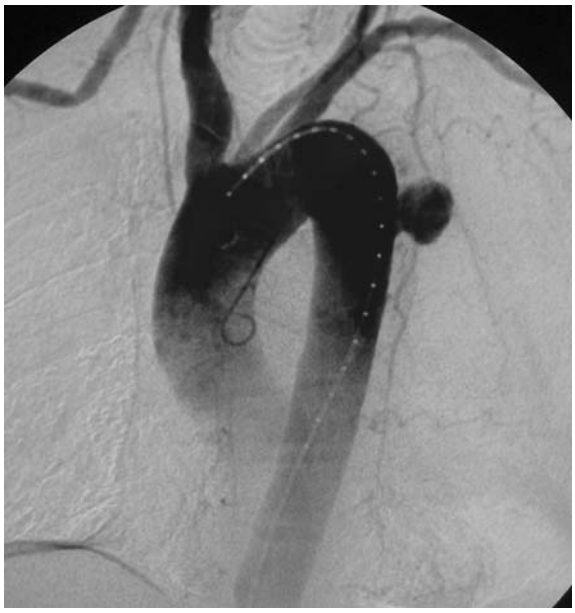

Fig. 26.1. Preoperative angiogram of a tuberculosis mycotic aneurysm of the descending aorta (68-year-old patient hospitalized for hemoptysis)

and small series reported in the literature [2, 27–39] with encouraging results (Table 26.2). All of the patients involved were usually contraindicated for classic open-chest surgery; with a very short life expectancy.

The first issue to be raised here is that of imaging. Because secondary infection of the arterial wall can arise anywhere it is recommended to perform a thoraco-abdomino-pelvic angio CT scan. This technique is now possible with recent multidetector row CT in a single contrast bolus and in single breath hold. Triphasic CT should be used because late enhancement of the arterial wall will help to diagnose inflammatory or infected aortic wall, as well as end-organ damage in the case of infective embolism. Jones et al. [2] reported on one early death related to a misdiagnosed remote false aneurysm. Magnetic resonance angiography can be used, but caution should be applied when interpreting images because calcifications are not visualized and spatial resolution is less optimal; thus, the relation to side branches can be misinterpreted.

Care should also be taken to carefully assess the access site at preoperative or perioperative angiography because these patients can have narrow and calcified native arteries, and complications during endograft delivery can be of concern.

The bacteria involved are similar to those found in surgical series. Even tuberculosis aneurysms have been reported to be successfully treated by an endovascular approach [41]. Figures 26.1 and 26.2 show a similar example of a tuberculosis thoracic mycotic aneurysm treated with a Talent (Medtronic, Minneapolis, USA) endoprosthesis.

The mortality rate of the patients in the reported cases is inferior to surgical rates. Note that the two "unrelated to the endovascular treatment" deaths were due to cardiac disease. And even if there is bias in the fact that usually only successful procedures are reported, the same bias exists in surgical results. In terms of morbidity, and as for the other endovascular indications, stent-grafts avoid full heparinization, aortic cross clamping, distal ischemia and the use of a shunt. All these aspects lead to a theoretically less aggressive surgery with earlier extubation, better perioperative hemodynamic state with less organ(s) failure and neurological complications [31]. However renal failure [28, 33], ischemic colitis [28, 33] and paraplegia [28] have been reported. The deployment of the device is without any specific aspect, although a perioperative rupture [2], a migration [33] and a malpositioning with a type I endoleak [2] have been described.

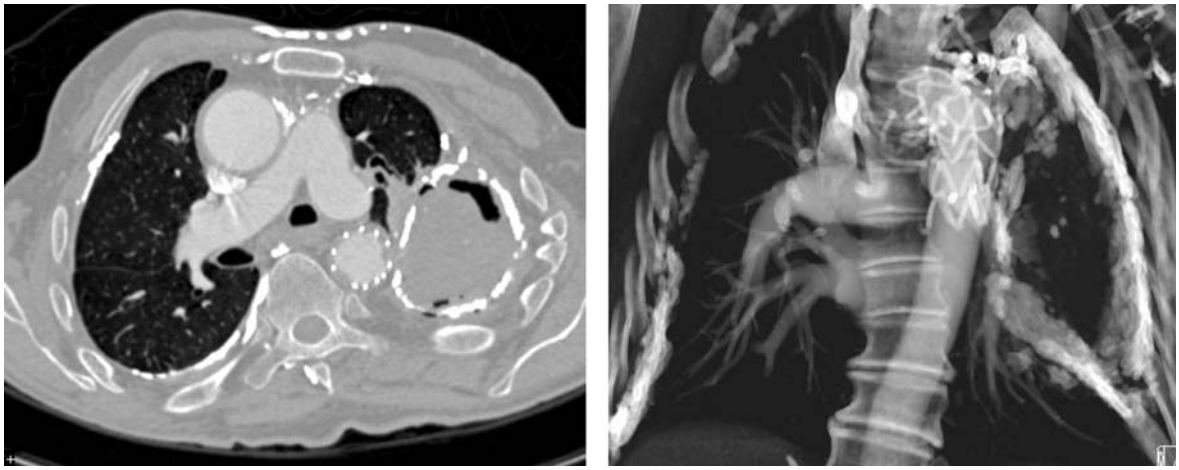

Fig. 26.2. Postoperative computed tomography scan with perfect exclusion of the tuberculosis aneurysm

Owing to the usually limited or sacciform aspect of mycotic aneurysms, the endovascular approach can be useful in paravisceral localization; and to deal with visceral perfusion, fenestrated stents [28, 29, 33, 41] are advocated.

Lastly, as for surgery, different types of devices are recommended. Some authors use homemade devices with Z Gianturco stents covered by an autologous arterial wall [28], but the simplest and theoretically most efficient method seems to use a commercial device with a Rifampicin- or vancomycin-soaked graft [33] (the antibiotherapy is injected perioperatively into the delivery system). Different devices have been used successfully, including the Talent and the Aneurx (Medtronic), the Cook thoracic and the TAG excluder (Gore). The fabric is either polyester or polytetrafluoroethylene (PTFE) and the metal is nitinol or surgical stainless steel. The possible higher resistance of PTFE to infection has been suggested but the available literature reported here is not sufficient to advocate one device over the other [42].

The stent-graft should be selected for availability, size and conformability to the lesion to be covered. Covering at least 2 cm above and below the arterial wall disruption should be advocated. In fact, enough security margins should be reserved because the likelihood of a more extended arterial lesion is always high in this setting.

The main limitation of this literature review is the limited follow-up with a mean delay around 1 year. At that time, it is obviously too early to say that patients are cured; even if in some cases imaging controls have shown reduction of the aneurysm sac size [34, 39]. The issue of the duration of systemic antibiotherapy is unclear. On one hand, it is recognized that even if mycotic aneurysms are an infectious disease, when debridement tissues are cultured 25% of them do not show any bacterial growth [2]. Moreover, negative blood cultures are frequent at the time of treatment. In the literature the largest series comprising nine patients is of interest regarding this issue. Antibiotherapy was not used at all in two cases and relatively short treatment was administered for the rest (up to 6 weeks) with no evidence of reinfection. In most series treatment for 6-months was performed [33, 36, 38, 40, 41]. In our opinion prolonged antibiotherapy seems reasonable but could be tailored to the general condition of the patient and to the results of blood cultures.

It is also very important to follow these patients lifelong. We suggest a protocol combining an annual angio CT scan and a lateral and postero-anterior chest radiograph to verify the position and integrity of the stent-graft. Strict long-term biological monitoring is also needed as a function of the patient condition.

26.4 Conclusion

Owing mainly to the rarity of the condition, this literature review is unable to conclude from a scientific point of view on the exact place of endovascular treatment for thoracic mycotic aneurysms.

However, endovascular treatment appears to be associated with morbidity and mortality rates similar to or below those of open surgery [43]. Associated with an

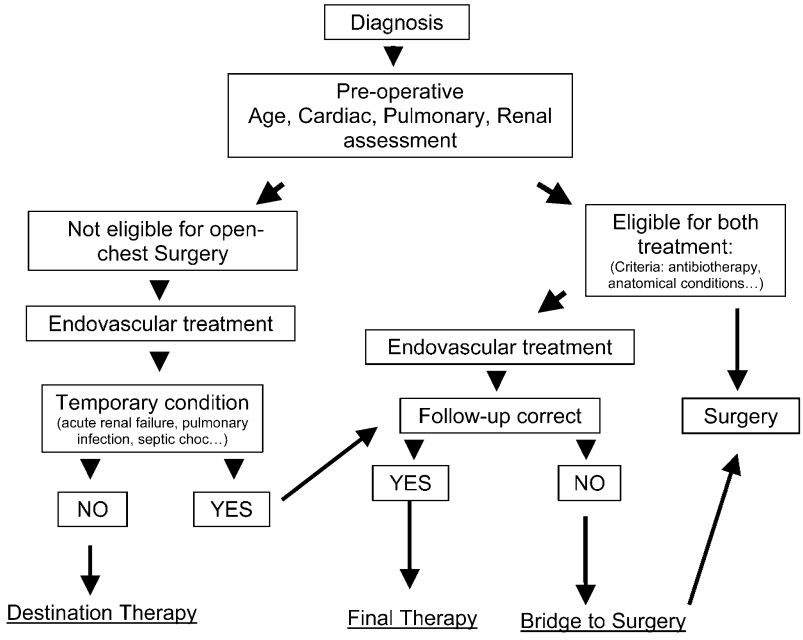

Fig. 26.3. Proposed medical strategy for treatment of thoracic mycotic aneurysms

aggressive and long-term antibiotherapy, it seems reasonable to conclude that in the case of good anatomical conditions, midterm control of the disease is possible.

So, a theoretical strategy can be proposed (Fig. 26.3) with three situations for the endovascular treatment: destination therapy, final therapy or bridge for surgery. If patients are not eligible for open-chest surgery (usually because of comorbidities), the endovascular approach is the only way to palliate rupture and death. For other patients, the endovascular option might be proposed either as a bridge in the case of temporary surgical contraindication or as a first "low-risk" surgical step with following strict monitoring. In this last case, the efficiency and the availability of long-term oral antibiotherapy and anatomical criteria (especially the landing zone) might be two of the main criteria of selection.

As surgical and radiologist teams are waiting for more data to optimize the strategy for treatment of thoracic mycotic aneurysms, an international registry seems necessary to confirm the long-term results of the endovascular treatment [42]. Because this review has shown at least equivalence if not superiority of the endovascular approach, we propose treating all anatomically suitable patients using stent-grafts and performing close and prolonged follow-up while in the meantime all consecutive patients could be entered in this registry. It is thus likely that enough data could be obtained to support or contraindicate this strategy.

References

1. Osler W. The Gulstonian lectures on malignant endocarditis. Br Med J 1885; 1:467.
2. Jones KG, Bell RE, Sabharwal T, Aukett M, Reidy JF, Taylor PR. Treatment of mycotic aortic aneurysms with endoluminal grafts. Eur J Vasc Endovasc Surg 2005; 29:139–144.
3. Yeager RA, Moneta GL, Taylor MM Jr, at al. Improving survival and limb salvage in patients with aortic graft infection. Am J Surg 1990; 159:446–449.
4. Reilly LM, Stoney RJ, Goldstone J, et al. Improved management of aortic graft infection: the influence of operation sequence and staging. J Vasc Surg 1987; 5:421–431.
5. Chan FY, Crawford ES, Coselli JS, et al. In situ prosthetic graft replacement for mycotic aneurysm of the aorta. Ann Thorac Surg 1989; 47:193–203.
6. Robinson JA, Johansen K. Aortic sepsis: is there a role for in situ graft reconstruction? J Vasc Surg 1991; 13:677–682.
7. Pasic M, Carrel T, von Segesser L, Turina M. In situ repair of mycotic aneurysm of the ascending aorta. J Thorac Cardiovasc Surg 1993; 105:321–326.
8. Hollier LH, Money SR, Creely B, Bower TC, Kazmier FJ. Direct replacement of mycotic thoracoabdominal aneurysms. J Vasc Surg 1993; 18:477–484.
9. Kieffer E, Bahnini A, Koskas F, Ruotolo C, Le Blevec D, Plissonnier D. In situ allograft replacement of infected infrarenal aortic prosthetic grafts: results in forty-three patients. J Vasc Surg 1993; 17:349–355.
10. Vogt PR, von Segesser LK, Goffin Y, Pasic M, Turina MI. Cryopreserved arterial homografts for in situ reconstruction of mycotic aneurysms and prosthetic graft infection. Eur J Cardiothorac Surg 1995; 9:502–506.
11. Knosalla C, Weng Y, Yankah AC, Hofmeister J, Hetzer R. Using aortic allograft material to treat mycotic aneurysms of the thoracic aorta. Ann Thorac Surg 1996; 61:1146–1152.
12. Vogt PR, Brunner-LaRocca HP, Lachat M, Ruef C, Turina MI. Technical details with the use of cryopreserved arterial allografts for aortic infection: influence on early and midterm mortality. J Vasc Surg 2002; 35:80–86.
13. Kieffer E, Plissonnier D, Bahnini A, Koskas F. Abdominal aortic graft excision and in situ allograft replacement. In: Calligaro KD, Veith FJ, editors. Management of infected arterial grafts. Quality Medical Publishing, St. Louis 1994. p. 82–94.
14. Lehalle B, Gschier C, Fiévé G, Stoltz JF. Early rupture and degeneration of cryopreserved arterial allografts. J Vasc Surg 1997; 25:751–752.
15. Teebken OE, Pichlmaier MA, Brand S, Haverich A. Cryopreserved arterial allografts for in situ reconstruction of infected arterial vessels. Eur J Vasc Endovasc Surg 2004; 27:597–602.
16. Kieffer E, Gomes D, Chiche L, Fleron MH, Koskas F, Bahnini A. Allograft replacement for infrarenal aortic graft infection: early and late results in 179 patients. J Vasc Surg 2004; 39:1009–1017.
17. Muller BT, Wegener OR, Grabitz K, Pillny M, Thomas L, Sandmann W. Mycotic aneurysms of the thoracic and abdominal aorta and iliac arteries: experience with anatomic and extra-anatomic repair in 33 cases. J Vasc Surg 2001; 33:106–113.
18. Hsu RB, Tsay YG, Wang SS, Chu SH. Surgical treatment for primary infected aneurysm of the descending thoracic aorta, abdominal aorta, and iliac arteries. J Vasc Surg 2002; 36:746–750.
19. Oderich GS, Panneton JM, Bower TC, Cherry KJ Jr, Rowland CM, Noel AA, Hallett JW Jr, Gloviczki P. Infected aortic aneurysms: aggressive presentation, complicated early outcome, but durable results. J Vasc Surg 2001; 34:900–908.
20. Cinà CS, Arena GO, Fiture AO, Clase CM, Doobay B. Ruptured mycotic thoracoabdominal aortic aneurysms: a report of three cases and a systematic review. J Vasc Surg 2001; 33:861–867.
21. Rosenman JE, Kempczinski RF, Berlatzky Y, Pearce WH, Ramalanjaona GR, Bjornson HS. Bacterial adherence to endothelial-seeded polytetrafluoroethylene grafts. Surgery 1985; 98:816–823.
22. Tambyraja AL, Wyatt MG, Clarke MJ, Chalmers RT. Autologous deep vein reconstruction of infected thoracoabdominal aortic patch graft. J Vasc Surg 2003; 38:852–854.
23. Chiba Y, Muraoka R, Ihaya A, Kimura T, Morioka K, Nara M, et al. Surgical treatment of infected thoracic and abdominal aneurysms. Cardiovasc Surg 1996; 62:35–39.
24. Malouf JF, Chandrasekaran K, Orzulak TA. Mycotic aneurysms of the thoracic aorta: a diagnostic challenge. Am J Med 2003; 15:489–496.
25. Ben-Haim S, Seabold JE, Hawes DR, Rooholamini SA. Leukocyte scintigraphy in the diagnosis of mycotic aneurysm. J Nucl Med 1992; 33:1486–1493.
26. Lee JT, White RA. Current status of thoracic aortic endograft repair. Surg Clin North Am 2004; 84:1295–1318, vi–vii
27. Semba CP, Sakai T, Slonim SM, Razavi MK, Kee ST, Jorgensen MJ, Hagberg RC, Lee GK, Mitchell RS, Miller DC, Dake MD. Mycotic aneurysms of the thoracic aorta: repair with use of endovascular stent-grafts. J Vasc Interv Radiol 1998; 9(1 Pt 1):33–40.
28. Madhavan P, McDonnell CO, Dowd MO, Sultan SA, Doyle M, Colgan MP, McEniff N, Molloy M, Moore DJ, Shanik GD. Suprarenal mycotic aneurysm exclusion using a stent

with a partial autologous covering. J Endovasc Ther 2000; 7:404–409.
29. Kinney EV, Kaebnick HW, Mitchell RA, Jung MT. Repair of mycotic paravisceral aneurysm with a fenestrated stent-graft. J Endovasc Ther 2000; 7:192–197.
30. Kramer S, Pamler R, Seifarth H, Brambs HJ, Sunder-Plassmann L, Gorich J. Endovascular grafting of traumatic aortic aneurysms in contaminated fields. J Endovasc Ther 2001; 8:262–267.
31. Lepore V, Lonn L, Delle M, Bugge M, Jeppsson A, Kjellman U, Radberg G, Risberg B. Endograft therapy for diseases of the descending thoracic aorta: results in 43 high-risk patients. J Endovasc Ther 2002; 9:829–837.
32. Ishida M, Kato N, Hirano T, Shimono T, Yasuda F, Tanaka K, Yada I, Takeda K. Limitations of endovascular treatment with stent-grafts for active mycotic thoracic aortic aneurysm. Cardiovasc Intervent Radiol 2002; 25:216–218.
33. Stanley BM, Semmens JB, Lawrence-Brown MM, Denton M, Grosser D. Endoluminal repair of mycotic thoracic aneurysms. J Endovasc Ther 2003; 10:511–515.
34. Bell RE, Taylor PR, Aukett M, Evans GH, Reidy JF. Successful endoluminal repair of an infected thoracic pseudoaneurysm caused by methicillin-resistant Staphylococcus aureus. J Endovasc Ther 2003; 10:29–32.
35. Lamme B, de Jonge IC, Reekers JA, de Mol BA, Balm R. Endovascular treatment of thoracic aortic pathology: feasibility and mid-term results. Eur J Vasc Endovasc Surg 2003; 25:532–539.
36. Stoica L, Chocron S, Falcoz PE, Etievent JP. Endovascular stent grafting for contained rupture of the descending thoracic aorta. Eur J Cardiothorac Surg 2003; 23:1068–1070.
37. Krohg-Sorensen K, Hafsahl G, Fosse E, Geiran OR. Acceptable short-term results after endovascular repair of diseases of the thoracic aorta in high risk patients. Eur J Cardiothorac Surg 2003; 24:379–387.
38. Ting AC, Cheng SW, Ho P, Poon JT. Endovascular repair for multiple Salmonella mycotic aneurysms of the thoracic aorta presenting with Cardiovocal syndrome. Eur J Cardiothorac Surg 2004; 26:221–224.
39. Nishimoto M, Hasegawa S, Asada K, Tsunemi K, Sasaki S. Stent-graft placement for mycotic aneurysm of the thoracic aorta: report of a case. Circ J 2004; 68:88–90.
40. Kotzampassakis N, Delanaye P, Masy F, Creemers E. Endovascular stent-graft for thoracic aorta aneurysm caused by Salmonella. Eur J Cardiothorac Surg 2004; 26:225–227.
41. Liu WC, Kwak BK, Kim KN, Kim SY, Woo JJ, Chung DJ, Hong JH, Kim HS, Lee CJ, Shim HJ. Tuberculous aneurysm of the abdominal aorta: endovascular repair using stent grafts in two cases. Korean J Radiol 2000; 1:215–218.
42. Bergamini TM, Bandyk DF, Govostis D, Kaebnick HW, Towne JB. Infection of vascular prostheses caused by bacterial biofilms. J Vasc Surg 1988; 7:21–30.
43. Smith JJ, Taylor PR. Endovascular treatment of mycotic aneurysms of the thoracic and abdominal aorta: the need for level 1 evidence. Eur J Endovasc Surg 2004; 27:569–570.

Intramural Aortic Hematoma and Aortic Ulcers, Physiopathology and Natural History

Isidre Vilacosta, Joaquín Ferreirós, Ana Bustos, José Alberto San Román, Paloma Aragoncillo

27

Contents

27.1 Introduction

Intramural aortic hematoma (IAH) and penetrating aortic ulcers (PAU) are part of the so-called acute aortic syndrome (AAS). This new cardiovascular syndrome embraces a heterogeneous group of patients with a similar clinical profile that includes classic aortic dissection, IAH and PAU (Fig. 27.1) [1]. The physiopathological mechanism that precipitates the appearance of each of these entities is different and the natural history of the last two aortic lesions is not well known. Currently, we know that IAH in some patients may evolve into an aortic dissection, that many cases with PAU are accompanied by some degree of intramural hemorrhage, and that occasionally PAU may act as the entrance tear of an aortic dissection (Fig. 27.1) [1–3]. In addition, some patients may exhibit several or all of these lesions. Is, therefore evident, the existence of a link between them. In this chapter the physiopathology and natural history (evolutive patterns) of IAH and PAU are discussed.

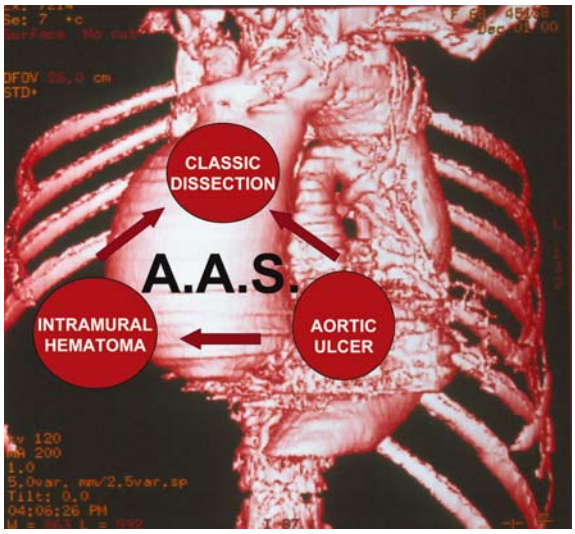

Fig. 27.1. The three elements that constitute the acute aortic syndrome (*AAS*) are depicted. *Arrows* indicate the possible progression of each of these aortic lesions

27.2 Intramural Aortic Hematoma

27.2.1 Physiopathology

IAH was described by Krukenberg [4] in 1920 as a "dissection without intimal tear." IAH has been defined as a novel variant of classic aortic dissection characterized by the absence of an entrance tear. It is, therefore, a noncommunicating type of dissection (Fig. 27.2) [5]. Here, the false lumen is created by a hemorrhage into the aortic media, most likely after rhexis of the vasa vasorum that penetrate the outer half of the aortic media from the adventitia and arborize at this level.

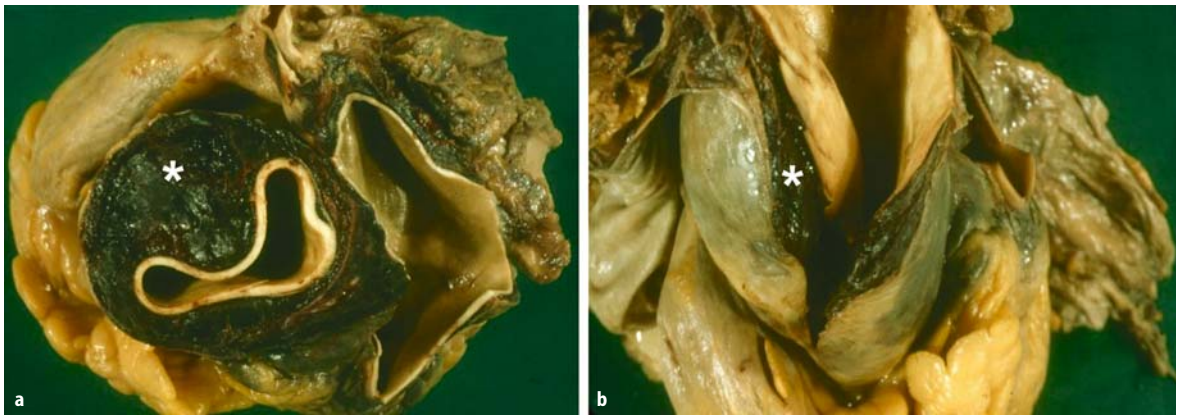

Fig. 27.2. Autopsy specimen of type A intramural aortic hematoma (*IAH*) (*asterisk*). Transversal (**a**) and longitudinal (**b**) sections. Notice the absence of an entrance tear

27.2.2 Vasa vasorum

In normal circumstances, the intima and the inner part of the aortic media are avascular. It is important to point out that the vasa vasorum are present in the medial layer only when this layer has more than 29 lamellar units and, in such cases, they will only be found in the region of the medial layer that is beyond these 29 units [6]. The region of the medial layer corresponding to the 29 subintimal units is an avascular area and one may presume that the nutrients flow via transintimal diffusion from the aortic lumen. Therefore, we may say that the thoracic aorta has a double, yet precarious, means of nutrient delivery: the adventitia and the outer third of the medial layer depend on the vasa vasorum, while the intima and the inner third of the medial layer are nourished via diffusion [6]. Accordingly, the middle third of the medial layer, where degenerative changes are most frequently seen [7], will nutritionally depend on both sources [7]. Clarke [8] described the aortic wall vasa vasorum being distributed so as to form a deep and superficial plexus. The vessels of the superficial plexus are arterioles 80–100 μm in diameter and they lie at the junction of the media and the adventitia; this superficial plexus leads to a deep plexus of vessels where small tortuous arterioles 10–20 μm in diameter penetrate into the medial layer and arborize in its two outer thirds [8]. Medial vasa vasorum have a larger role in nourishment of the aorta in aortic atherosclerosis, as blood flow through the vasa vasorum in the outer layers of the aortic wall is increased [9]. It appears that increased blood flow in the atherosclerotic aorta cannot be accounted for by dilatation of the existing vasa vasorum and must be produced by proliferation of new vessels in the aortic wall [9]. The morphology and structure of these new vessels differs from that of normal vasa vasorum [10]. Thus, the effectiveness and contribution of these new vasa vasorum to nourishment of the aorta is not well known. Proliferation of these vasa in the atherosclerotic aorta could have unfavorable effects and, in fact, some authors think that these vessel abnormalities may be involved in the pathogenesis of IAH [11].

The development of an IAH may not only be attributed to the spontaneous rupture of "sick" vasa vasorum, it can also be the result of a traumatic rupture of "healthy" vasa vasorum during a traumatism of the aortic wall [12, 13, 14]. A medial hemorrhage secondary to a fracture of an atherosclerotic plaque may also lead to an IAH [3, 5, 15].

27.2.3 PAU Versus Rupture of Vasa Vasorum

Although these aortic lesions (IAH and PAU) are physiopathologically different, in some cases it may be difficult to differentiate between them. Mohr-Kahaly et al. [5] identified 15 patients with IAH by transesophageal echocardiography (TEE) and analyzed the amount of aortic atherosclerosis of these patients. Atherosclerotic lesions were detected in 11 patients (mild in eight, moderate in two, and severe in one); there were no atherosclerotic plaques in the remaining four patients. Accordingly, these authors divided IAH in two physiopathologically different groups: patients with mild aortic atherosclerosis or without aortic atherosclerosis would have had a rupture of the vasa vasorum, whereas in those with severe atherosclerosis a complication of an atherosclerotic plaque was the most likely cause of IAH. This concept is shared by Sheldon et al. [15], who studied 20 patients with IAH identified by TEE; they also had two groups, one with moderate or severe atherosclerosis and another with mild atherosclerosis or without atherosclerosis. Patients from the first group were older and had coronary and peripheral vascular disease more frequently than the others. Sheldon et al.

attributed the origin of IAH associated with severe atherosclerosis to intimal atherosclerotic complications (atherosclerotic plaque rupture or PAU). The work of Sueyoshi et al. [16] supports the existence of a link between PAU and IAH. These investigators studied retrospectively 32 patients with IAH and they could identify the existence of PAU at hospital admission or at follow-up in 21 cases. When IAH originates from a complicated atherosclerotic plaque, the ulcerated aortic plaque behaves like an intimal tear.

27.2.4 Absence of Entrance Tear

In the literature [17, 18] and in our own experience, some patients with AAS have been initially diagnosed of IAH, and later, at surgery, a tiny intimomedial entrance tear with a clotted false lumen has been identified (Figs. 27.3, 27.4). In these cases, the false channel not been decompressed by a reentrance tear and an immediate thrombosis of the false lumen occurred; consequently there would be no possibility of detecting flow within the aortic wall. These observations raise the question of the diagnostic accuracy of noninvasive imaging techniques to detect the intimomedial tear, which is considered a critical criterion to differentiate classic "double channel aorta" from IAH. The fact is that some small entrance tears will not be visualized by current imaging modalities. One may also speculate that because of the rapid morphologic evolution of IAH, the tear found at surgery may have occurred as a decompression mechanism after admission of patients and the diagnostic imaging.

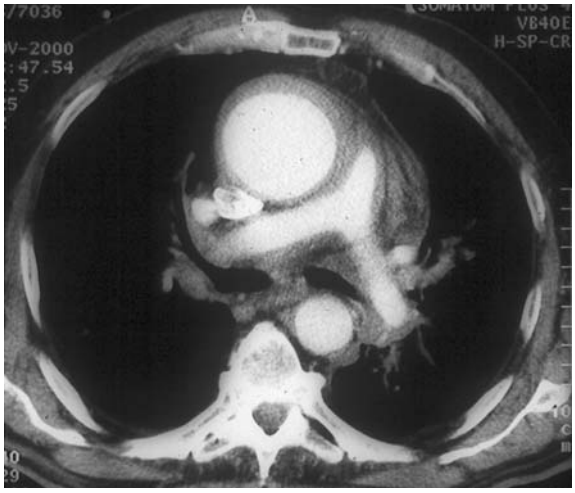

Fig. 27.3. Computed tomography of a patient with an AAS who was first diagnosed of having an IAH, axial section. Notice a clear thickening of the wall of the ascending aorta. No entrance tear nor flow within the aortic wall could be detected

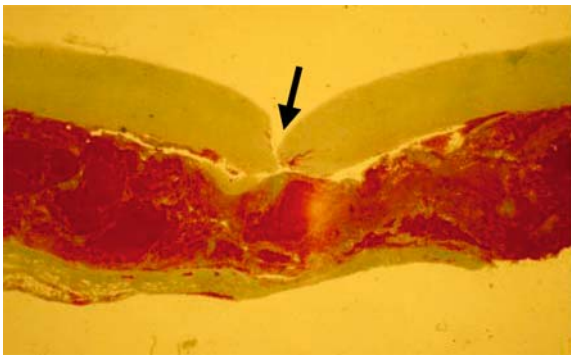

Fig. 27.4. Histological section (Mason's technique) of the ascending aorta of the patient from Fig. 27.3. Notice the existence of a small entrance tear (*arrow*)

If we take all these considerations into account, one may say that the distinctive event in IAH is the existence of a noncommunicating dissection. In our opinion, for an IAH to develop, it is important that a reentrance tear is absent. The entrance tear can be absent or, if present, it must be very small [19].

27.2.5 Intraparietal Hemorrhage

IAH has also been documented at autopsy. Necropsy series have demonstrated that in some patients (5–13%) with dissection the entrance tear is not evident [20–22]. On histologic analysis, a hematoma disrupting the aortic media is well documented (Fig. 27.5). In our experience, this hematoma is most often intramedial, but occasionally it is subadventitial (between the media and the adventitia). A subadventitial hematoma might have a greater risk of aortic rupture.

This intramedial or subadventitial hemorrhage results in a circumferentially oriented blood-containing

Fig. 27.5. Histological section (Mason's technique) of a patient with IAH. Splitting of the aortic media by a hematoma (*asterisk*) is clearly seen. Notice also a dysplastic arteriole with a hemorrhage inside

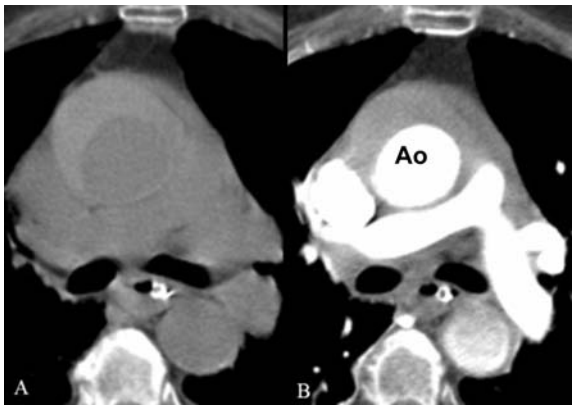

Fig. 27.6. Computed tomography (*CT*) of a patient with an IAH located in the ascending aorta without and with contrast medium. There is a circular high-attenuation area along the aortic wall without contrast, and notice that there is no enhancement of the aortic wall after contrast medium administration

space seen in echotomographic imaging studies (Fig. 27.6). Because there is no entrance tear, the intramedial hematoma does not communicate directly with the aortic lumen and, unlike the false lumen of classic aortic dissection, the presence of flow (color Doppler imaging on TEE) within the hematoma is not seen. For the same reason, this thickened aortic wall does not generally show enhancement with contrast administration on computed tomographic scanning (CT), MRI and angiography.

TEE may identify in many patients with IAH small echolucent zones within the aortic wall thickening. Sixty-seven percent of patients of our series [2], two thirds of patients from the series of Mohr-Kahaly et al. [5] and 19 out of 23 out aortic segments from the series of Harris et al. [23] presented with echo-free spaces within the aortic thickening; when these areas are located immediately below the intimomedial flap, the dissection flap can be seen [2]. These spaces were initially thought to represent areas of liquefaction within the intraparietal hematoma. Now, this aspect may be better studied by MRI and CT; we have observed that these areas correspond to pools of low blood flow that come from the aortic lumen through tiny flap ruptures or the ostia of the intercostal or lumbar arteries that have been severed by the dissecting hematoma (Fig. 27.7) [24]. Song et al. [25] studied the clinical significance of this finding in patients with type B IAH. Patients were classified according to the extent of the echo-free spaces; no differences with respect to in-hospital mortality, surgical intervention, development of an aortic dissection or complete resolution of the IAH between those with or without echo-free spaces were found. They concluded that the presence or development of echo-free spaces is not a poor prognostic sign.

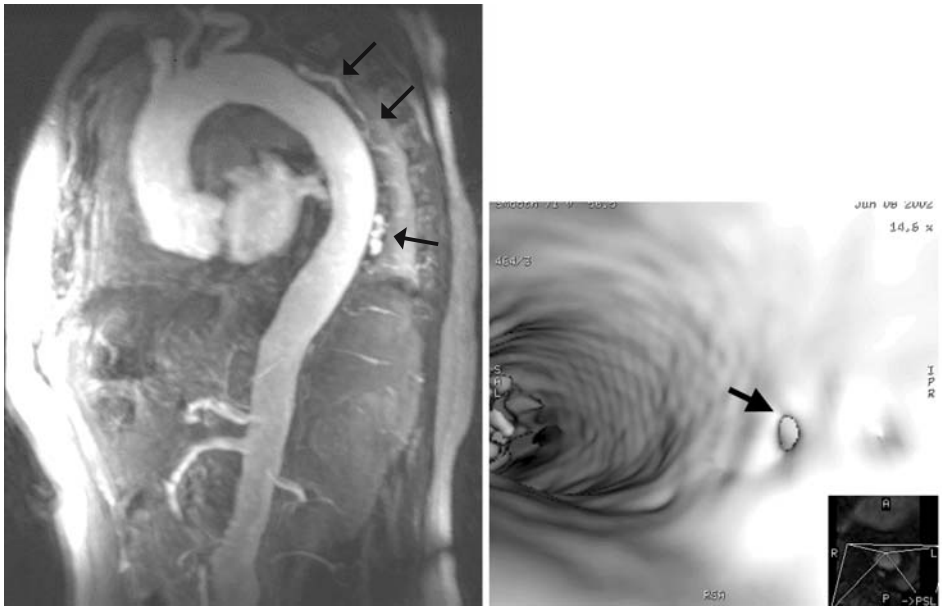

Fig. 27.7. 3D magnetic resonance angiography of a patient with a distal IAH (*left*). Notice the existence of small areas of contrast medium (*arrows*) within the hematoma. In a 3D intravascular reconstruction of the same case (*right*) one may see an intraluminal view of the descending aorta and the ostium (*arrow*) of an intercostal artery permitting flow to pass from the aortic lumen to the IAH

27.2.6 Classification

As in classic aortic dissection, patients with IAH are divided in two groups according to Stanford classification: type A, when the involved segment is the ascending aorta and type B when it is confined to the descending aorta. In the meta-analysis done by Maraj et al., type A IAH was commoner than type B (57% type A vs 43% type B), but in our experience type B is commoner than type A. From a surgical and prognostic standpoint we use the following classification: if the affected segment is the ascending aorta and/or the aortic arch – proximal IAH; if the involved segment is the descending aorta – distal IAH [1].

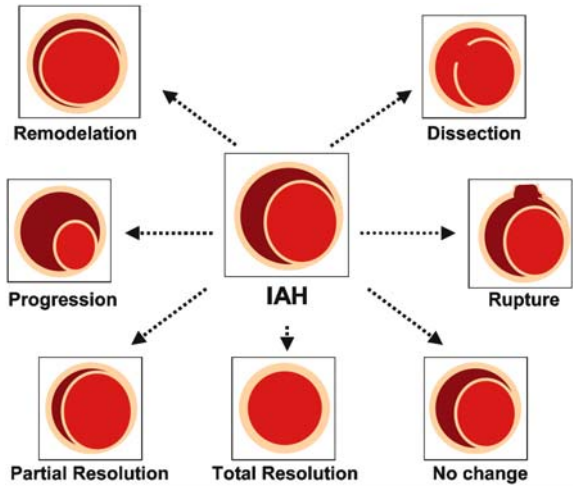

Fig. 27.8. Dynamic behavior of IAH. *Arrows* indicate the possible evolution of this type of acute aortic pathology

27.3 Natural History

One of the key features of IAH is its evolving behavior over time; therefore, the appearance of this lesion can be interpreted differently depending on when a diagnostic examination is performed. The clinical course of these patients is unpredictable, and in many cases, unfavorable. Thus, it is difficult to predict a precise evolution in a particular patient. We will describe in broad outline the evolutive patterns of patients with IAH (Fig. 27.8). It is worth emphasizing that documentation of progression or regression of IAH is closely related to the timing of the evaluation.

The most worrying of all the evolutive possibilities is the adventitial rupture and bleeding out to adjacent structures. Increased permeability of the aortic wall leading to a pericardial, pleural and mediastinal hemorrhage, and progression to an aortic rupture, has been reported [2, 26]. In contrast to evolution to overt aortic rupture, some authors have found that contained rupture from disintegration of outer layers of the aortic media is relatively frequent (28 out of 66 patients in the series of von Kodolitsch et al.) [26]. In some cases this segmental noncommunicating aortic dissection can progress to a localized communicating dissection owing to intimal disruption (Fig. 27.9) [2, 26–29].

Besides progression from IAH to communicating dissection, some patients may exhibit both lesions in different aortic segments at the same time, demonstrating a link between these acute aortic pathologies. The physiopathologic mechanism that fully explains these "hybrid" cases is unknown. Three hypothesis are plausible: (1) early and segmentary false lumen thrombosis

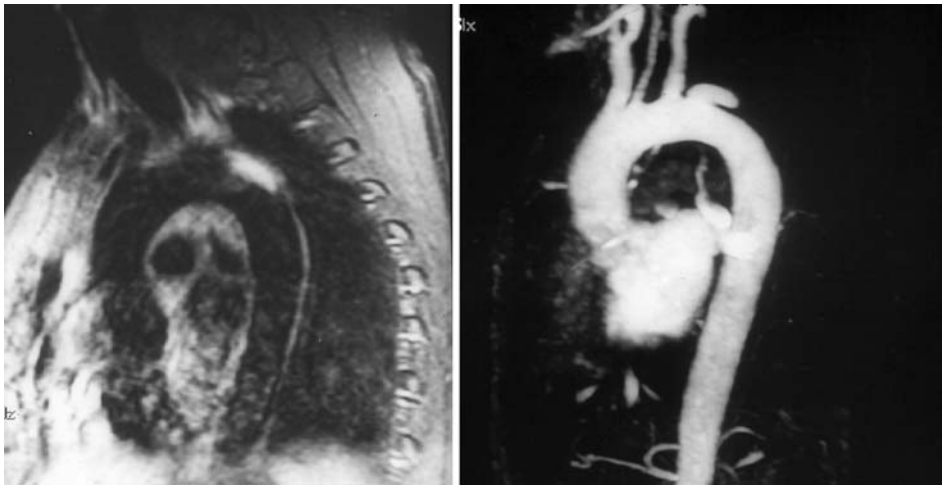

Fig. 27.9. MRI of a patient with a distal IAH. In the *left panel* an IAH localized immediately after the ostium of the left subclavian artery is seen as a hyperintense lesion. A magnetic resonance angiogram of the same patient 4 months later shows a localized small dissection (*right panel*)

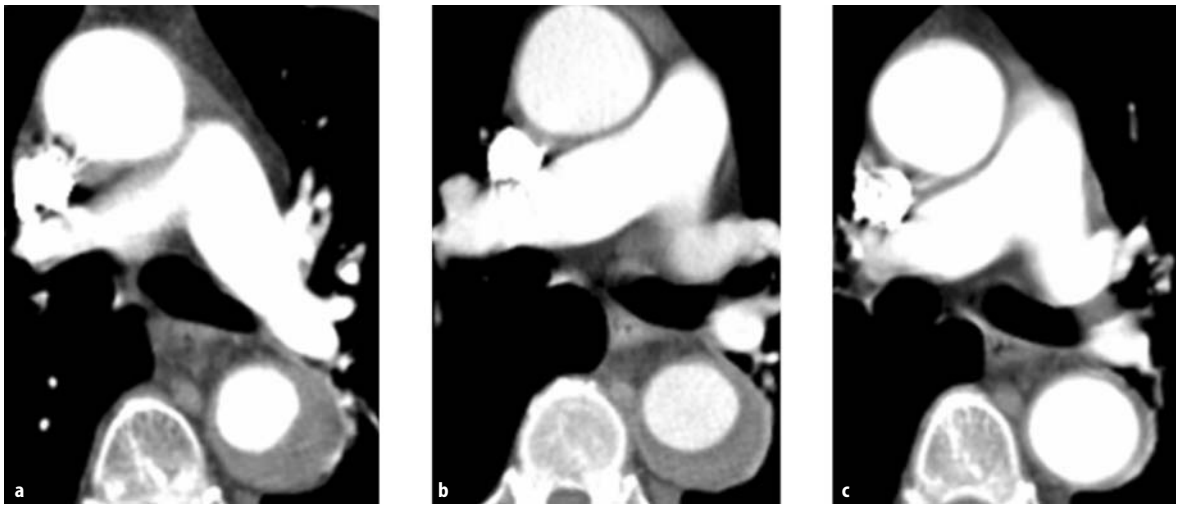

Fig. 27.10. CT evolutive sequence of a distal IAH. At admission (**a**), on the ninth day in hospital (**b**) and 2 months after admission (**c**)

of a patient with classic aortic dissection; (2) segmentary progression of an IAH to an overt communicating dissection without changing the remaining aortic segments; (3) AAS with different (IAH and aortic dissection) but simultaneous patterns in several aortic segments.

Growing and progression of IAH, with increment in the aortic wall thickness, can ensue if the medial hemorrhage continues. This morphologic evolution is not frequently seen on sequential imaging examinations. Conversely, IAH may regress partially or completely (Fig. 27.10). This spontaneous resolution of the process without clinical sequelae is frequently seen in distal IAH; edema will be reabsorbed through the capillaries, macrophages will phagocyte the hemosiderine, and finally fibroblasts will produce a collagen tissue scar. Given the weakness of the aortic wall, aortic remodeling of the diseased area can occur and a localized aneurysm may develop, warranting close surveillance to avoid progressive dilatation and rupture. Finally, in some cases the IAH will not change its appearance with time.

The factors involved in each of these outcomes are not well known, but a number of authors have contributed to find predictors of progression to complications (aneurysm, dissection and rupture). Currently, the two most important predictors of mortality in patients with IAH are involvement of the ascending aorta and maximum aortic diameter (50 mm or more) [26, 29, 30]. Kaji et al. [30] investigated the markers of progression or regression of proximal IAH by CT in 22 patients. They found that patients with a maximum aortic diameter at admission greater than 50 mm showed a tendency to progress to aortic enlargement or dissection with positive and negative predictive values of 83 and 100%, respectively. The aortic diameter is the main determinant of wall stress; therefore, an increased stress on the wall of a dilated aorta with IAH will lead to a greater risk of dissection and rupture.

Von Kodolitsch et al. [26] published a multicenter study of 66 patients with IAH. In this study a high incidence of proximal IAH was seen (38 patients). Progression to aortic dissection or rupture was observed in 30 patients (45%) and death occurred in 13 patients (20%) during the first month of follow-up. Proximal location of IAH was confirmed as an independent predictor of progression to dissection, contained rupture or aneurysm formation. More recently, Evangelista et al. [29], in a prospective study of 68 consecutive patients with IAH (12 type A, 56 type B) from a single center, studied the early evolution of these patients in the first 3 months. Eight patients with type A IAH underwent surgery, whereas only two patients with type B IAH were treated surgically. Thirteen patients died (19%), six with type A IAH, and seven with type B IAH. Predictors of mortality were maximum aortic diameter and ascending aorta involvement. The mortality of patients with an aortic diameter above 50 mm was 50%, and was only 2% in those cases with an aortic diameter less than 50 mm. Patients with ascending aorta involvement had 50% mortality, whereas mortality was 12% when the ascending aorta was spared. On the other hand, studies from Asian investigators showed that proximal IAH does not have such a dismal prognosis [31–33]. No definitive explanation has been found for this striking discrepancy, but it may be related to differences in the patients studied, racial factors, different diagnostic criteria, etc. [34, 35]. Other factors such as the thickness of the hematoma and the presence of pericardial or pleural effusions have been studied. Sohn et al. [31] in their study of patients with proximal IAH verified the disappearance of these effusions in most cases. In our experience, the presence of pleural or pericardial effu-

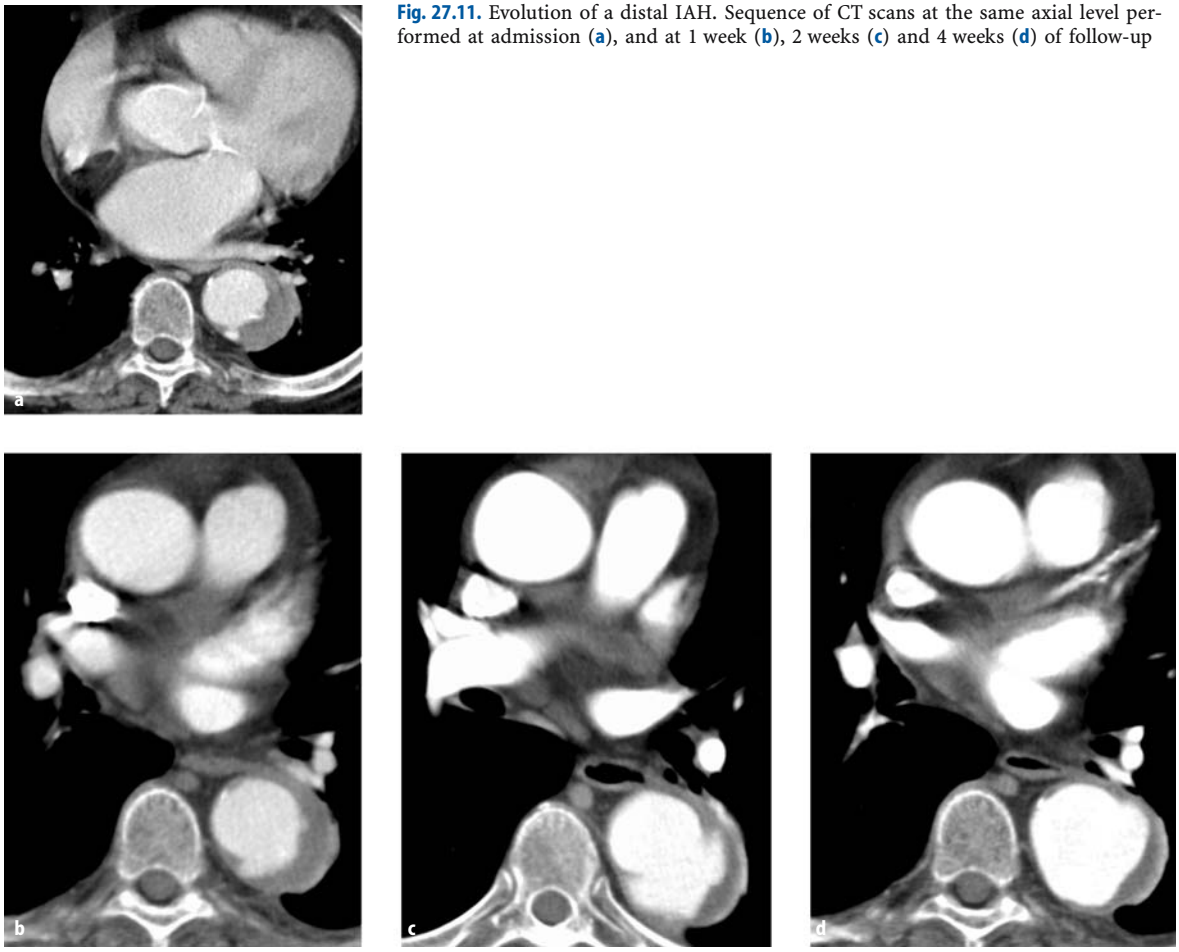

Fig. 27.11. Evolution of a distal IAH. Sequence of CT scans at the same axial level performed at admission (**a**), and at 1 week (**b**), 2 weeks (**c**) and 4 weeks (**d**) of follow-up

sions is only an ominous sign when they are large or progressive.

Sueyoshi et al. [36] studied 35 patients with type B IAH. They found that when the initial maximum aortic diameter was more than 40 mm, a progressive aortic dilatation will probably occur at follow-up (the progression rate was 7.52 mm/year) and that some of these cases may progress to an overt dissection or aortic rupture. These authors also found that wall thickness may be a predictor of progression of type B IAH. This is not surprising; as was to be expected, a large volume of hematoma compressing the aortic wall might weaken the intimal layer and lead to intimal disruption. Nonetheless, the positive predictive value of aortic wall thickening is not very high and, therefore, has a mild impact on patient management. Moizumi et al. [37] in a recent retrospective study with 94 cases of IAH (41 type A and 53 type B) defined two predictors of progression in type B IAH: maximum wall thickness at 2–4 weeks after admission and maximum aortic diameter on admission. They calculated that a wall thickness of 16 mm resulted in positive and negative predictive values of 60 and 86%, respectively, and that a cutoff value of 53 mm (aortic diameter) had positive and negative predictive values of 100 and 96%, respectively.

Some of the current predictive factors of IAH progression are shown in Table 27.1 [38–40]. Other authors distinguish two types of IAH: IAH associated with PAU and IAH without PAU [40, 41]. Although this distinction has a physiopathological rationale, the recognition and differentiation of IAH secondary to PAU with noninvasive imaging techniques remains difficult, because there is no imaging technique able to detect the distinguishing feature of PAU, the rupture of the internal elastic lamina. Probably, it is more appropriate to classify IAH into those with or without intimal erosions. In the retrospective study of Ganaha et al. [40], IAH with large intimal erosions (ulcerlike lesions) was significantly associated with a progressive disease course, whereas IAH without these intimal erosions had a stable course, especially when limited to the descending aorta. When a threshold of 20 mm was used for the maximum ulcerlike diameter, the positive and negative predictive values for disease progression were 100 and 71%, respectively. When the value for the maximum ulcerlike depth was set at 10 mm or greater, the positive

Table 27.1. Indicators of intramural aortic hematoma progression

Involvement of the ascending aorta
Maximum aortic diameter 50 mm or more on initial diagnostic imaging
Severe pericardial effusion
Huge or progressively increasing pleural effusion
Progressive aortic dilatation at follow-up
Persistent pain and/or hemodynamic instability
Increment of the aortic wall thickness
Large intimal erosion

and negative predictive values were 80 and 88%, respectively. A case of distal IAH associated with a tiny intimal erosion that evolves into a localized aortic dissection is shown in Fig. 27.11.

27.4 Penetrating Aortic Ulcers

27.4.1 Physiopathology

Most atherosclerotic aortic lesions with erosion of the atherosclerotic plaque involve only the intimal layer. The term "penetrating atherosclerotic aortic ulcer" describes the condition in which ulceration of an aortic atherosclerotic lesion penetrates the internal elastic lamina into the media [3, 42, 43] (Fig. 27.12). Aortic ulcers are usually focal lesions most frequently located in the descending thoracic aorta, but may be found along the whole aorta. PAU of the ascending aorta are uncommonly reported. These ulcerations may be single or multiple, and in some cases bilobulated. In the excavated area "crater" of these ulcerated lesions, necrotic debris, foam cells, cholesterol, and thrombotic material may be found (Fig. 27.13), and this might explain the high incidence of distal embolism in this entity. When the area of the aortic wall involved in these ulcers has been badly damaged it may even be translucent; usually these ulcers are associated with other atherosclerotic aortic lesions (Fig. 27.14). This entity is associated with a variable amount of intramural hemorrhage. In most patients this intramural (intramedial) hematoma is localized, but occasionally it may extend proximally or distally and sometimes it may involve the entire descending thoracic aorta [43]. Concomitant aneurysms of the descending aorta are commonly found [42].

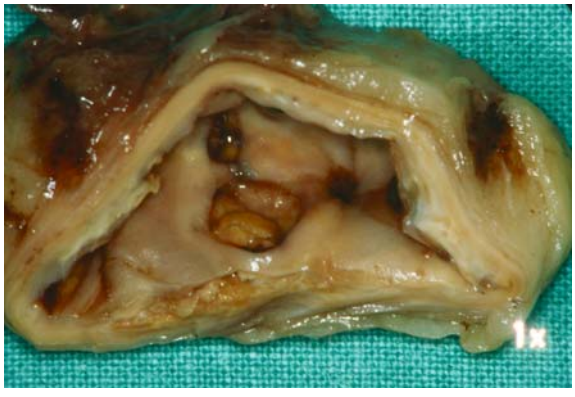

Fig. 27.12. Anatomical cross section of the descending thoracic aorta. A penetrating atherosclerotic aortic ulcer resembling an ulcerous gastric niche is clearly seen

27.4.2 Natural History

The natural history of PAU is unknown. Like IAH, several evolutive possibilities have been described (Fig. 27.15). Many patients with PAU do not need immediate aortic repair but they require close follow-up with serial imaging studies to document any progression of disease or the appearance of complications. These ulcers may be complicated by aneurysm formation "aortic remodelling"[44]. Although many authors have documented the propensity for aortic ulcers to develop progressive aneurysmal dilatation, the progression is usually slow [44]. Aortic ulcers may break through into the adventitia to form a pseudoaneurysm [3]; in this situation the hematoma is contained by the overlying adventitia and some authors consider this type of aortic lesion a contained aortic rupture [26, 43]. Spontaneous, complete, aortic rupture may occur; transmural aortic rupture into the mediastinum or the right and left hemithorax has rarely been reported [45, 46]. Penetrating atherosclerotic aortic ulcers may even precipitate an aortic dissection [3, 47, 48]. We neither know why most eroded atherosclerotic aortic lesions do not penetrate the internal elastic lamina into the media nor why some aortic ulcers perforate the adventitia and others are the genesis of an aortic dissection.

The diagnosis of these ulcers is made on CT, MRI (Fig. 27.16), angiography and TEE by demonstration of an outpouching of the aortic wall with jagged edges, usually in the presence of extensive aortic atheroma [3, 49–51]. The absence of an ulcer crater distinguishes IAH from PAU with intraparietal hemorrhage. Nonetheless, in practice, this distinction is not always possible. Many cases of IAH have intimal erosions that simulate PAU: "ulcerlike" images. The main handicap in the diagnosis of penetrating atherosclerotic aortic ulcers is that there is no technique available that can document the disruption of the internal elastic lamina, which is the definitive histological fact to make the diagnosis of PAU.

Aortic ulcers may be the origin of a dissection; in this case the entrance tear is the ulcerated crater [3]. This sort of dissection has distinctive features (Ta-

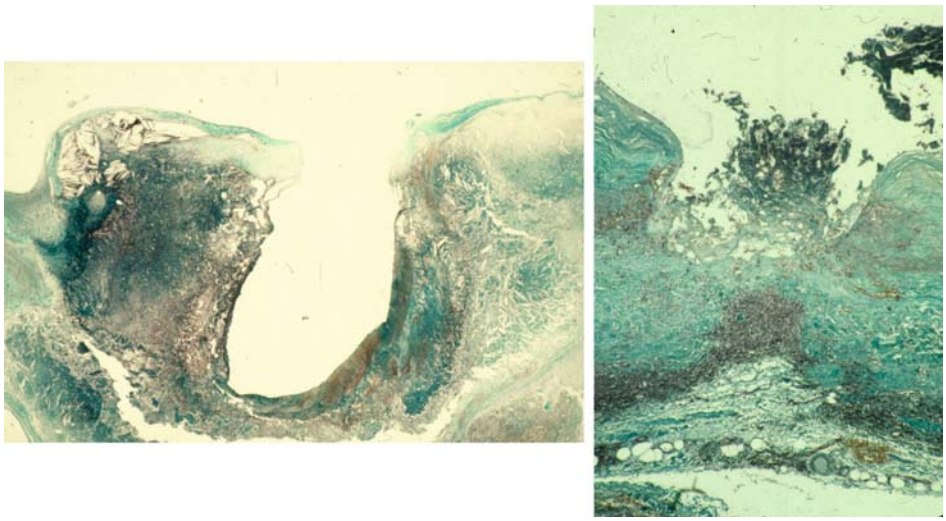

Fig. 27.13. Histological section (Mason's technique) of a penetrating aortic ulcer. Thrombotic material within the ulcerous crater is clearly seen

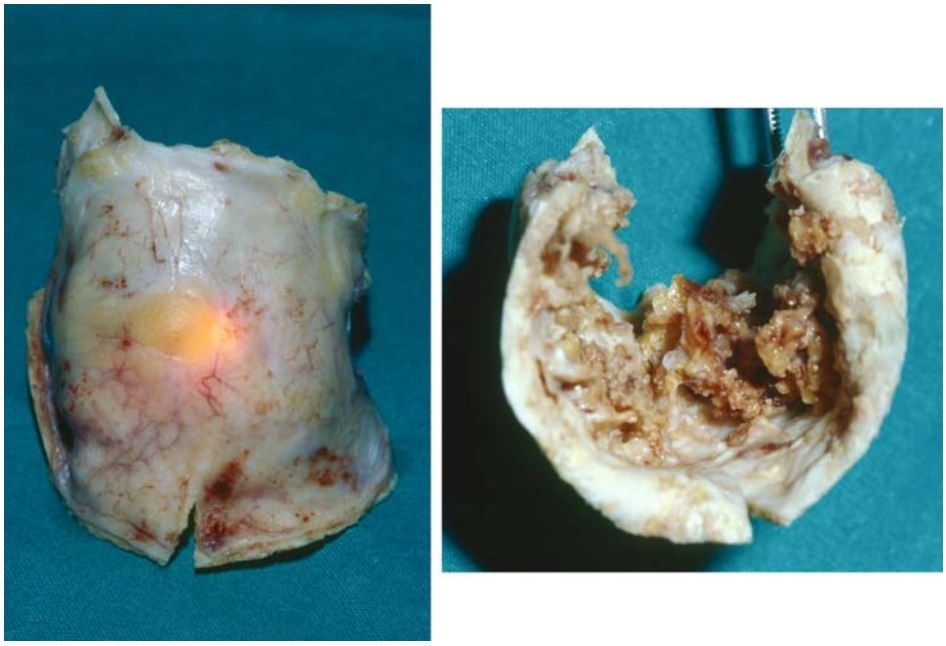

Fig. 27.14. Segment of the ascending aorta of a patient with an aortic ulcer. The external view demonstrates the existence of a central translucent area; the internal view shows the presence of other severe atherosclerotic lesions

ble 27.2). It is usually a type B dissection. In contradistinction to classic aortic dissection, aortic dissection secondary to an aortic ulcer is shorter in extension (localized dissection); PAU are uncommonly associated with extensive propagation of dissection. In spontaneous aortic dissection, the intimomedial tear typically begins in the ascending aorta a few centimeters distal to the aortic valve or in the descending aorta just distal to the origin of the left subclavian artery; here, the intimomedial tear is away from classic entrance tears. In aortic dissections secondary to aortic ulcers, the size of the true lumen is equal to or larger than that of the false lumen (Fig. 27.17), and they have a thicker, calcified and static intimomedial flap [3] (Fig. 27.18). This type of dissection, in an area of gross atherosclerosis, is usually limited by neighboring fibrosis and calcification; for this reason, in many cases it has a retrograde direction [3].

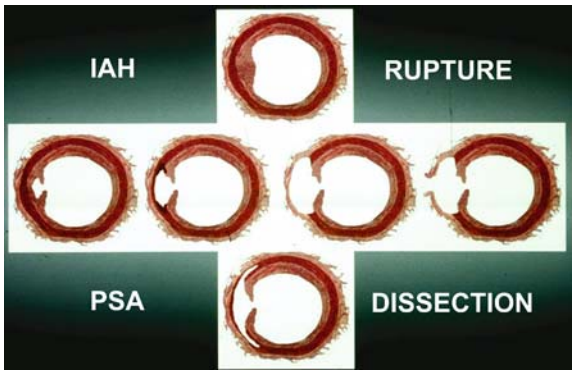

Fig. 27.15. Evolutive patterns of penetrating atherosclerotic aortic ulcers. *PSA* pseudoaneurysm

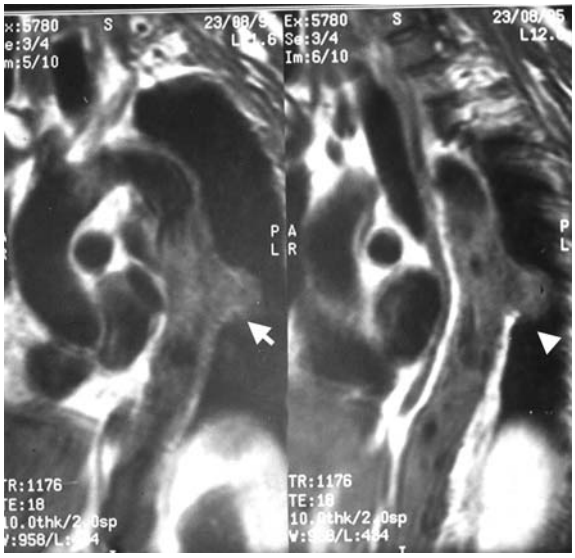

Fig. 27.16. Magnetic resonance study of a patient with an aortic ulcer (*arrow*) in the descending thoracic aorta

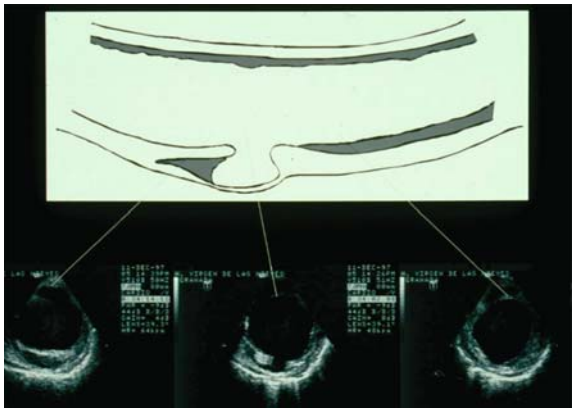

Fig. 27.17. Transesophageal echocardiographic scans of a patient with aortic dissection secondary to a penetrating aortic ulcer. The true lumen is larger than the false lumen. Other signs of aortic atherosclerosis may also be seen

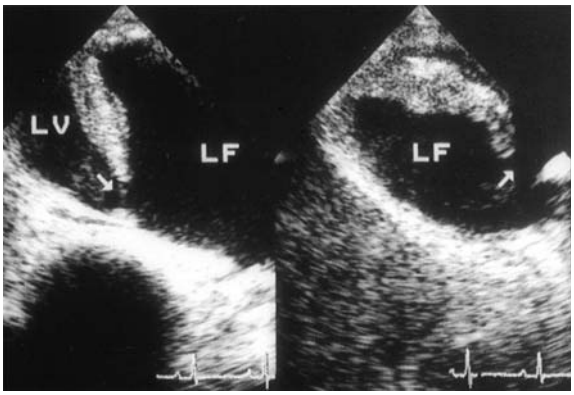

Fig. 27.18. Transesophageal echocardiographic scans of a patient with a limited acute aortic dissection secondary to an aortic ulcer. A thick, calcified, irregular flap can be seen. Longitudinal planes. *Arrow* entrance tear, *LF* false lumen, *LV* true lumen

Table 27.2. Distinctive features of dissections secondary to aortic ulcers

Type B dissection
Localized dissection (short longitudinal extension)
Away from classic entrance tears
Thick, calcified and static intimomedial flap
The true lumen is larger than the false lumen
Retrograde direction

Increased attention to the different aspects of AAS will result in a more accurate diagnosis of acute aortic pathology, better knowledge of the natural history, the recognition of important prognostic predictors and, as a consequence, we will be able to offer the most appropriate treatment to these patients.

References

1. Vilacosta I, San Román JA. Acute aortic syndrome. Heart 2001; 85:365–368.
2. Vilacosta I, San Román JA, Ferreirós J, et al. Natural history and serial morphology of aortic intramural hematoma: a novel variant of aortic dissection. Am Heart J 1997; 134:495–507.
3. Vilacosta I, San Román JA, Aragoncillo P, et al. Penetrating atherosclerotic aortic ulcer: documentation by transesophageal echocardiography. J Am Coll Cardiol 1998; 32:83–89.
4. Krukenberg E. Beiträge zur frage des aneurysma dissecans. Beitr Pathol Anat Allg Pathol 1920; 67:329–351.
5. Mohr-Kahaly S, Erbel R, Kearney P, Puth M, Meyer J. Aortic intramural hemorrhage visualized by transesophageal echocardiography: Findings and prognostic implications. J Am Coll Cardiol 1994; 23:658–664.
6. Wolinsky H, Glagov S. Comparison of abdominal and thoracic aortic medial structure in mammals. Deviation of man from the usual pattern. Circ Res 1969; 25:677–686.

7. Wilens SL, Malcolm JA, Vázquez JM. Experimental infarction (medial necrosis) of the dog's aorta. Am J Pathol 1965; 47:695–710.
8. Clarke JA. An X-ray microscopic study of the vasa vasorum of the normal human ascending aorta. Br Heart J 1965; 27:99–104.
9. Heistad DD, Armstrong ML, Marcus ML. Hyperemia of the aortic wall in atherosclerotic monkeys. Circ Res 1981; 48:669–675.
10. De Castro R, González L, Vilacosta I, et al. Angiogénesis en la disección aórtica. Rev Esp Cardiol 2002; 55(Suppl 2):48.
11. Heistad DD, Armstrong ML. Sick vessel syndrome. Can atherosclerotic arteries recover? Circulation 1994; 89:2447–2450.
12. Vilacosta I, San Román JA, Peral V, et al. Imaging aortic intramural hematoma. Identification of two groups of patients. Circulation 1995; 92(Suppl I):I307.
13. Vilacosta I, Castillo JA, Peral V, Batlle E, Rollán MJ, Sánchez-Harguindey L. Intramural aortic hematoma following intraaortic balloon counterpulsation. Documentation by transesophageal echocardiography. Eur Heart J 1995; 16:2015–2016.
14. Parmley LF, Mattingly TW, Manion WC, Jahnke EJ. Nonpenetrating traumatic injury of the aorta. Circulation 1958; 17:1086–1101.
15. Sheldon WS, Vandervoort PM, Black IW, Grimm RA, Stewart WJ. Aortic intramural hematoma in patients evaluated for aortic dissection: Clinical, echocardiographic, radiographic and pathologic findings. Circulation 1994; 90(Suppl I):I385.
16. Sueyoshi E, Matsuoka Y, Sakamoto I, Uetani M, Hayashi K, Narimatsu M. Fate of intramural hematoma of the aorta: CT evaluation. J Comput Assist Tomogr 1997; 21:931–938.
17. Berdat PA, Carret T. Aortic dissection limited to the ascending aorta mimicking intramural hematoma. Eur J Cardiothorac Surg 1999; 15:108–109.
18. Willens HJ, Kessler KM. Transesophageal echocardiography in the diagnosis of diseases of the thoracic aorta. Part 1. Aortic dissection, aortic intramural hematoma, and penetrating atherosclerotic ulcer of the aorta. Chest 1999; 116:1772–1779.
19. Vilacosta I, Martín de Dios R, González Pinto A. Aortic intramural hematoma during coronary angioplasty: Insights into the pathogenesis of intramedial hemorrhage. J Am Soc Echocardiogr 2000; 13:403–406.
20. Gore I. Pathogenesis of dissecting aneurysm of the aorta. Arch Pathol 1952; 53:142–153.
21. Wilson SK, Hutchins GM. Aortic dissecting aneurysms: Causative factors in 204 subjects. Arch Pathol Lab Med 1982; 106:175–180.
22. Hirst AE Jr, JohnsVJ Jr, Kime SY Jr. Dissecting aneurysm of the aorta: a review of 505 cases. Medicine 1958; 37:217–219.
23. Harris KM, Braverman AC, Gutiérrez FR, Barzilai B, Dávila-Román VG. Transesophageal echocardiographic and clinical features of aortic intramural hematoma. J Thorac Cardiovasc Surg 1997; 114:619–626.
24. Vilacosta I. Síndrome aórtico agudo. Rev Esp Cardiol 2003; 56(Suppl 1):29–39.
25. Song JM, Kang DH, Song JK, et al. Clinical significance of echo-free space detected by transesophageal echocardiography in patients with type B aortic intramural hematoma. Am J Cardiol 2002; 89:548–551.
26. von Kodolitsch Y, Csösz SK, Koschyk DH, et al. Intramural hematoma of the aorta. Predictors of progression to dissection and rupture. Circulation 2003; 107:1158–1163.
27. Nienaber CA, von Kodolitsch Y, Petersen B, et al. Intramural hemorrhage of the thoracic aorta: diagnostic and therapeutic implications. Circulation 1995; 92:1465–1472.
28. Neri E, Capannini G, Garone E, et al. Evolution toward dissection of an intramural hematoma of the ascending aorta. Ann Thorac Surg 1999; 68:1855–1856.
29. Evangelista A, Dominguez R, Sebastia C, et al. Prognostic value of clinical and morphologic findings in short-term evolution of aortic intramural hematoma. Eur Heart J 2004; 25:81–87.
30. Kaji S, Nishigami K, Akasaka T, et al. Prediction of progression or regression of type A aortic intramural hematoma by computed tomography. Circulation 1999; 100:(Suppl II):281–286.
31. Sohn D-W, Jung J-W, Oh B-H, et al. Should ascending aortic intramural hematoma be treated surgically? Am J Cardiol 2001; 87:1024–1026.
32. Kang D-H, Song J-K, Song M-G, et al. Clinical and echocardiographic outcomes of aortic intramural hemorrhage compared with acute aortic dissection. Am J Cardiol 1998; 81:202–206.
33. Song J-K, Kim H-S, Kang D-H, et al. Different clinical features of aortic intramural hematoma versus dissection involving the ascending aorta. J Am Coll Cardiol 2001; 37:1604–1610.
34. Mohr-Kahaly S. Aortic intramural hematoma: from observations to therapeutic strategies. J Am Coll Cardiol 2001; 37:1611–1613.
35. Nienaber C, Sievers H-H. Intramural hematoma in acute aortic syndromes: more than one variant of dissection? Circulation 2002; 106:284–285.
36. Sueyoshi E, Imada T, Sakamoto I, Matsuoka Y, Hayashi K. Analysis of predictive factors for progression of type B aortic intramural hematoma with computed tomography. J Vasc Surg 2002; 35:1179–1183.
37. Moizumi Y, Komatsu T, Motoyoshi N, Tabayashi K. Clinical features and long-term outcome of type A and type B intramural hematoma of the aorta. J Thorac Cardiovasc Surg 2004; 127:421–427.
38. Dake MD. Aortic intramural hematoma: current therapeutic strategy. Heart 2004; 90:375–378.
39. Nienaber CA, Richartz BM, Rehders T, Ince H, Petzsch M. Aortic intramural hematoma: natural history and predictive factors for complications. Heart 2004; 90:372–374.
40. Ganaha F, Miller DC, Sugimoto K, et al. The prognosis of aortic intramural hematoma with and without penetrating atherosclerotic ulcer: a clinical and radiological analysis. Circulation 2002; 106:342–348.
41. Quint LE, Williams DM, Francis IR, et al. Ulcer like lesions of the aorta: imaging features and natural history. Radiology 2000; 218:719–723.
42. Coady MA, Rizzo JA, Hammond GL, Pierce JG, Kopf GS, Elefteriades JA. Penetrating ulcer of the thoracic aorta: What is it? How do we recognize it? How do we manage it? J Vasc Surg 1998; 27:1006–1016.
43. Stanson AW, Kazmier FJ, Hollier LH, et al. Penetrating atherosclerotic ulcers of the thoracic aorta: natural history and clinicopathologic correlations. Ann Vasc Surg 1986; 1:15–23.
44. Harris JA, Bis KG, Glover JL, et al. Penetrating atherosclerotic ulcers of the aorta. J Vasc Surg 1994; 19:90–99.
45. Ando Y, Minami H, Muramoto H, et al. Rupture of thoracic aorta caused by penetrating aortic ulcer. Chest 1994; 106:624–626.
46. Vilacosta I, San Román JA, Aragoncillo P. Atherosclerotic aortic rupture: documentation by transesophageal echocardiography. J Am Soc Echocardiogr 2001; 14:152–154.
47. Tisnado J, Cho S, Beachley MC, et al. Ulcerlike projections: a precursor angiographic sign to thoracic aortic dissection. AJR Am J Roentgenol 1980; 135:719–722.
48. Hayashi H, Matsuoka Y, Sakamoto I, et al. Penetrating atherosclerotic ulcer of the aorta: imaging features and disease concept. Radiographics 2000; 20:995–1005.

49. Yucel EK, Steinberg FL, Egglin TK, et al. Penetrating aortic ulcers: diagnosis with MR imaging. Radiology 1990; 177:779–781.
50. Movsowitz HD, David M, Movsowitz C, et al. Penetrating atherosclerotic aortic ulcers: the role of transesophageal echocardiography in diagnosis and clinical management. Am Heart J 1993; 126:745–747.
51. Atar S, Nagai T, Birnbaum Y, et al. Transesophageal echocardiographic Doppler findings in patients with penetrating aortic ulcers. Am J Cardiol 1999; 83:133–135.

The Current Optimal Imaging Modality for Evaluating Acute Aortic Syndromes

Frederic Thony, Philippe Otal, Louis Boyer

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Contents

28.1 Introduction

Acute aortic syndrome is a new pathological concept [1, 2] that includes several aortic pathologies with a similar clinical profile and evolution. In this syndrome, the acute onset of symptoms denotes a weakness of the aortic wall and consequently, a risk of rupture and other complications. Therefore, diagnostic tools used to investigate these pathologies must be accurate and fast enough for decision-making. The acute aortic syndrome may be related to an aortic ulcer, an intramural hematoma (IMH) or a classic aortic dissection. If the chest X-ray is routinely performed on the admission of patients, its overall sensitivity and specificity is low [3] and the sole interest of this imaging technique is when dealing with a chest pain, to help focus on the thoracic aorta. Thus, the diagnostic approach, the pretherapeutic checkup and the follow-up will be based on transthoracic echocardiography (TTE), transesophageal echocardiography (TEE), multidetector row computed tomography (MD-CT) and MRI. Although angiography was previously considered the standard reference for the diagnosis of aortic diseases, in most cases it has been replaced by noninvasive imaging techniques.

28.2 Imaging of Acute Aortic Dissections

The analysis of the International Registry of Aortic Dissections (IRAD) [4, 5] showed that diagnostic methods currently used for aortic dissection were as follows: CT in 61% of cases, TTE and TEE in 33% of cases, angiography in 4% of cases and MRI in 2% of cases. These figures demonstrate that there is no consensus on the best diagnostic test for aortic dissection and that the choice of the latter depends either on the training of the medico-surgical team in charge of the diagnosis or on the equipment available at a given institution.

But what would be the best diagnostic imaging modality to investigate an aortic dissection? To answer this question we need to define the goals of the diagnosis in acute dissection. Because of the high mortality rate of aortic dissection and the risk involved in aortic surgery, the first aim is to prove the aortic dissection and to classify it as type A or B (Stanford classification) with excellent negative and predictive values. The second aim is diagnostic management as quick as possible in order to reduce the high mortality rate of this pathology during the first hours (1% per hour during the first 48 h [6]). The third aim is an exhaustive evaluation of the aortic dissection. This evaluation includes the extent of the damage to the heart, the localization of entry and reentry sites and the search for blood supply compromise of visceral arteries.

In the literature, the evaluation of the accuracy of the different diagnostic tests varies from one report to another [5, 7–9]. But, because of the rapid evolution of these techniques, none of these evaluations reflect the current performances of imaging modalities. In particular, we do not find in the literature an evaluation of MD-CT in the diagnosis of aortic dissection, yet this new technique has considerably improved the quality of aortic examinations [10–14]: the temporal resolution – less than 500 ms – and cardiac synchronization have dramatically decreased motion artefacts, the spatial resolution is improved and the increase in number of detector rows allows for investigation of the whole aorta in a short examination time. On the other hand, new technical improvements in MRI have increased its reliability and helped to achieve faster examination times [15] and TEE has benefited from multiplanar probes. So far, we can stipulate that the three noninvasive techniques currently used have high and similar accuracy to prove and localize an aortic dissection [5, 16].

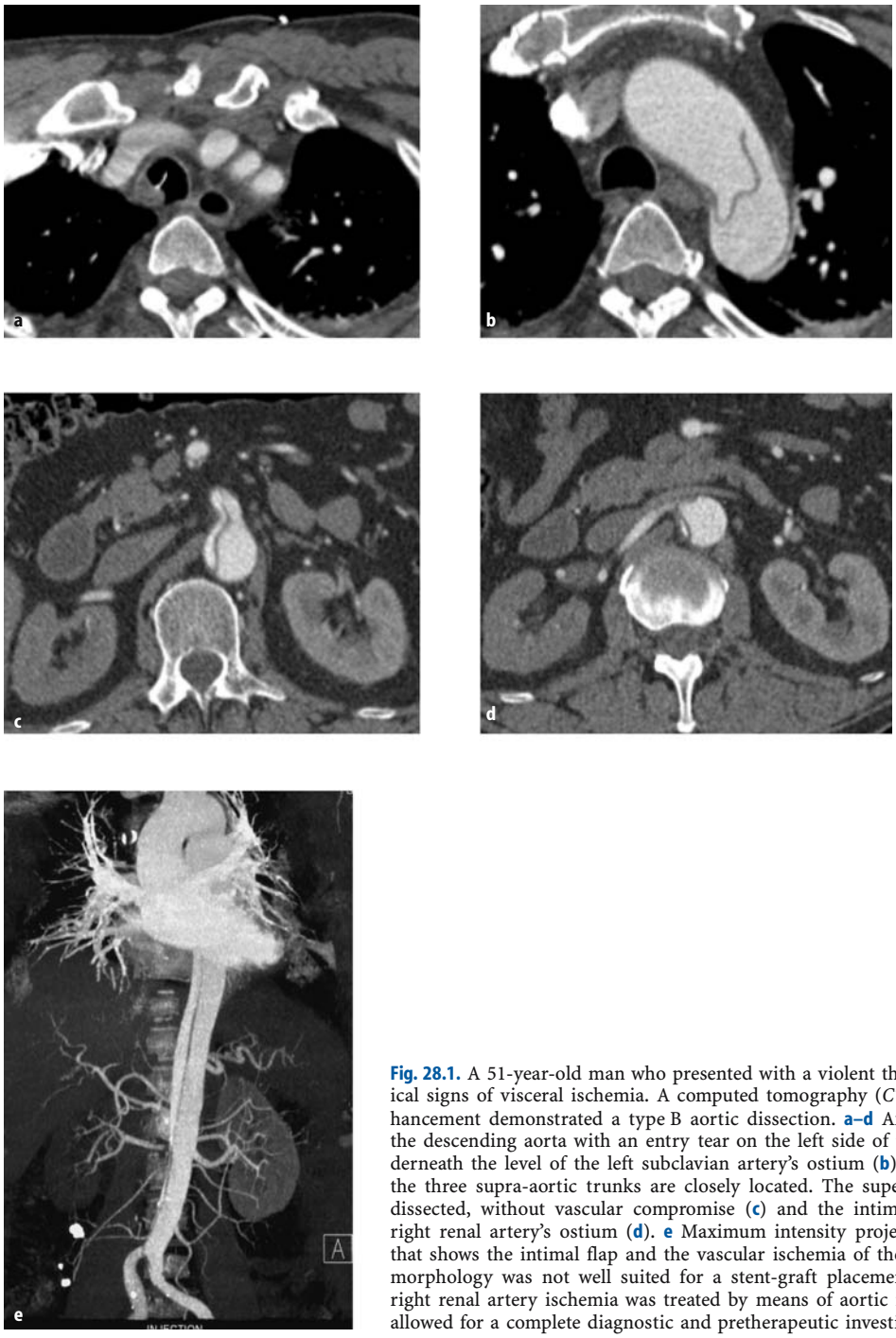

Fig. 28.1. A 51-year-old man who presented with a violent thoracic pain, without clinical signs of visceral ischemia. A computed tomography (*CT*) scan after contrast enhancement demonstrated a type B aortic dissection. **a–d** Axial images: dissection of the descending aorta with an entry tear on the left side of the thoracic arch (**a**), underneath the level of the left subclavian artery's ostium (**b**). Note that the origins of the three supra-aortic trunks are closely located. The superior mesenteric artery is dissected, without vascular compromise (**c**) and the intimal flap is pinned on the right renal artery's ostium (**d**). **e** Maximum intensity projection (*MIP*), frontal view that shows the intimal flap and the vascular ischemia of the right kidney. The aortic morphology was not well suited for a stent-graft placement and thus the dynamic right renal artery ischemia was treated by means of aortic fenestration. The CT scan allowed for a complete diagnostic and pretherapeutic investigation of the disease

In many centers the availability of echocardiography (TTE-TEE) allows a reduction of the time of diagnosis, and is therefore the first and only test performed to indicate surgical treatment [8, 9]. TEE may be performed at the patient's bedside, or more safely in the operative room under general anesthesia to avoid an increase in blood pressure that may favor an aortic rupture [17]. In other centers, MD-CT is preferred in order to better investigate the extension of the aortic dissection [13]. This diagnostic strategy is chosen when percutaneous treatment is planned for patients before surgery in the case of a visceral malperfusion. The aim of this strategy is to reduce the mortality rate of aortic dissection related to visceral ischemia (20% of aortic dissection with a mortality rate of 30–

50% [18]). MRI is less frequently used in emergent situations because of the lack of immediate availability, the limited access to the patient and restricted monitoring of vital signs [19]. In fact, in many medical facilities, the best diagnostic strategy for patients suffering from acute chest pain will depend on the performances of the different imaging machines and their availability, and on the skill level and expertise of the operators as well.

The damage to the heart includes the presence of pericardial fluid, aortic valve regurgitation and coronary artery involvement. Evidence of pericardial fluid (as well as pleural or mediastinal fluid) is a sign of impending rupture that may prompt the surgeon to intervene more quickly. It is well documented with all imaging techniques; however the ability of TEE and TTE to look for mediastinal or pleural suffusion is less than that of CT or MRI. Evaluation of the aortic valve efficiency is only effective with TEE and TTE; MRI can evaluate the aortic valve but with a prohibitive increase of the examination time in a critical situation [9]. The extension of the dissection to the coronary arteries was only well appreciated by coronarography, but because of its drawbacks [20, 21] this technique is no longer carried out [19]. However, in some institutions, stable patients who present with coexisting coronary artery disease are still investigated by coronarography prior to surgery [22]. TEE [23], MRI and CT [24] may in some cases be helpful to analyze the ostia or the first few centimeters of the coronary arteries, but to date, these techniques are not reliable for the investigation of coronary malperfusion in the emergent context of acute aortic dissections. It would be challenging for noninvasive techniques to completely investigate cardiac lesions; yet, this is not instrumental in decision-making because the evaluation of cardiac lesions will be made during surgery.

The best method to evaluate the extension of dissections towards visceral arteries so far is MD-CT (Fig. 28.1) [7, 25]. This technique allows a precise analysis of the intimal flap and the mechanisms of visceral ischemia [26, 27]. Moreover, MD-CT will help to identify the best route and therapeutic strategy for endovascular or surgical treatment of organ malperfusion. Intravascular ultrasound imaging has added information about the collateral involvement [26] but this technique is more invasive. Every aortic type A and B dissection must, as soon as possible, have a radiological evaluation of the extent towards the abdominal aorta and the visceral arteries. The evaluation will be scheduled prior to or soon after surgery, depending on the usual management of patients. This evaluation may also be done with MRI but the spatial resolution of this technique is less than that of MD-CT and therefore MRI should be dedicated to patients with acute or chronic renal insufficiency. However, time-resolved sequences in MRI investigation [15, 28] add a hemodynamic study of flows in the true and false channels of the dissected aorta as well as throughout entry tears that may sometimes be of importance for a comprehensive evaluation of the disease [29].

The search for entry sites may be instrumental in decision-making. In type B dissection, stent-graft occlusion of the entry tear will depend on its location. In type A dissection in a young patient, an entry tear in the second segment of the aorta will prompt the surgeon to use open surgery of the aortic arch with the aim of increasing the rate of false lumen thrombosis distal to the surgical graft. A type A dissection with an entry site in the isthmus of the aorta may benefit, without, during, or after surgical repair of the ascending aorta, from stent-grafting the descending aorta to collapse the false channel [30]. MD-CT has the advantage of a high spatial resolution to detect these intimal lesions [31]. TEE and TTE suffer from the blind zone that limits the evaluation of the ascending aorta near the ostium of the brachiocephalic trunk, but with current multiplanar TEE tranducers this zone is reduced to a small area. TTE, TEE and MRI have a lower spatial resolution but the advantage of a hemodynamic approach of blood circulation ensures a better analysis of flows through intimal tears [29]. In some cases, two or three imaging modalities are needed to look for these entry sites.

28.3 Imaging of Intramural Hematomas

IMH is classically defined as “an aortic wall hematoma without entry tear and intimal flap” [32, 33]. With different imaging techniques, it appears as a regular crescentic or circumferential aortic wall thickening, larger than 7 mm, with central displacement of intimal calcifications, typically hypoechoic on TTE-TEE [33], with a high attenuation value on unenhanced CT during the first week and with a high T1-weighted signal on MRI after the first week.

However, there is no consensus on diagnostic criteria for IMHs. Controversies concern, firstly, the presence of an intimal tear in the pathogenesis of IMHs; some authors consider that finding an intimal tear precludes the diagnosis [34–36], while others consider that some IHMs may be associated with intimal tears [33, 37–39]. Secondly, the frontiers between IHMs and other acute aortic syndromes (IMHs due to an aortic ulcer, Fig. 28.1, and aortic ulcers associated with an IMH [40–42], as well as IMHs with localized signs of circulation in the aortic wall, Fig. 28.2 and thrombosed aortic dissections). Consequently, it seems hazardous to compare different imaging modalities evaluated in separated reports and up until now there has been a lack of comparative studies in the literature.

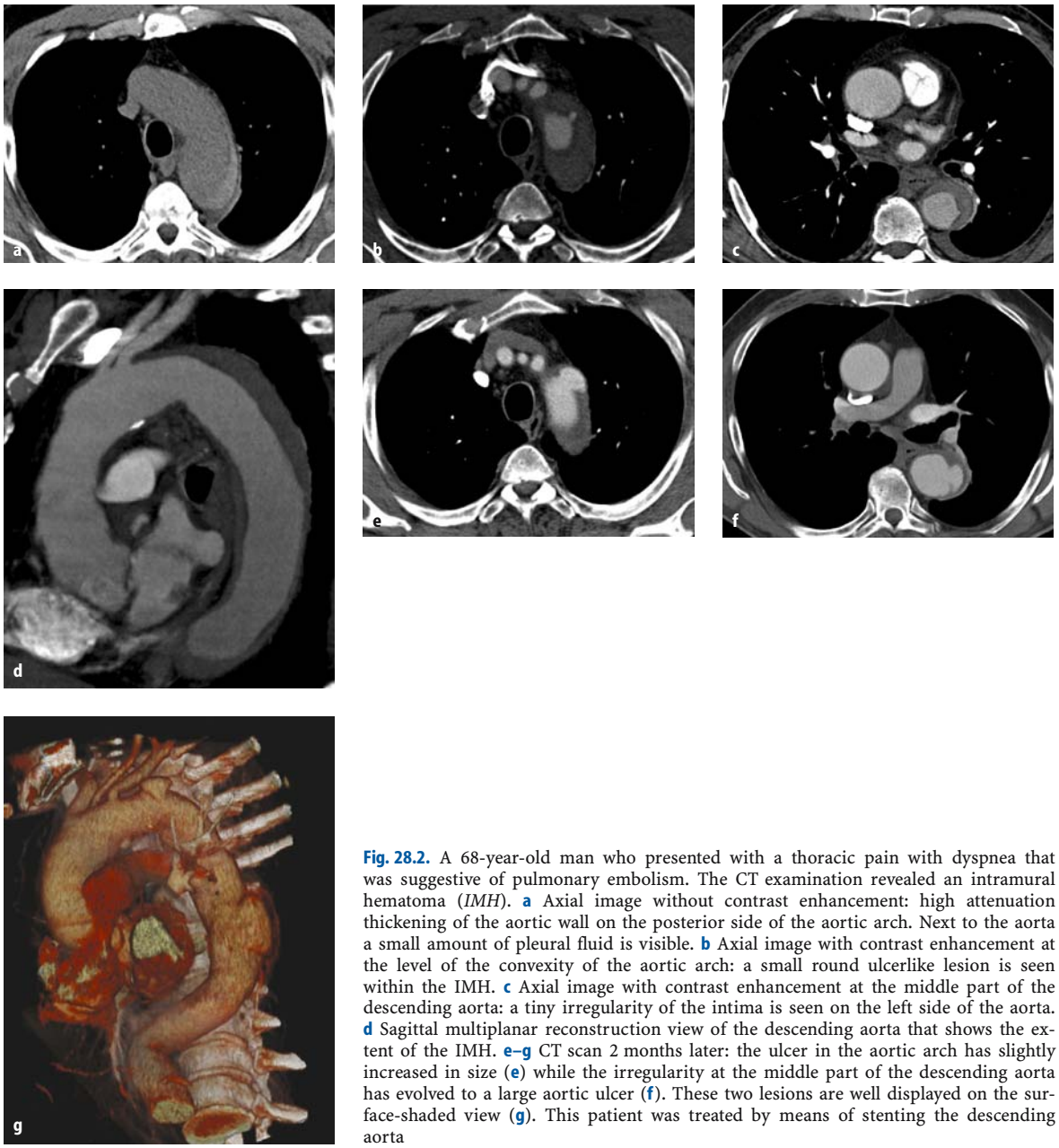

Fig. 28.2. A 68-year-old man who presented with a thoracic pain with dyspnea that was suggestive of pulmonary embolism. The CT examination revealed an intramural hematoma (*IMH*). **a** Axial image without contrast enhancement: high attenuation thickening of the aortic wall on the posterior side of the aortic arch. Next to the aorta a small amount of pleural fluid is visible. **b** Axial image with contrast enhancement at the level of the convexity of the aortic arch: a small round ulcerlike lesion is seen within the IMH. **c** Axial image with contrast enhancement at the middle part of the descending aorta: a tiny irregularity of the intima is seen on the left side of the aorta. **d** Sagittal multiplanar reconstruction view of the descending aorta that shows the extent of the IMH. **e–g** CT scan 2 months later: the ulcer in the aortic arch has slightly increased in size (**e**) while the irregularity at the middle part of the descending aorta has evolved to a large aortic ulcer (**f**). These two lesions are well displayed on the surface-shaded view (**g**). This patient was treated by means of stenting the descending aorta

In a meta-analysis of the literature, Maraj et al. [43] reported that IMHs were diagnosed in 81% of cases with CT and, with TEE, MRI or a combination of the two in the remainder of the cases. This distribution, different to that reported in the RAD for the diagnosis of aortic dissection, probably reflects the better accuracy of CT in detecting this disease. However, the advantage of CT and especially MD-CT for the assessment of IMHs has not been specifically reported.

Many reports described the imaging features of IMHs with echocardiography and emphasized the accuracy of this technique [33, 44]. However, in many cases the hypoechoic appearance of IMHs on TEE-TTE makes it difficult to differentiate IMHs from atheromatous plaques and may account for the poorer accuracy of echography in detecting IMH.

MRI may be used in the acute phase to detect IMHs. They appear with a high signal value on T2-weighted images and low signal intensity on T1-weighted images. The excellent tissue contrast of MRI, especially for blood, makes it a highly accurate method for screening IMHs. However, MRI will overall help to diagnose IMHs in the subacute phase (after 1 week) because of the typical high signal of blood on T1-weighted images [35].

CT is certainly the most efficient diagnostic imaging modality for IMHs (Fig. 28.2) [7, 12]. The high attenuation level of acute bleeding is typical of an IMH and the excellent spatial resolution of this technique allows for detection of subtle hematomas. However, it may be sometimes difficult on a CT scan to prove this diagnosis if the hematoma is very thin, or without a high attenuation value. Furthermore, if only images after contrast enhancement are acquired, the aortic wall thickening may simulate an atheromatous involvement of the aorta. This is the main reason why every aortic examination indicated for an acute aortic syndrome systematically requires images before and after intravenous contrast enhancement.

The management strategy of thoracic pains suggestive of an acute aortic syndrome should systematically include a CT (or MRI) examination in the case of a normal or noncontributory echocardiographic examination. This condition is mandatory for detecting IMHs. It may explain why the incidence rate varies from 10 to 30% in series reported in the literature [37, 44, 45].

IMHs are unstable lesions that may spontaneously heal or evolve to a dissection, an ulcer (Fig. 28.2) or a thoracic rupture [46]. Thus, they have to be carefully monitored by means of two or three CT examinations during the first week, 2 weeks later and then after 1 and 3 months. This follow-up will be assumed with CT and MRI and will continue for years because ulcers and intimal lesions associated with IMHs may evolve to aortic pseudoaneurysms or rupture.

The therapeutic strategy is not consensual. For some authors, type A IMHs are indicated for surgical repair [44, 46–48], while for others [36, 45] medical treatment is justified. Type B IMHs are medically treated but some of them may benefit from a stenting of the aorta [37]. Morphologic examinations have to detect and localize all the intimal lesions because it will be instrumental to plan the stent-graft treatment. If an endovascular treatment is planned, measurements of the aorta and visualization of the aorto-iliac route have to be ruled out. For this thoraco-abdominal aortic investigation, CT and MRI are the appropriate imaging tools.

28.4 Imaging of Aortic Ulcers

Atherosclerotic ulcers represent an unremarkable evolution of atheromatous lesions, frequently seen in the abdominal aorta and iliac arteries, which are usually stable over time and rarely prone to complications. Most aortic ulcers are incidentally discovered and are confined to the inner part of the aortic wall. However, in the thoracic aorta some of them may penetrate deeply into the wall and cause a localized or dissecting IMH (Fig. 28.3), a dissection or an aortic rupture. This specific evolution was first described by Stanson et al. [40], who defined penetrating ulcers as atherosclerotic lesions with an ulceration that penetrates the external elastic lamina. Even though these lesions will not be responsible for an acute aortic syndrome, their natural history may be a pseudoaneurismal evolution or distal embolisms [49–52] and thus they need to be monitored over a long period.

Penetrating ulcers occur in elderly patients with severe atherosclerotic lesions. The role of imaging investigations is to detect the lesion(s), to search for signs of complications (bleeding or dissection) or to estimate the risk for complications (aneurismal evolution, embolisms), to give information on the entire aorta and iliac arteries for therapeutic strategy and to monitor patients regularly thereafter. This implies three-dimensional noninvasive imaging with high spatial resolution.

MD-CT allows for detection of aortic ulcers even if they are small. It is efficient for the evaluation of their penetration and bleeding in or out of the aortic wall. Visualization of calcifications is of importance for grading the penetration of the ulcer through the arterial wall [49, 50]. If stent-grafting is indicated, it will help therapeutic management with sizing and investigation of the aorto-iliac route (diameter of iliac arteries, atheromatous lesion with a risk of embolism, tortuous arteries) [53, 54]. If surgical treatment is indicated, the imaging evaluation will search for other aortic ulcers to determine the length of the aortic segment that will be replaced.

Although MRI is not currently used in acute aortic syndromes, it may be helpful for investigation of aortic ulcers because many of these severely atherosclerotic patients suffer from chronic renal failure and will not be eligible for MD-CT. MRI is accurate for the investigation of aortic ulcers, especially for IMHs complicating aortic ulcers (Fig. 28.3) [55] but does not demonstrate aortic calcifications. Furthermore, some ulcer craters may be missed on spin-echo images because of stagnant blood flow within the ulcer [49]; thus, complementary sequences such as gadolinium-enhanced magnetic resonance angiography must be used [51].

Penetrating aortic ulcers are more difficult to identify with TEE although this examination may be helpful in the evaluation of a hematoma or dissection complicating the aortic ulcers [56]. Besides, there is only one series published in the literature about echocardiography in the diagnosis of penetrating ulcers [56].

28.5 Conclusion

Which imaging modality is more appropriate to investigate acute aortic syndromes depends, for a given pathology, on imaging criteria requested for the diagnosis, information relevant in patient management and on the ability of an imaging modality to provide them.

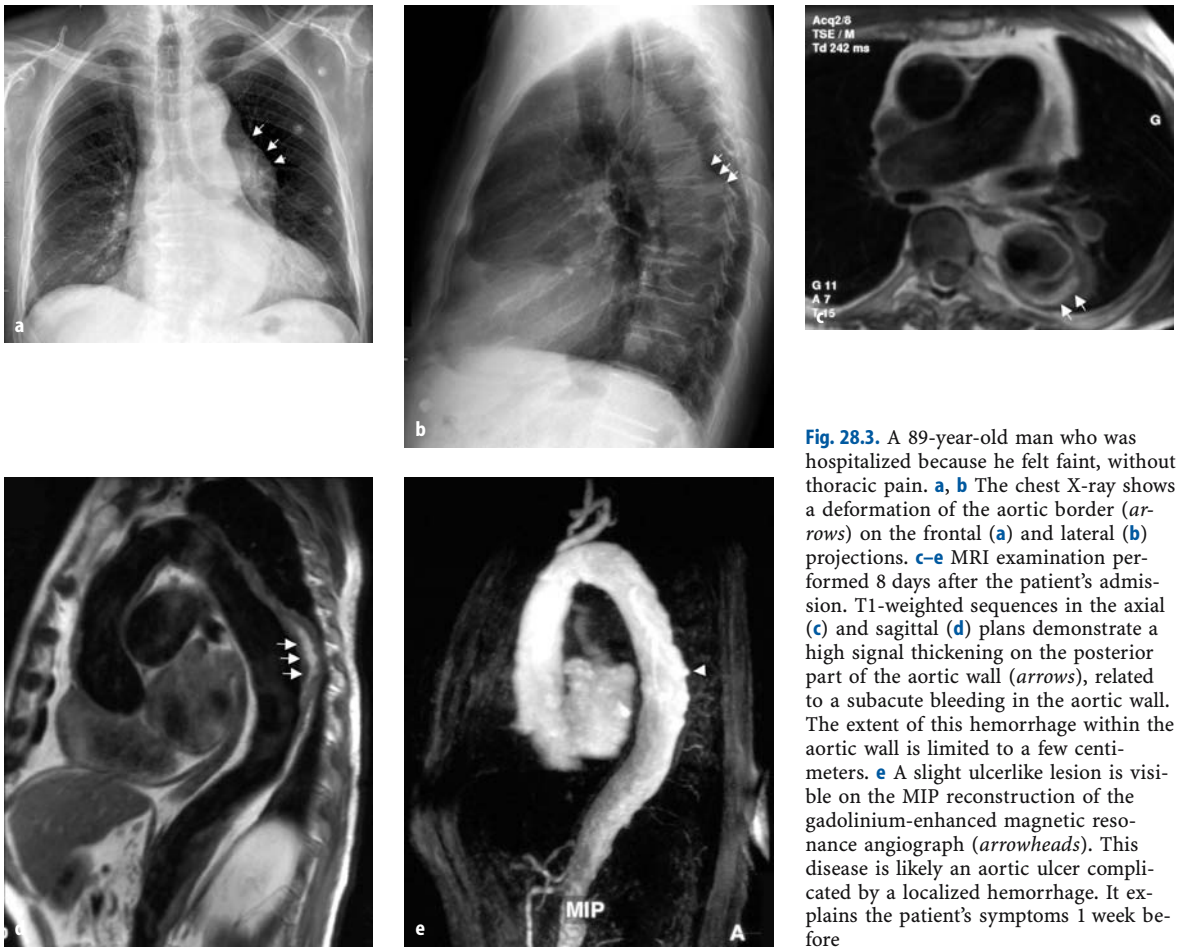

Fig. 28.3. A 89-year-old man who was hospitalized because he felt faint, without thoracic pain. **a**, **b** The chest X-ray shows a deformation of the aortic border (*arrows*) on the frontal (**a**) and lateral (**b**) projections. **c–e** MRI examination performed 8 days after the patient's admission. T1-weighted sequences in the axial (**c**) and sagittal (**d**) plans demonstrate a high signal thickening on the posterior part of the aortic wall (*arrows*), related to a subacute bleeding in the aortic wall. The extent of this hemorrhage within the aortic wall is limited to a few centimeters. **e** A slight ulcerlike lesion is visible on the MIP reconstruction of the gadolinium-enhanced magnetic resonance angiograph (*arrowheads*). This disease is likely an aortic ulcer complicated by a localized hemorrhage. It explains the patient's symptoms 1 week before

Over the past 2 decades technical improvements of imaging modalities have increased exponentially and make it difficult to give at the moment the state of the art of imaging in acute aortic syndromes. Finally, in a medical facility, the best way to investigate acute aortic syndromes will depend on the quality of imaging equipment, the skill and experience of physicians with an imaging technique, and diagnostic and therapeutic strategies elaborated for patient management.

References

1. Vilacosta I, Roman JA. Acute aortic syndrome. Heart 2001; 85:365–368.
2. Van der Loo B, Jenni R. Acute aortic syndrome: proposal for a novel classification. Heart 2003; 89:928.
3. von Kodolitsch Y, Nienaber CA, Dieckmann C, Schwartz AG, Hofmann T, Brekenfeld C, Nicolas V, Berger J, Meinertz T. Chest radiography for the diagnosis of acute aortic syndrome. Am J Med 2004; 116:73–77.
4. Hagan PG, Nienaber CA, Isselbacher EM, Bruckman D, Karavite DJ, Russman PL, Evangelista A, Fattori R, Suzuki T, Oh JK, Moore AG, Malouf JF, Pape LA, Gaca C, Sechtem U, Lenferink S, Deutsch HJ, Diedrichs H, Marcos y Robles J, Llovet A, Gilon D, Das SK, Armstrong WF, Deeb GM, Eagle KA. The International Registry of Acute Aortic Dissection (IRAD): new insights into an old disease. JAMA 2000; 283:897–903.
5. Moore AG, Eagle KA, Bruckman D, Moon BS, Malouf JF, Fattori R, Evangelista A, Isselbacher EM, Suzuki T, Nienaber CA, Gilon D, Oh JK. Choice of computed tomography, transesophageal echocardiography, magnetic resonance imaging, and aortography in acute aortic dissection: International Registry of Acute Aortic Dissection (IRAD). Am J Cardiol 2002; 89:1235–1238.
6. Hirst AE Jr, Johns VJ Jr, Kime SW Jr. Dissecting aneurysm of the aorta: a review of 505 cases. Medicine 1958; 37:217–279.
7. Yoshida S, Akiba H, Tamakawa M, Yama N, Hareyama M, Morishita K, Abe T. Thoracic involvement of type A aortic dissection and intramural hematoma: diagnostic accuracy—comparison of emergency helical CT and surgical findings. Radiology 2003; 228:430–435.
8. Nienaber CA, von Kodolitsch Y, Nicolas V, Siglow V, Piepho A, Brockhoff C, Koschyk DH, Spielmann RP. The diagnosis of thoracic aortic dissection by noninvasive imaging procedures. N Engl J Med 1993; 328:1–9.
9. Cigarroa JE, Isselbacher EM, DeSanctis RW, Eagle KA. Diagnostic imaging in the evaluation of suspected aortic dissection. Old standards and new directions. N Engl J Med 1993; 328:35–43.

10. Sharma U, Ghai S, Paul SB, Gulati MS, Bahl VK, Rajani M, Mukhopadhyay S. Helical CT evaluation of aortic aneurysms and dissection: a pictorial essay. Clin Imaging 2003; 27:273–280.
11. Prokop M. Multislice CT angiography. Eur J Radiol 2000; 36:86–96.
12. Rubin GD. MDCT imaging of the aorta and peripheral vessels. Eur J Radiol 2003; 45:S42–49.
13. Willoteaux S, Lions C, Gaxotte V, Negaiwi Z, Beregi JP. Imaging of aortic dissection by helical computed tomography (CT). Eur Radiol 2004; 14:1999–2008.
14. Hartnell GG. Imaging of aortic aneurysms and dissection: CT and MRI. J Thorac Imaging 2001; 16:35–46.
15. Pereles FS, McCarthy RM, Baskaran V, Carr JC, Kapoor V, Krupinski EA, Finn JP. Thoracic aortic dissection and aneurysm: evaluation with nonenhanced true FISP MR angiography in less than 4 minutes. Radiology 2002; 223:270–274.
16. Sommer T, Fehske W, Holzknecht N, Smekal AV, Keller E, Lutterbey G, Kreft B, Kuhl C, Gieseke J, Abu-Ramadan D, Schild H. Aortic dissection: a comparative study of diagnosis with spiral CT, multiplanar transesophageal echocardiography, and MR imaging. Radiology 1996; 199:347–352.
17. Silvey SV, Stoughton TL, Pearl W, Collazo WA, Belbel RJ. Rupture of the outer partition of aortic dissection during transesophageal echocardiography. Am J Cardiol 1991; 68:286–287.
18. Mehta RH, Bossone E, Evangelista A, O'Gara PT, Smith DE, Cooper JV, Oh JK, Januzzi JL, Hutchison S, Gilon D, Pape LA, Nienaber CA, Isselbacher EM, Eagle KA. International Registry of Acute Aortic Dissection Investigators. Acute type B aortic dissection in elderly patients: clinical features, outcomes, and simple risk stratification rule. Ann Thorac Surg 2004; 77:1622–1628.
19. Khan IA, Nair CK. Clinical, diagnostic, and management perspectives of aortic dissection. Chest 2002; 122:311–328.
20. Rizzo RJ, Aranki SF, Aklog L, Couper GS, Adams DH, Collins JJ Jr, Kinchla NM, Allred EN, Cohn LH. Rapid noninvasive diagnosis and surgical repair of acute ascending aortic dissection. Improved survival with less angiography. J Thorac Cardiovasc Surg 1994; 108:567–574.
21. Kern MJ, Serota H, Callicoat P, Deligonul U, Lee WH, Aguirre F, Lew B, Barner H, Willman V. Use of coronary arteriography in the preoperative management of patients undergoing urgent repair of the thoracic aorta. Am Heart J 1990; 119:143–148.
22. Miller JS, Lemaire SA, Coselli JS. Evaluating aortic dissection: when is coronary angiography indicated? Heart 2000; 83:615–616.
23. Nienaber CA, Eagle KA. Aortic dissection: new frontiers in diagnosis and management: part I: from etiology to diagnostic strategies. Circulation 2003; 108:628–635.
24. Fallenberg M, Juergens KU, Wichter T, Scheld HH, Fischbach R. Coronary artery aneurysm and type-A aortic dissection demonstrated by retrospectively ECG-gated multislice spiral CT. Eur Radiol 2002; 12:201–204.
25 Vernhet H, Serfaty JM, Serhal M, McFadden E, Bonnefoy E, Adeleine P, Revel D, Douek P. Abdominal CT angiography before surgery as a predictor of postoperative death in acute aortic dissection. AJR Am J Roentgenol 2004; 182:875–879.
26. Williams DM, Lee DY, Hamilton BH, Marx MV, Narasimham DL, Kazanjian SN, Prince MR, Andrews JC, Cho KJ, Deeb GM. The dissected aorta: part III. Anatomy and radiologic diagnosis of branch-vessel compromise. Radiology 1997; 203:37–44.
27. Gaxotte V, Cocheteux B, Haulon S, Vincentelli A, Lions C, Koussa M, Willoteaux S, Asseman P, Prat A, Beregi JP. Relationship of intimal flap position to endovascular treatment of malperfusion syndromes in aortic dissection. J Endovasc Ther 2003; 10:719–727.
28. Markl M, Draney MT, Hope MD, Levin JM, Chan FP, Alley MT, Pelc NJ, Herfkens RJ. Time-resolved 3-dimensional velocity mapping in the thoracic aorta: visualization of 3-directional blood flow patterns in healthy volunteers and patients. J Comput Assist Tomogr 2004; 28:459–468.
29. Nitatori T, Yokoyama K, Hachiya J, Yoshino A, Yamakami N, Katase S, Ichikawa T. Fast dynamic MRI of aortic dissection: flow assessment by subsecondal imaging. Radiat Med 1999; 17:9–14.
30. Dake MD, Kato N, Mitchell RS, Semba CP, Razavi MK, Shimono T, Hirano T, Takeda K, Yada I, Miller DC. Endovascular stent-graft placement for the treatment of acute aortic dissection. N Engl J Med. 1999; 340:1546–1552.
31. Quint LE, Platt JF, Sonnad SS, Deeb GM, Williams DM. Aortic intimal tears: detection with spiral computed tomography. J Endovasc Ther 2003; 10:505–510.
32. Yamada T, Tada S, Harada J. Aortic dissection without intimal rupture: diagnosis with MR imaging and CT. Radiology 1988; 168:347–352.
33. Mohr-Kahaly S, Erbel R, Kearney P, Puth M, Meyer J. Aortic intramural hemorrhage visualized by transesophageal echocardiography: findings and prognostic implications. J Am Coll Cardiol 1994; 23:658–664.
34. Sueyoshi E, Matsuoka Y, Imada T, Okimoto T, Sakamoto I, Hayashi K. New development of an ulcerlike projection in aortic intramural hematoma: CT evaluation. Radiology 2002; 224:536–541.
35. Murray JG, Manisali M, Flamm SD, et al. Intramural hematoma of the thoracic aorta: MR image findings and their prognostic implications. Radiology 1997; 204:349–355.
36. Kaji S, Nishigami K, Akasaka T, et al. Prediction of progression or regression of type A aortic intramural hematoma by computed tomography. Circulation 1999; 00:II281–286.
37. Ganaha F, Miller DC, Sugimoto K, et al. Prognosis of aortic intramural hematoma with and without penetrating atherosclerotic ulcer: a clinical and radiological analysis. Circulation 2002; 106:342–348.
38. Cambria RP. Regarding "Analysis of predictive factors for progression of type B aortic intramural hematoma with computed tomography". J Vasc Surg 2002; 35:1295–1296.
39. Muluk SC, Kaufman JA, Torchiana DF, Gertler JP, Cambria RP. Diagnosis and treatment of thoracic aortic intramural hematoma. J Vasc Surg 1996; 24:1022–1029.
40. Stanson AW, Kazmier FJ, Hollier LH, et al. Penetrating atherosclerotic ulcers of the thoracic aorta: natural history and clinicopathologic correlations. Ann Vasc Surg 1986; 1:15–23.
41. Hayashi H, Matsuoka Y, Sakamoto I, Sueyoshi E, Okimoto T, Hayashi K, Matsunaga N. Penetrating atherosclerotic ulcer of the aorta: imaging features and disease concept. Radiographics 2000; 20:995–1005.
42. Rubinowitz AN, Krinsky GA, Lee VS. Intramural hematoma of the ascending aorta secondary to descending thoracic aortic penetrating ulcer: findings in two patients. J Comput Assist Tomogr 2002; 26:613–616.
43. Maraj R, Rerkpattanapipat P, Jacobs LE, Makornwattana P, Kotler MN. Meta-analysis of 143 reported cases of aortic intramural hematoma. Am J Cardiol 2000; 86:664–668.
44. Nienaber CA, von Kodolitsch Y, Petersen B, et al. Intramural hemorrhage of the thoracic aorta. Diagnostic and therapeutic implications. Circulation 1995; 92:1465–1472.
45. Song JK, Kim HS, Kang DH, et al. Different clinical features of aortic intramural hematoma versus dissection involving the ascending aorta. J Am Coll Cardiol 2001; 37:1604–1610.
46. von Kodolitsch Y, Csosz SK, Koschyk DH, Schalwat I, Loose R, Karck M, Dieckmann C, Fattori R, Haverich A, Berger J, Meinertz T, Nienaber CA. Intramural hematoma of the aorta: predictors of progression to dissection and rupture. Circulation 2003; 107:1158–1163.

47. Kurimoto Y, Morishita K, Kawaharada N, Fukada J, Asai Y, Abe T. Initial management of acute type-a aortic dissection with a thrombosed false lumen: a retrospective cohort study. Surg Today 2004; 34:652–657.
48. Robbins RC, McManus RP, Mitchell RS, et al. Management of patients with intramural hematoma of the thoracic aorta. Circulation 1993; 88:1–10.
49. Harris JA, Bis KG, Glover JL, Bendick PJ, Shetty A, Brown OW. Penetrating atherosclerotic ulcers of the aorta. J Vasc Surg 1994; 19:90–98.
50. Kazerooni EA, Bree RL, Williams DM. Penetrating atherosclerotic ulcers of the descending thoracic aorta: evaluation with CT and distinction from aortic dissection. Radiology 1992; 183:759–765.
51. Levy JR, Heiken JP, Gutierrez FR. Imaging of penetrating atherosclerotic ulcers of the aorta. AJR Am J Roentgenol 1999; 73:151–154.
52. Tittle SL, Lynch RJ, Cole PE, Singh HS, Rizzo JA, Kopf GS, Elefteriades JA. Midterm follow-up of penetrating ulcer and intramural hematoma of the aorta. J Thorac Cardiovasc Surg 2002; 123:1051–1059.
53. Kos X, Bouchard L, Otal P, Chabbert V, Chemla P, Soula P, Meites G, Joffre F, Rousseau H. Stent-graft treatment of penetrating thoracic aortic ulcers. J Endovasc Ther 2002; 9:II25–31.
54. Schoder M, Grabenwoger M, Holzenbein T, Domanovits H, Fleischmann D, Wolf F, Cejna M, Lammer J. Endovascular stent-graft repair of complicated penetrating atherosclerotic ulcers of the descending thoracic aorta. J Vasc Surg 2002; 36:720–726.
55. Yucel EK, Steinberg FL, Egglin TK, Geller SC, Waltman AC, Athanasoulis CA. Penetrating aortic ulcers: diagnosis with MR imaging. Radiology 1990; 177:779–781.
56. Vilacosta I, San Roman JA, Aragoncillo P, Ferreiros J, Mendez R, Graupner C, Batlle E, Serrano J, Pinto A, Oyonarte JM. Penetrating atherosclerotic aortic ulcer: documentation by transesophageal echocardiography. J Am Coll Cardiol 1998; 32:83–89

Management of Aortic Hematomas and Ulcers: Evaluation Scoring

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Contents

29.1 Introduction

The management of intramural hematomas (IMH) and atherosclerotic penetrating ulcers (APU) of the aorta relies, as that of aortic dissections, on the localization of the lesion according to the Stanford classification, type A being located on the ascending aorta, and treated surgically, type B on the descending aorta, and treated medically. Recent publications [1–4] have suggested that medical therapy could be successfully applied to type A IMH in high-surgical-risk patients. Besides, advances in endovascular techniques allow a more aggressive approach of complicated type B. These new management trends make necessary a score to predict low-risk type A and high-risk type B.

After a literature review of therapeutic modalities and risk factors, we propose an evolutivity risk score and a decisional algorithm for IMH and APU management.

29.2 Therapeutic Principles

29.2.1 Medical Treatment

Medical treatment is based on the control of systolic blood pressure to decrease the chance of rupture. At the acute phase (first 2 weeks) it is mandatory to administrate a beta blocker via an intravenous route. The patient is to be monitored in an intensive care unit, with continuous measurement of systolic blood pressure, with an arterial line if needed. If the blood pressure is difficult to control, a calcium channel antagonist, or a nitrate, can be used. Systolic blood pressure must be lower than 120 mmHg, and bursts are to be avoided by a strict rest in bed.

Analgesia must control pain. Morphine can be given if required by the intensity of the pain, but persisting or aggravating pain must lead to the search for a potential evolution by repeating computed tomography (CT) scanner control.

A pericardial effusion at the initial stage mandates an ultrasound control twice a week, and particular clinical attention with respect to the risk of tamponade.

After the acute phase, oral administration of antihypertensive drugs can be initiated. Systolic blood pressure control remains the key aim of the medical management.

29.2.2 Surgical Treatment

Surgical treatment is based on the currently validated techniques of replacement of the pathologic segment. The basic principle is to realize prostheto-aortic sutures in areas of normal wall, sometimes reinforced by a Teflon banding according to the fragility of the aortic wall. The sealing of the suture can be completed by the use of biological glues (cf. previous chapters).

Because of an older age, and a greater frequency of comorbidities [5], the surgical risk is higher in patients with IMH or APU than that of patients with aortic dissection.

The open repair requires local excision and graft interposition. This is a major undertaking in a population of patients with a high incidence of comorbidity, with a high risk of complications including paraplegia and cerebrovascular accident. Thus, the desire to prevent spontaneous complications of the disease's course by open surgery must be cautiously considered with respect to the patient status, and the patient and his or her family duly informed. In this respect, endovascular techniques afford an encouraging alternative to treat intimal lesions of the descending aorta [6].

29.2.3 Endovascular Treatment

Today, endovascular treatment is mainly available for the descending aorta. It relies on stent-grafts. Their main use is to provide protection from the risk of rupture in the case of an intimal lesion. The landing zone must include a sufficient proximal and distal area of normal aortic wall. It seems preferable to use completely covered stent-grafts, without bare stents or hooks. Given the intima fragility, it seems unwise to use a modeling balloon to complete the stent-graft deployment.

Up to now, systematic use of stent-grafts in IMH without an intimal lesion has not been validated. Only randomized studies could justify such a therapeutic strategy.

This technique requires a careful imaging protocol in order to better select the feasibility of the endovascular access (quality of the iliac arteries), and the diameter and length of the stent-graft [7–9]. The main branches must be precisely located with respect to the lesion, specially the subclavian and left carotid proximally, and the celiac and superior mesenteric distally.

This technique should be offered to elderly patients at high surgical risk for conventional surgical repair. Ideal anatomic targets are localized lesions with normal-sized, minimally angulated, cylindrical proximal and distal landing zones of adequate length. Adequate vascular access in terms of arterial size and lack of excessive tortuosity and occlusive disease is also critical for a safe and successful stent-graft deployment [10].

Complications (namely paraplegias) are less frequent than with conventional surgical repair.

29.3 Evolutive Risk Factors

The assessment of evolutive risk factors will determine the therapeutic strategy. The evolution must be assessed with repeated imaging controls, principally a CT scanner. Screening at the end of the first week, 1 and 6 months, 1 year and yearly thereafter until complete normal restitution seems a reasonable and safe protocol. An intermediate control can be necessary in the case of modifications. At the chronic phase, MRI can be proposed as an alternative. The choice of the imaging modality depends on the local equipment and expertise.

29.3.1 Clinical Risk Factors

29.3.1.1 Difficulties in Blood Pressure Control

This is a pejorative factor which, without justifying an interventional attitude in itself, leads to a more aggressive management, especially in the presence of an intimal lesion.

29.3.1.2 Persistent or Recurrent Pain

Thoracic pain difficult to control is a significant risk factor in all the studies. It represents a syndrome of menace of rupture if it is associated with an increase of pericardial or pleural effusions [5].

29.3.2 Anatomo-radiologic Risk Factors

29.3.2.1 Site

The site of the IMH or APU defines the type, A or B. Type A and proximal type B have a worse outcome than distal type B [5, 11–13].

29.3.2.2 Aorta Diameter

It is commonly accepted that the cutoff diameters for surgery of aneurisms (ascending 50–55 mm, descending 60–70 mm) can be applied to IMH and APU.

29.3.2.3 Hematoma Thickness

A thickness greater than 7 mm defines the hematoma. A thickness greater than 10–12 mm is a factor of a bad outcome [11]. In the study by Song et al. [1] it is the only independent predictor for adverse outcomes (death, aortic surgery, and overt aortic dissection) in type A IMH, with an 11-mm cutoff value.

29.3.2.4 Intimal Lesion

By definition there is always an intimal lesion in the APU. In IMH, intimal lesions most often represent ostial disruptions (mainly of intercostal arteries) called "ulcerlike projections." They are more frequent on the descending aorta than on the ascending aorta. Their onset during the course of the disease is a predictor of worse outcome [4]. Different thresholds of size and

depth have been proposed. In the study by Ganaha et al. [5], the cutoff was a diameter of 20 mm and a depth of 10 mm.

The presence of an intimal tear can foretell the evolution towards overt dissection [5]; thus, it must be searched for with great care [14, 15], the smallest ones necessitating close scrutiny for detection. Careful follow-up of the evolution must always be done.

29.3.2.5 Effusions

Pleural or pericardial effusions can witness transudation of the IMH or a hemothorax. In the absence of characteristic thrombus hyperdensity on the CT scanner image, it is difficult to distinguish serous or hemorrhagic nature without pleural puncture. More than their existence in itself, their increase is a predictor of rupture [5, 6].

29.4 Management Strategy

IMH usually appear on aortas with little atheroma lesions, oppositely to APU. So, evolution towards a frank dissection is frequent in the case of IMH, by media splitting, whereas in the case of UPA, fibrous changes of the aortic wall due to atheroma limit the extension of the dissecting process. Evolution towards localized dissection can be completely silent [1, 2].

Association of persistent or recurrent pain, evolving serous or hemorrhagic effusion, and dynamic instability constitute a syndrome of menace of rupture. APU carry a high risk or rupture, whereas in the case of IMH, without an intimal lesion, the healing process is not infrequent. So, to us, the strategy in the acute phase will essentially rely on the existence or not of an intimal lesion, and rupture risk factors. This justifies a close imaging follow-up, systematic in the case of an asymptomatic patient, and in case of clinical change in the case of a symptomatic patient.

At the chronic phase, in both cases, patient follow-up must aim at looking for aneurism evolution, generally fusiform in the case of IMH without an intimal lesion, sacciform in other cases.

29.4.1 Type A

Surgery remains the only treatment option for hemodynamically unstable patients with type A lesions.

Medical treatment of type A IMH without an intimal tear, bed rest with antihypertensive treatment to minimize the risk of evolution towards frank dissection, can only be conceived in the case of important comorbidity and in the absence of menace of rupture. Supportive medical treatment with frequent follow-up imaging studies and timed surgical repair in cases with complications must remain the rule [1–3].

Aggressive management is recommended for APU, and suspicion for rupture must be maintained during the acute phase. Type A APU should be treated surgically.

29.4.2 Type B

Medical management is recommended for type B APU [16]. Stent-grafts permit a higher degree of protection against rupture than medical therapy alone. Because APU affect older persons, one must consider the patient's age, overall physical condition, and anticipated life expectancy in the decision to use operative treatment. If patients tolerate medical management without clinical deterioration, they may continue conservative follow-up care with reasonable safety [10]. This medical treatment is permissible in high-surgical-risk patients, when a close clinical and imaging follow-up is possible, in uncomplicated forms, and when the aorta diameter is smaller than 50 mm.

29.4.3 Gravity Score

On the basis of the analysis of literature, the authors suggest a gravity score based on two clinical items and four radiological items to compose a gravity score. Each item is weighted by its severity in terms of prediction of risk.

Clinical items	
Persistent or recurrent thoracic pain in spite of best medical treatment	2
Increasing effusion	1
Radiological items	
Type A	2
Intimal tear	1
Increase of aorta diameter	1
Increase of IMU thickness or APU depth	1

The lowest score is 0 and the maximum score is 8. If the score is more than or equal to 3, prediction of rupture is high and treatment (type A surgical, type B endovascular) is indicated. If the score is below 3, the risk is low. Medical treatment is the rule in type B. It can be applied to type A (i.e., good control of pain and blood pressure, without radiological evolution despite repeated CT scanner controls).

29.4.4 Decision Algorithm

In view of recent publications [6, 17, 18], the authors suggest the following:

Type A	Intimal lesion	Surgery
Type A	No intimal lesion; no comorbidity; risk score less than 3	Medical treatment
Type B	Intimal lesion; risk score 3 or more	Stent-graft
Type B	No intimal tear; risk score less than 3	Medical treatment

29.5 Conclusion

Whom to treat?

The key is whether there is an intimal tear [16]. Studies have demonstrated that IMH without an intimal tear evolve in the short term and can be reabsorbed or progress to classic dissection or aortic rupture.

Long-term follow-up is mandatory to detect aneurismal evolution, even in the absence of an intimal lesion, because of the aortic wall stress [16].

Most studies describing IMH have used very small study populations; thus, owing to the paucity of clinical experience with IMH, the optimal therapy for this condition is still largely undefined.

These are provisional recommendations regarding the treatment of penetrating ulcers. As more knowledge is acquired, better understanding of this disease could lead to a more accurate definition of risk factors.

References

1. Song JM, Kim HS, Song JK, Kang DH, Hong MK, Kim JJ, Park SW, Park SJ, Lim, TH, Song MG. Usefulness of the initial non invasive imaging study to predict the adverse outcomes in the medical treatment of acute type A aortic intramural hematoma. Circulation 2003; 108(Suppl 1): II324–328.
2. Song JK, Kim HS, Kang DH, Lim TH, Song MG, Park SW, Park SJ. Different clinical features of aortic intramural hematoma versus dissection involving the ascending aorta. J Am Coll Cardiol 2001; 37:1604–1610.
3. Song JK, Kim HS, Song JM, Kang DH, Ha JW, Rim SJ, Chung N, Kim KS, Park SW, Kim YJ, Sohn DW. Outcomes of medically treated patients with aortic intramural hematoma. Am J Med 2002; 113:181–187.
4. Kaji S, Akasaka T, Katayama M, Yamamuro A, Yamabe K, Tamita K, Akiyama M, Watanabe N, Tanemoto K, Morioka S, Yoshida K. Long-term prognosis of patients with type B aortic intramural hematoma. Circulation 2003; 108(Suppl 1):II307–311.
5. Ganaha F, Miller DC, Sugimoto K, et al. Prognosis of aortic intramural hematoma with and without penetrating atherosclerotic ulcer: a clinical and radiological analysis. Circulation 2002; 106:342–348.
6. Troxler M, Mavor AI, Homer-Vanniasinkam S. Penetrating atherosclerotic ulcers of the aorta. Br J Surg 2001; 88:1169–1177.
7. Sailer J, Peloschek P, Rand T, Grabenwoger M, Thurnher S, Lammer J. Endovascular treatment of aortic type B dissection and penetrating ulcer using commercially available stent-grafts. AJR Am J Roentgenol 2001; 177:1365–1369.
8. Cambria RP, Brewster DC, Lauterbach SR, Kaufman JL, Geller S, Fan CM, Greenfield A, Hilgenberg A, Clouse WD. Evolving experience with thoracic aortic stent graft repair. J Vasc Surg 2002; 35:1129–1136.
9. Schoder M, Grabenwoger M, Holzenbein T, Domanovits H, Fleischmann D, Wolf F, Cejna M, Lammer J. Endovascular stent-graft repair of complicated penetrating atherosclerotic ulcers of the descending thoracic aorta. J Vasc Surg 2002; 36:720–726.
10. Demers P, Miller DC, Mitchell RS, Kee ST, Chagonjian L, Dake MD. Stent-graft repair of penetrating atherosclerotic ulcers in the descending thoracic aorta: mid-term results. Ann Thorac Surg 2004; 77:81–86.
11. Moizumi Y, Komatsu T, Motoyoshi N, Tabayashi K. Clinical features and long-term outcome of type A and type B intramural hematoma of the aorta. J Thorac Cardiovasc Surg 2004; 127:421–427.
12. Evangelista A, Dominguez R, Sebastia C, Salas A, Permanyer-Miralda G, Avegliano G, Gomez-Bosh Z, Gonzalez-Alujas T, Garcia del Castillo H, Soler-Soler J. Prognostic value of clinical and morphologic findings in short-term evolution of aortic intramural haematoma. Therapeutic implications. Eur Heart J 2004; 25:81–87.
13. von Kodolitsch Y, Csosz SK, Koschyk DH, Schalwat I, Loose R, Karck M, Dieckmann C, Fattori R, Haverich A, Berger J, Meinertz T, Nienaber CA. Intramural hematoma of the aorta: predictors of progression to dissection and rupture. Circulation 2003; 107:1158–1163.
14. Quint LE, Platt JF, Sonnad SS, Deeb GM, Williams DM. Aortic intimal tears: detection with spiral computed tomography. J Endovasc Ther 2003; 10:505–510.
15. Macura KJ, Corl FM, Fishman EK, Bluemke DA. Pathogenesis in acute aortic syndromes: aortic dissection, intramural hematoma, and penetrating atherosclerotic aortic ulcer. AJR Am J Roentgenol 2003; 181:309–316.
16. Tittle SL, Lynch RJ, Cole PE, Singh HS, Rizzo JA, Kopf GS, Elefteriades JA. Midterm follow-up of penetrating ulcer and intramural hematoma of the aorta. J Thorac Cardiovasc Surg 2002; 123:1051–1059.
17. Maraj R, Rerkpattanapipat P, Jacobs LE, Makornwattana P, Kotler MN. Meta-analysis of 143 reported cases of aortic intramural hematoma. Am J Cardiol 2000; 86:664–668.
18. Motoyoshi N, Moizumi Y, Komatsu T, Tabayashi K. Intramural hematoma and dissection involving ascending aorta: the clinical features and prognosis. Eur J Cardiothorac Surg 2003; 24:237–242; discussion 242.

Endograft Management of Aortic Hematomas and Ulcers

David M. Williams, Bora Peynircioglu

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Contents

30.1 Introduction

In evaluating a symptomatic patient with intramural hematoma (IMH) of the thoracic aorta, the clinician is occasionally presented with difficult and unanswerable questions such as these: Is an intimal defect present or not? Does it have a bearing on the hematoma? If a definite defect is present, is it an intimal tear related to an incipient classic dissection, or is it a penetrating ulcer? How do these distinctions help us decide proper patient management? That these distinctions do matter has been established by the Stanford group, who found that IMH in symptomatic patients was significantly more often associated with disease progression when accompanied by penetrating ulcer than when not [4].

IMH or intramural hemorrhage of the thoracic aorta is a condition representing localized hemorrhage within the aortic media. When the term is used strictly, no intimal defect such as a tear or an ulcer is present. In practice, the term is loosely used to mean a mostly thrombosed false lumen regardless of intimal defect. Furthermore, it may be difficult by imaging means to completely exclude an intimal defect. When the intimal defect is identified, it may be difficult to classify it. The literature reflects these difficulties by a commonly encountered vagueness or even inconsistency in the description of how the diagnosis of strict IMH was confirmed, or an intimal defect excluded, or an atherosclerotic etiology verified.

In clinical practice, several authors have noted that patients with IMH share a clinical profile and prognosis with patients with a classic dissection affecting the same aortic territory [6, 7, 11]. Most aortic dissections have intimal tears in classic locations near the sinotubular ridge in the ascending aorta or just beyond the attachment of the ligamentum arteriosum in the descending aorta [8]. Whether patients with IMH would, if not treated medically, progress to full-blown dissection complete with the classic spectrum of "entry" tears has not been established.

The penetrating atherosclerotic ulcer of the thoracic aorta was described in classic papers by Stanson et al. [9] and Cooke et al. [1] nearly 20 years ago. Numerous authors have contributed to the literature on ulcers since that time, bearing on the presentation, natural history, and treatment of this troublesome lesion. Nevertheless, uncertainty in the pathophysiology of the ulceration, nonspecific features of the lesion at aortography and computerized tomography (CT) examination, and frequent appeal to imaging (most of which is unavailable to reviewer and reader alike) rather than histological proof of disease all contribute to day-to-day practical uncertainties in identifying and treating the penetrating ulcer.

30.2 Pathological Description

The distinguishing pathological feature of this lesion is a localized "ulceration," a gaping communication between the lumen and the medial layer of the aorta, which can result in external rupture or intramural hemorrhage. When intramural hemorrhage accompanies the ulcer, it lies within the aortic media and therefore comprises an aortic dissection. Two surgical specimens of ulcers were depicted in the Mayo papers: a longitudi-

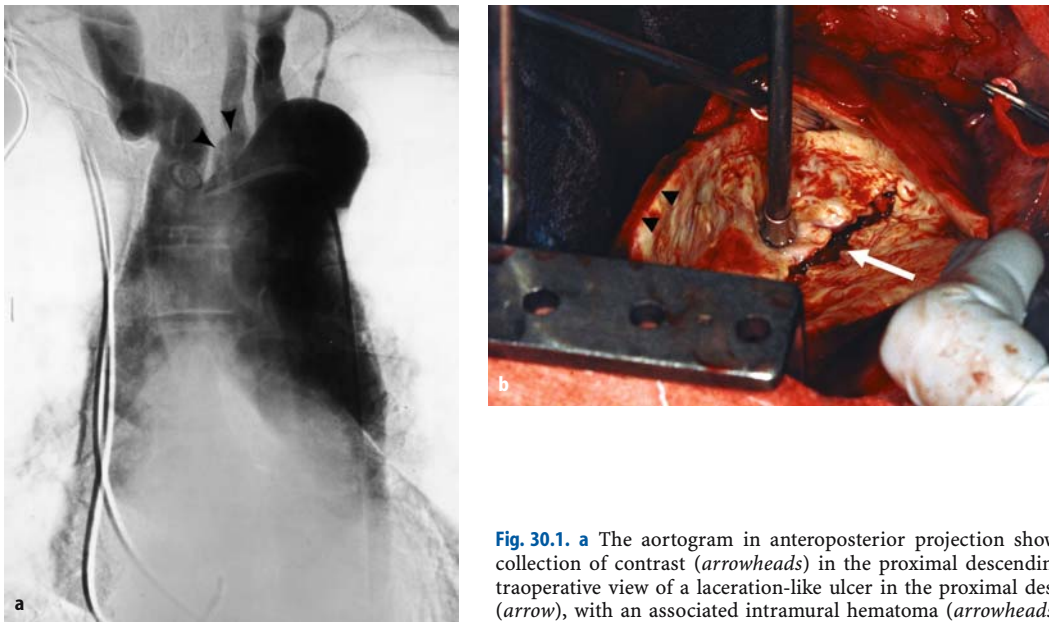

Fig. 30.1. a The aortogram in anteroposterior projection shows a lobulated collection of contrast (*arrowheads*) in the proximal descending aorta. **b** Intraoperative view of a laceration-like ulcer in the proximal descending aorta (*arrow*), with an associated intramural hematoma (*arrowheads*)

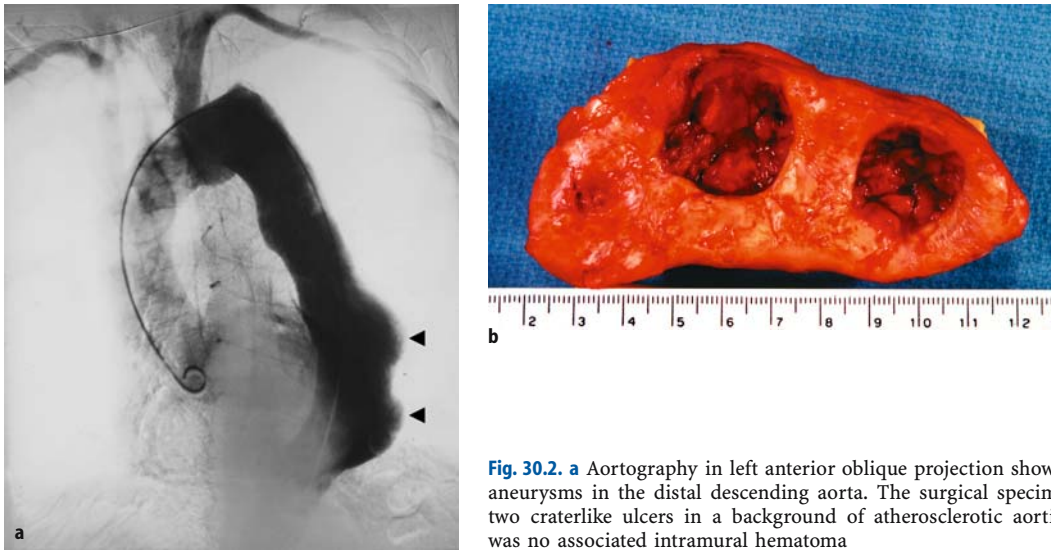

Fig. 30.2. a Aortography in left anterior oblique projection shows two tandem aneurysms in the distal descending aorta. The surgical specimen (**b**) shows two craterlike ulcers in a background of atherosclerotic aortic wall. There was no associated intramural hematoma

nally-oriented laceration-like defect from the mid descending thoracic aorta and a craterlike saccular aneurysm from the proximal descending aorta. In our own experience, the laceration-like ulcers are frequently accompanied by intramural hemorrhage (Fig. 30.1), whereas the craterlike lesions are not (Fig. 30.2). To our knowledge, no systematic survey of the histopathological features of intimal defects has been carried out, and so at the present time this gross anatomical distinction does not have a histological or imaging correlate.

30.3 Imaging Features

The imaging appearance of ulcers varies. Originally described in relation to its angiographic appearance, the ulcer seen in profile (Fig. 30.3) resembles the gastric ulcer as seen on classic barium studies: an outpouching of the aortic lumen with thick, overhanging edges. On CT, MRI, or transesophageal echocardiography, the ulcer appears as a nipplelike projection of the aortic lumen communicating with an intramural cavity. When intramural hemorrhage accompanies the ulcer, the aortic wall is thickened. On cross-sectional studies, the

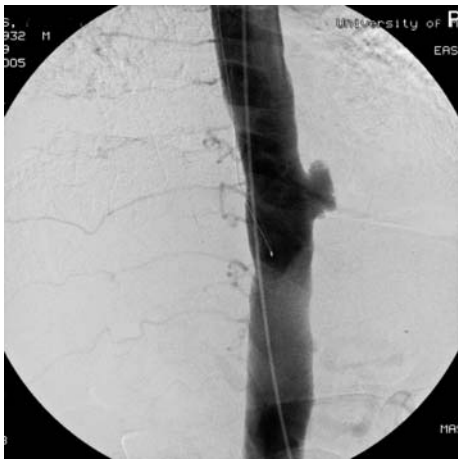

Fig. 30.3. Thoracic aortography in right anterior oblique projection shows the classic appearance of a penetrating ulcer in the mid descending aorta. Five centimeters above the lesion, the total aortic diameter was 37 mm, and the partially collapsed true lumen diameters were 27×28 mm

fresh hemorrhage in this thickened wall has a distinctive appearance. Although penetrating ulcers tend to involve the distal descending aorta preferentially, they have been described in the proximal descending and even ascending as well as abdominal aorta.

Two other lesions may be confused with the penetrating ulcer. One is the bland intimal tear associated with aortic dissection in which the false lumen is thrombosed (Fig. 30.4). In practice, it can be difficult to distinguish, on the basis of a CT scan, between an ulcer with IMH and a bland tear with IMH. Extensive calcifications in the aortic wall or localized (versus extensive) dissection may favor ulcer over bland tear, but it is uncertain whether this imaging distinction reflects a difference of etiology or of varying local response to the same intramural hemorrhage. Although the distinction between ulcer and bland tear may seem academic, since both are intimal defects communicating with the media after all, it is possible that the freely dissecting aorta may respond differently to an endograft than the relatively dissection-resistant atherosclerotic aorta.

The second lesion to be distinguished from the ulcer is a branch artery pseudoaneurysm (Fig. 30.5). This lesion can rival the penetrating ulcer in size of the blood-filled cavity and extent of IMH, but is distinguished by a lack of a gaping communication with the aortic lumen. Occasionally a vessel may be seen exiting the cavity, especially on current-generation CT scans.

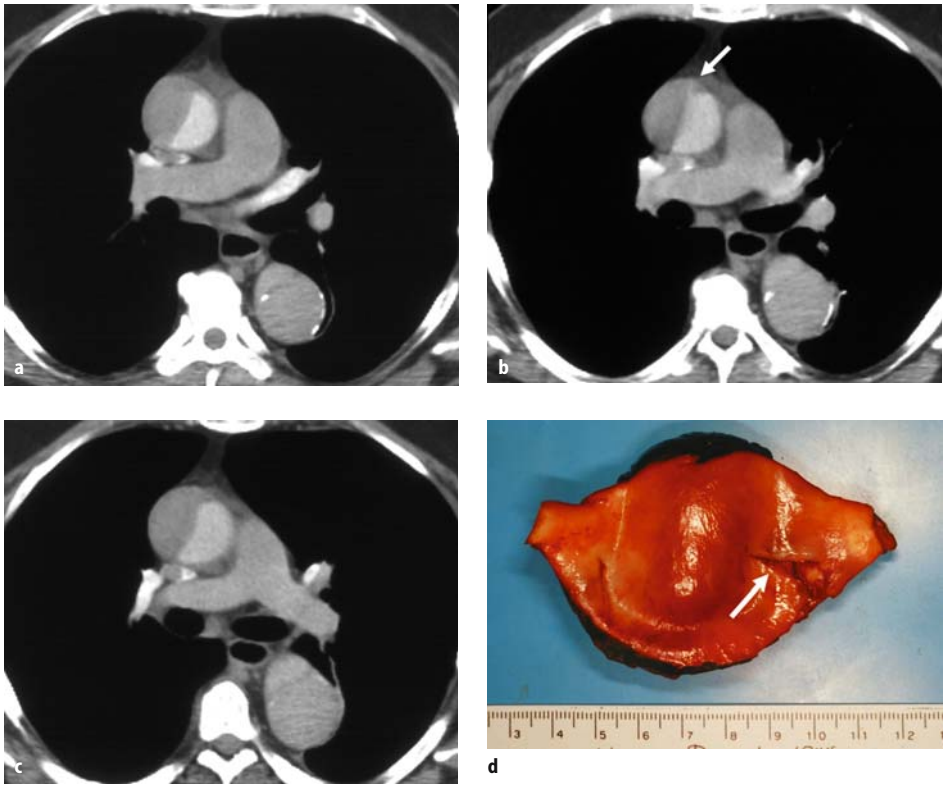

Fig. 30.4. a–c Contiguous computerized tomography (*CT*) sections in a patient with a known chronic type B dissection who presented with an acute type A intramural hematoma. A small break in the intimal contour (**b**, *arrow*) allows contrast pooling in a localized collection in the otherwise thrombosed false lumen. The surgical specimen contains a bland intimal tear (**d**, *arrow*)

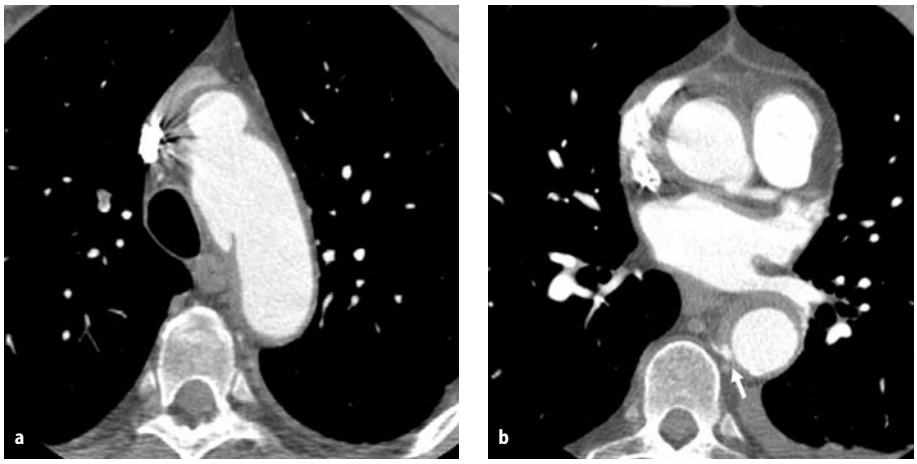

Fig. 30.5. An 80-year-old man presented with back pain. Chest CT showed a penetrating ulcer in the aortic arch (**a**) with gaping communication between the ulcer cavity and the aortic lumen. Lower in the chest, (**b**) a second collection of contrast fills a branch artery pseudoaneurysm, from which an intercostal artery originates (*arrow*)

The pseudoaneurysm results as a complication of IMH, and is created as the propagating hematoma shears off the origin of a branch artery from the aorta. As the vessel origin on the intimal flap separates from the trunk of the branch artery on the outer wall of the aorta, blood may continue to flow from the aortic lumen, through a small cavity in the false lumen, out the trunk. The cavity, which contains flowing blood in an otherwise thrombosed aortic false lumen, constitutes the branch artery pseudoaneurysm. Because no intimal defect is present in the aorta at the site of the pseudoaneurysm, many of these will respond to medical management of the IMH and heal without formation of an aortic aneurysm. However, occasionally these lesions can be symptomatic, may amplify the hemodynamic forces of IMH, and can require treatment.

30.4 Principles of Treatment

The goals of treatment are to eliminate or reduce symptoms, prevent aortic rupture, prevent progression to full-blown classic dissection, substitute elective for emergent surgery, and reduce the complexity of unavoidable aortic surgery. The first priority in all these patients, especially those who are symptomatic, is aggressive medical treatment with beta-blockers and antihypertensives, as soon as the diagnosis of IMH has been established. The application of endografts to IMH and ulcers will be discussed with respect to three overlapping groups of patients: intimal defect without IMH, intimal defect with IMH, and IMH without an intimal defect.

30.5 Intimal Defect Without IMH

These are localized lesions and involve a limited segment of the aorta. They are often an incidental finding. By imaging criteria, they are indistinguishable from saccular aneurysms of the aorta; indeed, some have suggested that most saccular aneurysms of the thoracic aorta originate from penetrating ulcers [5]. As such, these lesions are the most suitable of the three groups for treatment by endografts, since by treating a limited segment of the aorta the interventionalist can easily exclude them from the circulation.

30.6 Intimal Defect with IMH

The intimal defect in this lesion again presents a target lesion for endovascular treatment. As noted earlier, it may be difficult in practice to classify a given defect as a penetrating ulcer or a bland entry tear. Two considerations affect the length of the aorta neighboring the intimal defect which is targeted for treatment. Evidence of atheromatous wall should favor more extensive treatment of the aorta with longer endografts, since radiographic imaging is relatively insensitive to shallow ulcerated atheromas, and the ulcer typically arises in a bed of atheromatous intima. Longer treatment provides a safety margin against undertreating the intimal defect. The second consideration is the extent of associated IMH. The self-expanding endograft creates torsion on the aortic intima at the ends of the device, and may tear through the intimal surface into underlying thrombosed false lumen (Fig. 30.6). We have incomplete data at the present time to blame device-related intimal tears on stiff early-generation devices, or on friable inti-

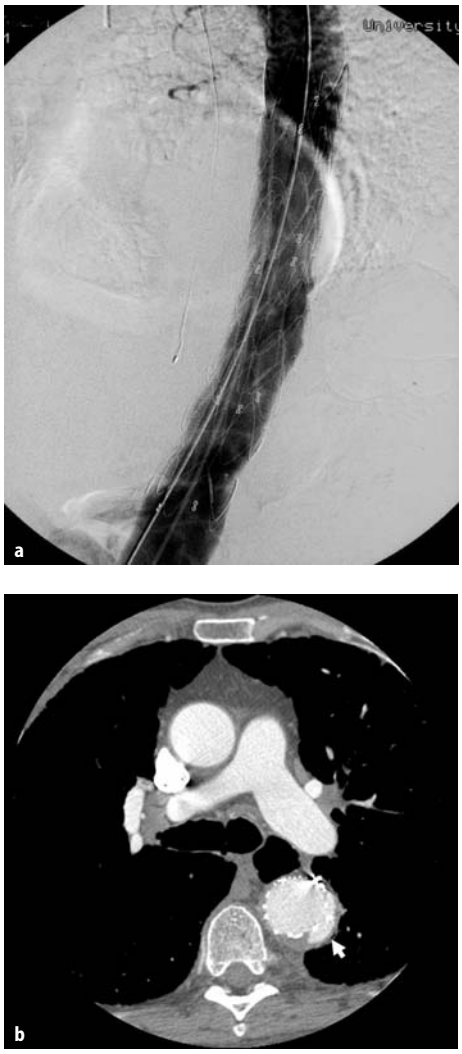

Fig. 30.6. The same patient as in Fig. 30.3. Endovascular treatment of the ulcer (**a**) consisted of implantation of two endografts, the upper measuring 38 mm and the lower measuring 42 mm. The endografts were not ballooned after implantation. At 6 weeks follow-up (**b**), a focal dissection has developed at the upper margin of the endograft, related to the bare wires (*arrow*). Total aortic diameter at the level of the tear was 44 mm, and the patient was asymptomatic

mal surfaces and soft and yielding unorganized thrombus in the acute phase When possible, therefore, it is preferable to anchor the endograft in nondissected wall above and below the intimal defect.

30.7 IMH Without Intimal Defect

As noted earlier, some authors recommend treating IMH as aortic dissection in the corresponding aortic territory. Others recommend aggressive treatment regardless of location or aortic diameter [10]. However,

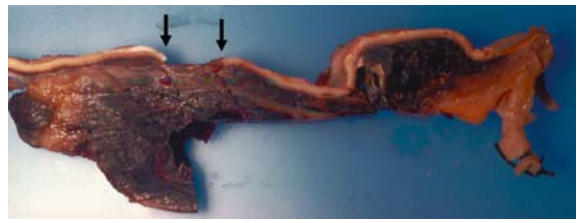

Fig. 30.7. Cross section shows a laceration-like penetrating ulcer with separation of the intima (*arrows*). Thrombus has filled the ulcer cavity flush with the aortic lumen. At CT, this defect was not visible (not shown)

small patient series, incomplete anatomical description of case material, and lack of explicit anatomical or clinical guidelines indicating open aortic repair make it difficult to generalize from the literature. The absence of an intimal defect in pure IMH presents a diagnostic as well as a treatment challenge. Intimal tears can be extremely subtle, depending on the size of the intimal tear and the amount of intramedial thrombus, which can sometimes fill the cavity flush with the aortic lumen (Fig. 30.7). The tear may be remote in the aorta (Fig. 30.8). IMH in a normal-caliber aorta without an intimal tear precludes limited treatment of a target lesion and, if the patient remains symptomatic despite aggressive medical treatment with antihypertensives and beta-blockers, presents the interventionalist with a difficult dilemma. How should this aorta be treated? There are no data supporting prophylactic implantation of endografts covering the entire descending aorta (proximally so as to exclude small bland tears of dissection, distally so as to exclude small penetrating ulcers), yet in unusual circumstances one may be driven to propose such treatment. IMH in an aneurysmal aorta presents a particularly urgent problem, since this complication may be a precursor to aneurysm rupture. Again, the literature gives us no compelling guidelines for treatment. To our knowledge, there are no reports of describing the presence of IMH associated with leaking thoracic aneurysms in a large group of patients, and none describing the natural history of IMH accompanying aortic aneurysms.

30.8 Treatment Results

Most reports of endograft treatment of penetrating ulcers consist of single case reports or small-series patients embedded in large series of mixed thoracic aortic disease, from which it is difficult to elicit general principles of patient selection and anatomical features predictive of treatment failure. The Stanford group has published the results of endograft treatment of its first 26 patients with penetrating ulcers with or without intramural hemorrhage [3]. Treatment was between 1993

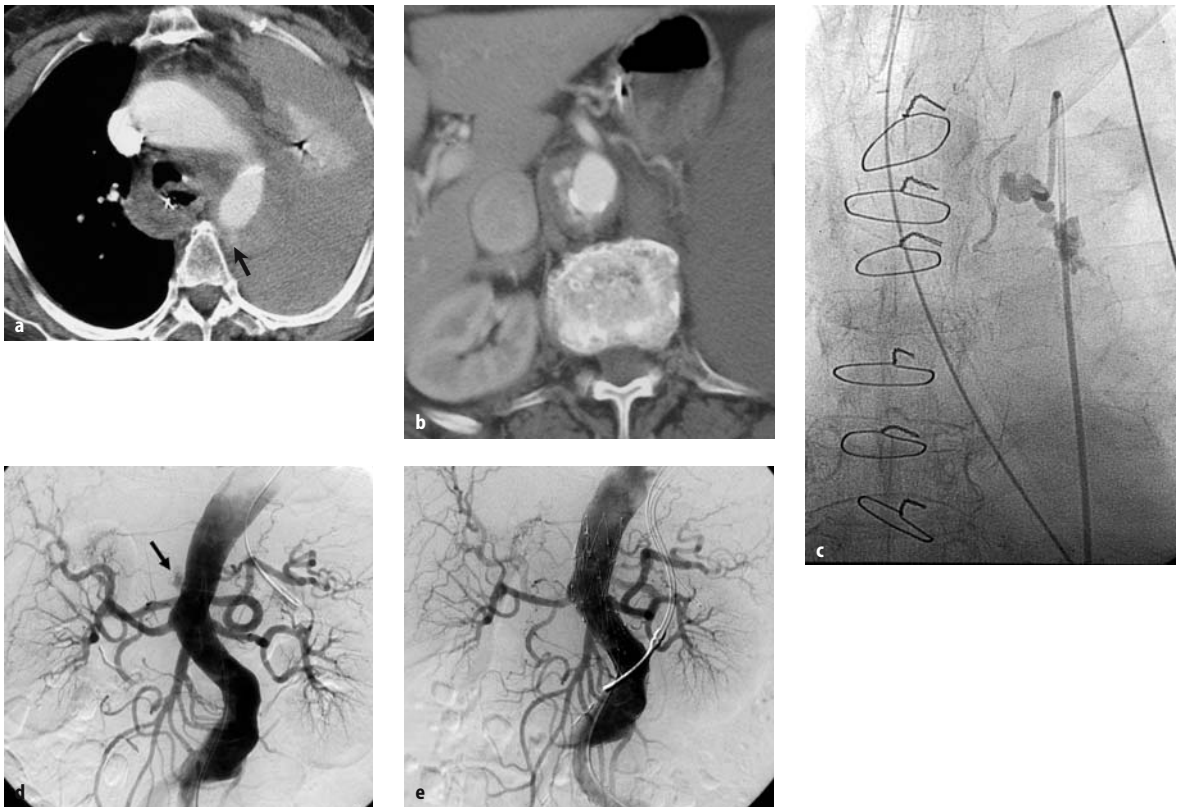

Fig. 30.8. a CT of the chest shows the left hemothorax with ill-defined collection of contrast within the false lumen of the upper thoracic aorta (arrow). **b** CT at the level of the superior mesenteric artery origin shows extravasation of contrast posterior and to the right. The origin of an intercostal artery was cannulated (**c**) and injected in the proximal descending aorta, demonstrating that the ill-defined collection in **a** was an intercostal artery pseudoaneurysm. The right hemothorax was judged to be secondary to the abdominal aortic ulcer with retrograde in tramural hematoma. A tubular endograft was modified by removing graft material for half the circumference along its length, and was then implanted across the ulcer. Aortography before implantation (**d**) shows contrast extravasation, which was successfully excluded by the endograft, as documented on the follow-up study (**e**). The patient's symptoms resolved and did not recur. She died 16 months later owing to myocardial infarction

and 2000 with first- and second-generation devices. Treatment failure was a composite which included early death, any aortic-related death, any sudden unexplained late death unless autopsy excluded aortic death, endoleak at any time after the implantation procedure, stent-graft mechanical defect, and reintervention. At 1, 3, and 5 years, the respective actuarial survival estimates were 85 ± 8, 76 ± 8, and 70 ± 10%, and freedom from all-cause treatment failure were 81 ± 8, 71 ± 9, and 65 ± 10%. Independent predictors of death included previous cerebrovascular accident and female gender, and independent predictors of treatment failure were larger maximum aortic diameter and female gender. An occasional complication noted in these patients, which was not emphasized by the Stanford group, is focal dissection, extension of dissection, or aneurysm formation at the margin of the endograft [2]. Whether this is a hazard of endografts with bare wire proximally or a feature of the disease process awaits further experience with newer-generation devices.

30.9 Conclusion

Limited aortic lesions such as penetrating atherosclerotic ulcers and IHMs with associated intimal defects present ideal lesions for treatment by endografts. Numerous case reports and small series confirm their short-term safety and efficacy in treating symptomatic disease. Proving long-term efficacy will require further improvement of devices and careful matching of endograft treatment with extent and etiology of disease.

References

1. Cooke JP, Kazmier FJ, et al. (1988) The penetrating aortic ulcer: pathologic manifestations, diagnosis, and management. Mayo Clin Proc 63:718–725.
2. Czermak BV, Waldenberger P, et al. (2002) Placement of endovascular stent-grafts for emergency treatment of

acute disease of the descending thoracic aorta. Am J Roentgenol 179:337–345.
3. Demers P, Miller DC, et al. (2004). Stent-graft repair of penetrating atherosclerotic ulcers in the descending thoracic aorta: mid-term results. Ann Thorac Surg 77:81–86.
4. Ganaha F, Miller DC, et al. (2002) Prognosis of aortic intramural hematoma with and without penetrating atherosclerotic ulcer. A clinical and radiological analysis. Circulation 106:342–348.
5. Harris JA, Bis KG, et al. (1994) Penetrating atherosclerotic ulcers of the aorta. J Vasc Surg 19:90–99.
6. Muluk SC, Kaufman JA, et al. (1996) Diagnosis and treatment of thoracic aortic intramural hematoma. J Vasc Surg 24:1022–1029.
7. Nienaber CA, von Kodolitsch Y, et al. (1995) Intramural hemorrhage of the thoracic aorta. Diagnostic and therapeutic implications. Circulation 92:1465–1472.
8. Roberts WC (1981) Aortic dissection: anatomy, consequences, and causes. Am Heart J 101:195–214.
9. Stanson AW, Kazmier FJ, et al. (1986) Penetrating atherosclerotic ulcers of the thoracic aorta: Natural history and clinicopathologic correlations. Ann Vasc Surg 1:15–23.
10. Tittle SL, Lynch RJ, et al. (2002) Midterm follow-up of penetrating ulcer and intramural hematoma of the aorta. J Thorac Cardiovasc Surg 123:1051–1059.
11. v Kodolitsch Y, Spielmann RP, et al. (1995) Intramural hemorrhage as a precursor of aortic dissection (in German). Z Kardiol 84:939–946.

Traumatic Aortic Rupture

Rosella Fattori, Davide Pacini

31

Contents

31.1 Introduction

Traumatic aortic rupture (TAR) is a lesion involving the aortic wall from the intima to the adventitia, occurring as a result of blunt trauma.

The first annotation of TAR was in 1557 by Vesalius, who described a patient with an aortic rupture after a fall from a horse. In 1923 Dshanelidze in Russia reported the first successful repair of TAR in a penetrating lesion of the ascending aorta, followed in the 1950s by the surgical reports of Gerbode et al., Klassen et al., and Passaro and Pace [1]. In the same period Loren Parmley, a pathologist in the US Armed Forces, performed an historic analysis on 296 cases of TAR at autopsy [2]. This study, which is up to now the widest pathological series, clearly defined the characteristics of the aortic lesion and emphasized the time relationships between the trauma and subsequent death, underlining the high lethality of untreated lesions. The era of high-speed motor vehicles has brought an increased incidence of TAR. Between 1936 and 1942, in a cohort of 7,000 autopsies, Strassman [3] found only 51 patients with TAR secondary to vehicular collision, whereas several recent investigations have shown that TAR occurs in 10–30% of adults sustaining fatal blunt trauma. Richens et al. [4] reported 21% of mortality due to aortic rupture in a sample of 613 fatalities of road traffic accidents. TAR therefore represents one of the commonest causes of death at the scene of vehicular accidents, accounting for 8,000 victims per year in the USA [5].

31.2 Pathogenesis

This lesion may be generated by many different types of sudden-deceleration injury, including car and motorcycle collisions, falls from a height, blast injuries, airplane and train crashes, and skiing and equestrian accidents. In a demographic analysis of 144 patients with aortic rupture, Hunt et al. [6] reported motor vehicle crashes in 83% of cases, motorcycle crashes in 4.9% of cases, pedestrian injuries in 7% of cases and falls in 2.1% of cases.

The use of the seat belt has partially modified the characteristics of the trauma impact that leads to aortic rupture and there has been a decreasing incidence of rupture of the ascending aorta.

Although frontal collision is the commonest mechanism causing traumatic injury of the aorta, broadside impact accounts for 20–40% of cases in recent studies [4]. The shearing forces in lateral collision seem to produce most frequently a partial laceration involving the lesser curvature of the distal part of the aortic arch, just above the isthmus [7]. Air bags and seat belts do not protect against this type of impact. Such injuries can be expected to gain prominence in road traffic injury statistics, since the frequency of lethal injuries in head-on collisions is lowered by the mandatory use of restraints, which protect the victim from thoracic and head lesions but not from the mechanism producing aortic rupture [4, 8].

The commonest cause of TAR is the force generated by rapid deceleration of the body in either the vertical or the horizontal plane, that set up between the various portions of the aorta depending on their structure, location and attachments. The region subjected to the greatest strain is the isthmus, where the relatively mobile thoracic aorta joins the fixed arch and the insertion

of the ligamentum arteriosus. Aortic ruptures occur at this site in 80% of cases in the pathological series and in 90–95% of cases in the clinical series [2, 6, 9]. The ascending aorta may be involved in the proximity of the innominate artery or in its proximal segment immediately superior to the aortic valve. Because of the high immediate mortality of traumatic rupture of the ascending aorta, this location has been reported in 10–20% of cases in the autopsy series versus 5% of the surgical cases [2, 7, 9]. Other less common locations are distal segments of the descending aorta (12%) or the abdominal infrarenal segment (4.7%). Multiple sites of aortic tears are found in some reports [2]. Different theories have been advanced to explain the mechanism of aortic injury. The most widely accepted theory is that aortic rupture results from unequal rates of deceleration in different portions of the aorta at points of fixation. In high-speed-deceleration injuries the central portion of the descending aorta is snapped forward by the momentum of the deceleration force and the mass of the aorta's blood content. Another hypothesis considers a major role in bending stress by chest compression: a direct impact produces flexion of the aortic arch upon hilar structures acting as a fulcrum [10]. Additionally, Sevitt [11] proposed that the superior aorta stretches cranially, thus tearing the areas of the aorta which are fixed. The tensile strength of the aorta, however, exceeds the gravitational forces generated in trauma; thus, an additional force such as a sudden increase in hydrostatic pressure, acting with a "water hammer" effect, has been postulated.

Considering the different causes and types of impact which produce the aortic lesion, it is reasonable to propose that not only one mechanism but a combination of many is involved in its determination.

31.3 Pathology

According to the study of Parmley et al. [2], the lesion may be classified as (1) intimal hemorrhage, (2) intimal hemorrhage with laceration, (3) medial laceration, (4) complete laceration of the aorta, (5) false aneurysm formation, and (6) periaortic hemorrhage. The intimal hemorrhage may have an intact endothelian layer or may be associated with circumscribed laceration of the endothelial and internal elastic lamina of the intima. Recent reports indicate that intimal hemorrhage with or without partial intimal laceration tends to heal spontaneously. When the lesion involves intimal and medial layers, false aneurysm formation occurs. The aneurysm is fusiform in the case of a circumferential lesion involving the entire wall on the transversal plane, while in a partial lesion in which only a portion of the wall is lacerated, it appears as localized diverticulum. Periaortic hemorrhage occurred independently of the type of lesion.

Soon after the injury, the pouch of the aneurysm contains a thrombus consisting of fibrin and enmeshed red blood cells. It follows fibroblastic proliferation and early vascularization in the aortic wall. After 2–3 weeks the thrombus becomes organized and the wall of the pouch lined with endothelial cells. Complete rupture of the aorta including the adventitia and the periadventitial connective tissue leads to immediate death; however, false aneurysm formation or occlusion of the site of rupture may permit temporary survival. In the report of Parmley et al., nine of 38 patients who survived temporarily had complete transection, their survival being dependent on the formation of a hematoma contained in periaortic and mediastinal tissues.

31.4 Clinical Presentation

Despite the severe nature of the injury the clinical signs are ambiguously meager. In the diagnosis of acute TAR, it is imperative to maintain a high index of suspicion of the likelihood of this lesion in victims of high-speed-deceleration injuries, whether or not there is external evidence of thoracic injury.

The signs of aortic rupture are not specific and when head, facial, orthopedic, and visceral lesions coexist, their own clinical features attract the attention of the physician. Chest pain and dyspnea are the prominent symptoms presented by victims of aortic trauma. The pain is often localized in the back, midscapular, or may be retrosternal, and is reported in 20–76% of cases. Loss of consciousness and hypotension are also frequent, as generally reported in polytraumatized patients, while generalized hypertension is reported in about 17% of cases [12]. Systolic blood pressure below 90 mmHg despite adequate fluid resuscitation is considered to be a sign of hemodynamic instability and is associated with higher mortality [13]. Less frequently encountered symptoms include dysphagia, due to esophageal compression, and hoarseness. Symptoms of upper extremity ischemia and paraplegia, due to impaired blood flow beyond aortic transection, are also reported. However, a small number of patients (6%) have paraplegia without flow reduction. Difference in pulse amplitude between upper and lower extremities, attributed to compression of the aortic lumen by a periaortic hematoma, accounted for 23–37% of cases on physical examination [12]. If the intimal and medial tear forms a flap which acts as a ball valve, partial aortic obstruction occurs, with upper extremity hypertension reported as "acute coarctation syndrome" or "pseudocoartation" [14]. The hypertension may also be secondary to stretching or stimulation of the cardiac plexus that is located in the area of the isthmus. This mechanism could also account for the postoperative hypertension that is seen in one third of cases.

Signs of impending rupture are difficult to determine despite an attempt being made to identify them in several

clinical series [15–17]. Hypotension below 90 mmHg despite an adequate fluid volume resuscitation and free exsanguination into the pleural space, often recurrent despite thoracotomy, are considered to be signs of forthcoming free aortic rupture [13]. Careful attention must also be paid to manifestations of expanding aneurysm, such as vocal cord palsy or tracheal and superior vena cava compression.

Associated lesions are present in almost all patients with TAR, and are often predominant in the clinical presentation. In particular, fractures involving the bony thorax and long bones are far commoner, occurring in more than half the patients, followed in frequency by fractures to the pelvis and spine [12]. Head injuries have an average incidence of 20% in the literature review, with sporadic higher incidence in some series [18]. Spleen and liver injuries predominate among the abdominal lesions. As a result of blunt thoracic trauma, 36% of cases with pulmonary contusions is reported [19]; pulmonary contusion results in edema and interstitial hemorrhage of lung parenchyma, potentially progressing into respiratory insufficiency. Cardiac contusion caused by compression of the heart between the sternum and the vertebral column is associated with TAR in nearly 20% of cases, frequently if the ascending aorta is involved. Finally, negative physical examination is reported in 5–14% of cases [9, 12].

31.5 Natural History

TAR has been long considered a surgical emergency. This concept is primarily based on the historical study by Parmley et al. [2] in 1958, who reported autopsy findings in 296 nonpenetrating TARs among Korean War victims. Remarkably, the analysis of Parmley et al. estimated that 85% of the victims died on the scene from free aortic rupture; of those who survived at least for 1 h, 30% died within 6 h, 49% within 24 h, and 90% within 4 months. The impressive negative natural history of TAR victims gave rise to the statement that this lesion requires immediate surgical repair, with absolute priority over any other associated injury. The critical combination of a cardiovascular intervention in a severely injured patient led to an operative mortality from 15 to 45–50%, representing the highest rates in vascular surgery (Table 31.1) [15–24]. Despite progress in cardiac surgery and anesthesiology during the last few years, perioperative and postoperative mortality in TAR have not altered perceptibly. This finding stimulated the need for new strategies along with a critical review of the data of Parmley et al. As underlined by Pate et al. [25, 26] in several editorials and reports, the Armed Forces Institute of Pathology series of the 1950s is a cohort which probably does not apply to the current clinical reality. Moreover in the report of Parmley et al., as well as in other pathological series, a clear relation between free aorta rupture and death is not reported, nor is how much the other potentially fatal injuries, occurring in more than half of the patients, actually contribute to death.

New strategies have been considered in the past few years in the attempt to modify this negative prognosis [17, 25–30]. In aortic trauma, the aortic lesion sited at the aortic isthmus is a transverse tear variably extending from intimal to adventitial layers. In the majority of

Table 31.1. Morbidity and mortality of emergency surgery of traumatic injuries according to different surgical techniques

Authors	Year	Patients (*N*)	Mortality *N* (%)	Paraplegia *N* (%)
Clamp and sew				
Von Oppell et al. [17][a]	1994	443	71 (16%)	85 (19.2%)
Fabian et al. [20]	1997	73	11 (15.1%)	12 (16.4%)
Razzouk et al. [24]	2000	83	15 (18.1%)	5 (6%)
Jahromi et al. [21][a]	2001	220	33 (15%)	14/194 (7%)
Passive shunt				
Von Oppell et al. [17][a]	1994	424	52 (12.3%)	47 (11.1%)
Fabian et al. [20]	1997	4	0	0
Jahromi et al. [21][a]	2001	52	4 (8%)	2/48 (4%)
Left heart bypass				
Von Oppell et al. [17][a]	1994	71	7 (9.9%)	1 (1.7%)
Fabian et al. [20]	1997	69	10 (14.5%)	2 (2.9%)
Jahromi et al. [21][a]	2001	100	17 (17%)	0
Partial cardiopulmonary bypass				
Von Oppell et al. [17][a]	1994	490	89 (18.2%)	12 (2.4%)
Fabian et al. [20]	1997	39	5 (12.8%)	3 (7.7%)
Jahromi et al. [21][a]	2001	246	23 (9.3%)	5/227 (2.2%)
Downing et al. [22]	2000	50	5 (10%)	0
Jamieson et al. [23]	2002	35	5 (14.3%)	0

[a] Meta-analysis

cases, a complete transection occurs with instantaneous death, while in about 15% of cases the adventitial wall and mediastinal structures contain the rupture, allowing survival. In these patients if antihypertensive therapy acting to reduce wall stress is prompt, the risk of aortic rupture is limited. Purposeful delay in surgical intervention in polytraumatized patients with TAR gives time to treat other life-threatening injuries, improving overall mortality rates, and several surgical series in the last few years support this concept.

Recently, the development of endovascular technique has provided additional opportunities in the treatment of descending aorta diseases [31–36]. Results of clinical studies have shown the feasibility of endovascular procedures in the treatment of traumatic aortic injury.

31.6 Management

Despite the improvement in resuscitation techniques and emergency transport, TAR secondary to a blunt chest trauma results in a high mortality rate and all patients who reach the hospital alive are candidates for surgical repair. The best time to intervene in the aortic lesion and whether it should be preceded or followed by the treatment of associated traumatic lesions remains a matter of debate since most patients have associated traumatic lesions in other organs which may influence the outcome.

Emergency surgery was universally accepted in any circumstances for the treatment of aortic traumatic rupture. This strategy was largely based on the work by Parmley et al. [2], which demonstrated that the majority of patients die within 6 h of trauma, with fewer than 9% surviving for 24 h. Immediate surgery has been characterized by a high mortality and morbidity rate: in a report of 144 patients undergoing surgery within an average of 6 h after arrival in hospital, there was an intraoperative mortality of 10.2% and a postoperative mortality of 18.4%, with major postoperative morbidity such as paraplegia reaching 10.5% [6]. A comparison between the rates of hospital mortality and paraplegia can be performed according to the surgical technique used during the surgical repair. Patients treated with heparinless methods of providing distal perfusion had lower hospital mortality compared with systemically fully heparinized patients in whom cardiopulmonary bypass was used. In fact the full systemic heparinization may adversely affect associated lesion, mainly brain or pulmonary contusion leading to fatal hemorrhage. A distal perfusion system decreased significantly the risk of paraplegia compared with the simple aortic cross-clamping technique. The difference between active and passive perfusion systems also appears significant (Table 31.1).

Because of these unsatisfactory results of surgery alternative treatment protocols were investigated following a critical review of the report of Parmley et al. [25, 26]. Firstly, it was noted how the characteristics of the patients selected by Parmley et al. differed from those of the patients with aortic rupture that are commonly admitted to hospitals. The series of Parmley et al. was highly heterogeneous and included autopsy files of soldiers from the Armed Forces Institute of Pathology, many patients presenting with multiple associated fatal lesions. Secondly, the percentage of aortic isthmus injury was lower (45%) than that encountered in clinical practice (90%). Akins et al. [27] in 1981 showed good results on preoperative mortality delaying surgical intervention on the aorta in a small group of severely polytraumatized patients. Selected criteria to exclude immediate surgery were severe central nervous system trauma, respiratory insufficiency, extensive burns, contaminated open wounds, and sepsis. According to the data reported by Kalmar et al. [37] and Hartford et al. [38], mostly based on patients with aortic rupture caused by car accidents, the risk of a complete rupture of the aorta is not very high in the posttraumatic period, especially if the lesion is not circumferential, provided the patients, once admitted to hospital, are subjected to immediate aggressive resuscitation and medical treatment with controlled hypotension.

In a study based on the treatment of patients with traumatic rupture of the aortic isthmus who arrive in hospital alive, Maggisano et al. [28] demonstrated how there are two populations of patients with TAR. The first group is represented by patients who reach the hospital in unstable hemodynamic conditions with signs of active bleeding in the pleural space. The survival rate of these patients is low; the majority do not survive to aortography and despite an immediate thoracotomy, only 17.7% of them survive. The second group of patients include those that are hemodynamically stable and the diagnosis of TAR is obtained by chest X-ray findings and aortography. In these patients the surgical repair can be delayed if there are severe coexisting injuries that can increase the risk of operative mortality and morbidity. The risk of fatal free rupture of the periaortic hematoma in these group of patients is very low (4.5% within 72 h) and is not enhanced by increasing the length of time between injury and repair (Table 31.2). Holmes et al. [39] reported 30 patients who had undergone a period of nonoperative management: 15 underwent delayed operation and 15 never underwent repair. A total of eight deaths occurred, with only one due to aortic rupture. Two patients died because of intraoperative cardiac arrest, and five of 15 patients in the nonoperative group died because of head injuries.

If a complete rupture of the aorta with massive hemorrhage does not occur at the time of trauma, the adventitia and the surrounding mediastinal structures guarantee the continuity of the aortic wall with the development of an adventitial hematoma [40].

This first phase after the trauma is life-threatening and accident victims should be taken to hospital as

Table 31.2. Operative mortality in patients operated on with delayed surgery for traumatic aortic rupture

Authors	Year	Patients (*N*)	Overall mortality *N* (%)	Mortality related to aortic rupture (%)
Akins et al. [27]	1981	19	2 (10.5)	–
Kipfer et al. [44]	1994	10	0 (0)	0 (0%)
Maggisano et al. [28]	1995	44	2 (4.5)	–
Pate et al. [26]	1995	112	21 (18.8)	6 (5.4)
Fabian et al. [20]	1997	21	11 (52.4)	0 (0)
Holmes et al. [39]	2002	30	8 (26.7)	1 (3.3)
Kwon et al. [42]	2002	10	1 (10)	0 (0)
Langanay et al. [43]	2002	19	3 (15.8)	0 (0)
Pacini et al. [46]	2005	48	2 (4.2%)	1 (2.1)

quickly as possible. A prompt diagnosis of aortic wall injury is mandatory and an aggressive intravenous therapy with vasodilators and beta-blocking drugs must be started to reduce the aortic wall stress and the risk of lethal aortic rupture. The risk of rupture of a periaortic hematoma contained in the mediastinum can be avoided if the systolic blood pressure is constantly maintained below 140 mmHg. Pate et al. [26] analyzed 15 years of English-language literature, and their experience with 112 patients, in their search for evidence of the risk of aortic free hemorrhage in patients affected by acute TAR in the interval between diagnosis and delayed surgical repair. Of the 492 patients in reports specifying the cause of death, 22 (4.5%) died of aortic rupture, mostly presenting with hemodynamic instability and actively bleeding into the pleural space on arrival; in patients in whom the pseudoaneurysm or hematoma is contained within the mediastinum, and who do not present with signs of hemodynamic instability or exsanguination into the pleural space, free rupture appears to be uncommon.

On the subsequent days after the trauma, a process of organization of the hematoma usually develops and with time it will turn into a strong fibrous tissue, with the formation of a pseudoaneurysm that has the same risk of rupture as a true aneurysm of similar size. Patients must be admitted to an intensive care unit with continuous monitoring of ECG, arterial and central venous pressure, renal function and peripheral metabolism. An arterial systolic pressure exceeding 90 mmHg should be an indication to limit fluid replacement and any hemodynamic support in hypotensive patients. Monitoring of respiratory function and eventual intubation and mechanical ventilation is fundamental in polytraumatized patients with respiratory insufficiency due to central nervous system injury, pulmonary contusion and pleural effusion with measurement of chest tube outputs [26, 41].

Considering this possible evolution, the strategy to delay the surgical repair of posttraumatic aortic aneurysms in selected patients offers some clear advantages [39–44]. The overall mortality and the incidence of major complications are lower when it is possible to delay surgery than when unstable patients have to undergo an emergency operation. All the necessary procedures of distal aortic perfusion can be safely performed and the mortality is also reduced by prior treatment of potentially lethal associated lesions, often encountered in polytraumatizated patients. It is important to remember that 90% of patients with aortic rupture have associated other open and closed traumatic lesions of different areas (orthopedic 81%, abdominal 42%, closed-head injury 40%) which may cause a rapid evolution into shock and coma, thus influencing the patient's outcome [20, 45] (Table 31.2). Therefore, the treatment of associated lesions is fundamental in these patients and it is another incentive to delay surgical intervention in the aorta.

In our experience [30, 46] delaying aortic surgery in polytraumatized patients offers many advantages and is aided by increasingly sophisticated diagnostic techniques. The spiral CT scan and MRI offer noninvasive assessment of the anatomical characteristics of the aortic lesions and can be used to monitor their evolution [47].

However, delayed surgery cannot be applied in every case. Even if the majority of TARs are stable lesions, in approximately 5% of them the risk of rupture may be high in the acute phase. Signs of impending rupture such as periaortic hematoma, repeated hemothorax, contrast medium extravasation, and uncontrolled blood pressure are considered signs of instability. Sometimes the aortic tear, acting with a valve mechanism, may cause obstruction and reduction of flow in the descending aorta with lower extremity ischemia. Pseudocoarctation syndrome, which represents a surgical emergency, is reported in a high number of cases.

The correct timing of aortic repair in a polytraumatized patient should be considered and balanced along with other severe injuries, without a fixed priority. Therefore, stent graft repair can be performed after trauma earlier than surgical repair and also soon after the management of other life-threatening lesions. In patients who do not have severe associated lesions, delaying the treatment of traumatic rupture of the thoracic aorta does not provide any advantage and it should be performed as soon as possible.

31.7 Endovascular Treatment

For many years traumatic aortic injury has been considered a highly lethal lesion and a potential cause of death in blunt chest trauma. Despite evidence in the literature of lower morbidity and mortality, initial medical management of uncomplicated aortic injury and subsequent delayed surgery have not been easily accepted in the clinical practice.

From 1996 the introduction of endovascular techniques for the thoracic aorta in the clinical practice opened up a less invasive option for these patients for whom emergency treatment is necessary and these techniques represent a viable alternative with very low risk and limited impact on trauma destabilization. After initial limited series and case reports, endovascular treatment is going to become the method of choice in management of TAR [31–36, 48, 49]. Because of the lower invasivity, avoiding thoracotomy and the use of heparin, endovascular repair can be applied in acute patients without the risk of threatening pulmonary, head or abdominal traumatic lesions. The risk of paraplegia seems to be very low in endovascular techniques, even in extensive atherosclerotic aneurysms in which the coverage of the stent graft extends from the left subclavian artery to the celiac axis. Therefore, we may expect a very low rate of or absent paraplegia for the short stent-graft coverage of a posttraumatic aneurysm.

At present, standard measurements of thoracic stent grafts are available, allowing their use in an emergency. Actually, in an unstable patient, endovascular techniques offer a suitable alternative to open repair.

For a chronic post-traumatic aneurysm endovascular treatment represents a favorable alternative treatment of asymptomatic disease that is frequently recognized several years after the trauma. Chronic posttraumatic aneurysms are potential evolving lesions. Death from rupture may occur many years after injury sometimes without onset of any signs and symptoms. Because it is impossible to predict which aneurysm still remains quiescent, elective repair is always recommended for both symptomatic and asymptomatic lesions.

References

1. Passaro E, Pace WG. Traumatic rupture of the aorta. Surgery 1959; 46:787–791.
2. Parmley LF, Mattingly TW, Manion WC, Jahnke EJ Jr. Nonpenetrating traumatic injury of the aorta. Circulation 1958; 17:1086–1101.
3. Strassman G. Traumatic rupture of the aorta. Am Heart J 1947; 33:508–515.
4. Richens D, Kotidis K, Neale M, et al. Rupture of the aorta following road traffic accidents in the United Kingdom 1992–1999. The results of the co-operative crash injury study. Eur J Cardiothor Surg 2003; 23:143–148.
5. National Safety Council. Accident Facts. Preliminary condensed edition, March 1983.
6. Hunt JP, Baker CC, Lentz CW, Rutledge RR, Oller DW, Flowe KM, Nayduch DA, Smith C, Clancy TV, Thomason MH, Meredith JW. Thoracic aorta injuries: management and outcome of 144 patients. J Trauma 1996; 40:547–556.
7. Ben-Menachem Y. Rupture of the thoracic aorta by broadside impacts in road traffic and other collisions: further angiographic observations and preliminary autopsy findings. J Trauma 1993; 35:363–367.
8. Arajarvi E, Santarvirta S, Tolonen J. Aortic ruptures in seat belt wearers. J Thorac Cardiovasc Surg 1989; 98:355–361.
9. Kodali S, Jamieson WRE, Leia-Stephens M, Miyagishima RT, Janusz MT, Tyers GFO. Traumatic rupture of the thoracic aorta. A 20-year review: 1969–1989. Circulation 1991; 84(Suppl III):III40–46.
10. Lundevall J. The mechanism of traumatic rupture of the aorta. Acta Pathol Microbiol Scand 1966; 62:34–36.
11. Sevitt S. The mechanisms of traumatic rupture of thoracic aorta. Br J Surg 1977; 64:166–173.
12. Kouchoukos NT, Blackstone EH, Doty DB, Hanley FL, Karp RB. Acute traumatic aortic transection. In: Kirklin JW, Barrat B, editors. Cardiac surgery. Churchill Livingstone, New York, 1986. p. 1799–1819.
13. Eddy CA, Rush VW, Marchioro T, Ashbaugh D, Verrier ED, Dillard D. Treatment of traumatic rupture of the thoracic aorta. Arch Surg 1990; 125:1351–1355.
14. Malm JR, Deterling RH. Traumatic aneurysm of the thoracic aorta simulating coarctation. J Thoracic Cardiovasc Surg 1960; 40:271–278.
15. Cowley RA, Turney SZ, Hankins JR, Rodriguez A, Attar S, Shankar BS. Rupture of thoracic aorta caused by blunt trauma. A fifteeen-year experience. J Thorac Cardiovasc Surg 1990; 100:652–661.
16. Cernaianu AC, CilleyJH, Baldino WA, Spence RK, Del Rossi AJ. Determinants of outcome in lesions of the thorcic aorta in patients with multiorgan system trauma. Chest 1992; 101:331–335.
17. Von Oppell UO, Dunne TT, de Groot MK, Zilla P. Traumatic aortic rupture: twenty-year metaanalysis of mortality and risk of paraplegia. Ann Thorac Surg 1994; 58:585–593.
18. Williams JS, Graff JA, Uku JM, Stening JP. Aortic injury in vehicular trauma. Ann Thorac Surg 1994; 57:726–730.
19. Shorr RM, Crittenden M, Indeck M, Hartunian SL, Rodriguez A. Blunt thoracic trauma. Analysis of 515 patients. Ann Surg 1987; 206:200–205.
20. Fabian TC, Richardson JD, Croce MA, et al. Prospective study of blunt aortic injury: multicenter trial of the American Association for the Surgery of Trauma. J Trauma 1997; 42:374–383.
21. Jahromi AS, Kazemi K, Safar HA, Doobay B, Cinà CS. Traumatic rupture of the thoracic aorta: cohort study and systematic review. J Vasc Surg 2001; 34:1029–1034.
22. Downing SW, Cardarelli MG, Sperling J, et al. Heparinless partial cardiopulmonary bypass for the repair of aortic trauma. J Thorac Cardiovasc Surg 2000; 120:1104–1111.
23. Jamieson WRE, Janusz MT, Gudas VM, Burr LH, Fradet GJ, Henderson C. Traumatic rupture of the thoracic aorta: third decade of experience. Am J Surg 2002; 183:571–575.
24. Razzouk AJ, Gundry SR, Wang N, del Rio MJ, Varnell D, Bailey LL. Repair of traumatic aortic rupture: a 25-year experience. Arch Surg 2000; 135:913–918.
25. Pate JW. Is traumatic rupture of the aorta misunderstood? Ann Thorac Surg 1994; 57:530–531.
26. Pate JW, Fabian TC, Walker W. Traumatic rupture of the aortic isthmus: an emergency? World J Surg 1995; 19:119–126.

27. Akins CW, Buckley MJ, Dagget W, McIlduff JB, Austen WG. Acute traumatic aortic disruption of the thoracic aorta: a ten-year experience. Ann Thorac Cardiovasc Surg 1981; 31:305–309.
28. Maggisano R, Nathens A, Alexandrova NA, et al. Traumatic rupture of the thoracic aorta: should one always operate immediately? Ann Vasc Surg 1995; 9:44–52.
29. Hess PJ, Howe HR, Robicsek F, et al. Traumatic tears of the thoracic aorta: improved results using the Bio-Medicus pump. Ann Thorac Surg 1989; 48:6–9.
30. Galli R, Pacini D, Di Bartolomeo R, et al. Surgical indication and timing of repair of traumatic aortic ruptures of the thoracic aorta. Ann Thorac Surg 1998; 62:462–464.
31. Dake MD, Miller DC, Semba CP, et al. Transluminal placement of endovascular stent-grafts for the treatment of descending thoracic aortic aneurysm. N Engl J Med 1994; 331:1729–1734.
32. Grabenwoeger M, Hutshala D, Ehrlich MP, et al. Thoracic aortic aneurysms: treatment with endovascular self-expandable stent grafts. Ann Thorac Surg 2000; 69:441–445.
33. Mitchell RS, Miller DC, Dake MD, et al. Thoracic aortic aneurysm repair with an endovascular stent graft: the "First Generation". Ann Thorac Surg 1999; 67:1971–1974.
34. Fujikawa T, Yukioka T, Ishimaru S, et al. Endovascular stent grafting for the treatment of blunt thoracic aortic injury. J Trauma 2001; 50:223–229.
35. Fattori R, Napoli G, Lovato L et all. Indications for, timing of and results after treatment of catheter based treatment of the injury of aorta. AJR Am J Roentgenol 2002; 178:125–132.
36. Lachat M, Pfammatter T, Witzke H, at al. Acute traumatic aortic rupture: early stent graft repair. Eur J Cardiothorac Surg 2003; 21:959–963.
37. Kalmar P, Otto CB, Rodewald G. Selection of the proper time for operation of traumatic thoracic aortic aneurysms. Thorac Cardiovasc Surg 1982; 30:36–37.
38. Hartford JM, Fayer RL, Shaver TE, et al. Transection of the thoracic aorta: assessment of a trauma system. Am J Surg 1986; 151:224–229.
39. Holmes JH, Bloch RD, Hall RA, Carter YM, Karmy-Jones RC. Natural history of traumatic rupture of the thoracic aorta managed nonoperatively: a longitudinal analysis. Ann Thorac Surg 2002; 73:1149–1154.
40. Stulz P, Reimond MA, Bertschmann W, Graedel E. Decision-making aspects in the timing of surgical intervention in aortic rupture. Eur J Cardiothorac Surg. 1991; 5:623–627.
41. Fattori R, Celletti F, Bertaccini P, et al. Delayed surgery of traumatic aortic rupture: role of magnetic resonance imaging. Circulation 1996; 94:2865–2870.
42. Kwon CC, Gill IS, Fallon WF, et al. Delayed operative intervention in the management of traumatic descending thoracic aortic rupture. Ann Thorac Surg 2002; 74:S1888–1891.
43. Langanay T, Verhoye J, Corbineau H, et al. Surgical treatment of acute traumatic rupture of the thoracic aorta: a timing reappraisal? Eur J Cardiothorac Surg 2002; 21: 282–287.
44. Kipfer B, Leupi F, Schuepbach P, Friedli D, Althaus U. Acute traumatic rupture of the thoracic aorta: immediate or delayed surgical repair. Eur J Cardiothorac Surg 1994; 8:30–33.
45. Del Rossi AJ, Cernaianu AC, Madden LD, Cilley JH, Spence RK, Alexander JB, Ross SE, Camishion RC. Traumatic disruptions of the thoracic aorta: treatment and outcome. Surgery 1990; 108:864–870.
46. Pacini D, Angeli E, Fattori R, et al. Traumatic rupture of the thoracic aorta: ten years of delayed management. J Thorac Cardiovasc Surg 2005; 129:880–884.
47. Fattori R, Celletti F, Descovich B, et al. Evolution of posttraumatic aneurysm in the subacute phase: magnetic resonance imaging follow-up as a support of the surgical timing. Eur J Cardiothorac Surg 1998; 13:582–587.
48. Rousseau H, Soula P, Perreault P, Bui B, Janne d'Othee B, Massabuau P, Meites G, Concina P, Mazerolles M, Joffre F, Otal P. Delayed treatment of traumatic rupture of the thoracic aorta with endoluminal covered stent. Circulation 1999; 99:498–504.
49. Fattori R, Napoli G, Lovato L, et al. Descending thoracic aortic diseases: stent-graft repair. Radiology 2003; 229:176–183.

Surgical Treatment of an Acute Isthmus Traumatic Rupture

Thierry Langanay, Bertrand De Latour, Alain Leguerrier

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Contents

32.1 Introduction

Acute ruptures of the aortic isthmus account for about 85% of aortic injuries due to blunt trauma. They are generally related to a violent crash involving a sudden deceleration. Polytraumatisms and other life-threatening injuries are often associated with cardiovascular lesions. It is generally admitted that about 80% of casualties die at the accident scene and that among the survivors only 20% would survive without emergent surgical repair of the aortic injury.

After surgery, however, the hospital mortality rate remains high, and stands around 20% in most reports in the literature [1, 2]. This high mortality rate seems to be mostly linked to lesions associated with aortic rupture. On the other hand, paraplegia is the most feared complication after surgery requiring aortic cross-clamping. The use of cardiopulmonary bypass (CPB), which provides distal perfusion during the duration of aortic cross-clamping, appears to dramatically reduce the risk and the actual rate of postoperative spinal cord injury [2]. But the necessity of full systemic heparinization during CPB entails the risk of inducing or severely worsening bleeding in a coexisting internal wound and particularly brain or pulmonary contusion, leading to fatal hemorrhage in many cases. This raises the difficult question of surgical priority and/or of delaying the aortic repair until the associated life-threatening lesions are sufficiently healed or under control [3–5].

32.2 Clinical Features

32.2.1 Patients

From October 1976 to October 2004, 62 patients (52 men and ten women) were operated on for an acute rupture of the thoracic aorta in our institution. The age ranged between 14 and 72 years with a mean of 28 ± 10.5 years. Forty patients (63%) were less than 30 years old (Fig. 32.1).

The patients' files were analyzed retrospectively from the data collected at the time of hospitalization. Those data together with the data collected during the follow-up were entered into the database of our center, and were treated statistically with a Hewlett-Packard 9000 computer using Statview statistical software.

All patients had been victims of a violent accident involving a mechanism of sudden deceleration. Fifty-six patients (90%) experienced a traffic accident: car crash in 41 cases (66%), motorcycle crash in 13 cases (21%), and pedestrian knock over in two cases (3%). Six patients (10%) had been the victim of fall (8–10 m).

On admission, 26 patients (42%) showed evidence of hypovolemic shock with unstable hemodynamics. Ten patients (16%) presented with acute respiratory distress, in connectionwith a flail chest in six patients (10%). Five patients (8%) suffered from a pseudocoarctation syndrome with complete abolition of the femoral pulses. In two of those (3%) there was evidence of ischemia of the lower limbs in relation to a complete thrombosis of the distal aorta.

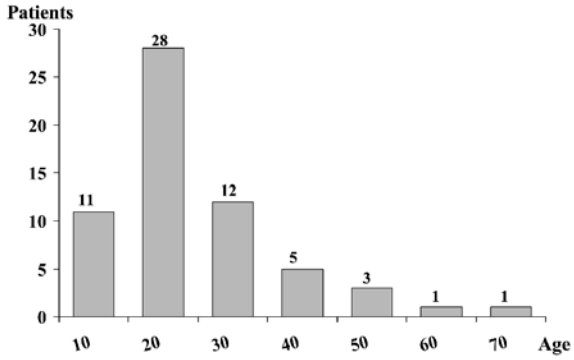

Fig. 32.1. Repartition of patients according to age

One patient (1.5%) had paraplegia due to a coexisting spine fracture and spinal cord lesion, one patient (1.5%) had paraparesis and one patient (1.5%) suffered from neurological deficit of the right upper limb.

32.2.2 Diagnosis

The possibility of an aortic rupture was suggested by several signs associated in various manners. Widening of the upper mediastinum was present on plain chest film in 51 patients (82%) (Fig. 32.2). In 23 patients (37%) the aortic rupture was suspected because of the loss of parallelism of the aortic walls or the widening of the aortic isthmus on routine computed tomography (CT) scans performed to check the thoracic lesions of the polytraumatism (Fig. 32.3).

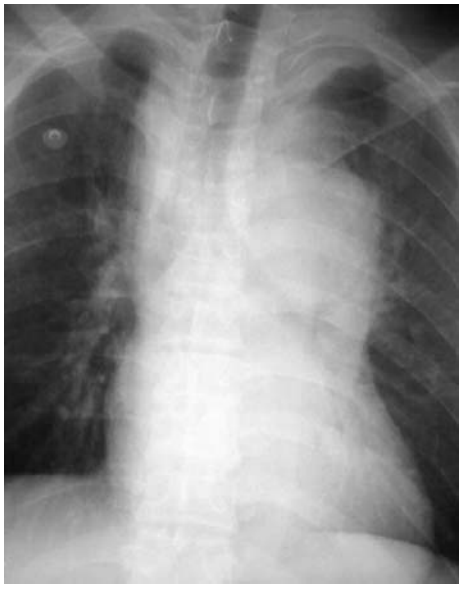

Fig. 32.2. Widening of the upper mediastinum on the standard chest X-ray

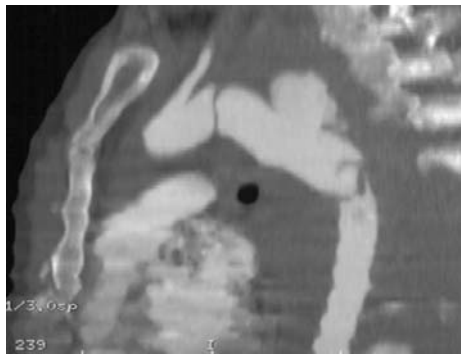

Fig. 32.3. Aortic rupture on the computed tomography scan

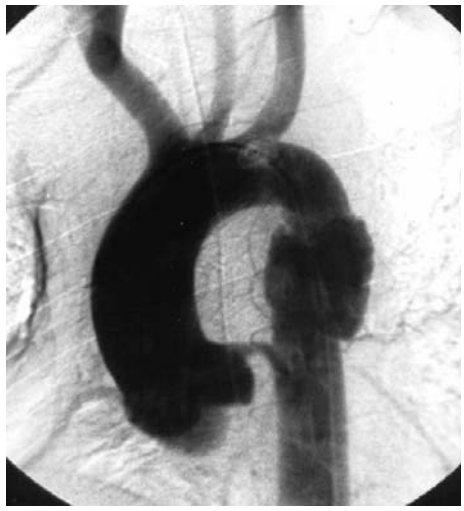

Fig. 32.4. Aortogram showing the loss of parallelism of the aortic walls

Table 32.1. Lesions associated with aortic rupture

	Patients	*N*	Percentage
Thoracic lesions	37		60
Rib fracture		46	74
Flail chest		12	19
Sternal fracture		7	11
Head injury	25		40
Skull fracture		2	3
Brain contusion and coma		13	21
Orthopedic injury	47		76
Lower limb fracture		27	43
Upper limb fracture		15	24
Pelvic fracture		19	30
Rachis fracture		4	6
Maxillo-facial fracture		8	13
Clavicule fracture		3	5
Abdominal lesions	21		34
Ruptured spleen		10	16
Kidney contusion		7	11
Liver wound or contusion		7	11
Ruptured diaphragm		2	3
Other		2	3

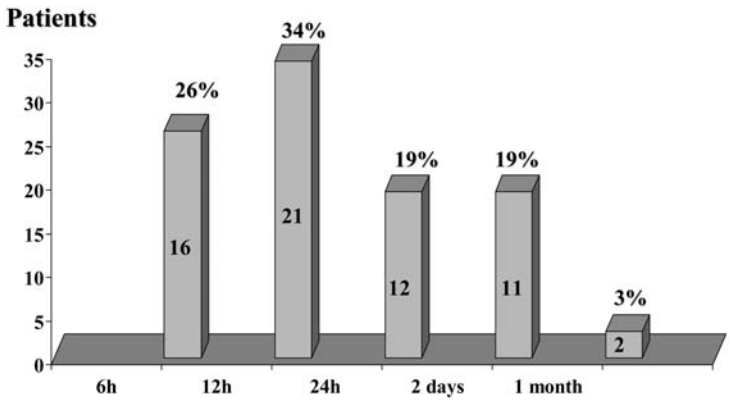

Fig. 32.5. Delay between the accident and the aortic repair

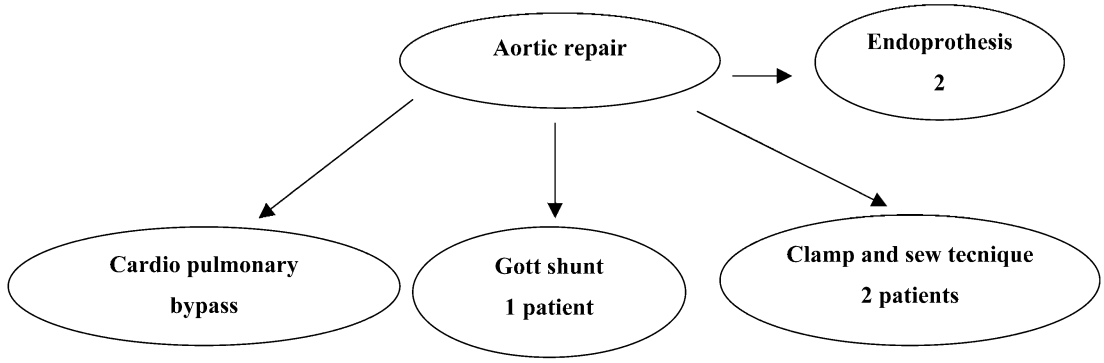

Fig. 32.6. Techniques of aortic repair and spinal cord protection

In one patient (1.6%) the occurrence of a systolic murmur 11 days after the accident led to the diagnosis, which was confirmed by a transesophageal echocardiogram (TEE) and a subsequent aortogram.

Forty-four patients (71%) underwent an aortogram (Fig. 32.4). For the remaining 18 patients (29%), an aortogram was not obtained either because the CT scan convincingly demonstrated the presence of the aortic lesion (16 cases, 26%) or because the clinical condition was too unstable to allow any further delay to surgery. For those two patients, the diagnosis was confirmed at emergency thoracotomy. If an aortogram was the rule in the early years of this series, it has now been replaced by CT scan and for the last twelve patients no aortogram was obtained.

The aortic lesion was isolated in only five patients (8%). All other patients (57–92%) sustained major associated injuries, reflecting the magnitude of the violence of the accident. The associated injuries are summarized in Table 32.1. They were responsible for coma in 13 cases (21%), and an emergency laparotomy was performed prior to the aortic repair in 17 cases (28%).

32.2.3 Surgical Treatment

Thirty-seven patients (60%) underwent aortic repair within 24 h of the accident (Fig. 32.5). Conversely, 25 patients (40%) were treated after a delay extending over 1 month, 23 patients were operated on and two patients were treated with an endoprosthesis. This delay was either due to a late diagnosis, the aortic rupture being obscured by major coexisting lesions in 12 patients, or was made on purpose for 13 patients because of the presence of severe associated injuries (four polytraumas with multiple and severe orthopedic lesions, two ruptured spleens, one liver wound, one coma grade III and several pulmonary contusions) thought to make the emergency aortic repair riskier than continued intensive medical therapy.

Sixty patients were operated on by conventional surgery and two were treated with an endoprosthesis (Fig. 32.6).

During surgery, the patients were intubated with a double-lumen tube in order to allow separate ventilation of the lungs. The isthmic aorta was approached through a left posterior thoracotomy in the fourth intercostal space in 58 patients (96%). In the remaining two patients, a sternotomy was carried out for resuscitation

purposes. Spinal cord protection and perfusion of distal organs were achieved by the use of a conventional CPB whenever possible. This was the case for 57 patients (95%), the remaining three patients being operated on either with a Gott shunt (one patient) or with the clamp-and-sew technique (two patients). The CPB was established in various manners. The aortic clamping time ranged from 21 to 110 min (mean, 58 min). There was no difference in clamping time depending on the presence or the absence of CPB.

In two cases (3%) the aortic repair had to be carried out during circulatory arrest at deep hypothermia because of the proximal extension of the aortic tear to the transverse arch.

The aortic rupture was circumferential in 39 patients (65%), partial in 20 (33%) and bifocal in one (2%). The aortic repair could be achieved through direct suture in 26 patients (43%) but required a Dacron prosthesis interposition in the remaining 34 patients (57%).

For the last two cases, because of coexisting lesions (polytraumatism and lung contusion) and an unstable aortic lesion, an endoprosthesis was implanted on the second day after the accident. The immediate outcome was uneventful.

32.2.4 Results

The overall hospital mortality amounts to 16% (ten patients). Four patients died in the operating theater. Six patients died during the postoperative course. The time, circumstances and causes of death are summarized in Table 32.2.

Several nonfatal complications were observed during the postoperative course. One patient experienced paraplegia (T-3 level), which appeared 72 h after the surgical procedure and was totally regressive within 3 months (2%). This patient had been operated on with the aid of CPB with a cross–clamping time of 59 min, a mean distal arterial pressure of 80 mmHg during CPB and a total blood loss of 450 ml for the first postoperative 24 h. The only deleterious element could have been the intraoperative suppression of two pairs of intercostal arteries. However, this delayed spinal cord injury might have been the result of some reperfusion syndrome with spinal cord edema. This could then explain the total regression of the neurological deficit in a rather short time.

Eleven survivors (22%) showed evidence of arterial hypertension. The mean age of this subgroup of patients was 22.7 ± 6.4 years and all but two ruptures were treated by a Dacron tube interposition. No particular reason could be found; the arterial hypertension was controlled by medical therapy.

32.3 Technique of Surgical Repair

The patient is placed in the right lateral decubitus position and then the hips are rolled back toward a more supine position so that the left femoral vessels are accessible (Fig. 32.7) [6, 7].

During surgery, the patient is intubated with a double-lumen tube in order to allow separate ventilation of the lungs. A catheter is inserted in the patient's right radial artery and another one in the right pedious artery, opposite to the femoral arterial cannulation, to continuously monitor blood pressure and the distal perfusion. One or two large-bore needles are positioned securely in a peripheral vein after placement of a central vein catheter. A Swan–Ganz catheter might be useful depending on the general condition of the patient (advanced age, cardiac or renal insufficiency). Vesical and gastric tubes are also inserted.

The isthmic aorta is approached through a wide left posterior thoracotomy in the fourth intercostal space. This provides excellent viewing on the aortic isthmus but allows also access to the aortic arch, the pulmonary artery, the descending aorta and the left side of the heart. The arterial cannulation is realized before the thoracotomy because it allows rapid and massive retransfusion in the case of an aortic rupture occurring during the thoracotomy, especially when the lung compression on the aortic adventitia is released during dis-

Table 32.2. Circumstances, dates and causes of hospital deaths

Surgery/accident	Associated lesions	Death/surgery	Causes
5th day	Brain contusion	Day 0	Intracerebral bleeding
11th day	Lung contusion	Day 0	Pulmonary bleeding
Emergency	Resuscitation	Day 0	Multiorgan failure + hemorrhage
Emergency	Lung contusion	Day 0	Pulmonary bleeding
Emergency	Brain contusion	Day 1	Intracerebral bleeding
Emergency	Distal malperfusion	Day 1	Multiorgan failure
2nd day	Distal malperfusion	Day 2	Multiorgan failure
Emergency	Preoperative inhalation	Day 2	ARDS
Emergency	Bronchial rupture + lung contusion	Day 10	Septicemia
2nd day endoprothesis	Brain lung contusion	Day 31	ARDS

ARDS acute respiratory distress syndrome

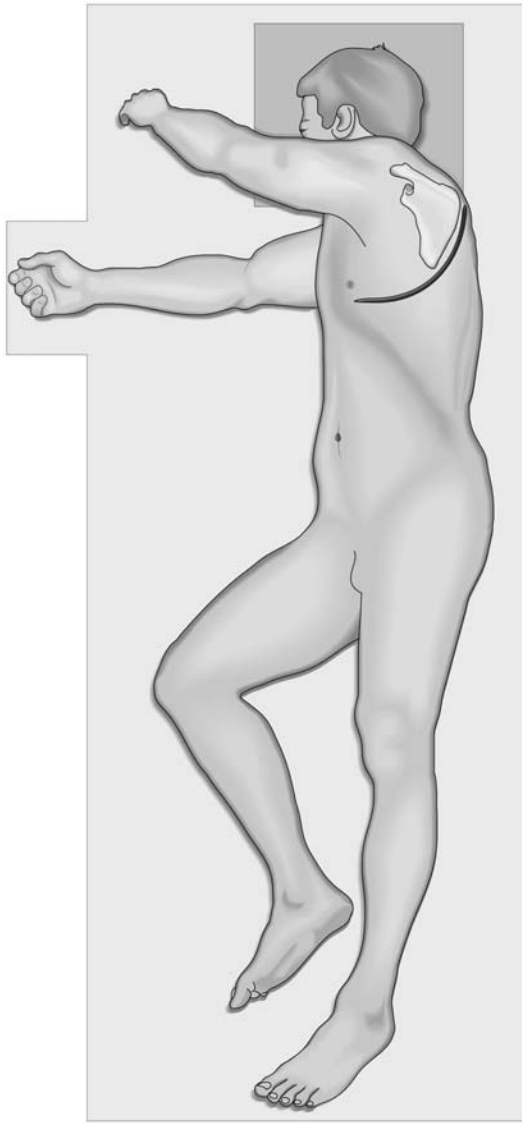

Fig. 32.7. The patient is positioned in the right lateral decubitus position

section. A cell-saver device is used to suck the blood out of the thorax so that it permits an autotransfusion either by the CPB or by the peripheral veins.

A median sternotomy can be preferred in the case of an unstable hemodynamic state because of the easiest and fastest realization. It allows the installation of a CPB and an aortic cross-clamping.

Great care must be taken during the dissection not to provoke a hemorrhage by disturbing the mediastinal hematoma, which usually holds back the tear and prevents active bleeding in the pleural space. If this does occur, the use of the cell-saver and cardiotomy suction will allow immediate and massive autotransfusion via the femoral arterial cannula and maintenance of a stable hemodynamic condition during the control of the aorta. To avoid such a situation, the lung is cautiously retracted and the aorta controlled proximally and distally before entering the hematoma. Most of the time, this requires separate control of the distal arch and the left subclavian artery.

The mediastinal pleura is opened beyond the hematoma over the distal transverse arch, the left subclavian artery and the upper descending aorta. The dissection is carried around the vessels, and once the circumferential control has been obtained three tapes are placed, so that a cross-clamp can be placed immediately in case a rupture occurs during the dissection of the hematoma which is conducted step by step toward the tear. The hematoma is largely removed; the distal clamp is then moved proximally as far as possible to avoid keeping intercostal arteries in the excluded part of the aorta by the clamping which would provoke retrograde bleeding and to allow retrograde flow to go into the intercostal arteries. The dissection is conducted toward the transection, staying in the periaortic tissue plane. Usually there is some bleeding into the field from the intercostal arteries between the clamps. They should not be ligated nor oversewn if possible in order to preserve spinal cord vascularization and the aorta is tailored to preserve their origins in the repair. The dissection is often more difficult in the case of delayed repair, compared with fresh rupture, because of fibrosis of the hematoma that already exists. In all cases, identification of the recurrent nerve is difficult, so it might be injured by the surgical act as well as by the accident itself (a postoperative recurrent paralysis is not so rare in our experience) (Fig. 32.8).

A transversal aortotomy is realized in front of the lesion, which is then analyzed; the tear might be circumferential, incomplete with a preserved posterior wall or more complex with a spiroid tear. Aortic continuity is reestablished either by a direct end-to-end suture or by a graft interposition. Whenever possible, we prefer to realize a direct reconstruction, with a continuous running suture with 4-0 (3-0) polypropylene as it permits us to obtain an ad integrum restitution of the aorta without any sequelae. To avoid inadequate tractions on the suture, it might be necessary to mobilize the two extremities of the aorta by means of a larger dissection. A direct repair is usually possible when the rupture is incomplete because the intact part of the aortic wall prevents the retraction of the two extremities. It might be more difficult in the case of a spiroid tear concerning a lack of tissue or in the case of delayed surgery. In such situations, a graft interposition with a pretreated collagen-woven Dacron tube will be realized (Fig. 32.9).

One must remember that cross-clamping the distal aortic arch rather than the aorta beyond the left subclavian artery induces a greater increase in left ventricular afterload and decreases the collateral flow to the lower part of the body and the spinal cord through the left

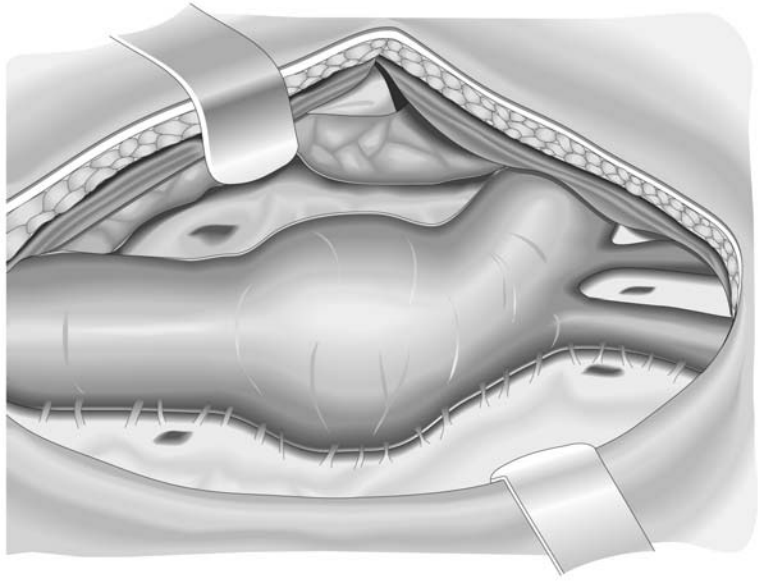

Fig. 32.8. Operative view of the aortic rupture

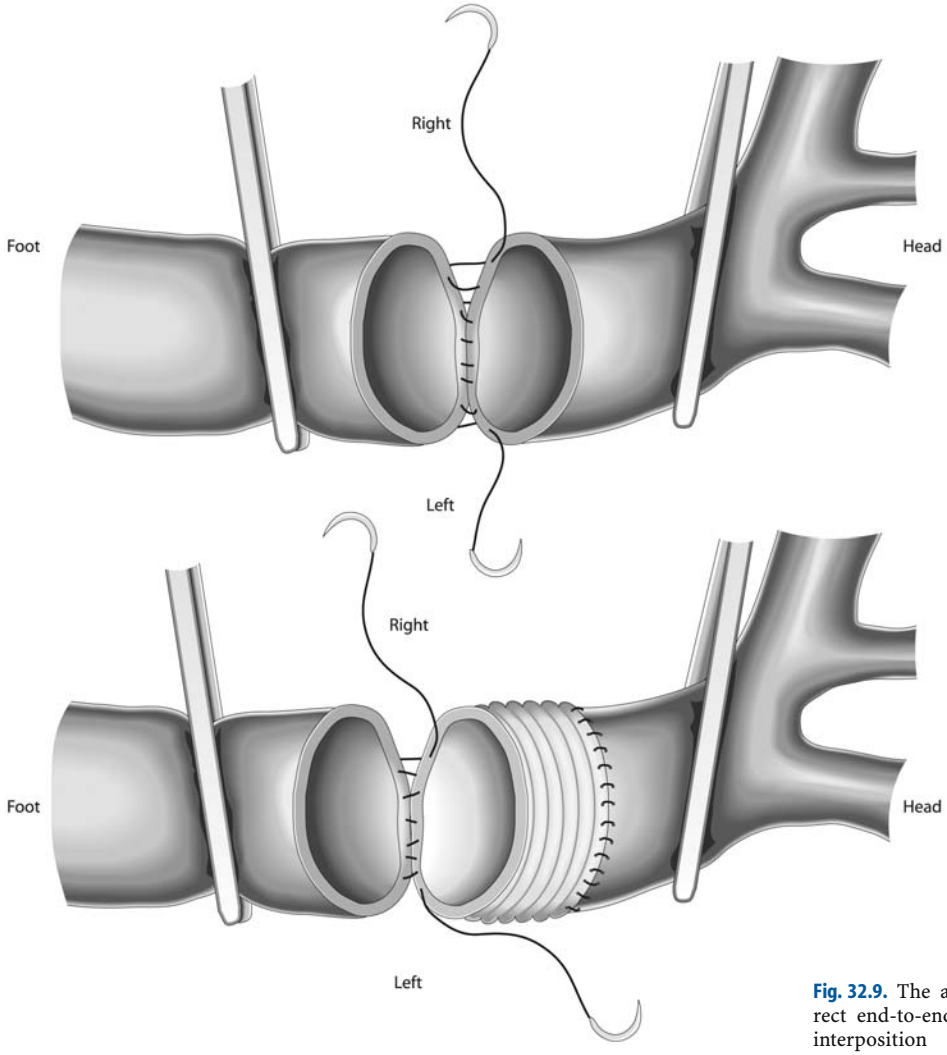

Fig. 32.9. The aorta is repaired by a direct end-to-end anastomosis or a graft interposition

subclavian artery. So if this can be done, the clamp should be moved beyond the left subclavian artery.

32.4 Special Situations and Controversies

32.4.1 Update in Natural History

Parmley et al. [8] reported, in their classic autopsy study, that 89.7% of patients who sustain a traumatic rupture of the thoracic aorta will die within 6 h following the accident and that only 9% will survive beyond 24 h. Since 1958, therefore, traumatic aortic rupture has been considered as an absolute surgical emergency and the fear of "impending rupture" has led the surgical community to rush for aortic repair. It appeared with time and through increasing reported experiences that this surgical attitude could be debated, as it could be, in some instances, more harmful than useful. Many reports, indeed, have demonstrated that the aortic lesion is seldom isolated [9, 10]. In a study by Pate et al. [9], only two out of 59 patients had an isolated rupture of the thoracic aorta. The authors questioned the conclusions of the report of Parmley et al. emphasizing the fact that it was a retrospective necropsic study implying many selections biases. Similarly, Williams et al. [11] consider that Parmley et al. overestimated the risk of delayed rupture of the aorta and that many patients could undergo laparotomy or orthopedic surgery prior to the aortic repair with very little risk of sudden rupture of the aortic false aneurysm. In a study concerning 33 cases of isthmic aortic rupture, Cernaianu et al. [12] demonstrated a close relationship between the patients' survival rates and the delay separating the accident and the hospital referral. Conversely, they were unable to establish any relationship between the survival rate and the delay separating the hospitalization from the diagnosis, on the one hand, and the diagnosis from the aortic repair, on the other hand.

32.4.2 Associated Lesions

The literature emphasizes that aortic rupture is seldom isolated and that associated lesions are responsible for hospital mortality in the majority of cases (Table 32.3). This stems from four main reasons:

1. The coexisting lesion can be life-threatening in itself (e.g., spleen rupture, liver contusion and brain trauma).
2. The number and gravity of the coexisting lesions may induce an intractable condition of hypovolemic shock and multiorgan failure.
3. The full systemic heparinization required by the CPB may adversely affect a brain or pulmonary contusion, leading to fatal hemorrhage.
4. Some lesions (open fractures, voluminous limb hematomas) may become septic.

Recent literature [12–14] reports mortality rates ranging from 5 to 35% and is in accordance with the figures reported by Von Oppell et al. [2] in their meta-analysis.

32.4.3 Postoperative Paraplegia

Paraplegia may complicate the surgical repair in 3–33% of cases according to the literature [2, 14–16]. In a well-known meta-analysis, carried out from 87 reports and including 1,492 patients operated on for acute traumatic rupture of the aorta, Von Oppell et al. [2] compared the rates of hospital mortality and paraplegia according to the surgical technique used during the aortic repair (Table 32.4). When a distal perfusion system was used, the risk of paraplegia decreased significantly compared with that for the simple aortic cross-clamping technique (6.1 vs 19.2%, $p < 0.0001$). The difference between "active" and "passive" perfusion systems also appeared significant (2.3 vs 11.1% paraplegias).

Similar data have been reported by several groups. From a review of the literature including 749 patients, Zeiger et al. [17] observed 2.9% paraplegias with the use of CPB vs 20.4% with simple cross-clamping. Kodali et al. [13] reported a difference of 3.2 vs 28.5% and Pate et al. a difference of 3.8 vs 26.7% [10].

In contrast, the use of CPB, either total or partial, requiring full heparinization of the patient, has been held responsible for an increase in mortality and morbidity. In particular this technique can induce fatal hemorrhage of brain and pulmonary contusions. This possibly explains the high mortality observed in the group of patients operated on with total heparinization (18.2%) compared with that of those operated on without heparin (11.9%, $p < 0.01$) in the meta-analysis of

Table 32.3. Role of associated lesions in hospital mortality (from the literature)

	Ruptures (N)	Deaths (N)	Number of deaths related to associated lesions	Percentage of deaths related to associated lesions
Katz et al. [15]	35	5	4	80
Mattox et al. [14]	32	6	6	100
Pate et al. [19]	59	6	2	33
Langanay et al. [5]	57	9	5	55

Table 32.4. Comparison of mortality and paraplegia rates according to the method of spinal cord protection. (From Von Oppell [2])

	1,492 patients	Mortality (%)	Paraplegia (%)
Clamp and sew	443	16	19.2
Total distal perfusion	985	15	6.1
Passive	424	12.3	11.1
Active	561	17.1	2.3

Von Oppell et al. [2]. In 1984, Mattox et al. [14] recommended the technique of simple aortic cross-clamping without any adjunct for intraoperative management of the traumatic injury of the descending aorta. In their series, the rate of paraplegia was not significantly different whether CPB was used or not (4.5 vs 8.3%, respectively). This led many surgeons to believe that they could avoid using CPB and to consider that the clamp-and-sew technique was as safe as the distal perfusion technique. However, Katz et al. [15] have demonstrated that beyond 30 min of cross-clamping without distal perfusion, the risk of spinal cord injury dramatically increases. Therefore, considering the very significant differences in the rate of paraplegia highlighted by many authors, there is presently an obvious trend within the surgical community to clearly advocate the use of active distal perfusion systems during the time of aortic repair for acute traumatic isthmic rupture [18, 19].

To reduce the conflict between the necessary use of distal perfusion and the increased risk linked to heparinization, it has been recommended to use heparinless bypass systems with a centrifugal pump [2]. Heparin-coated circuits could also represent a tempting alternative as they make theoretically possible the reduction or the suppression of total heparinization. But those systems are still being evaluated and the possible risk of thrombosis entailed by the circuits limits their indications and makes their use still controversial.

32.4.4 Endovascular Therapy

The endovascular implantation of a prosthesis has been proposed, for around 10 years now, for the elective but also emergent treatment of thoracic aortic rupture. It is a less invasive technique which necessitates only a surgical or percutaneous femoral artery access, with only light systemic heparinization (or even not in case of contraindication). Hospital mortality appears low, from 0 to 6% [20–26]. In addition, procedure-related morbidity is lower than under conventional surgery. No paraplegia and no renal insufficiency have been reported. But this new technique is not free of problems, i.e., access failure because of small and calcified iliac arteries, iliac dissection and primary endovascular leaks. This means that patients have to fulfill certain anatomic prerequisites.

In view of literature data, emergency endovascular treatment of acute lesions appears safe and efficient, showing encouraging early and midterm results. It is particularity indicated in complex multitrauma patients avoiding CPB and allowing for prompt treatment of associated lesions. But questions regarding long-term complications and durability of stent grafts remain unanswered and long-term follow-up will therefore be necessary and allow for a definitive conclusion. So today conventional surgical treatment remains our first choice and endovascular treatment is proposed only for high-risk patients.

32.4.5 Medical Treatment

The concept of pharmacological treatment and medical support of acute aortic dissection introduced by Wheat et al. [27] in 1984 was first proposed by Aronstam et al. [28] for the treatment of traumatic rupture of the aorta. This attitude was confirmed by several groups in the ensuing years [29, 30]. Walker et al. [31] in an extensive review of the literature found 64 patients medically treated waiting for aortic surgery. Stulz et al. [35] in 1991 did not observe any death among patients treated in a conservative manner. Those good results associated with the higher mortality due to the coexisting lesions have led many surgeons to question the dogma of "no-delay" emergency aortic repair in any case and to redefine the therapeutic priorities. Therefore, new strategies have recently been reported for the medical and surgical management of traumatic rupture of the aorta [3, 4, 19, 32–35]. Even if most of these authors have reported no death while waiting for the aortic repair, one cannot consider that there is no risk as Maggisano et al. [35] reported two deaths as a result of aortic rupture within 72 h of admission to an intensive care unit [35]. Fortunately, this seems to be very rare because except in cases of complete rupture the adventitia and surrounding mediastinal structures may form a solid fibrous wall, reducing the risk of delayed rupture [31, 33, 34].

32.5 Current Therapeutic Strategy

The prevalence and the gravity of the lesions associated with the aortic rupture (Table 32.1) in our series are in accordance with data recently published. It is to be noted that no patient died from hemorrhage. Six deaths out of ten (60%) were directly related to an associated lesion, five being possibly worsened by full heparinization during CPB: two cases of intracerebral hematoma following a major head injury and three cases of respi-

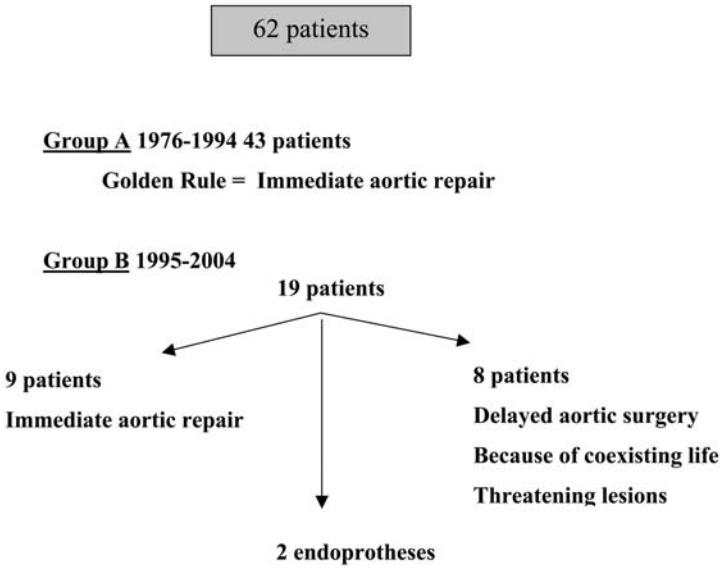

Fig. 32.10. The two periods of our therapeutic strategy

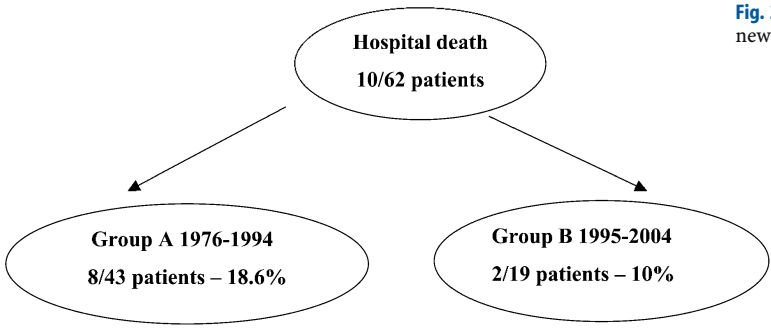

Fig. 32.11. Hospital mortality according to our new strategy

ratory distress syndrome after lung contusion. The fourth case of respiratory disease complicated the outcome of an endoprosthesis.

Considering our experience and literature data, we decided in 1995 to modify our therapeutic strategy. Between 1976 and 1994, 43 patients (group A) were treated according to the golden rule of "immediate aortic repair" and since 1995, 19 patients (group B) have been managed taking into account associated lesions (Fig. 32.10). Though it is always very difficult to compare different patients operated at different periods, operative mortality appears much lower, 10 vs 18.6% in group B (Fig. 32.11). It is also to be noted that no patient died from aortic rupture in the case of delayed aortic repair.

32.6 Proposal for a Timing Reappraisal of Aortic Repair

In view of literature and our recent results, we are now convinced that the best chance for patients is based on first treating surgically the most life-threatening lesion. This policy is summarized in Fig. 32.12. The aortic repair should be undertaken immediately if the aortic rupture is isolated or associated with a non-life-threatening lesion. In the case of a severe life-threatening associated lesion with a stable aortic lesion, the aortic repair should be performed in a second stage after treatment or healing of the coexisting lesion. In this case, the patient should be maintained in a surgical intensive care unit, the aortic evolution being closely monitored by CT scan or TEE under strict control of blood pressure and aortic wall stress through the use of beta-blocking therapy. In the case of unstable aortic lesion (e.g., recurring left hemothorax or pseudocoarctation syndrome), requiring an emergency repair despite the presence of severe associated lesions, endovascular repair represents the technique of choice today. If it does not meet the required conditions the aortic repair should be carried out with the use of heparinless systems such as centrifugal pumps and not by using the clamp-and-sew technique.

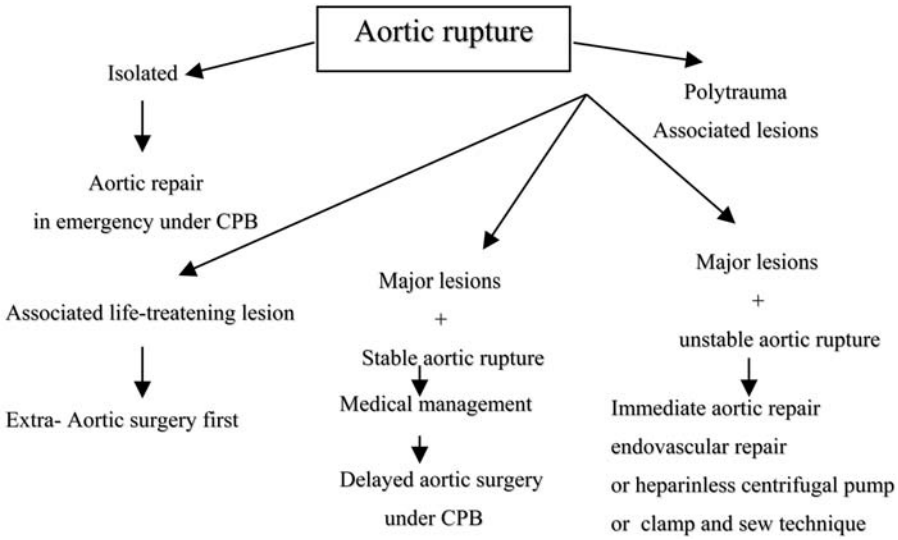

Fig. 32.12. Algorithm representing our proposition for a modern therapeutic strategy. *CPB* cardiopulmonary bypass

32.7 Conclusion

Acute traumatic rupture of the thoracic aorta is, indeed, a life-threatening lesion which deserves surgical repair. It is, however, generally associated with other severe life-threatening lesions and may be hidden among those. It, therefore, justifies early, active, exhaustive diagnostic procedures in the case of polytraumatism. Should the patient show evidence of impending rupture or major distal malperfusion, emergency surgical repair is mandatory. But in some instances, surgical treatment of the aortic rupture must be delayed under strict monitoring. This attitude allows management of other severe life-threatening lesions which, otherwise, would deeply increase the risk of the aortic repair, and which are responsible for the major contributor to hospital mortality in those patients. Whatever the circumstances of surgery, distal perfusion downstream from the aortic cross-clamping must be maintained, using either CPB or a heparinless centrifugal pump.

References

1. Fabian TC, Richardson JD, Croce MA, Smith JS, Rodman G Jr, Kearney PA. Prospective study of blunt aortic injury: multicenter trial of the American Association for the surgery of trauma. J Trauma 1996; 42:374–383.
2. Von Oppell VD, Dunne TT, De Groot MK, Zilla P. Traumatic aortic rupture: twenty year metanalysis of mortality and risk of paraplegia. Ann Thorac Surg 1994; 58:585–593.
3. Kipfer B, Leupi F, Schuepach P, Friedli D, Althaus U. Acute traumatic rupture of the thoracic aorta immediate or delayed surgical repair? Eur J Cardiothorac Surg 1994; 8:30–33.
4. Pate JW. Is traumatic rupture of the aorta misunderstood? Ann Thorac Surg 1994; 57:530–531.
5. Langanay T, Verhoye JP, Corbineau H, et al. Surgica treatment of acute traumatic rupture of the thoracic aorta, a timing reappraisal? Eur J Cardiothoracic Surg 2002; 21:282–287.
6. Kirklin JW, Barrat-Boyes BG. Acute traumatic transection. In: Cardiac surgery. Kirklin JW, Barrat-Boyes BG, editors. New York: Churchill Livingstone; 1993; p. 1701–1709.
7. Gandjbakhch I, Jault F, Lima L, Pavie A. Rupture traumatique de l'aorte. In: Carli P, Gandjbackch I, Jancovici R, Ollivier JP, editors. Plaies et traumatismes du thorax. Paris: Arnette; 1997; p. 313–323.
8. Parmley LF, Mattingly TW, Manion WC, Jahnke EJ. Nonpenetrating traumatic injury of the aorta. Circulation 1958; 17:1085–1101.
9. Merill WA, Lee RB, Hammon JW, Frist WH, Stewart JR, Bender HW. Surgical treatment of acute traumatic tear of the thoracic aorta. Ann Surg 1988; 207:699–706.
10. Pate JW. Traumatic rupture of the thoracic aorta: emergency operation. Ann Thorac Surg 1985; 39:531–537.
11. Williams JS, Graff JA, Uku JM, Steinig JP. Aortic injury in vehicular trauma. Ann Thorac Surg 1994; 57:726–730.
12. Cernaianu AC, Cilley JH Jr, Baldino WA, Spence RK, Delkassi Ad. Determinants of outcome in lesions of the thoracic aorta in patients with multi-organ system trauma. Chest 1992; 101:331–335.
13. Kodali S, Jamieson WRE, Leia-Stephens M, Miyagishima RT, Janusz MT, Tyers GFO. Traumatic rupture of the thoracic aorta. A 20 year review: 1969–1989. Circulation 1991; 84(Suppl III):III40–46.
14. Mattox KL, Holzman M, Pickard LR, Beall AC Jr, De Bakey ME. Clamp/repair: a safe technique for treatment of blunt injury to the descending thoracic aorta. Ann Thorac Surg 1985; 40:456–463.
15. Katz NM, Blackstone EH, Kirklin JW, Karp RB. Incremental risk factors for spinal cord injury following operation for acute traumatic aortic transection. J Thorac Cardiovasc Surg 1981; 81:669–674.
16. Nicolosi AC, Almassi HG, Bousamra M II, Haasler GB, Olinger GN. Mortality and neurologic morbidity after repair of traumatic aortic disruption. Ann Thorac Surg 1996; 61:875–878.

17. Zeiger MA, Clark DE, Morton JR. Reappraisal of surgical treatment of traumatic transection of the thoracic aorta. J Cardiovasc Surg 1990; 31:607–610.
18. Read RA, Moore EE, Moore FA, Haenel JB. Partial left heart bypass for thoracic aorta repair. Survival without paraplegia. Arch Surg 1993; 128:746.
19. Pate JW, Fabian TC, Walker WA. Acute traumatic rupture of the aortic isthmus: repair with cardiopulmonary bypass. Ann Thorac Surg 1995; 59:90–99.
20. Rousseau H, Soula P, Perreault P, et al. Delayed treatment of traumatic rupture of the thoracic aorta with endoluminal covered stent. Circulation 1999; 99:498–504.
21. Meites G, Conil C, Rousseau H, et al. Place des endoprothèses dans le traitement des ruptures traumatiques de l'aorte thoracique. Ann Fr Anesth Reanim. In press 2005.
22. Duham MB, Zygun D, Petrasek P, et al. Endovascular stent grafts for acute blunt aortic injury. J Trauma 2004; 56:1173–1178.
23. Doss M, Balzer J, Martens S, et al. Surgical vs endovascular treatment of acute thoracic aortic rupture: a single-center experience. Ann Thorac Surg 2003; 76:1465–1470
24. Iannelli G, Piscione F, Di Tommaso L, Monaco M, Chiariello M, Spampinato N. Thoracic aortic emergencies: impact of endovascular surgery. Ann Thorac Surg 2004; 77: 591–596.
25. Richeux L, Dambrin C, Marcheix B, et al. Vers une nouvelle prise en charge des ruptures traumatiques aigus de l'isthme aortique. J Radiol 2004; 85:101–106.
26. Rousseau H, Dambrin C, Marcheix B, et al. Acute traumatic aortic rupture: a comparison of surgical and stent-graft repair. J Thorac Cardiovasc Surg 2005; 129:1050–1055.
27. Wheat MW, Palmer RF, Bartley TD, Seelman RC. Treatment of dissecting aneurysms of the aorta without surgery. J Thorac Cardiovasc Surg 1965; 50:364–373.
28. Aronstam EM, Gomez AC, O'Connell TJ, Geiger JP. Recent surgical and pharmacological experience with acute dissecting and traumatic aneurysms. J Thorac Cardiovasc Surg 1970; 59:231–238.
29. Akins CW, Buckley MJ, Daggett W, Mellduff JB, Austen WG. Acute traumatic disruption of the thoracic aorta: a ten year experience. Ann Thorac Surg 1981; 31:305–309.
30. Svensson LG, Antunes MJ, Kinsley RH. Traumatic rupture of the thoracic aorta. A report of 14 cases and a review of the literature. S Afr Med J 1985; 67:853–857.
31. Walker WA, Pate JW. Medical management of acute traumatic rupture of the aorta. Ann Thorac Surg 1990; 50:965–967.
32. Stulz P, Reymond MA, Bertschmann W, Graedel E. Decision making aspects in the timing of surgical intervention in aortic rupture. Eur J Cardiothorac Surg 1991; 5:623–627.
33. Galli R, Pacini D, Di Bartolomeo R, Fattori R, Turinetto B, Grillone G, Pierangeli A. Surgical indications and timing of repair of traumatic ruptures of the thoracic aorta. Ann Thorac Surg 1998; 65:461–464.
34. Lee RB, Stahlman GC, Sharp KW. Treatment priorities in patients with traumatic rupture of the thoracic aorta. Am Surg 1992; 58:37–43.
35. Maggisano R, Nathens A, Alexandrova NA, Cina C, Boulanger B, McKenzie R, Harrison AW. Traumatic rupture of the thoracic aorta: should one always operate immediately? Ann Vasc Surg 1995; 9:44–52.

Acute Traumatic Aortic Rupture: Stent-Graft Repair

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Contents

33.1 Introduction

For many decades, standard surgical practice has dictated that traumatic rupture of the thoracic aorta must be diagnosed quickly and managed aggressively by immediate surgical repair. More recently, with the introduction of endoluminal aortic stent-graft therapy, a new approach was introduced for treatment of traumatic aortic ruptures (TAR). The goal of endovascular stenting is to provide a durable exclusion of the lesion while minimizing the morbidity and mortality of the open procedure. The advantages include the avoidance of thoracotomy, possible heparinization and the likely lower risk of paraplegia.

33.2 Pathophysiology

Blunt aortic injury is relatively frequent and accounts for up to 20% of fatal motor vehicle accidents, with extremely high prehospital mortality rates between 80 and 90% [1, 2]. Without appropriate treatment, 30% of survivors who reach the hospital die within the first 6 h [3]. Trauma to the thoracic aorta occurs mostly as a consequence of rapid deceleration forces. In order of frequency, rupture occurs at the aortic isthmus, the ascending aorta, the aortic arch, the distal descending aorta, and the abdominal aorta. Feczko et al. [4] and Williams et al. [5] reviewed autopsies of blunt trauma victims and found that 55–65% of injuries occurred at the aortic isthmus and 10–14% occurred in the ascending aorta or the aortic arch.

The rapid deceleration forces that tear the aorta often lead to other organ injuries. Pate et al. [6] found that associated injuries were present in more than 90% of patients with aortic transection and 24% of those patients required a major operation before aortic repair.

The aortic tear may be limited to the intima or may extend to both the intima and media or to all aortic layers [2, 7]. In the vast majority of patients who survive the initial traumatic impact, the tear involves both the intima and the media [2].

33.3 Conventional Treatment

Since the classic study of Parmley et al. [2] in 1958, the extremely high death rate of patients with acute blunt rupture of the thoracic aorta has led surgeons to repair the aortic tear as quickly as possible. But despite advances in surgical and reanimation techniques, surgery is still associated with significant morbidity and mortality rates [1, 8]. The overall death rate reported by Von Oppell et al. [8] in a meta-analysis of articles including 1,492 hemodynamically stable patients who reached the operating room was 21.3%, ranging from 0 to 54.2% depending on the study. The majority of these deaths occurred in the postoperative period. In a more recent review of the literature, the surgical mortality rate ranged between 8 and 15%, depending on whether circulatory assistance was used or not to maintain satisfactory perfusion of the distal aorta [9]. Risk factors as-

sociated with a high rate of postoperative mortality include the presence and severity of associated traumatic lesions, preoperative shock (of which only 25% was related to aortic rupture), and coronaropathy or other cardiac anomaly. Paraplegia is a main complication of surgical treatment. When aortic repair is achieved without circulatory assistance, the postoperative paraplegia rate can be as high as 19%, and this risk increases significantly when the aorta is clamped for more than 30 min [8]. With circulatory assistance, the rate is about 2% [9]. On the other hand, the systemic anticoagulation required for the extracorporeal circulation, even at a reduced dose as with heparin-coated systems, is undesirable in traumatic patients with multiple fractures and/or parenchymatous or cerebral lesions. Postoperative complications, including renal, pulmonary, cardiac and neurological, have been reported with rates as high as 50%.

33.4 Concept of Delaying Repair

During the early 1970s, Akins et al. [10] began to delay the repair of blunt aortic tears in selected patients with associated major injuries. Before the aortic repair, they were treated with antihypertensive drugs and no rupture of the traumatic false aneurysm was reported. Similarly, in 1995, Pate et al. [6] reported no rupture of pseudoaneurysm of the thoracic aorta in 41 patients whose arterial pressure was maintained below 140 mmHg and who underwent delayed repair of the aortic tear between 12 h and 24 weeks after the event. Since that time, several studies showed, for stable and nonbleeding lesions, that surgical mortality after aortic injury can be significantly reduced when surgical repair is deliberately delayed [6, 10–14]. These studies support the fact that free rupture of a contained acute traumatic tear of the thoracic aorta is unlikely to occur under proper control of blood pressure. Therefore, it appears safe to allow patients who suffered a major trauma to be stabilized, undergo other emergent operations if needed, and then have elective repair of the aortic tear. The satisfactory results obtained with this management have led some authors to systematically propose delayed surgery. Although this attitude is justified by objective data [15, 16], it is not entirely risk-free because as many as 4% of patients awaiting surgery die of a ruptured aorta usually within 1 week of the traumatic injury [1, 13, 17]. Current indications to delay the aortic repair include the following: trauma to the central nervous system, contaminated wounds, respiratory insufficiency from lung contusion or other causes, surface burns, blunt cardiac injury (myocardial contusion), tears of solid organs that will not undergo surgical management, retroperitoneal hematoma, age of 50 years or older, and medical comorbidities. However, in the case of active bleeding or obstruction of the aortic lumen, immediate treatment has to be provided.

33.5 Stent-Graft

The advent of endovascular stent-graft technology provided a less invasive alternative to thoracic aortic injury treatment. This substitute to open thoracic aortic replacement is attractive for several reasons: much of the surgical morbidity is reduced, sparing thoracotomy, aortic cross-clamping, and cardiopulmonary bypass. Moreover, spinal cord ischemic complications are infrequent probably because the duration of medullary hypotension is significantly reduced.

Until now, the largest series of thoracic aortic stent-graft installations reported mortality and paraplegia rates of 8.7 and 3.6%, respectively [18], knowing that these results improved for second- and third-generation devices [19]. Advancements in device and delivery system design, such as thinner profile and greater flexibility, have markedly improved our ability to repair aortic abnormalities with endovascular grafts.

However, a few elements of TAR treatment with an endovascular stent should be borne in mind. Adequate computed tomography (CT) scan measurements of proximal and distal diameters are needed, as well as the length of the proximal neck. Also, sufficient femoral diameter is needed because of the relatively large introducer sheath used.

33.6 Our Therapeutic Strategy

On arrival in the intensive care unit, patients are immediately submitted to intensive resuscitation with continuous monitoring of ECG, arterial and central venous pressures, renal function, as well as all other hemodynamic and clinical measurements. In the case of hypertension, a drug regimen of beta-blocking agents and arterial vasodilators (nitroprusside and calcium-blocking drugs) is given in order to maintain systolic blood pressure below 120 mmHg. Once the patient is hemodynamically stable, the antihypertensive therapy is given orally. The delay and the choice of treatment are dictated by the general conditions of the patient, the surgical risk factors, and the type of aortic trauma.

Diagnosis and feasibility of stent-graft therapy are evaluated by contrast-enhanced CT, and so far the endovascular option is considered for patients with a contained rupture having a proximal neck longer than 10 mm (Fig. 33.1). The stent-graft diameter is oversized by 15% to achieve a tight seal and the length is, at least, 4 cm longer than the lesion to be treated. Usually one straight stent-graft of 24–36-mm diameter and 80–100 mm in length is used. The introducer caliber ranges between 18 and 24 F (i.e., 6–7.2 mm in diameter), depending on the device available.

The endovascular procedure is performed under general anesthesia with tracheal intubation and mechanical

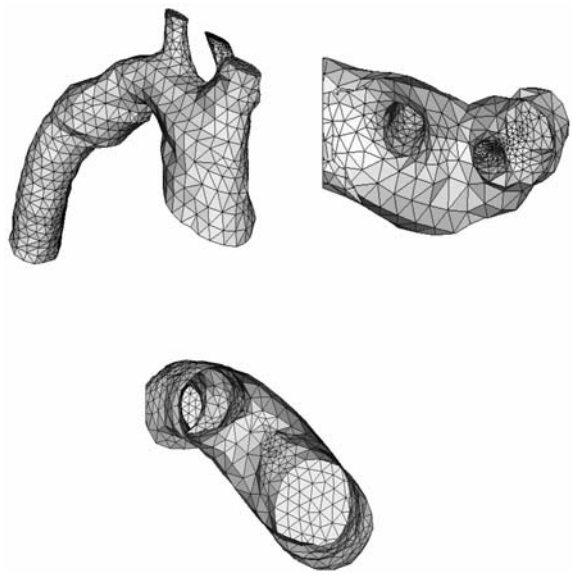


Fig. 33.1. The success of the endovascular procedure greatly depends on the rigorous respect of anatomic criteria, mainly the diameter and the length of the proximal neck, which must be 10 mm or more beneath the origin of the left subclavian artery. Diagnosis and feasibility of stent-graft therapy are evaluated by contrast-enhanced computed tomography (*CT*), with 3D reconstructions. The stent-graft diameters are oversized by 15% to achieve a tight seal and the length is, at least, 4 cm longer than the lesion to be treated. The reference diameter is the diameter of the normal aorta at the level of the left carotid artery

ventilation. Patients are put in the dorsal decubitus position. Drapes are placed to include the abdomen and both groins in the operative field, thus permitting access to the common femoral arteries and, if needed, the iliac arteries or the abdominal aorta. The femoral artery is surgically exposed and a transverse arteriotomy is performed after giving an intravenous heparin bolus of 5,000 IU. Per procedural transesophageal echocardiography (TEE) is done to guide the stent-graft procedure before and after deployment of the device. An initial aortogram with a 5-F pigtail catheter introduced through the left brachial access helps visualization of the arterial anatomy. A 260-cm-long, 0.035 stiff guide wire (Back up Meier, Boston) is advanced up to the aortic arch under fluoroscopic guidance. If an Excluder (Gore) stent-graft is used, a 24-F Cook introducer sheath is inserted. For the Talent device, the stent-graft is contained inside the sheath which helped to insert it. The delivery system is positioned at the preestablished level of the aortic tear. A mean arterial pressure below 70 mmHg is maintained during implantation. The outer sheath is slowly withdrawn to fully deploy the implant. Thereafter, a compliant balloon is inflated to fully anchor the stent into the proximal and distal neck of the aorta.

In our practice, the uncovered portion of the stent-graft was intentionally deployed over the ostium of the left subclavian artery because of the close proximity of the pseudoaneurysmal sac in 17 of the 29 patients treated without occlusion of this artery in all cases. The origin of the left subclavian artery was intentionally overstented in six of the 29 patients without significant clinical consequences and therefore a carotid to subclavian artery bypass was not needed [20].

Finally, the introducer delivery system is removed and the arteriotomy is repaired with interrupted 5-0 polypropylene sutures after arteriographic and TEE controls (Figs. 33.2, 33.3). Anticoagulation is maintained for 48 h and is then followed by aspirin (250 mg/day).

Patient surveillance must be strict to ensure that the false aneurysm is properly excluded. Further imaging

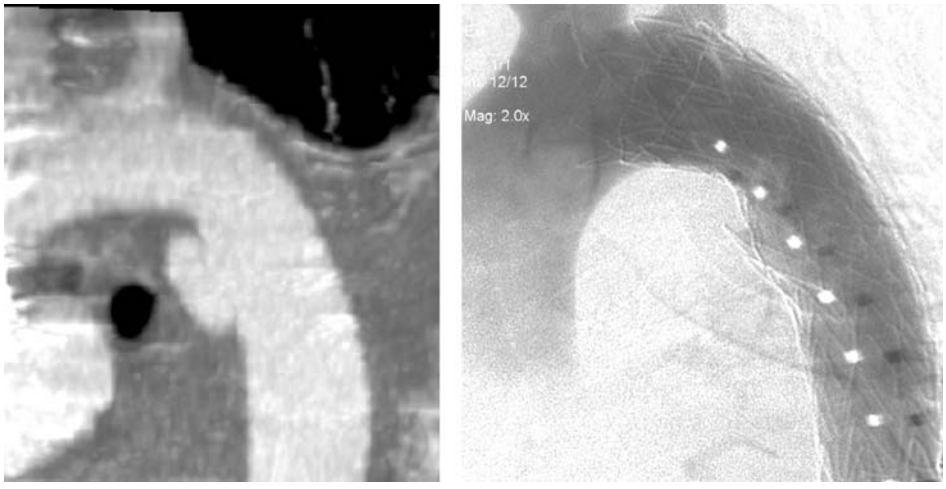


Fig. 33.2. *Left*: Spiral CT shows a typical aortic injury of the isthmus before stent-graft treatment. *Right*: Angiographic control immediately after the intervention shows the proximal extremity of device soon after the left subclavian artery ostium, with a complete exclusion of the pseudoaneurysm. There is a slight indentation of the expanded poly(tetrafluoroethylene) graft at the site of the rupture (Gore device)

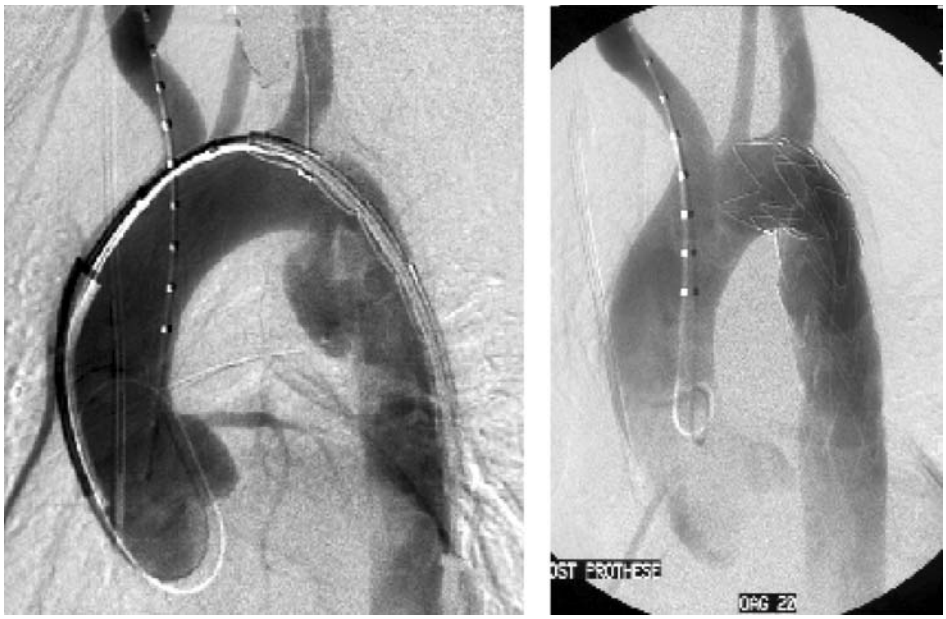


Fig. 33.3. Angiography before and just after the implantation of the uncovered part of the Talent device over the left subclavian artery ostium, with complete exclusion of the pseudoaneurysm

follow-up consists of TEE and spiral CT or MRI (before discharge and at 3, 6, and 12 months, then annually) after the intervention. If there is a complete shrinking of the aorta over the stent-graft on follow-up CT scans at 1 year, only plain X-ray study follow-up from several angles could be done to avoid expensive studies and irradiation of young patients.

33.7 Results

In our experience of 29 patients, digital subtraction angiography and per operative TEE revealed complete exclusion of the pseudoaneurysm in all but one patient who showed an immediate minor proximal endoleak that spontaneously resolved on CT follow-up after 1 month. Only one stent-graft was needed in each patient. The mean procedure time was 96 ± 24 min (median, 83 min; range, 75–180 min) [20]. No significant kinking, twisting, stenosis, intragraft thrombosis, migration, perigraft leak, pseudoaneurysmal expansion, or rupture was observed. In one case, an iliac bypass was performed during the same procedure to repair an iliac rupture.

No death, neurological complication, or infection was observed. However, early after intervention, fever, neutrophilic hyperleukocytosis, and biological inflammatory syndrome were observed in six patients for 1–5 days (mean, 2.7 days); no causal infectious agent could be identified. Blind broad-spectrum antibiotics were given to the first two patients to cover an eventual stent-graft infection.

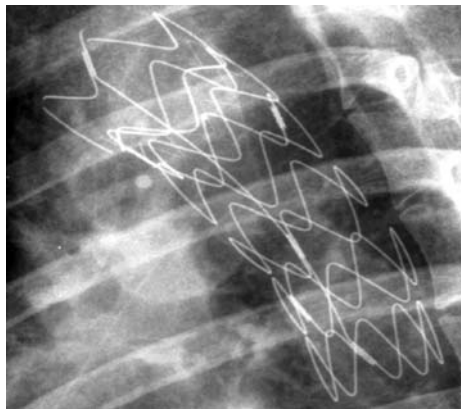


Fig. 33.4. This simple plain film control at 5-years follow-up demonstrated the fractures of the nitinol filaments of the uncovered part of this Talent device

Acute compression of the left main bronchus and homolateral pulmonary atelectasis occurred soon after one procedure; it was believed to be related to a sudden rise in pressure inside the freshly thrombosed pseudoaneurysmal sac. An endobronchial silicone stent was placed with good clinical and bronchoscopic results; it was retrieved 3 months later. After a 7-year follow-up, this patient still presents no sequelae.

We had one case of deteriorated prosthetic material without clinical consequence on late follow-up. None

Table 33.1. Endovascular treatment: results of literature review

	n	Mortality	Paraplegia	Complications (*n*)
Thompson et al. [33]	5	0	0	0
Fujikowa et al. [29]	6 [a]	1 [b]	0	0
Orend et al. [34]	11	1 [b]	0	2 secondary vascular surgery
Lachat et al. [35]	12 [a]	1 [b]	0	1 endoleak secondarystent-graft
Daenen et al. [37]	7	1 [b]	0	0
Czermak et al. [28]	6	0	0	1 endoleak secondary stent graft
Melnitchouk et al. [32]	15	1	0	Type I endoleak (1)
Scheinert et al. [39]	10	0	0	Renal failure (1)
Marty-Ané et al. [38]	9	0	0	0
Orford et al. [36]	9	1	0	Arm ischemia (1)
Amabile et al. [41]	9	0	0	0
Personal experience	29	0	0	1 atelectasia
Total	128	6 (5%)	0	

[a] Emergency cases, [b] Not procedure related

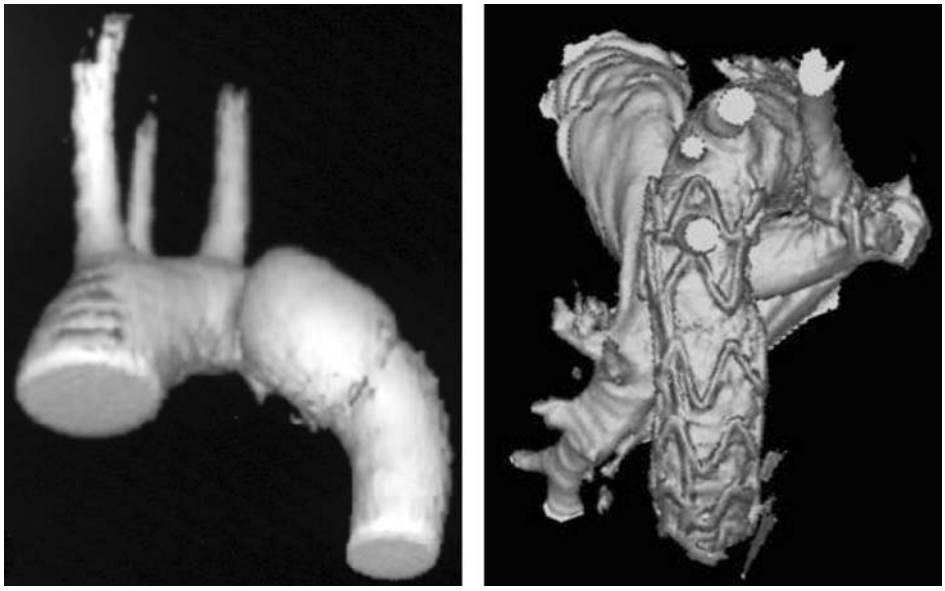
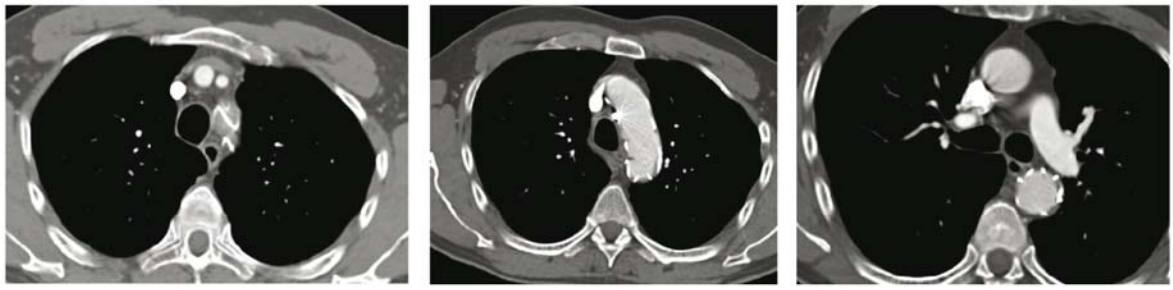


Fig. 33.5. Spiral CT with 3D surface-shaded display reconstructions, before (*left*) and 48 months after (*right*) treatment, showing complete regression of the pseudoaneurysm and the initial noncovered portion of stent-graft over left subclavian artery ostium, which stays patent

were reported in other series exclusively based on aortic trauma including only midterm results [21]. This could be explained by the fact that we observed the fracture on late follow-up 5-years after the procedure (Figs. 33.4). We must keep in mind that if the stent deteriorates during follow-up, it is always possible to treat the complication either by elective endovascular or surgical conversion. The presence of a stent-graft does not seem to have significant effect on secondary surgery [22]. It must be remembered that surgical treatment itself is not entirely devoid of late complications, mainly false aneurysms, anastomotic stenosis, or, rarely, infected prosthetic materials for which the prognosis is catastrophic.

As expected from other studies in the literature (Table 33.1), our patients showed complete healing of the aortic wall without any residual pseudoaneurysm and complete shrinking of the aorta over the stent-graft on follow-up CT scans (mean follow-up of 46 months) (Figs. 33.5, 33.6) [14, 20, 23–41]. This good result is probably explained by the fact that the aorta is usually healthy proximally and distally from the rupture, which means that a satisfactory seal can easily be accomplished without type I endoleak. As the rupture is always limited to the aortic isthmus no or just a few intercostal arteries arise from the pathologic aortic segment, limiting the risk of type II endoleak. Further-



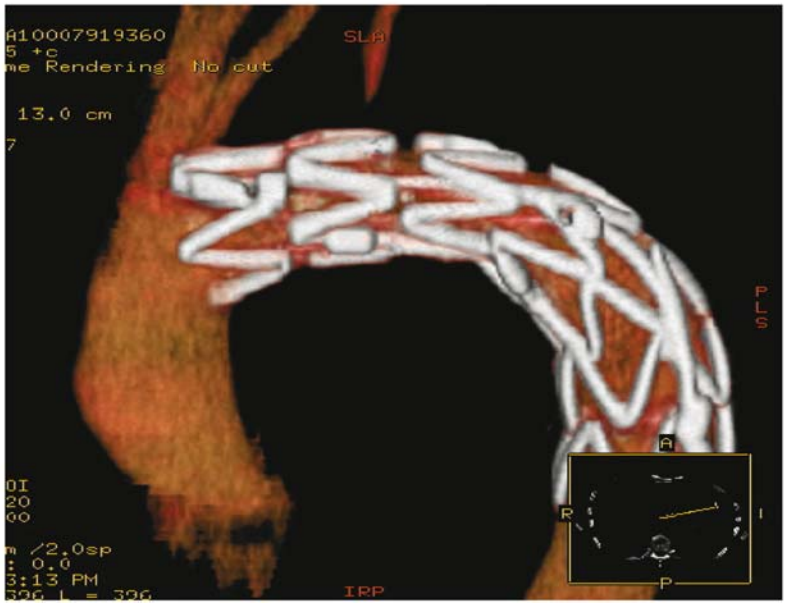


Fig. 33.6. The CT control at 1 year demonstrates the complete healing of the aortic wall, without any endoleak. Note the intentional exclusion of the left subclavian artery, with a reverse flow from the left vertebral artery. The patient did not complain of any symptoms

more, as a single stent-graft is used, the risk of type III endoleak is avoided.

Finally, our comparative study (with similar lesions and severity scores, ISS) confirms that stent-graft therapy is an advantageous alternative to conventional open surgery to treat aortic rupture. The mortality and the paraplegia rates were 21 and 7%, respectively, for the 35 patients treated surgically compared with 0% for the 29 patients treated with a stent-graft with a mean follow-up of 46 months (range, 13–90) [20].

33.8 Potential Limitations

The potential limitations to endovascular treatment are the site of the rupture in regard to other anatomic landmarks, the difficulty of vascular access, and the availability of the device in an emergency situation.

The success of the endovascular procedure greatly depends on rigorous respect of anatomic criteria, mainly the length of the proximal neck, which must be 10 mm or more beneath the origin of the left subclavian artery. If needed, covering the left subclavian artery to lengthen the proximal neck could be a good alternative as we did in six out of our 29 patients (Fig. 33.7) [20]. The safety of overstenting the subclavian artery was demonstrated in different series [20, 42, 43]; thus, transposition of the subclavian artery onto the carotid artery before thoracic stent-graft implantation is not mandatory [44] but could be done in a second step in the event of vertebrobasilar insufficiency or upper limb ischemia. But before excluding the left subclavian artery, a strict check of the patency of collaterals between

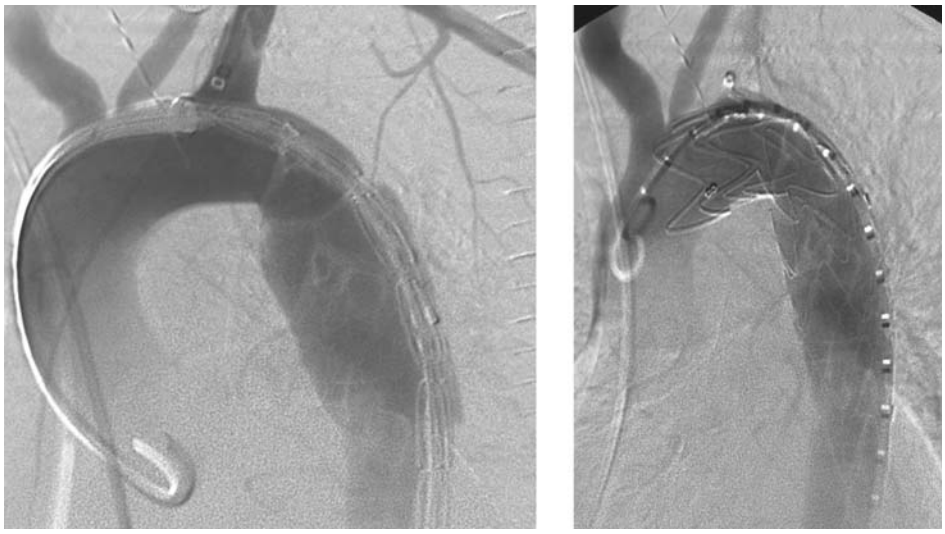


Fig. 33.7. The length of the proximal neck must be 10 mm or more beneath the origin of the left subclavian artery. If needed like in this case, covering the left subclavian artery to lengthen the proximal neck could be a good alternative. A radioopaque marker inside the ostium of the left subclavian artery is very useful to implant accurately the stent-graft

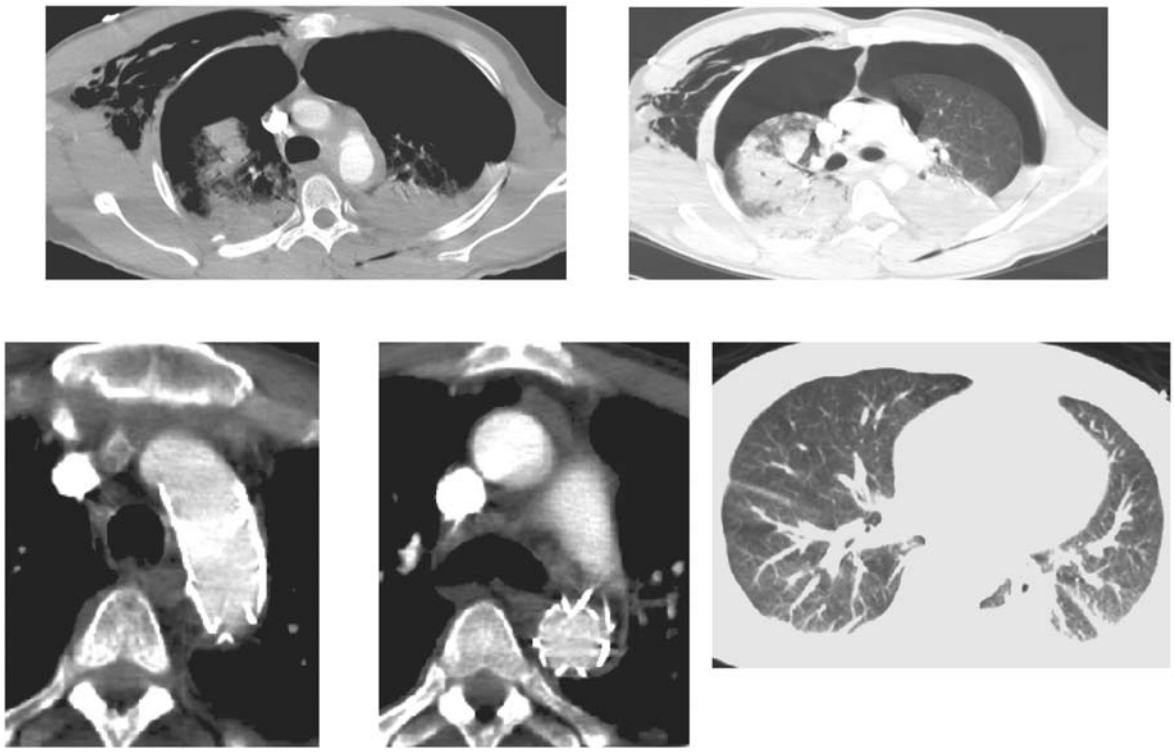


Fig. 33.8. CT scan immediately before and 1 week after implantation. The spiral CT at 1 week shows the complete regression of the pseudoaneurysm with a good apposition of the stent-graft to the aortic wall. The bilateral pneumothorax is also resolved

the vertebral arteries is mandatory. This can be done by angiography just before the implantation.

Because most injuries occur at the aortic isthmus, much concern has been raised regarding the placement of rigid devices in an angulated aortic arch; however, this has been largely overcome with the newer, more flexible devices.

Vascular access is another determinant in the technical success of the endovascular procedure and is sometimes difficult in an emergency situation. Stenosis, tor-

tuosity, calcifications, or an iliofemoral axis of less than 8 mm in diameter can make the progression of a large introducer sheath very hazardous. Spasm can also be a frequent complication in young patients.

So far, most of the reported cases of aortic rupture treated with an endovascular stent-graft have been done in a subacute or chronic setting. With a mortality rate of 8% (one in 12 patients), Lachat et al. [35] suggest that the method might also be valid in an acute situation (Fig. 33.8). As discussed before, stent-graft treatment shows considerable advantages over open surgery. Unfortunately, the costs of current devices make shelf stock impractical in most hospitals and therefore require individual ordering of each device, a distinct disadvantage in emergencies. But as a single length of stent-graft is sufficient, because most cases of rupture are short and limited, we only keep a few stent-grafts of various diameters in stock. In this way, implantation can be done before or immediately after treatment of other life-threatening injuries and in patients for whom conventional surgery is contraindicated, because the procedure is short and has little physiologic effect. The stent-graft insertion could also be done without anticoagulation in some cases of major neurological complications.

33.9 Discussion

Although some authors reserve endovascular treatment for patients in whom standard surgery is contraindicated [38], one might raise the issue of extending the indication to all patients with traumatic injury of the thoracic aorta. Controversy remains regarding the best method of management. As a whole, for patients with signs of imminent aortic rupture who are hemodynamically unstable, immediate treatment is mandatory. Open surgery is still the most accepted treatment but acute endovascular management when feasible shows many advantages compared with conventional surgery, meaning that stent-grafts of different diameters are in stock in the department and there is a team ready "on the clock" to perform this implantation 24 h a day.

If the patient is unstable but the aortic rupture is contained without signs of active bleeding, based on the fact that a contained pseudoaneurysmal traumatic lesion of the thoracic aorta is unlikely to rupture under proper blood pressure control, delayed repair of the aortic injury may be undertaken. This method permits the patient to achieve hemodynamic and physiologic stabilization and to first undergo emergent operations of other injuries if needed. But contrary to situation with surgery, as the stent-grafts can be placed without heparin and without true complication, the benefit of a delayed treatment is questionable as the risk of rupture is always possible.

Finally, for stable patients with isolated thoracic lesion, we believe that little is gained by delaying repair either by conventional surgery for young patients or by a stent-graft for older patients with more comorbidities.

References

1. Fabian TC, Richardson JD, Croce M, et al. Prospective study of blunt injury: multicenter trial of the American Association for Surgery of Trauma. J Trauma 1997; 42:374–380.
2. Parmley LF, Mattingly TW, Manion WC, et al. Non-penetrating traumatic injury of the aorta. Circulation 1958; 17:1086–1101.
3. Avery JE, Hall DP, Adams JE, Headrick JR, Nipp RE. Traumatic rupture of the aorta. South Med J 1979; 72:1238, 1240, 1245.
4. Feczko JD, Lynch L, Pless JE, et al. An autopsy case review of 142 non-penetrating (blunt) injuries of the aorta. J Trauma 1992; 33:846–849.
5. Williams JS, Graff JA, Uku JM, et al. Aortic injury in vehicular trauma. Ann Thorac Surg 1994; 57:726–730.
6. Pate JW, Fabian TC, Walker W. Traumatic rupture of the aortic isthmus: an emergency? World J Surg 1995; 19:119–126.
7. Moar TJ. Traumatic rupture of the thoracic aorta. South Afr Med J 1985; 67:383–385.
8. Von Oppell UO, Dunne TT, DeGroot MK, et al. Traumatic aortic rupture: 20-year meta-analysis of mortality and risk of paraplegia. Ann Thorac Surg 1994; 58:585–593.
9. Jahromi AS, Kazemi K, Safar HA, Doobay B, Cina CS. Traumatic rupture of the thoracic aorta: cohort study and systematic review. J Vasc Surg 2001; 34:1029–1034.
10. Akins CW, Buckley MK, Daggett W, et al. Acute traumatic disruption of the aorta: a 10-year experience. Ann Thorac Surg 1981; 31:305–309.
11. Stulz P, Reymond MA, Bertschmann W, et al. Decision-making aspects in the timing of surgical intervention in aortic rupture. Eur J Cardiothorac Surg 1991; 5:623–627.
12. Kipfer B, Leupi F, Schuepbach P, et al. Traumatic rupture of the thoracic aorta: immediate or delayed surgical repair? Eur J Cardiothorac Surg 1994; 8:30–33.
13. Maggisano R, Nathens A, Alexandrova N. Traumatic rupture of the thoracic aorta: should one always operate immediately? Ann Vasc Surg 1995; 9:44–52.
14. Rousseau H, Soula P, Perreault P, et al. Delayed treatment of traumatic rupture of the thoracic aorta with endoluminal covered stent. Circulation 1999; 99:498–504.
15. Pierangeli A, Turinetto B, Galli R, Caldarera R, Fattori R, Gavelli G. Delayed treatment of isthmic aortic rupture. Cardiovasc Surg 2000; 8:280–283.
16. Langanay T, Verhoye JP, Corbineau H, Agnino A, Derieux T, Menestret P, et al. Surgical treatment of acute traumatic rupture of the thoracic aorta: timing reappraisal. Eur J Cardiothorac Surg 2002; 21:282–287.
17. Holmes JH, Bloch RD, Hall RA, Carter YM, Karmy-Jones RC. Natural history of traumatic rupture of the thoracic aorta managed nonoperatively: a longitudinal analysis. Ann Thorac Surg 2002; 73:1149–1154.
18. Dake MD, Miller DC, Mitchell RS, Semba CP, Moore KA, Sakai T. The "first generation" of endovascular stent-grafts for patients with aneurysms of the descending thoracic aorta. J Thorac Cardiovasc Surg 1998; 116:689–703.
19. Greenberg R, Resch T, Nyman U, et al. Endovascular repair of descending thoracic aortic aneurysms: an early experience with intermediate-term follow-up. J Vasc Surg 2000; 31:147–156.

20. Rousseau H, Dambrin C, Marcheix B, Richeux L, Mazerolles M, Cron C, Watkinson A, Mugniot A, Soula P, Chabbert V, Canevet G, Roux D, Massabuau P, Meites G, Tran Van T, Otal P. Acute traumatic aortic rupture: a comparison of surgical or stent-graft repair. J Thorac Cardiovasc Surg 2005; 129:1050–1055.
21. Jacobs TS, Won J, Gravereaux EC, Faries PL, Morrissey N, Teodorescu VJ, et al. Mechanical failure of prosthetic human implants: a 10-year experience with aortic stent graft devices. J Vasc Surg 2003; 37:16–26.
22. Patel AP, Langan EM 3rd, Taylor SM, Snyder BA, Cull DL, Carsten CG 3rd, Youkey JR, Gray BH, Sullivan TM. Has the emergence of endovascular treatment for aneurysmal and occlusive aortic disease increased the complexity and difficulty of open aortic operations? Ann Vasc Surg 2004; 18:212–217.
23. Semba CP, Kato N, Kee ST, Lee GK, Mitchel RS, Miller DC, et al. Acute rupture of the descending aorta: repair with the use of endovascular stent grafts, J Vasc Interv Radiol 1997; 8:337–342.
24. Kato N, Dake MD, Miller DC, et al. Traumatic thoracic aortic aneurysm: Treatment with endovascular stent-grafts. Radiology 1997; 205:657–662.
25. Perreault P, Soula P, Rousseau H, et al. Acute traumatic rupture of the thoracic aorta: delayed treatment with endoluminal covered stent. A report of two cases. J Vasc Surg 1998; 27:538–544.
26. Deshpande A, Mossop P, Gurry J, et al. Treatment of traumatic false aneurysm of the thoracic aorta with endoluminal grafts. J Endovasc Surg 1998; 5:120–125.
27. Schonholz C, Donnini F, Naselli J, et al. Acute rupture of an aortic false aneurysm treated with a stent-graft. Endovasc Surg 1999; 6:293–296.
28. Czermak BV, Waldenberger P, Perkmann R, Rieger M, Steingruber I, Mallouhi A, Fraedrich G, Jaschke W. Placement of endovascular stent-grafts for emergency treatment of acute disease of the descending thoracic aorta. AJR Am J Roentgenol 2002; 179:337–345.
29. Fujikawa T, Yukioka T, Ishimaru S, et al. Endovascular stent grafting for the treatment of blunt thoracic aortic injury. J Trauma 2001; 50:223–229.
30. Fattori R, Napoli G, Lovato L, Russo V, Pacini D, Pierangeli A, Gavelli G. Indications for, timing of, and results of catheter-based treatment of traumatic injury to the aorta. AJR Am J Roentgenol 2002; 179:603–609.
31. Hoffer EK, Karmy-Jones R, Bloch RD, et al. Treatment of acute thoracic aortic injury with commercially available abdominal aortic stent-grafts. J Vasc Interv Radiol 2002; 13:1037–1041.
32. Melnitchouk S, Pfammatter T, Kadner A, Dave H, Witzke H, Trentz O, et al. Emergency stent-graft placement for hemorrhage control in thoracic aortic rupture. Eur J Cardiothorac Surg 2004; 25:1032–1038.
33. Thompson CS, Rodriguez JA, Damaia VG, DiMugno L, Shafique S, Olsen D, et al. Acute traumatic rupture of the aorta treated with endoluminal stent grafts. J Trauma 2002; 52:1173–1177.
34. Orend KH, Pamler R, Kapfer X, Liewald F, Gorich J, Sunder-Plassman L. Endovascular repair of traumatic descending aortic transection. J Endovasc Ther 2002; 9:573–578.
35. Lachat M, Pfammatter T, Witzke H, et al. Acute traumatic aortic rupture: early stent-graft repair. Eur J Cardiothorac Surg 2002; 26:959–963.
36. Orford VP, Atkinson NR, Thomson K, Milne PY, Campbell WA, Roberts A, et al. Blunt traumatic aortic transection. Ann Thorac Surg 2003; 75:100–111.
37. Daenen G, Maleux G, Daenens K, Fourneau I, Nevelsteen A. Thoracic aorta endoprosthesis: the final countdown for open surgery after traumatic aortic rupture. Ann Vasc Surg 2003; 17:185–191.
38. Marty-Ané CH, Berthet JP, Branchereau P, Mary H, Alric P. Endovascular repair for acute traumatic rupture of the thoracic aorta. Ann Thorac Surg 2003; 75:1803–1807.
39. Scheinert D, Krakenberg H, Schmidt A, Gummert JF, Nitzsche S, Braunlich S, et al. Endoluminal stent-graft placement for acute rupture of the descending thoracic aorta. Eur Heart J 2004; 8:694–700.
40. Iannelli G, Piscione F, Di Tommaso L, Monaco M, Chiariello M, Spampinato N. Thoracic aortic emergencies: impact of endovascular surgery. Ann Thorac Surg 2004; 77:591–596.
41. Amabile P, Collart F, Gariboldi V, Rollet G, Bartoli JM, Piquet P. Surgical versus endovascular treatment of traumatic thoracic aortic rupture. J Vasc Surg 2004; 40:873–879.
42. Hausegger KA, Oberwalder P, Tiesenhausen K, Tauss J, Stanger O, Schedlbauer P, Deutschmann H, Rigler B. Intentional left subclavian artery occlusion by thoracic aortic stent-grafts without surgical transposition. J Endovasc Ther 2001; 8:472–476.
43. Gorich J, Ermis C, Kramer SC, Fleiter T, Wisianowsky C, Basche S, Gottfried HW, Volkmer BG. Interventional treatment of traumatic priapism. J Endovasc Ther 2002; 9:614–617.
44. Dake MD. Endovascular stent-graft management of thoracic aortic diseases. Eur J Radiol 2001; 39:42–44.

Surgical Treatment and Endovascular Issue in the Traumatic Rupture of the Descending Aorta

Pascal Leprince, Philippe Cluzel, Alain Pavie

34

Contents

34.1 Introduction

Acute traumatic rupture of the aorta (ATRA) is a life-threatening complication of blunt chest traumas, which are mostly related to car crashes [1]. While more than 80% of patients showing this complication die on site, only 10–20% can be transferred alive to the emergency care unit. This represents four per 1,000 patients transferred to the emergency care unit after car accidents [8].

In clinical series, the tear is located at the isthmus of the aorta in 90% of cases (Fig. 34.1). However, in necropsy series, isthmic location represents only 50% of the cases, highlighting the high rate of death associated with other locations. Furthermore, 90% of patients show polytraumatism and have other life-threatening injuries.

In the past few decades, it was admitted that ATRA must be managed aggressively with immediate surgical repair. However, postoperative mortality remained high, mostly related to associated lesions. Moreover, different papers recently showed that surgical treatment could be delayed with very low risk of rupture, as long as adequate antihypertensive treatment is given [5, 6, 11]. Finally, during the last decade, endovascular stent-grafting was established as an alternative to open surgery.

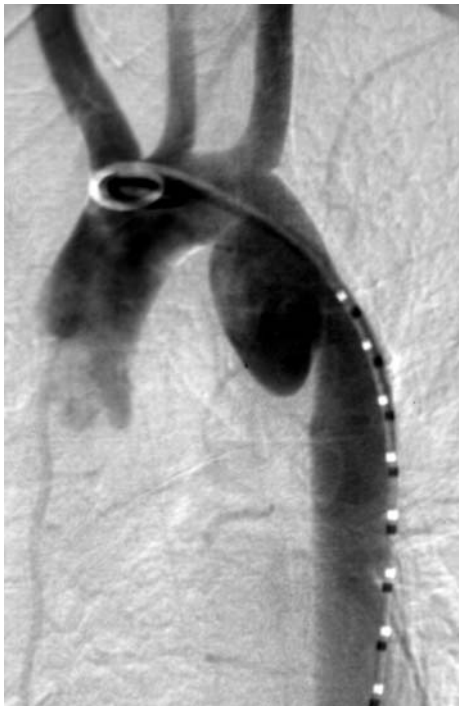


Fig. 34.1. Angiography showing isthmic location of the false aneurysm

So, owing to these new approaches surgical treatment of ATRA has to be reevaluated.

34.2 Conventional Surgical Treatment

Surgical approach is made through a left postero-lateral thoracotomy in the fourth intercostal space, which allows access to the descending thoracic aorta as well as the heart and the trunk of the pulmonary artery. The goal of the surgical treatment is to clamp the aorta proximally and distally to the lesion, open the tear and

repair it. This treatment leads to two types of discussion: firstly, how to repair the lesion (direct repair or graft interposition) and, secondly, how to protect the spinal cord from ischemia?

34.2.1 Type of Repair

34.2.1.1 Direct Repair

Direct suture of the tear should be used whenever it can be done since it allows complete healing of the aortic wall. Direct repair (Fig. 34.2 a, c) is easy in the case of incomplete rupture since there is no retraction of the two ends of the rupture. In complete rupture, direct suture can be helped by moving the proximal and the distal part of the aorta. Direct repair becomes impossible in the case of old lesions or very complex and extensive lesions.

34.2.1.2 Graft Interposition

Replacement of the diseased segment of the aorta with a synthetic graft is easy to perform. However, graft interposition (Fig. 34.2 b, d) may lead to the occurrence of several complications (inadequate length or diameter, anastomotic false aneurysm, infection) which can be surgically challenging to treat. This technique must be used only when direct suture is not possible.

34.2.2 Spinal Cord Protection During the Aortic Cross Clamp

Three techniques can be used.

1. No protection: "clamp and sew." This method is the simplest. It does not require cardiopulmonary bypass (CPB) and can be performed without heparin; however, it is associated with a high risk of paraplegia. The risk is proportional to the duration of the aortic cross clamp. Close to 0% under 20 min of cross-clamp time, this risk goes up to 20, 60 and 100% for clamping times of 30, 60 and 90 min, respectively [4, 10]. Nowadays, this method is rarely used since patients with contraindications to CPB are postponed and/or treated with a covered stent graft.
2. Heparinized shunt (Fig. 34.3). A coated shunt can be used to bypass the interrupted segment of the aorta. This allows perfusion of the distal aorta without using CPB and can be performed with no heparin. However, the output of the shunt is not controlled; in the case of sudden hemorrhage, it is not possible to immediately reinfuse the blood; the system does not prevent hemodynamic instability or oxygenation impairment that can occur during this surgery. With

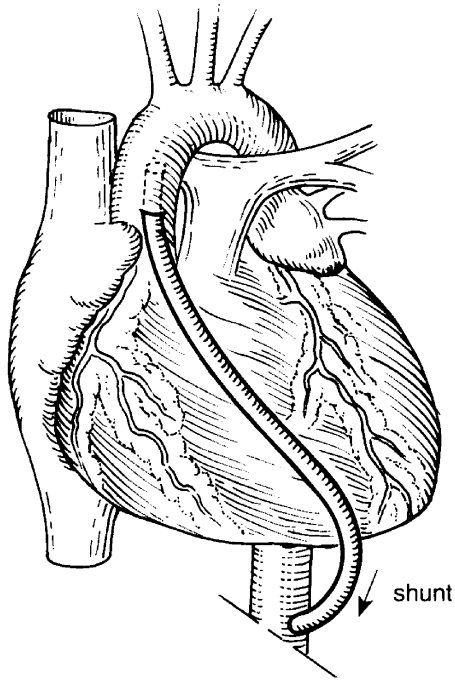


Fig. 34.3. Passive shunt

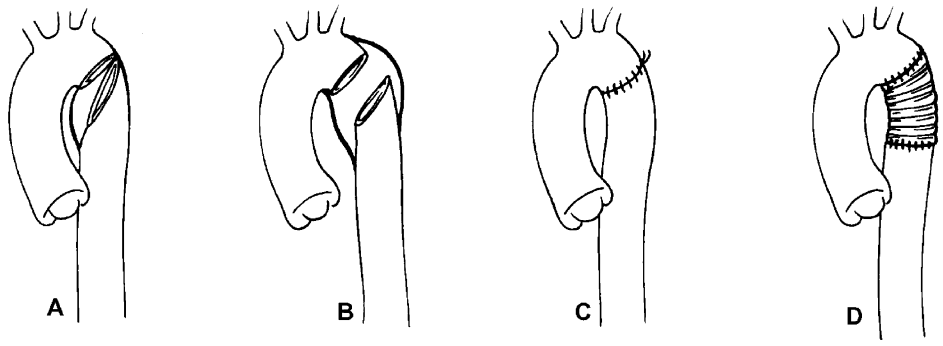


Fig. 34.2. Types of lesions and repair: **A** incomplete rupture with no retraction; **B** complete rupture with retraction; **C** direct repair; **D** graft interposition

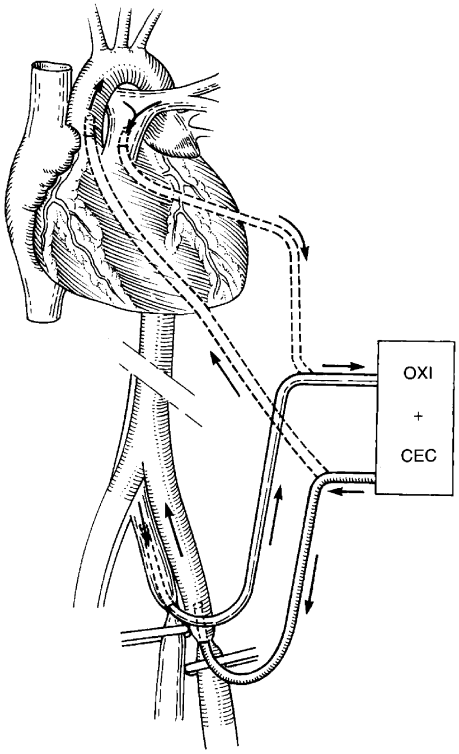


Fig. 34.4. Cardiopulmonary bypass

this technique, the rate of paraplegia is about 11% [4, 7, 10].

3. CPB (Fig. 34.4). Venous blood is drained from the right atrium through a cannula inserted through the femoral vein or from the pulmonary artery and is reinfused distally to the clamped segment, mostly into the femoral artery. The method has many advantages: oxygenation of the reinfused blood, control of the output, control of the bleeding through blood reinfusion directly with the CPB. This method allows us to repair complex lesions requiring a long cross-clamp time with a rate of paraplegia lower than 2% [10]. However, the use of CPB requires the infusion of a high dose of heparin (3 mg/kg). This dramatically increases the risk of bleeding complications in patients with polytraumatism, particularly bleeding into the brain or the lungs.

34.2.3 Results of the Surgery

Postoperative mortality is reported to be between 6 and 35%, mainly related to associated lesions [4, 7, 10]. This is why, in the case of associated lesions with a risk of bleeding, the surgery is postponed and other lesions are treated primarily. Then the postoperative rate of death is lowered to 0–5% [5].

As described before, the rate of spinal cord ischemia related complication depends on the surgical technique. A definitive lesion of the left laryngeal nerve is reported in 6–8% of cases [4, 7].

In the case of direct repair, the long-term prognosis is excellent with an *ad integrum* restitution of the aortic wall and preservation of growth potential in children and adolescents.

34.3 Endovascular Treatment

Over the last decade, the covered stent graft became more and more an alternative to open repair in patients with acute and chronic disease of the thoracic aorta. In 1999, Rousseau et al. [9] reported a series of five subacute and four chronic aortic traumatic ruptures treated with a covered stent graft. They reported 100% success of the exclusion of the false aneurysm, no death and only two major complications: one occlusion of the ostium of the left subclavian artery treated with stents and one transitory compression of the left main bronchus. Similar results were reported by Kato et al. [3]. In a recent paper, Dunham et al. [2] analyzed a total of nine series published between 2001 and 2003 and reporting at least four patients with ATRA treated with a covered stent graft. These series represent a total of 68 patients with a technical success rate of 98.5%, an overall mortality of 5.9%, a graft-related death rate of 1.5%, an endoleak rate of 7.4% and no postoperative paralysis. These results compare favorably with those of surgical series.

The prerequisites for ATRA treatment with covered stent graft are essentially anatomical: a proximal and distal landing zone of at least 1.5-cm length with a diameter not bigger than the available graft (46 mm), and an iliac artery diameter of at least 8 mm. If necessary the proximal landing zone can extend proximally to the left subclavian artery. This artery can be left occluded, the left upper limb being perfused through collaterals, or a carotid–suclavian bypass can be performed. In the review by Dunham et al., there was one case of secondary left arm claudication. Also, in their own series, the authors reported a case of posterior fossa infarction after occlusion of a dominant vertebral artery.

Long-term results remain unknown. Most of the series report a mean follow-up of less than 2 years. Patients need to be followed with repeated imaging to survey for stent-graft failure and secondary occurrence of an endoleak. If the occurrence of a secondary endoleak related to evolving aortic disease or covered stent-graft failure is a major concern, it may not be relevant in patients with ATRA. Indeed, once the false aneurysm has been excluded, the aortic tear heals underneath the stent and the false aneurysm shrinks and finally disappears (Fig. 34.5).

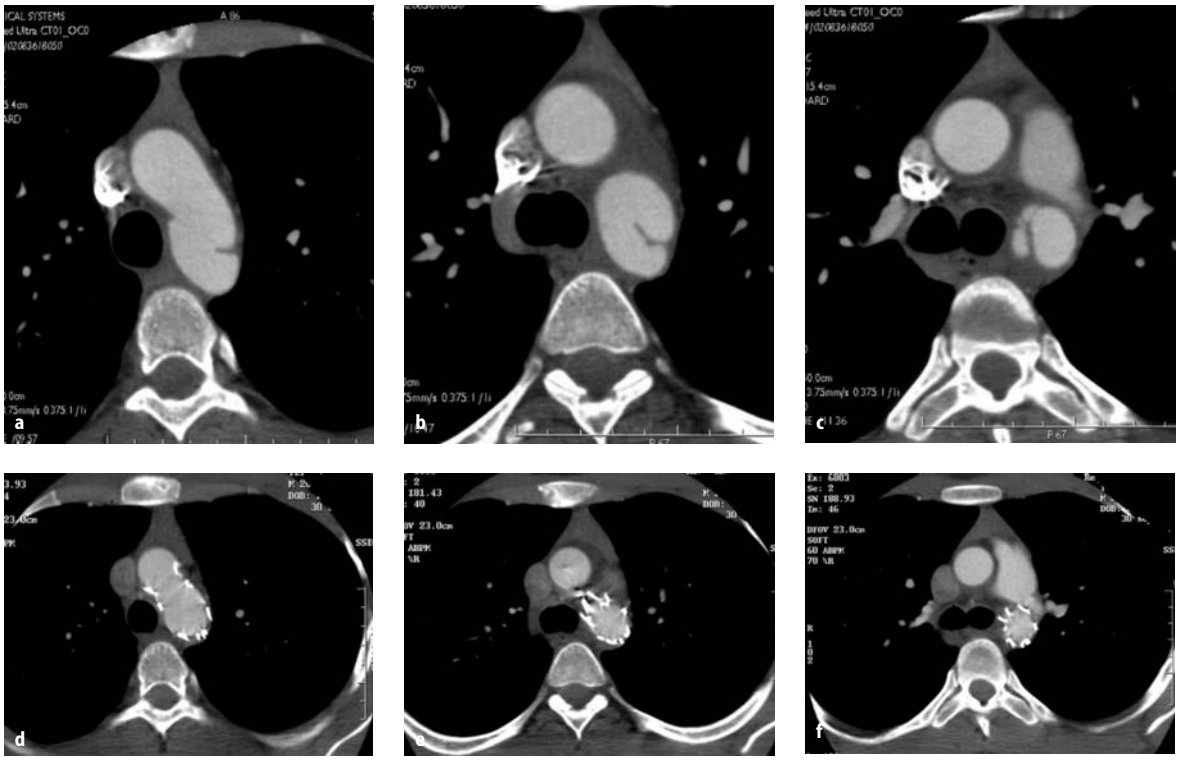


Fig. 34.5. Computed tomography scan imaging showing **a–c** acute traumatic rupture of the aorta before treatment and **d–f** 1-year follow-up after covered stent-graft placement. The false aneurysm disappeared

34.4 Conclusion

ATRA is a life-threatening lesion but if the patient survives the acute trauma the risk of secondary rupture remains low under strict blood-pressure control. Thus, treatment of the aortic lesion can be postponed particularly if the patient shows multiple injuries. The use of a covered stent graft appears promising with good immediate results and shrinking of the false aneurysm cavity occurring at midterm follow-up.

References

1. Brundage SI, Harruff R et al. (1998) The epidemiology of thoracic aortic injuries in pedestrians. J Trauma 45:1010–1014.
2. Dunham MB, Zygun D et al. (2004) Endovascular stent grafts for acute blunt aortic injury. J Trauma 56:1173–1178.
3. Kato N, Dake MD et al. (1997) Traumatic thoracic aortic aneurysm: treatment with endovascular stent-grafts. Radiology 205:657–662.
4. Kodali S, Jamieson WR et al. (1991) Traumatic rupture of the thoracic aorta. A 20-year review: 1969–1989. Circulation 84:III40–46.
5. Langanay T, Verhoye JP et al. (2002) Surgical treatment of acute traumatic rupture of the thoracic aorta a timing reappraisal? Eur J Cardiothorac Surg 21:282–287.
6. Maggisano R, Nathens A et al. (1995) Traumatic rupture of the thoracic aorta: should one always operate immediately? Ann Vasc Surg 9:44–52.
7. Pate JW, Fabian TC et al. (1995) Traumatic rupture of the aortic isthmus: an emergency? World J Surg 19:119–125; discussion 125-116.
8. Pate JW, Fabian TC et al. (1995) Acute traumatic rupture of the aortic isthmus: repair with cardiopulmonary bypass. Ann Thorac Surg 59:90–98; discussion 98–99.
9. Rousseau H, Soula P et al. (1999) Delayed treatment of traumatic rupture of the thoracic aorta with endoluminal covered stent. Circulation 99:498–504.
10. von Oppell UO, Dunne TT et al. (1994) Traumatic aortic rupture: twenty-year metaanalysis of mortality and risk of paraplegia. Ann Thorac Surg 58:585–593.
11. Walker WA, Pate JW (1990) Medical management of acute traumatic rupture of the aorta. Ann Thorac Surg 50:965–967.

35

Classification and Decision Algorithm of Posttraumatic Chronic Lesions of the Isthmus and the Descending Thoracic Aorta

Jean-Philippe Verhoye, Bertrand De Latour, Cyryl Kakon, Jean-François Heautot

Contents

35.1 Introduction

The natural history of chronic isthmus and descending aorta posttraumatic false aneurysms has been directly related to the limitations of diagnostic imaging. The considerable progress made in noninvasive angiography during the last 10 years (mainly through the easy access to multislice computed tomography, CT, scanners) will probably contribute to the disappearance of chronic lesions discovered fortuitously by revealing the injuries at the acute stage.

The lesion is often an intimal tear, more or less circumferential, misdiagnosed at the initial stage, which evolves towards a saccular pseudoaneurysm, incidentally demonstrated by a thoracic imaging study performed for another reason (Fig. 35.1). Some become symptomatic by a mechanism of compression (either

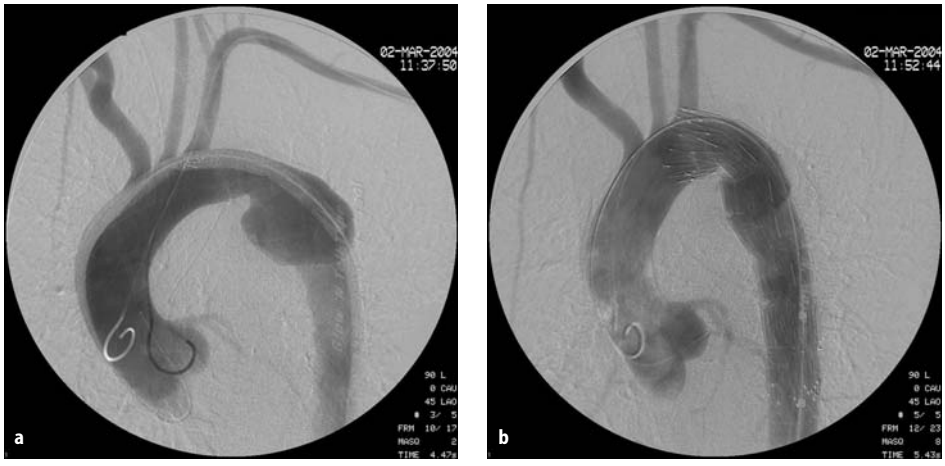


Fig. 35.1. a Angiography during endovascular treatment of a chronic posttraumatic pseudoaneurysm, showing the stent-graft in its sheath. **b** After deployment, angiographic control shows the complete exclusion of the aneurysm

tracheo-bronchial or recurrent nerve) and are discovered by a targeted imaging study.

Today the progress in intensive care and the wide accessibility to efficient vascular imaging studies in emergency situations have allowed better management of polytrauma patients. The advances in intensive care have induced an evolution of therapeutic strategy of acute ruptures of the aortic isthmus towards delayed surgery [1], the imaging advances have contributed to a drastic decrease, nearly disappear of misdiagnosed chronic false aneurysms.

According to the criteria defined by Langanay et al. (Chap. 32), the only remaining surgical indication in an emergency is isolated lesions of less than 24 h, hemodynamically unstable, without associated lesion contraindicating a cardiopulmonary bypass.

It is easy to figure out now, in the precarious context of a polytrauma patient, that an isthmus lesion can be medically controlled and treated after a delay, to limit the inherent morbidity/mortality of the surgical procedure under cardiopulmonary bypass in an emergency. It is now a consciously "delayed acute" surgical management, where the lesion is voluntarily "chronicized."

In spite of intensive care and careful follow-up, patients have suffered ruptures during these periods of "controlled chronicization."

Stent-grafts will probably help to prevent these sudden early ruptures while allowing a quick initial treatment of the lesion. This technique does not command systemic anticoagulation during or after the procedure, thus limiting the hemorrhagic complications in polytrauma patients. Encouraging results are currently being published [1, 2]. The challenge of this new management is linked to the midterm and long-term exclusion of the lesion in a definitive way like conventional surgery does.

The nonendothelialization of the stent-graft and the increasing aortic diameter with the patient's age carries a risk of late type I endoleaks which could potentially activate a degeneration of the initial lesion into a chronic false aneurysm. In this case, the nonendothelialization would be an advantage by facilitating the surgical explantation of the stent-graft and conventional repair of the aorta, even a long time after the endovascular procedure (Fig. 35.2).

The endovascular therapy is a major step in the history of therapeutic management of traumatic injuries of the isthmus and the descending aorta. Because of this trend, it has appeared necessary to us to propose a new classification of these lesions, to better define the management, whichever therapeutic solution is used. The classification must allow us to define stages for the purpose of comparing therapeutic results among homogeneous groups of patients. It must also propose a decision algorithm to better select the most appropriate therapeutic choice with respect to the priorities in patient management.

35.2 Classification of Patients with Posttraumatic Injuries of the Aortic Isthmus or the Descending Aorta

Class I: acute (< 48 h)	
A: Isolated lesion	B: Polytrauma
1: Stable	2: Unstable

Class I corresponds to a post-raumatic lesion of the isthmus or the descending aorta, with two subclasses:

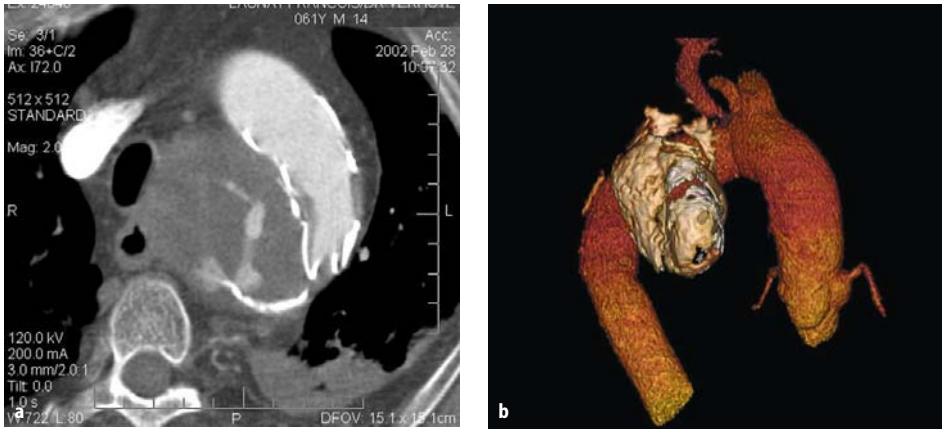


Fig. 35.2. a CT angiography. Control 6 months after stent-graft treatment of a chronic posttraumatic pseudoaneurysm, showing a type I endoleak. The endoleak was monitored and spontaneously resolved, but at 3 years the patient suffered bronchial compression due to endotension. Surgical conversion had to be performed (graft interposition and aneurysm thrombus resection). **b** CT angiography, 3D reconstruction, volume rendering. Control after surgical conversion

the lesion is either isolated (A) or associated with others injuries (polytrauma, B), and the patient is hemodynamically stable (1) or unstable (2).

Class II: delayed acute (>48 h)	
A: Isolated lesion	B: Polytrauma
1: Stable	2: Unstable

Class II corresponds to a lesion initially not treated because of misdiagnosis or surgical contraindication. The lesion is either isolated (A) or associated with other injuries (polytrauma, B), and the patient is hemodynamically stable (1) or unstable (2).

Class III: incidental chronic	
A: Stable diameters/unknown evolutivity	B: Increasing
1: Asymptomatic	2: Symptomatic

Class III corresponds to an incidental posttraumatic chronic pseudoaneurysm of the isthmus or the descending aorta. This lesion can be stable, or its evolutivity unknown (A), or increasing (more than 1 cm/year) or a contained ruptured (B). It can also be asymptomatic (1) or symptomatic (dysphonia, cough, bronchitis, chest pain, pleural effusion) (2).

35.3 Decision Algorithm

Starting from this classification, it is possible to define a decision algorithm taking into account the surgical and endovascular results of the last 10 years. Surgery assisted by cardiopulmonary bypass has proven its long-term efficacy at the cost of reduced postoperative morbidity/mortality in patients younger than 70, with no major risk factor.

The follow-up for patients treated by a stent-graft is hardly 8 years in the most expert teams, but the best indications are already being defined. To deploy a stent-graft is not to cure because we know now that stent-grafts do not get endothelialized, which can cause mid-term and long-term endoleaks and endotension, which reactivate the aneurysmal process and the risk of sudden rupture.

Regarding this technique, the current strategy is rather based on getting over the acute phase to avoid rupture in the critical context of a polytrauma patient. The surgical access is limited to the groin (depending on the quality of the iliac arteries) even if it is preferable to perform the operation in an operating room with cardiopulmonary bypass at hand. According to the patient status, it can be performed in an acute emergency, a delayed emergency, or after a period of controlled chronicization.

A careful CT scan follow-up is mandatory, at 1 and 6 months, and yearly thereafter, for the current generations of stent-grafts. The patients must be informed of this requisite and that late disorders can occur, which can then lead to elective surgery.

The other field of endovascular treatment is the management of patients older than 70, in which surgery carries a significantly higher risk. The lesions are often incidentally diagnosed, asymptomatic, and often large (maximum diameter frequently more than 60 mm), after trauma occurred several decades before. The risk of rupture of these lesions is not known, and endovascular solution seems a better first choice for these patients.

So, a therapeutic decision algorithm is proposed is as follows:

Class I, II	A1 < 70 years old	Surgery except contra-indication
	A1 > 70 years old, A2 and B	Stent-graft
Class III	A1	CT follow-up
	A2 < 70 years old	Surgery, except contra-indication
	A2 > 70 years, B	Stent-graft

35.4 Results of a Multicenter Retrospective Study

In order to validate the appropriateness of this classification and algorithm, a retrospective study was conducted in six French university centers. We report the midterm results for 47 class II and III patients. The aortic injuries were diagnosed at the time of the trauma (63.8%, n=30), or incidentally (36.2%, n=17). Between January 1996 and June 2004, endovascular repair of the descending thoracic aorta with commercially available stent-grafts was performed in 47 patients (mean age, 43 ± 19 years) at an average of 6 ± 11 years after the injury. Because of comorbidities, eight patients (17%) were judged not to be reasonable surgical candidates for a conventional surgical approach. Follow-up was 100% complete and averaged 18 ± 13 months.

Stent-graft deployment was successful in all patients. No early death occurred. One late transient paraparesia occurred. Two patients had a primary endoleak, one type I and one type II which spontaneously resolved at 1 and 6 months, respectively. Two endotensions were described after 36 months (currently being monitored) and 30 months (surgical conversion). The actuarial survival estimates at 1 and 3 years were 97.7 ± 2.3 and

87.9 ± 9.5%, respectively. The actuarial freedom from reintervention on the descending thoracic aorta was 100 and 90.9 ± 8.7% at 1 and 3 years, respectively. The actuarial freedom from treatment failure (a conservative, all-encompassing performance indicator including endoleak, device mechanical fault, reintervention, late aortic-related death, or sudden, unexplained late death) at 1 and 3 years was 97.7 ± 2.3 and 74.6 ± 11.9, respectively. The mean diameter of the pseudoaneurysm was 44 ± 18 mm before treatment and decreased significantly ($p<0.001$) to 40 ± 18 mm after treatment.

35.5 Results from the Literature

These results from the literature are summarized in Tables 35.1 and 35.2.

Table 35.1. Surgical results from the literature

	Finkelmeyer et al. [3]	McCollum et al. [4]	Soyer et al. [5]	Roques et al. [6]
Patients (*N*)	413	50	20	19
Operative mortality (%)	4.6	4	0	0
Respiratory complications (%)	0.7	2	–	26
Paraplegia (%)	1.4	–	–	–
Paraparesia (%)	1.4	–	15	–
Stroke (%)	1.1	–	–	–
Renal failure (%)	1.4	2	–	–
Recurrent paralysis (%)	6.7	4	–	10

Table 35.2. Endovascular results from the literature

	Demers et al. [7]	Kato et al. [8]	Rousseau et al. [9]	French multicenter study
Patients (*N*)	15	10	8	47
Operative mortality	1	0	0	0
Respiratory complications	–	1	1	–
Paraplegia	–	–	–	0
Paraparesia	–	–	–	1
Stroke	–	–	–	–
Renal failure	–	–	–	–
Recurrent paralysis	–	–	–	–
Vascular access complication	–	1	1	2

35.6 Discussion

Elective surgery of posttraumatic pseudoaneurysms has proven efficient. Direct suturing with cardiopulmonary bypass is possible in nearly half of cases. It carries a low mortality, and a low renal and respiratory morbidity. The rate of paraplegia is close to zero in the best series. So, in these cases, the only advantage of endovascular techniques is the mini-invasivity. Stent-graft treatment has proven its feasibility. As the adjacent aortic wall is normal, nondegenerative, late endoleaks are more unlikely than in cases of degenerative aneurysms [7]. The limits are known. Long proximal necks and long one-piece stent-grafts are required to achieve good preliminary results. This will probably make more frequent prior surgical bypass of the left supra-aortic vessels (Fig. 35.3) in order (1) to get a longer proximal neck and (2) to maintain the patency of the left subclavian artery, essential for spinal cord blood perfusion as has been shown by surgery studies, because long stent-grafts will increase the risk of paraplegia if the left subclavian artery has to be intentionally occluded [10].

Fig. 35.3. Computed tomography (*CT*) angiography, 3D reconstruction, volume rendering. Control of a stent-graft 4 years after endovascular treatment of a chronic posttraumatic pseudoaneurysm. The left supra-aortic vessels have been bypassed (*arrow*), in order to get a longer proximal neck

35.7 Conclusion

The management of acute and chronic lesions of the isthmus and the descending aorta has markedly evolved with advances of imaging and intensive care.

Endovascular techniques, limiting the morbidity of the treatment at the acute, delayed acute and controlled chronic phases in unstable and trauma patients, do not preclude delayed surgical options, currently the gold standard for definitive lesion exclusion.

The endovascular techniques also seem a good option in incidental lesions, with favourable anatomy, in elderly patients.

It must be kept in mind that currently to deploy is not to cure, and that life-long imaging follow-up is necessary.

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References

1. Rousseau H, Dambrin C, Marcheix B, Richeux L, Mazerolles M, Cron C, Watkinson A, Mugniot A, Soula P, Chabbert V, Canevet G, Roux D, Massabuau P, Meites G, Tran Van T, Otal P. Acute traumatic aortic rupture: a comparison of surgical and stent-graft repair. J Thorac Cardiovasc Surg 2005; 129:1050–1055.
2. Bortone AS, Schena S, D'Agostino D, Dialetto G, Paradiso V, Mannatrizio G, Fiore T, Cotrufo M, de Luca Tupputi Schinosa L. Immediate vs delayed endovascular treatment of post-traumatic aortic pseudoaneurysms and type B dissections: retrospective analysis and premises to the upcoming European trial. Circulation 2002; 106:I234–240.
3. Finkelmeier BA, Mentzer RM Jr, Kaiser DL, Tegtmeyer CJ, Nolan SP. Chronic traumatic thoracic aneurysm. Influence of operative treatment on natural history: an analysis of reported cases, 1950–1980. J Thorac Cardiovasc Surg 1982; 84:257–266.
4. McCollum CH, Graham JM, Noon GP, De Bakey MC. Chronic traumatic aneurysms of the thoracic aorta: an analysis of 50 patients. J Trauma 1979; 19:248–252.
5. Soyer R, Brunet A, Piwnica A, Blondeau P, Carpentier A, Donzeau-Gouge P, Bical O, Dubost C. Traumatic rupture of the thoracic aorta with reference to 34 operated cases. J Cardiovasc Surg (Torino) 1981; 22:103–108.
6. Roques X, Remes J, Laborde MN, Guibaud JP, Rosato F, MacBride T, Baudet E. Surgery of chronic traumatic aneurysm of the aortic isthmus: benefit of direct suture. Eur J Cardiothorac Sur. 2003; 23:46–49.
7. Demers P, Miller C, Scott Mitchell R, Kee ST, Lynn Chagonjian RN, Dake MD. Chronic traumatic aneurysms of the descending thoracic aorta: mid-term results of endovascular repair using first and second-generation stent-grafts. Eur J Cardiothorac Surg 2004; 25:394–400.
8. Kato N, Dake MD, Miller DC, Semba CP, Mitchell RS, Razavi MK, Kee ST. Traumatic thoracic aortic aneurysm: treatment with endovascular stent-grafts. Radiology 1997; 205:657–662.
9. Rousseau H, Soula P, Perreault P, Bui B, Janne d'Othee B, Massabuau P, Meites G, Concina P, Mazerolles M, Joffre F, Otal P. Delayed treatment of traumatic rupture of the thoracic aorta with endoluminal covered stent. Circulation 1999; 99:498–504.
10. Rehders TC, Petzsch M, Ince H, Kische S, Korber T, Koschyk DH, Chatterjee T, Weber F, Nienaber CA. Intentional occlusion of the left subclavian artery during stent-graft implantation in the thoracic aorta: risk and relevance. J Endovasc Ther 2004; 11:659–666.

Neonatal and Early Childhood Thoracic Aorta Abnormalities and Their Current Surgical Treatment

Francois G. Lacour-Gayet, John H. Artrip

36

Contents

36.1 Introduction

Thoracic aortic abnormalities encountered with neonates and young children are primarily confined to the aortic arch and isthmus. The International Congenital Heart Surgery Nomenclature defines the aortic arch as the segment of aorta between the braciocephalic artery and the left subclavian artery and the aortic isthmus as the segment of aorta between the left subclavian artery and the ductus arteriosus [3]. Malformations in this region include aortic coarctation, interrupted aortic arch (IAA) and vascular ring malformations.

36.2 Aortic Coarctation

36.2.1 Anatomy

Coarctation encompasses a variety of obstructive lesions of the aorta. Bonnet [6] was the first to recognize distinct anatomical subsets of coarctation and classify them into an adult and an infantile type. The adult type depicts a discrete obstructive lesion just distal to the left subclavian artery, whereas the infantile type depicts a diffuse narrowing of the aortic isthmus (Fig. 36.1). Terms such as “preductal” and “postductal” are employed to describe the lesion in relation to the ductus arteriosus. Although these terms are widely used clinically, they are anatomically incorrect. Coarctation is almost always juxtaductal and positioned between the isthmus and the descending aorta [24]. When the ductus is patent, the coarctation can be shown to be a curtain of ductal tissue encircling the aortic isthmus; this becomes less obvious as the ductus closes [5]. The segment of aorta proximal to the coarctation usually tapers gradually, but this is distinct from tubular hypoplasia, where there is uniform narrowing of an entire aortic segment. Tubular hypoplasia of the aortic arch is rarely seen with isolated coarctation; however, it is commonly present when the coarctation exists with complex intracardiac abnormalities (transposition of the great arteries with ventricular septal defect, hypoplastic left heart syndrome, etc.) [15]. Arch hypoplasia usually involves the distal arch but it can involve the proximal arch, creating a hypoplasia of the total transverse arch.

36.2.2 Occurrence

Coarctation occurs in 20–60 per 100,000 live births and represents 5–8% of all congenital cardiovascular lesions [11, 13]. It is an isolated lesion 82% of the time and is approximately twice as common in male [14]. The reported frequency of important associated cardiac malformations depends on the patient population studied.

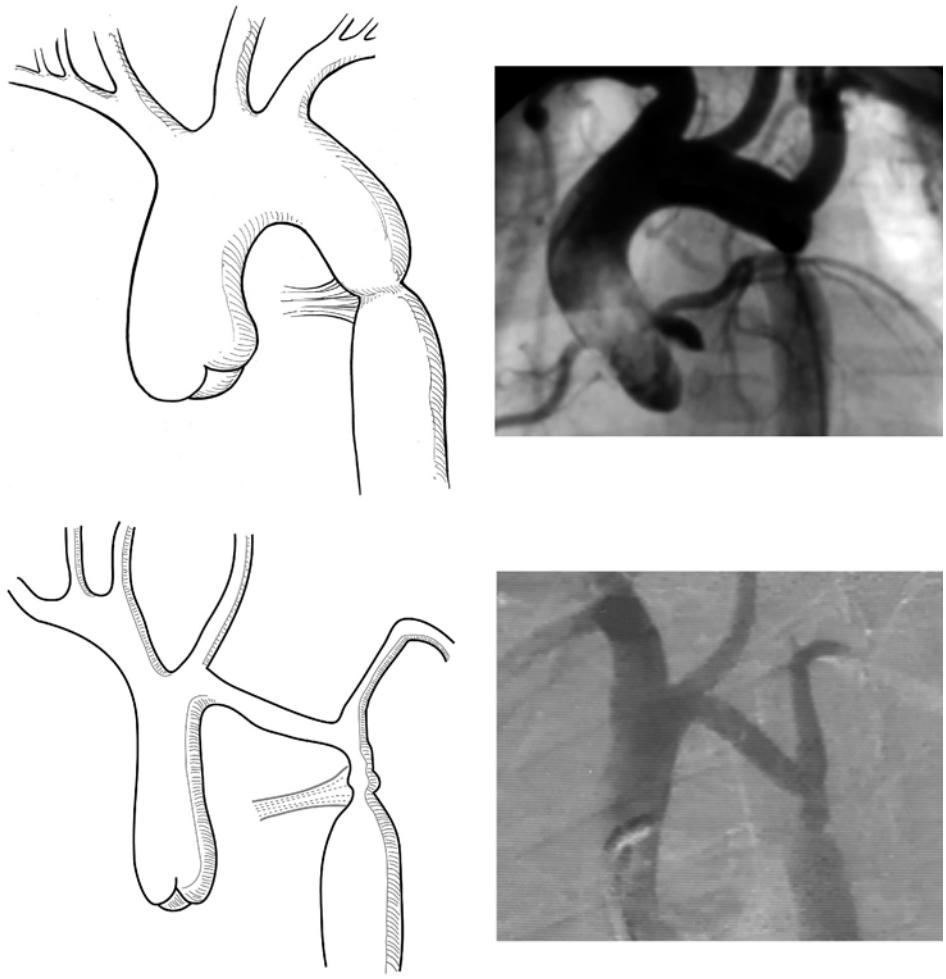

Fig. 36.1. *Top:* Illustration and angiogram of an "adult"-type coarctation with a typical "shelflike" lesion distal to the left subclavian artery. The large arterial vessels present on the angiogram supply collateral circulation to the descending aorta. *Bottom*: Illustration and angiogram of an "infantile"-type coarctation with tubular hypoplasia of the aortic arch and the isthmus. The angiogram demonstrates early washout of contrast material in the descending aorta from a patent ductus arteriosus

Ventricular septal defects occur in 11% of cases when coarctation occurs in infancy or childhood; however, this rises to 36% when coarctation occurs in the neonate [17]. Bicuspid aortic valve occurs in 27–46% of cases with coarctation. Coarctation accompanies other cardiovascular lesions and is present in 7% of major congenital cardiac malformations [14]: single ventricle anatomy, 7%; transposition of the great arteries, 6%; atrioventricular septal defects, 4%; and double-outlet right ventricle, 2–3% [17].

36.2.3 Clinical Presentation and Diagnosis

The neonate with coarctation may have severe heart failure with acidosis, tachypnea and a profound diaphoresis with feeding. Depending on the patency of the ductus arteriosus and the severity of the coarctation, differential cyanosis may be present. Severe obstruction at the isthmus and ductus arteriosus requires intravenous infusion of prostaglandin E_1 in the neonate. This relaxes the ductal tissue, lowering the resistance of flow through the aorta, improving ventricular function. Echocardiography allows the diagnosis of coarctation and associated cardiac malformations. Rarely is cardiac catheterization or MRI needed to confirm the diagnosis.

Older infants and children uncommonly have associated cardiac lesions. Systemic hypertension with a differential noted on upper and lower extremity blood pressures is the usual presentation. A differential of more than 20 mmHg should warrant further investigation. Echocardiography is performed to rule out associated cardiac lesions, and computed tomography (CT) scan of the chest or MRI is performed to precisely define the anatomy and extent of arterial collaterals.

36.2.4 Surgical Treatment

Several techniques for repair of coarctation are advocated by various authors. The choice of the particular technique depends on the anatomy confronted by the surgeon and the experience of the surgeon with each procedure. Tubular hypoplasia of the transverse arch is an important anatomic feature dictating surgical method. A simple formula used to assess the adequacy of the arch in the neonate is the weight of the child in kilograms plus 1 should approximate the diameter of the arch in millimeters. It has been suggested that hypoplasia of the arch will enlarge with time, especially if associated intracardiac lesions are fixed at the time of coarctation repair. Although this may be uncommonly true, it is prudent to repair the arch hypoplasia. The techniques the surgeon should be familiar with are the standard end-to-end anastomosis [8], the subclavian flap angioplasty [26], the extended end-to-end anastomosis [27] and the end-to-side anastomosis [25].

Standard end-to-end coarctation repair remains the procedure of choice in infants less than 3 months of age and in young children. A left posterolateral thoracotomy utilizing the fourth interspace is performed (Fig. 36.2). If associated cardiac lesions are being repaired at the same time, a sternotomy is preferred. The lung is retracted anteriorly and inferiorly with stay sutures placed on the pleural reflection. The vagus and recurrent laryngeal nerve are identified and preserved. The aorta is dissected from the left carotid artery to the second set of intercostal arteries. The aorta should be freely mobilized to prevent tension on the anastomosis; often this requires sacrificing one to two sets of intercostal arteries. This can be done without consequence in the neonate and infant. Systemic heparinization (1 mg/kg) has been advocated by some surgeons; however, this is not necessary in neonates and infants. The ligamentum or ductus arteriosus is ligated. Aortic clamps are placed proximally at the base of the origin of the left subclavian artery and distally below the coarctation. The coarctation is excised and a polypropylene 6-0 or 7-0 suture is used for standard running anastomosis. The distal aortic clamp is first released and the anastomosis is deaired and examined for hemostasis. The proximal aortic clamp is then released, which may precipitate considerable hypotension and acidosis. Administration of sodium bicarbonate and replacement of the proximal aortic clamp may be needed until acidosis is corrected and the ventricle has been properly volume loaded.

Subclavian flap angioplasty is rarely used today in neonates because it does not address the arch hypoplasia. The sacrifice of the left subclavian artery can be associated in rare cases with severe left arm ischemia and is not recommended for infants older than 3 months of age. Surgical incision and aortic mobilization are similar to the standard end-to-end repair (Fig. 36.3). The left subclavian artery is further mobilized to the point of origin of the vertebral artery and ligated. The ductus arteriosus is ligated and aortic clamps are placed proximally on the arch at the base of the left common carotid artery and distally beyond the coarctation. The left

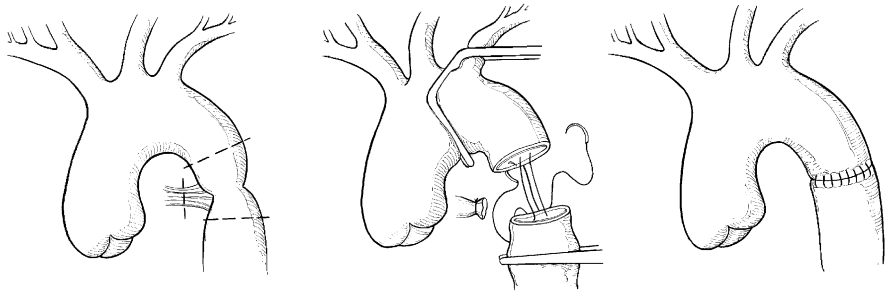

Fig. 36.2. Standard end-to-end coarctation repair

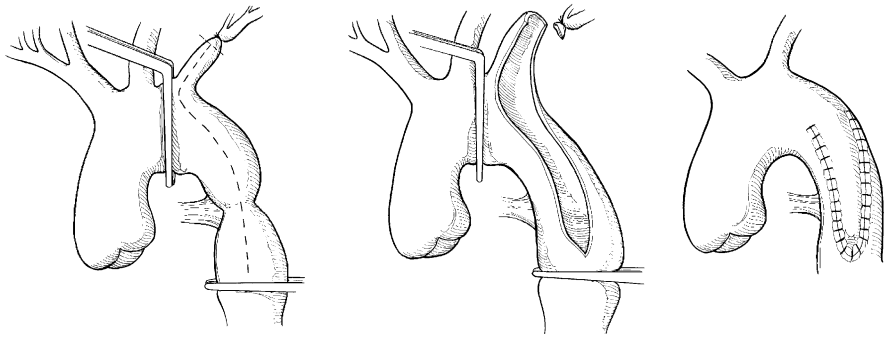

Fig. 36.3. Subclavian flap angioplasty. The left subclavian artery is divided and an incision is made posteriorly on the aorta extending inferiorly across the coarctation. The subclavian artery is folded downwards over the coarctation and sewn

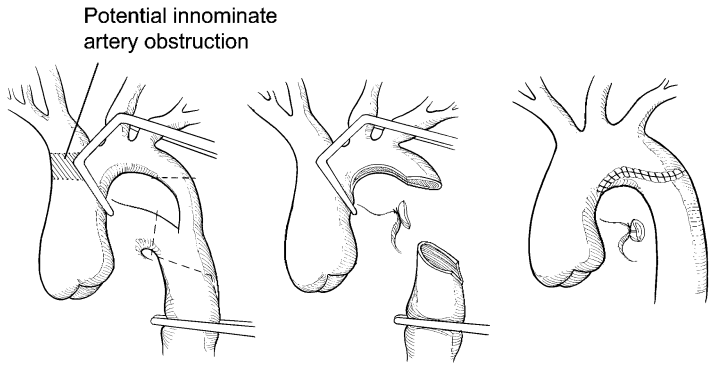

Fig. 36.4. Extended end-to-end repair. The aortic isthmus is hypoplastic. An incision is made on the undersurface of the aortic arch to the level of the left common carotid artery. The descending aorta is sewn to the concavity of the aortic arch

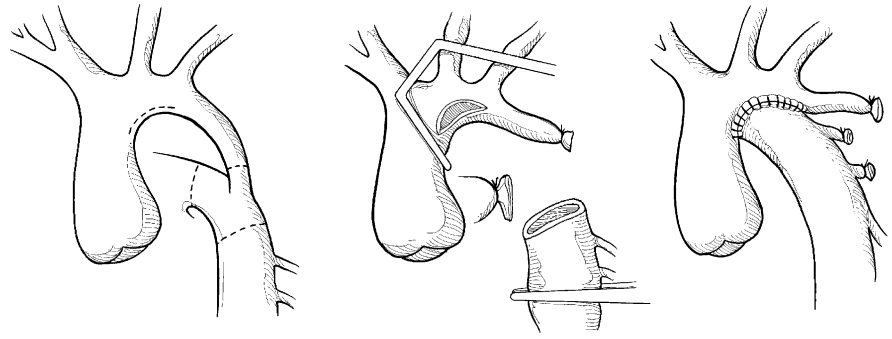

Fig. 36.5. End-to-side repair. The hypoplastic isthmus is ligated and divided. An incision is made on the undersurface of the aortic arch encroaching upon the ascending aorta. The descending aorta is sewn to the concavity of the aortic arch

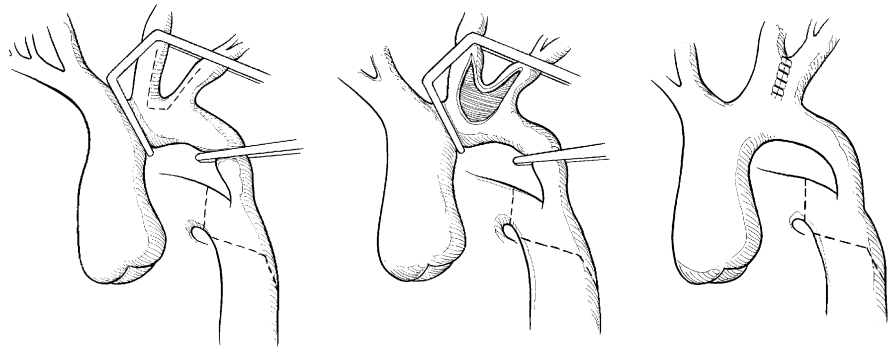

Fig. 36.6. Subclavian augmentation procedure. An incision is made on the lateral wall of the left common carotid artery and continued across the arch onto the medial wall of the left subclavian artery. The left common carotid and subclavian arteries are sewn together creating an effective large aortic orifice. This can be done with the ductus arteriosus patent to preserve blood flow to the lower extremities. An extended end-to-end or end-to-side anastomosis is then performed

subclavian artery is divided distally and a longitudinal incision is made in the descending aorta and carried across the coarctation and into the transected left subclavian artery. The subclavian flap is then folded down into the aortic incision and sewn with a running 7-0 polypropylene suture.

The procedure of choice in neonatal coarctation is resection and extended end-to-end anastomosis [15, 28]. This technique addresses coarctation and the associated hypoplasia of the transverse arch (Fig. 36.4). An extended mobilization of the transverse arch, left subclavian artery, left carotid artery and descending aorta requiring sacrificing one or two intercostal arteries is required. An aortic clamp is placed proximally across the aortic arch at the base of the innominate artery while occluding the left common carotid and left subclavian arteries. The clamp should not obstruct flow through the innominate artery, which is monitored by arterial pressure measurement in the right arm. The ductus arteriosus is ligated and a distal aortic clamp is placed beyond the coarctation. The coarctation is completely excised and an incision is made on the undersurface of the aortic arch crossing under the left common carotid artery. Failing to bring the incision proxi-

mal will result in obstructed flow across the aortic arch. A running 7-0 polypropylene suture is used to complete the anastomosis. A longitudinal incision placed posteriorly on the descending aorta may be needed to enlarge the anastomosis and receive the segment of arch containing the left subclavian artery.

Occasionally, there is a long segment of hypoplastic arch that despite the use of an extended end-to-end technique will result in obstructed flow across the proximal aortic arch. An end-to-side technique that brings the distal aorta underneath the proximal arch is well adapted to this severe form of arch hypoplasia. Depending on the degree of proximal arch hypoplasia, this approach may require sternotomy and cardiopulmonary bypass. An aortic clamp is placed across the proximal aortic arch occluding the left common carotid and left subclavian arteries (Fig. 36.5). The ductus arteriosus and aortic isthmus are ligated and the coarctation is completely excised. An incision is made on the undersurface of the transverse arch coursing proximal into the ascending aorta. A running 7-0 polypropylene suture is used to perform an end-to-side anastomosis. A subclavian augmentation procedure of the distal arch may be required to further enlarge the transverse arch (Fig. 36.6) [2]. An incision is made in the lateral wall of the left common carotid artery and the medial wall of the left subclavian artery. A 7-0 polypropylene suture is used to bring these vessels together, creating an effective larger aortic arch. This can be performed prior to an extended end-to-end or end-to-side anastomosis with clamps placed proximally on the transverse arch and distally on the aortic isthmus above the ductus arteriosus to preserve flow to the lower extremities.

36.2.5 Surgical Results

The incidence of recoarctation defined as a peak gradient of more than 20 mmHg is estimated to be approximately 10% in neonates [15]. Nevertheless, new or existing gradients warrant cardiac catheterization. Percutaneous balloon angioplasty can be performed safely 6 weeks following surgical repair and can easily dilate most recoarctations. Occasionally, surgery is required for recoarctation and the techniques already described, especially the addition of a subclavian augmentation procedure, may be needed for repair. Rarely is an interposition graft necessary for aortic repair and it is not recommended in infancy or childhood.

36.2.6 Interventional Approach to Coarctation

Percutaneous balloon angioplasty is associated with lower hospital charges, shorter lengths of stay and fewer complications than surgical repair, and is suggested by some authors to be used for primary coarctation, as well as recoarctation [22]. However, angioplasty does not remove ductal tissue, but rather creates intimal disruption, analogous to a "controlled dissection" [10]. Review of recent literature concludes that during the first 2 months of life mortality is higher for balloon angioplasty (8 versus 2–4% for surgery), reintervention rates are higher (28 versus 7% for surgery) and late aneurysm formation or dissection occurs up to 8% of the time following angioplasty [16]. Surgical repair of coarctation remains the best option for neonates and young infants.

36.3 Interrupted Aortic Arch

36.3.1 Anatomy

Interruption of the aortic arch is seen in neonates with survival depending on the patency of the ductus arteriosus. Rare cases of aortic atresia of the distal arch and the isthmus have been encountered in childhood where the ductus is closed and distal aortic perfusion is via a large

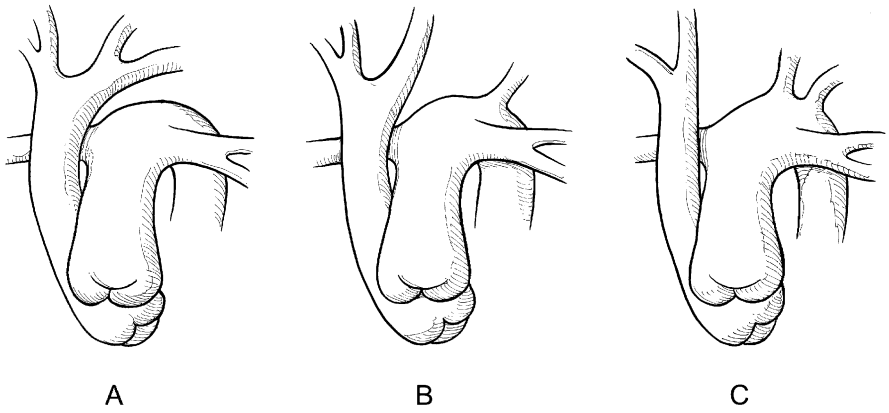

Fig. 36.7. Classification of interrupted aortic arch (*IAA*). Type *A*, there is interruption between the left subclavian artery and the ductus arteriosus. Type *B*, there is interruption between the left subclavian and left common carotid arteries. Type *C*, there is interruption between the brachiocephalic and left common carotid arteries

collateral network. The classification of arch interruption put forth by Celoria and Patton [7] has been almost uniformly accepted and defines three anatomic types based on the location of the interruption (Fig. 36.7). Type B is the commonest, representing 55% of the cases, followed by type A (40%) and type C (5%) [23]. An aberrant origin of the right subclavian artery from the distal aortic arch may accompany type B interruptions.

36.3.2 Occurrence

Interruption of the aortic arch is a rare lesion occurring in 0.3 per 100,000 live births and representing 1.3% of all congenital cardiovascular lesions [23]. Type B interruptions are commonly associated with chromosome 22q11.2 deletion in the context of DiGeorge syndrome [9]. A conoventricular ventricular septal defect is usually present with a posterior malalignment of the outlet septum. Severe subaortic obstruction from the malaligned septum may require modification in surgical approach (Fig. 36.8). As with other aortic arch abnormalities, bicuspid aortic valve occurs frequently with IAA. Major other congenital heart malformations accompanying IAA include the following: truncus arteriosus, 10%; aortopulmonary window; 4%; transposition of the great arteries, 3% [12]. IAA may be part of a complex set of lesions constituting hypoplastic left heart syndrome.

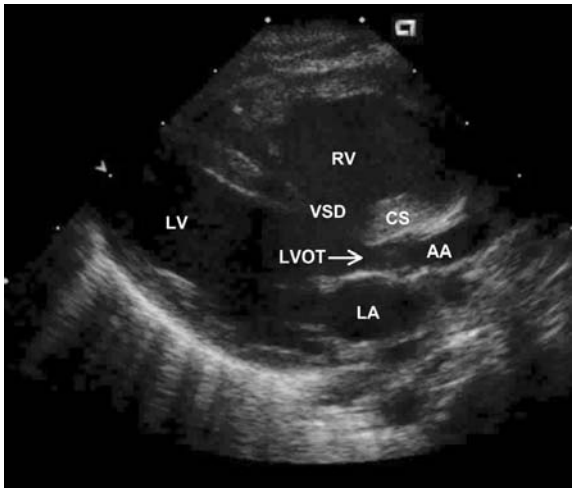

Fig. 36.8. Echocardiogram of a patient with IAA. The conal septum (*CS*) is malaligned posteriorly creating a ventricular septal defect and obstruction of the left ventricular outflow tract (*LVOT*). *AA* ascending aorta, *RV* right ventricle, *LV* left ventricle, *LA* left atrium

36.3.3 Clinical Presentation and Diagnosis

The neonate with IAA is critically ill. As the ductus arteriosus closes, severe heart failure develops secondary to the volume overload from the ventricular septal defect and the increased afterload of the arch obstruction. Intravenous administration of prostaglandin E_1 is started immediately to maintain the ductal patency. With a patent ductus arteriosus, anticipated differential cyanosis may not be present owing to a large intracardiac shunt minimizing the O_2 saturation difference between the right and left ventricular chambers. Echocardiography establishes the diagnosis of IAA and provides the necessary information on the ventricular septal defect and the severity of left ventricular outflow tract obstruction. Cardiac catheterization is rarely needed to confirm the diagnosis.

36.3.4 Surgical Treatment

Currently IAA is repaired in the neonate utilizing a one-stage approach that addresses both the arch anomaly and the associated intracardiac lesion. The two-stage approach is reserved for treatment of the neonate with a subarachnoid hemorrhage, contraindicating systemic heparinization and cardiopulmonary bypass [20]. The staged correction consists of an arch repair and pulmonary artery banding in the neonatal period followed by ventricular septal defect closure and debanding at 2–3 months of age. With a one-stage approach, a median sternotomy is performed and the arch vessels, branch pulmonary arteries, ductus arteriosus and the proximal portion of the descending aorta are fully mobilized. The classic approach utilizes deep hypothermia (18–20°C) with circulatory arrest. More recently, the arch is repaired without circulatory arrest using selective antegrade cerebral perfusion and hypothermia (20–22°C) (Fig. 36.9). A single aortic cannulation technique can be used if uniform cooling is achieved between the upper and lower extremities. If the lower extremities fail to cool, a second cannula is placed in the main pulmonary artery with the branch pulmonary arteries snared. Cardioplegia is administered antegrade through the aorta cannula with the head vessels snared. The aorta cannula is then moved into the innominate artery, and the flow is reduced to 30–50 ml/kg. The pulmonary cannula is removed and the ductus is ligated and divided. All ductal tissue should be removed. A longitudinal incision is made on the left side of the ascending aorta and an end-side aortic anastomosis is performed with a 7-0 polypropylene suture. The descending aorta often cannot reach the ascending aorta despite adequate mobilization. Dividing the left subclavian artery will provide further length to the descending aorta. If an aberrant

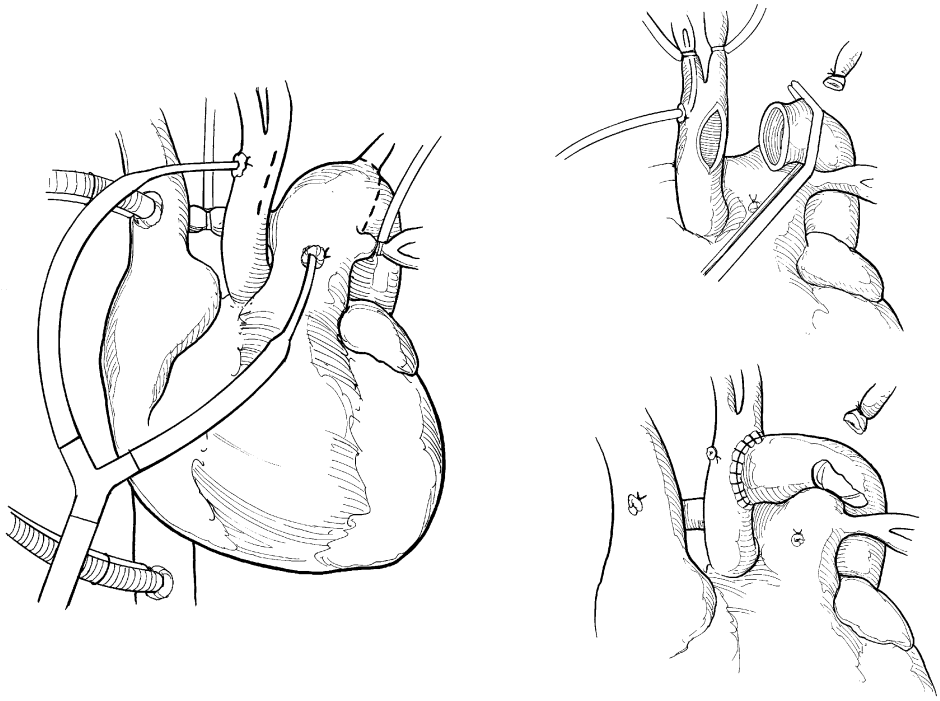

Fig. 36.9. Repair of type B IAA. *Left*: Two arterial cannulas are placed, one in the ascending aorta and one in the pulmonary artery. The branch pulmonary arteries are snared. *Upper right*: The arterial cannula is placed into the brachiocephalic artery and the other arterial cannula is removed. The ductus arteriosus and left subclavian arteries are ligated and divided. *Lower right*: An end-to-side anastomosis is performed

right subclavian artery is present, this is divided to fully mobilize the descending aorta. The use of interposition grafts should be avoided. In cases of severe tension on the anastomosis, a homograft patch of pulmonary autograft is placed on the anterior aspect of the anastomosis [19]. Closure of the ventricular septal defect is performed and depending on the length of conal septum, a right atrial or right ventricular approach is preferred.

36.3.5 Surgical Results

Current data from the Congenital Heart Surgeons Society suggest that 14% of patients undergoing direct arch anastomosis will require reintervention within 3 years [12]. Avoidance of the use of interposition grafts and balloon angioplasty of recurrent obstruction has virtually eliminated the need for surgical reintervention.

36.4 Vascular Rings

36.4.1 Anatomy and Embryology

Vascular rings are congenital malformations of the aortic arch where vascular structures completely encircle and compress the trachea and esophagus. In the embryonic arch system, six primitive aortic arches arise from the primitive aortic sac. These arches terminate between a ventral and dorsal aorta. Although six pairs of aortic arches eventually develop, they are not present at the same time. When the sixth set of arches develops, the first two sets have already regressed. The formation of vascular rings depends on the preservation or absence of specific segments of the rudimentary arch complex.

Normally, the right fourth arch involutes at 36–38 days of gestation, leaving the left fourth arch to form the normal adult arch system. If the right fourth aortic arches persist, a double arch system is formed. The ascending aorta gives rise to two arches that pass on both sides of the trachea and esophagus and join the descending aorta forming a complete ring (Fig. 36.10). Of infants presenting with a double aortic arch, 75% have a dominant right arch, 20% have a dominant left arch, and 5% have equal-sized arches. With a right dominant pattern, the left arch is frequently severely narrowed or

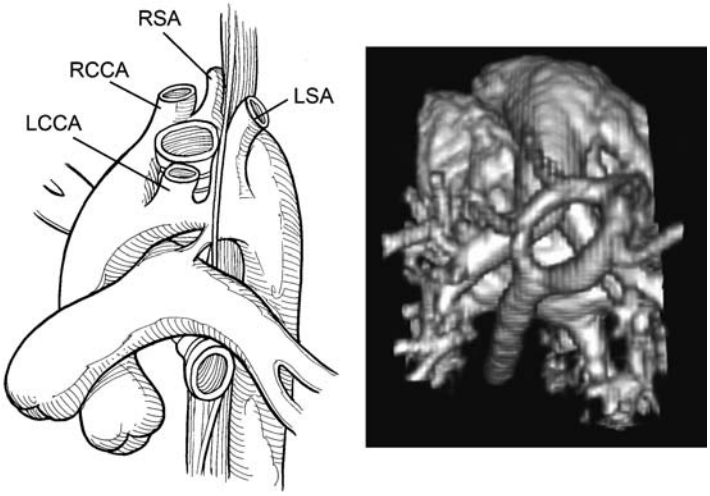

Fig. 36.10. Double aortic arch. *Left*: Cartoon illustrating a double aortic arch. *Right*: Magnetic resonance angiogram nicely illustrating the vascular ring that forms from the double aortic arch. *LCCA* left common carotid artery, *RCCA* right common carotid artery, *LSA* left subclavian artery, *RSA* right subclavian artery

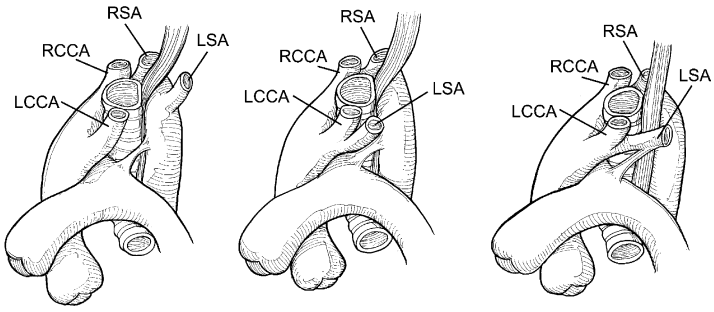

Fig. 36.11. Three types of right aortic arches. Note that a vascular ring is not created if the ligamentum arteriosus connects to an anterior left subclavian artery (*right*). *LCCA* left common carotid artery, *RCCA* right common carotid artery, *LSA* left subclavian artery, *RSA* right subclavian artery

atretic in the segment distal to the origin of the left subclavian artery. This is represented by a fibrous cord joining the descending aorta, often at the site of a diverticulum – Kommerell's diverticulum. With a left dominant pattern, the right arch is rarely atretic.

If the left arch involutes, a right aortic arch is formed. The aortic arch is to the right of the trachea and passes behind the esophagus to join the descending aorta. Depending on the site of involution of the left arch and the branching pattern of the head and upper extremity arteries, different configurations are possible (Fig. 36.11). The commonest variant of right aortic arch has the left subclavian artery arising from the descending aorta (retroesophageal left subclavian) with the ligamentum arteriosus connecting the pulmonary artery to the descending aorta, completing a vascular ring. If the left subclavian artery originates anterior to the esophagus from a left-sided brachiocephalic vessel (mirror-image branching) a vascular ring is created if the ligamentum connects the pulmonary artery to the descending aorta. No vascular ring is present if the ligamentum connects the pulmonary artery to the left subclavian artery. The latter configuration is common with tetralogy of Fallot and truncus arteriosus.

Other variations of aortic arch configuration and branching pattern of the head and upper extremity arteries exist. Largely, these other malformations do not form a complete ring around the trachea and esophagus. These partial or incomplete vascular rings are rarely of clinical significance. An aberrant origin of the right subclavian artery from the descending aorta occurs in 0.5% of the general population [1]. Because this artery passes behind the esophagus, it has been implicated as a rare cause of dysphagia – the so called dysphagia lusoria. An abnormal leftward and posterior coursing of the brachiocephalic artery may be drawn taut against the anterior surface of the trachea, causing respiratory compromise. The "innominate artery compression syndrome" is uncommon.

36.4.2 Occurrence

Vascular ring malformations usually account for 1–2% of all congenital cardiovascular lesions [14]. Because of the variability of arch pattern and the severity of symptoms at presentation, it is difficult to know the incidence of each arch malformation. The frequencies of double aortic arch and right aortic arch are approximately equal for all patients presenting with complete vascular rings; however, infants presenting with clini-

cally significant airway obstruction are more likely to have double aortic arch malformations. Tracheomalacia may be found in a small percentage of infants with severely compressed airways. A double aortic arch occurs uncommonly with other congenital cardiac lesion, whereas a right-sided aortic arch frequently accompanies other conotruncal abnormalities.

36.4.3 Clinical Presentation and Diagnosis

Most children with complete vascular ring malformations present with symptoms of stridor and respiratory distress in early infancy. Older children may present with a "seal bark" cough and a history of recurrent respiratory tract infections. These malformations are often misdiagnosed as childhood- or exercise-induced asthma. Symptoms of feeding intolerance or dysphagia may be present, especially when the infant is transitioned to solid foods. The diagnosis is suspected on a plain chest radiograph demonstrating a right aortic arch. A barium esophagogram can reliably diagnose a vascular ring and differentiate this from other anatomic causes of airway obstruction (Fig. 36.12). Determining the exact type of vascular ring malformation requires vascular imaging. A contrast-enhanced CT scan or MRI will reliably differentiate the various arch patterns. There is little role for cardiac catheterization.

36.4.4 Surgical Treatment

With rare exception, vascular ring malformations are repaired through a left thoracotomy using the fourth interspace. The surgical dissection of the vascular ring should be complete enough to clearly identify the anatomy including the left subclavian artery and the ligamentum arteriosum. The vagus and recurrent laryngeal nerves are identified and preserved. With right aortic arch abnormalities, simple division of the ligamentum arteriosum is all that may be needed. With double aortic arch abnormalities, division of the vascular ring, as well as division of the ligamentum arteriosus, needs to be performed. The vascular ring caused by a double aortic arch is released by dividing the lesser of the two arches, usually the posterior arch (Fig. 36.13). Clamps are placed proximally and distally on the lesser arch. The segment is divided and oversewn with a simple 6-0 polypropylene suture. If a diverticulum is present this should be resected to prevent potential compression on the airway or esophagus. All adhesive bands around the trachea and esophagus are lysed. Various procedures have been advocated for other specific arch anomalies, including aortic uncrossing procedures for a "circumflex aorta" [18] and left subclavian to left common carotid artery transfer for a right aortic arch with a left ligamentum and a Kommerell's diverticulum [4]. Robotic and videoscopic surgery for simple vascular ring repair has recently been proposed [21]; however, experience is limited with this procedure.

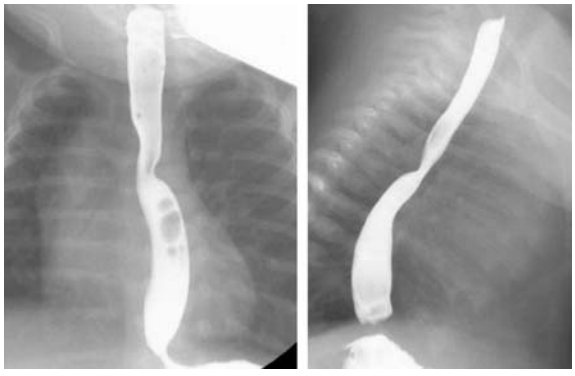

Fig. 36.12. Anterior-posterior (*left*) and lateral (*right*) projections of an esophagogram demonstrating a double aortic arch type vascular ring malformation

36.4.5 Surgical Results

Immediate relief of respiratory symptoms may not be present in the postoperative period; local inflammation and edema may actually worsen symptoms. Tracheomalacia and bronchomalacia are frequent and may be severe, requiring prolonged periods of positive pressure ventilation. At 1-year follow-up, an estimated 95% of patients are asymptomatic, yet up to 50% may still demonstrate abnormal flow patterns on pulmonary testing.

36.5 Conclusions

Thoracic aorta abnormalities in the neonate and young child encompass a wide spectrum of congenital defects. Surgical repair can be performed in the neonate and small infant with little mortality or morbidity. Precise anatomic detail of the specific arch abnormality and associated intracardiac lesions must be obtained prior to attempting surgical repair. Most lesions can be repaired in one stage through a thoracotomy or sternotomy. Staged repair is currently reserved for rare circumstances presenting contraindications for cardiopulmonary bypass.

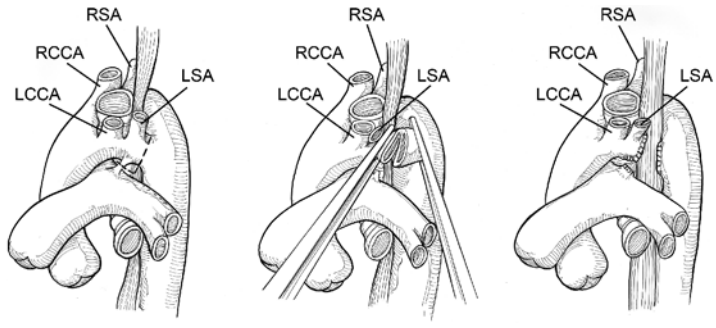

Fig. 36.13. Division of the left arch into a double aortic arch

References

1. Abbott ME (1936) Atlas of congenital heart disease. American Heart Association, New York.
2. Amato JJ, Rheinlander HF, Cleveland RJ (1985) A method of enlarging the distal transverse arch in infants with hypoplasia and coarctation of the aorta. Ann Thorac Surg 40:274.
3. Backer CL, Mavroudis C (2000) Congenital Heart Surgery Nomenclature and Database Project: patent ductus arteriosus, coarctation of the aorta, interrupted aortic arch. Ann Thorac Surg 69(Suppl):298.
4. Backer CL, Hillman N, Mavroudis C, Holinger LD (2002) Resection of Kommerell's diverticulum and left subclavian artery transfer for recurrent symptoms after vascular ring division. Eur J Cardiothorac Surg 22:64.
5. Becker AE, Anderson RH (1981) Pathology of congenital heart disease. Butterworth, London.
6. Bonnet LM (1903) Sur la lésion dite stenose congénitale de l'aorte dans la région de l'isthme. Rev Med 23:108.
7. Celoria GC, Patton RP (1959) Congenital absence of the aortic arch. Am Heart J 58:407.
8. Crafoord C, Nylin G (1945) Congenital coarctation of the aorta and its surgical treatment. J Thorac Surg 14:347.
9. de la Chapelle A, Herva R, Koivisto M, Aula P (1981) A deletion in chromosome 22 can cause DiGeorge syndrome. Hum Genet 57:253.
10. Fletcher SE, Cheatham JP, Froeming S (1998) Aortic aneurysm following primary balloon angioplasty and secondary endovascular stent placement in the treatment of native coarctation of the aorta. Cathet Cardiovasc Diagn 44:40.
11. Fyler DC (1980) Report of the New England Regional Infant Cardiac Program. Pediatrics 65(Suppl):375.
12. Jonas RA, Quaegebeur JM, Kirklin JW, Blackstone EH, Daicoff G (1994) Outcomes in patients with interrupted aortic arch and ventricular septal defect. A multiinstitutional study. Congenital Heart Surgeons Society. J Thorac Cardiovasc Surg 107:1099.
13. Keith JD (1968) Coarctation of the aorta. In: Watson H (ed) Pediatric cardiology. Lloyd-Luke, London, pp 175–223.
14. Kouchoukos NT, Blackstone EH, Doty DB, Hanley FL, Karp RB (2003) Coarctation of the aorta and aortic arch interruption. In: Kouchoukos NT, Blackstone EH, Doty DB, Hanley FL, Karp RB (eds) Kirklin/Barratt-Boyes cardiac surgery, 3rd edn. Churchill Livingstone, New York, pp 1315–1376.
15. Lacour-Gayet F, Bruniaux J, Serraf A, Chambran P, Blaysat G, Losay J, Petit J, Kachaner J, Planche C (1990) Hypoplastic transverse arch and coarctation in neonates. Surgical reconstruction of the aortic arch: a study of sixty-six patients. J Thorac Cardiovasc Surg 100:808.
16. Ovaert C, Benson LN, Nykanen D, Freedom RM (1988) Transcatheter treatment of coarctation of the aorta: a review (comments by Waldman JD). Pediatr Cardiol 19:27.
17. Quaegebar JM, Jonas RA, Weinberg AD, Blackstone EH, Kirklin JW (1994) Outcomes in seriously ill neonates with coarctation of the aorta: A multiinstitutional study. J Thorac Cardiovasc Surg 108:841.
18. Robotin MC, Bruniaux J, Serraf A, Uva MS, Roussin R, Lacour-Gayet F, Planche C (1996) Unusual forms of tracheobronchial compression in infants with congenital heart disease. J Thorac Cardiovasc Surg 112:415.
19. Roussin R, Belli E, Lacour-Gayet F, Godart F, Rey C, Bruniaux J, Planche C, Serraf A (2002) Aortic arch reconstruction with pulmonary autograft patch aortoplasty. J Thorac Cardiovasc Surg 123:443.
20. Serraf A, Lacour-Gayet F, Robotin M, Bruniaux J, Sousa-Uva M, Roussin R, Planche C (1996) Repair of interrupted aortic arch: a ten-year experience. J Thorac Cardiovasc Surg 112:1150.
21. Suematsu Y, del Nido PJ (2004) Robotic pediatric cardiac surgery: present and future perspectives. Am J Surg 188(4A Suppl):S98.
22. Shim D, Lloyd TR, Moorehead CP, Bove EL, Mosca RS, Beekman RH 3rd (1997) Comparison of hospital charges for balloon angioplasty and surgical repair in children with native coarctation of the aorta. Am J Cardiol 79:1143.
23. Van Praagh R, Bernhard WF, Rosenthal A, Parisi LF, Fyler DC (1971) Interrupted aortic arch: surgical treatment. Am J Cardiol 27:200.
24. Van Praagh R, O'Connor B, Chacko KA (1988) Aortic coarctation: pathology of the malformation. Abstract, First World Congress of Pediatric Surgery, Bergamo, Italy, p 5.
25. Vouhe PR, Trinquet F, Lecompte Y, Vernant F, Roux PM, Touati G, Pome G, Leca F, Neveux JY (1988) Aortic coarctation with hypoplastic aortic arch. Results of extended end-end aortic arch anastomosis. J Thorac Cardiovasc Surg 96:557.
26. Waldhausen JA, Nahrwold DL (1966) Repair of coarctation of the aorta with a subclavian flap. J Thorac Cardiovasc Surg 51:532.
27. Zannini L, Lecompte Y, Galli R, Gargiulo G, Musiani A, Ghiselli A, Pierangeli A (1985) (Aortic coarctation with hypoplasia of the arch: description of a new surgical technique). G Ital Cardiol 15:1045.
28. Zannini L, Gargiulo G, Albanese SB, Santorelli MC, Frascaroli G, Picchio FM, Pierangeli A (1993) Aortic coarctation with hypoplastic arch in neonates: a spectrum of anatomic lesions requiring different surgical options. Ann Thorac Surg 56:288.

Endovascular Treatment Strategies for Coarctation of the Aorta

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Contents

37.1 Introduction

Advances in the surgical treatment of coarctation of the aorta have increased life expectancy and reduced mortality [1]. Unfortunately, the average lifespan after repair remains only 35–50 years [2] and significant morbidity persists as a result of coronary artery disease, aneurysm formation, hypertension and stroke [3]. In addition, follow-up studies have revealed that restenosis rates of 30%, hypertension at rest and during exercise and compromised cardiac function can persist with only mild residual disease [4–6].

The invasive nature of surgical repair coupled with the shorter hospitalization, reduced pain and decreased cost associated with transcatheter therapies has led to balloon angioplasty and, most recently, stent implantation playing increasing roles in the treatment of aortic coarctation. As with the early surgical literature, transcatheter studies conducted over the last 2 decades have focused on the feasibility of treatment and on assessing the ability of these devices to reduce the gradient across a coarctation site. These studies have documented several important sequelae of transcatheter techniques, including aortic dissections and aneurysm formation [7–10]. This chapter will review the current indications, limitations and suggested guidelines associated with the use of balloon angioplasty and stent implantation for the treatment of coarctation of the aorta, and suggest a new paradigm aimed at optimizing transcatheter and surgical treatment strategies and reducing the associated long-term morbidity.

37.2 Endovascular Treatments for Coarctation of the Aorta

37.2.1 Balloon Angioplasty for Recurrent Coarctation

In a recent study of patients who underwent surgical correction for coarctation at a mean age of 10 years, the cumulative 40-year survival rate was 79%. Recoarctation was observed in 16% of these survivors [11]. Repeat surgical procedures are often more complicated than the original surgery and only moderately successful [12]. In one recent study examining the efficacy of repeat surgery for recurrent coarctation primarily in infants, 24% of the patients had residual pressure gradients of 30–48 mmHg an average of 2.5 years after the reoperation [12]. Findings such as these prompted Singer et al. [13] to attempt balloon angioplasty for the treatment of this group of patients and have made balloon angioplasty the current treatment of choice for most patients with recoarctation of the aorta [14, 15].

From a purely technical standpoint, the technique of balloon angioplasty for native or recurrent coarctation is one of the simplest of pediatric interventions. Access is obtained in the femoral artery and vein. Right heart catheterization is performed in the standard fashion, obtaining saturations and/or blood pressure measurements in the superior vena cava, right atrium, right

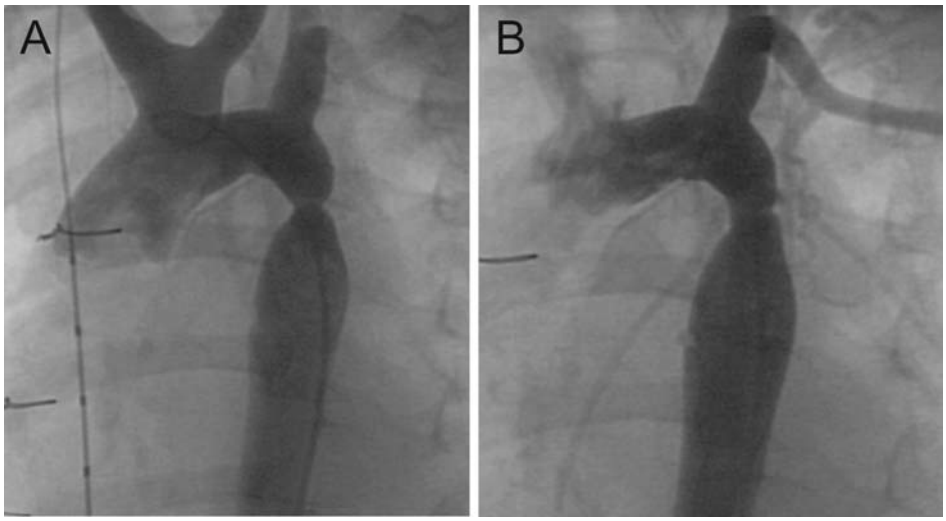

Fig. 37.1. Angiographic images of a coarctation before (**A**) and after (**B**) balloon angioplasty

ventricle and pulmonary arteries. In the absence of intracardiac shunts, the thermodilution method is used to measure the cardiac output, otherwise the Fick method, based on the mixed venous saturation, is employed.

Balloon dilation of the coarctation can be performed using antegrade or retrograde approaches, with the decision being a matter of clinician preference. In the antegrade approach, a trans-septal or Brockenbrough puncture is used to enter the left atrium, followed by catheter manipulation through the left ventricle and into the ascending aorta [10, 16]. Simultaneous ascending and descending aortic pressures or a pullback pressure measurement is made. The coarctation is then crossed and the balloon delivered from the femoral vein. This method decreases the size of the sheath required in the femoral artery and the likelihood of arterial injury.

Most clinicians prefer the retrograde technique owing to its simplicity, speed and potential complications associated with trans-septal puncture and subsequent catheter/balloon course [15, 17]. In mild coarctations, a pigtail catheter may be directed across the obstruction, while with severer stenoses, a diagnostic catheter and soft-tipped wire may be required to traverse the narrowest area. The catheter is manipulated to the right subclavian artery or the ascending aorta and a J-tipped wire is advanced through the catheter and left in place to guide the balloon. Simultaneous pressure measurements from the catheter and femoral arterial sheath provide the gradient across the coarctation. The chosen balloon is advanced over the wire to the level of the coarctation and then inflated (Fig. 37.1). The balloon is deflated and removed and angiography is performed to look for intimal tears, dissections or extravasation of contrast outside the vessel. Larger balloons or stents may be required if a significant gradient remains.

Balloon angioplasty for the treatment of recurrent coarctation has been accepted as the treatment of choice based on the assumption that scar tissue in the coarctation region is resistant to rupture or aneurysm formation [18]. Histological reports have revealed that the acute increase in lumen size and reduction in systolic pressure gradients resulting from balloon angioplasty are a result of tears in the aorta. These are generally confined to the intimal and medial layers, but in rare instances may be transmedial [19, 20]. The intimal and medial tears appear to heal partially or completely [19, 21], while the transmedial tears have been associated with aneurysms and, occasionally, aortic dissection [8, 9].

Mortality associated with balloon angioplasty for the treatment of recurrent coarctation varies with age and concurrent cardiac abnormalities [22]. In infants it is 2– 10% [16], with aneurysms occurring in 1% of cases [16]. In children and adults the mortality rates are approximately 2.5 and 1%, respectively [22, 23].

Balloon angioplasty has, in some instances, been unable to reduce the gradient in cases of recurrent coarctation [10, 16, 24]. The prevalence of residual pressure gradients greater than 20 mmHg has ranged from 11 to 26%. Severe preprocedure systolic pressure gradients and the presence of transverse arch hypoplasia were predictive of poor procedural outcomes in this study.

37.2.2 Balloon Angioplasty for Native Coarctation

Following the first documented treatment of balloon angioplasty for recurrent coarctation [13], this technique was applied to native coarctation in a critically ill neonate [25] and led to several clinical studies [26–28]. The

greatest limitation of balloon angioplasty for the treatment of native coarctation is the occurrence of aortic aneurysms [28]. Patients treated for coarctation by surgical correction or stent implantation are also susceptible to aneurysms [9, 29], but there is an increased susceptibility with balloon angioplasty of native coarctation that is particularly pronounced in infants. This susceptibility has prevented several institutions from applying this technology to this patient population [10, 30]. Not surprisingly, recoarctation after balloon angioplasty for native coarctation is also pronounced in neonates and infants (31–83%) [28, 31] as compared with children (11–36%) [14, 27] and adults (6–19%) [17, 32].

Balloon angioplasty has been unable to reduce pressure gradients in some cases of native coarctation, specifically those with isthmus hypoplasia [10, 26, 33]. In a study of patients with a mean age of approximately 5 years, half the patients with isthmus hypoplasia required additional procedures [26]. Use of this technology has also met with suboptimal results in cases of mild, long segment or tortuous coarctations [34, 35]. Symptomatic restenosis resulting from enduring ductal tissue, vascular recoil or neointimal hyperplasia in patients with smaller aortic diameters may contribute to residual narrowing and systolic pressure gradients greater than 20 mmHg following balloon angioplasty for native coarctation [23, 36].

Smaller peripheral arteries in neonates and infants are susceptible to femoral artery occlusion in 10–16% of patients [26–28]. The loss of femoral artery pulses is fairly common, but can be successfully treated by intravenous heparin or tissue plasminogen activator [27, 37]. To minimize these risks, some operators prefer to gain vascular access through the umbilical vessels [38].

Most institutions currently choose to treat neonates, infants and young children with severe aortic coarctation surgically. Others justify primary balloon angioplasty since the procedure does not preclude future surgery [14, 26, 39]. Angioplasty may also be chosen in cases of discrete coarctation when other catheter-based techniques are being used to treat concomitant cardiac defects [39].

The prevalence of aneurysm formation, aortic dissection and recoarctation from restenosis or residual obstruction varies greatly after balloon angioplasty. This disparity is likely due, in part, to the absence of universally accepted guidelines for the procedure. The selection of an appropriate balloon diameter, type of system (standard versus high pressure) and the number and duration of inflations has been inconsistent between studies [10, 16, 28, 31, 32, 37]. Numerous studies have attempted to correlate a variety of balloon-to-coarctation diameter ratios with postoperative results [10, 22, 26]. Table 37.1 provides a sampling of the criteria that have been used for balloon dilation. The Valvuloplasty and Angioplasty of Congenital Anomalies registry revealed that the average balloon-to-coarctation ratio among 92 patients was 3.1 ± 1.0. Although indications for treatment and catheter selection were not regulated in the registry [22], the results showed that patients with minimal residual pressure gradients up to 12 months after the procedure were treated using a balloon-to-coarctation ratio of approximately 3. Interestingly, those with residual gradients greater than 20 mmHg had balloon-to-coarctation ratios closer to 4. The few reported cases of aneurysm formation corresponded to a ratio of 2.7 ± 0.9, suggesting that these ratios, in isolation, are a poor predictor of procedural outcome and aneurysm formation [34].

This conclusion is further supported by seemingly "routine" procedures of transcatheter intervention that have resulted in unexpected mortality [16, 40]. These cases suggest the preoperative integrity of the aortic wall may be a more useful indicator of proper balloon diameter sizing and the feasibility of angioplasty for a given lesion. Several studies have calculated acute gain, stretch and recoil during treatment for postoperative correlation to recoarctation, but the collective results are contradictory [36, 41]. Only one study to date has performed preoperative assessment of aortic integrity prior to intervention [42]. In this study, aortic stiffness, distensibility and compliance were calculated offline using intravascular ultrasound diameter and pressure measurements obtained proximal, distal and within the

Table 37.1. Suggested balloon diameters for the treatment of coarctation of the aorta

Balloon inflation diameter	Reference(s)
2 or more times the coarctation diameter, and less than the diameter of the aorta at the diaphragm	Rao et al. [14, 28, 31]
Diameter of the aorta at the diaphragm	Anjos et al. [37], Maheshwari et al. [82]
1–2 mm less than or equal to the diameter of the aorta at the diaphragm	Fawzy et al. [15, 83]
Average of the aortic diameter at the diaphragm and proximal to the origin of the subclavian artery	Huggon et al. [84]
Balloon-to-isthmus diameter ratio approximately equal to 1	Mendelsohn et al. [27]
Less than or equal to the diameter of the aorta at the subclavian plus 2 mm	Fletcher et al. [26], Ovaert et al. [10]
Balloon-to-native aorta ratio less than or equal to 1.1:1 (excluding coarctation, hypoplasia, and pre- and post-stenotic dilatation)	de Giovanni et al. [85]
Less than or equal to the diameter of the aorta at the isthmus plus 2 mm	Park et al. [38]
150% of the diameter of the aorta proximal to the coarctation	Yetman et al. [16]
Less than or equal to the diameter of the aorta at the diaphragm plus 2 mm	Koerselman et al. [17], Walhout et al. [24, 86]
2–3 times the coarctation diameter, and less than or equal to the diameter of the aorta at the diaphragm	Patel et al. [30]

region of the coarctation. Aortic stiffness, compliance and distensibility were elevated prior to balloon angioplasty compared with for patients without coarctation. These indices were unchanged within and proximal to the coarctation region after angioplasty and were unrelated to the severity of the resulting pressure gradient [42]. These results support the finding that coarctation is associated with temporal adaptations in vascular morphology [43].

37.2.3 Stent Implantation

The use of stents has recently been applied to the treatment of coarctation for the same minimally invasive reasons that prompted the popularity of balloon angioplasty in this patient population. Stenting works by stretching and scaffolding rather than tearing the aorta and this likely accounts for the observed lower short-term instances of aneurysms and recoarctation as compared with those from balloon angioplasty alone. The popularity and enthusiasm resulting from studies conducted over the last 15 years may eventually lead to the preferential use of stents in the treatment of coarctation [44]. Before stenting can be universally applied for the treatment of coarctation however, several important considerations must be addressed by the research and clinical communities. Most notably, studies describing the long-term efficacy of stent implantation must be completed.

37.2.4 Immediate and Intermediate-Term Outcomes After Stenting

In 1991 O'Laughlin et al. [45] reported the first use of a Palmaz iliac artery stent to reduce the pressure gradient across a coarctation in the thoracic aorta (50–25 mmHg) of a 12-year-old patient previously treated using balloon angioplasty. Subsequent case reports documented successful deployment of stents for palliative treatment of patients with severe coarctation that had been treated by surgery [46], balloon angioplasty [47] or both [44]. Larger studies then emerged with six to 54 patients [9, 48–56]. To date, no cases of mortality have been officially reported, but correspondence between interventionalists indicates that they do exist [57]. The majority of these reports include a mixture of patients with native and recurrent coarctation and the results demonstrate that stents generally restore systolic pressure gradients to 20 mmHg or lower in both patient populations. However, the mean patient age in these studies ranges from infants to older adults. Follow-up times have also fluctuated and success is typically measured according to current lower limits for mortality, aneurysm formation, recoarctation and hypertension. Table 37.2 summarizes the follow-up of this group of patients reported since the onset of this procedure. These studies have revealed an overall rate of aneurysm formation of 0–12% [9]. Many patients were hypertensive at rest prior to stent implantation and this hypertension was often attenuated after treatment [9, 54].

The technique for stent implantation is similar to that for balloon angioplasty with the obvious difference that a stent is left in place at the end of the procedure. In nearly all cases, the stent is delivered in a retrograde fashion. A long sheath (typically 35–70 cm in length) is advanced across the coarctation to protect both the stent while in transit and the coarctation site. It also facilitates passage of the stent through tight or tortuous coarctations. An additional pigtail catheter placed in the ascending aorta via a trans-septal approach is more commonly employed in this instance than with balloon angioplasty and is used for angiographic assistance in exact stent placement. Angiography can be performed through the long sheath if the operator chooses not to place a second catheter in the ascending aorta.

In tight lesions, some operators choose to gently inflate a balloon at the coarctation site to "get a feel" for

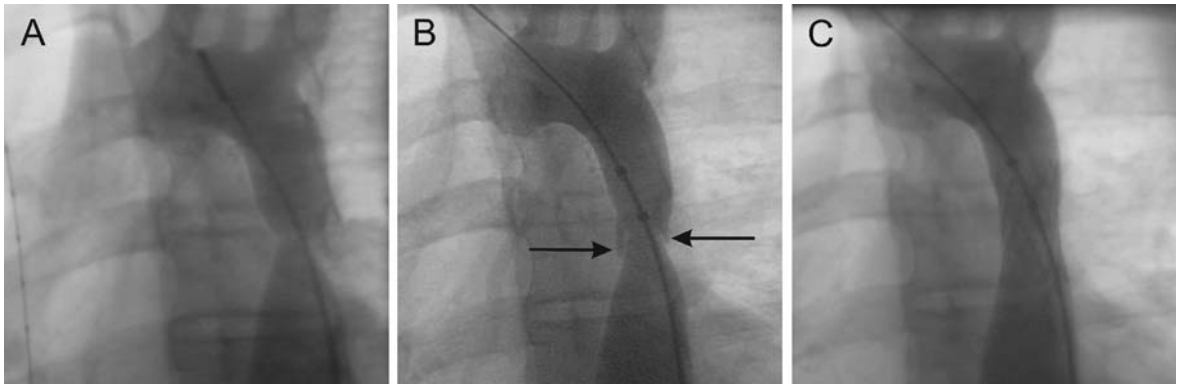

Fig. 37.2. Angiographic images of a coarctation before (**A**) and after (**B**) balloon angioplasty and subsequent stent implantation (**C**). Stent implantation can stabilize intimal flaps (*arrows*) caused by balloon angioplasty while providing relief of the coarctation

Table 37.2. Summary of characteristics and results in groups of patients treated for coarctation of the aorta by stent implantation

Reference(s)	Patients			Follow-up (months)	Stent diameter	Aneurysm	Hypertension	Recoarctation	Systolic gradient (mmHg)		
	Number	Prior surgeries	Age (years)						Preimplantation	Postimplantation	Follow-up
Bulbul et al. [49]	6	4	20±5	8	16±3	0	3/6 (50%)	1/6 (17%)	37±17	13±23	–
Ebeid et al. [51]	9	7	14–63	18	15	0	2/9 (22%)	1/9 (11%)	37±7[a]	4±1[a]	7±2[a]
Magee et al. [54]	17	17	17	7.5	11	1/17 (6%)	10/17 (59%)	2/17 (12%)	26	5	–
Suárez de Lezo et al. [55]	48	17	14	25	12±3	2/30 (7%)	0	8/30 (27%)	42±12	3±4	4±8
Thanopoulos et al. [56]	17	9	11[b]	33	14±2	0	2/17 (12%)	0	50±25	2±2	7±5
Hamdan et al. [52]	34	21	16±8	29±17	–	0	1/22 (5%)	0	64±21	3±4	–
Harrison et al. [9]	27	27	30	16	17	3/26 (12%)	7/26 (27%)	7/26 (27%)	46±20	3±5	4±8
Ledesma et al. [48]	54	–	23	25	–	3/53 (6%)	15/53 (28%)	2/53 (4%)	50±20	5±8	–
Zabal et al. [33]	22	–	26	22	–	0	1/22 (5%)	0	64±21	3±4	–
Johnston et al. [53]	32	23	15	18	16±3	0	3/6 (50%)	1/6 (17%)	37±17	13±23	–

The number of total patients listed under the aneurysm, hypertension and recoarctation columns represents the number of patients observed at follow-up and not necessarily the number of patients initially treated.
The data are presented as the mean ± standard deviation except where indicated.
[a] Mean ± standard error of the mean.
[b] Median

the resistance to dilation [58]. The stent is then mounted on a balloon of the appropriate size and advanced over the wire through the long sheath. The long sheath is retracted to allow expansion of the balloon and its associated stent. The balloon is then inflated and the stent fully apposed to the wall of the aorta. Repeat pressure measurement and angiography are performed and the stent may be further dilated if necessary. There is considerable debate around the need for flaring of the stent ends after implantation. Poor proximal and distal stent apposition was reported in 13 of 18 patients 1 year after stent implantation [9]. Although there were no ramifications of these observations, some clinicians have elected to flare the proximal and distal stent edges to achieve better aortic apposition [51–53]. This may reduce the instances of stent migration and embolization occasionally observed during treatment of coarctation [52], but may also increase the potential for aortic puncture due to the sharpness of stent struts or drastic mismatch between the compliant aorta and the rigid stent. Currently most operators feel that flaring is not necessary if the stent is well apposed to the aorta proximal to the original coarctation site.

Stents also have the ability to stabilize intimal tears resulting from balloon angioplasty (Fig. 37.2). This stability may be derived from scaffolding and supporting the intimal flaps or the development of neointimal hyperplasia that facilitates healing of the vessel and decreases the potential for aortic dissection. In coarctation patients with stenotic aortic valves or modestly calcified aortas, preoperative stent implantation prior to surgical valve replacement may be practical and may decrease the overall risk of surgery [35].

37.2.5 Complications Associated with Stent Implantation

Recoarctation following stent implantation may occur as a result of neointimal hyperplasia or patient growth. Some amount of neointimal hyperplasia occurs after non-drug-eluting stent implantation in all vascular beds [59], but is typically inconsequential in comparison to the diameter of the aorta [9]. Stent overexpansion has been correlated with the severity of neointimal hyperplasia in the aorta and other vascular beds [60, 61]. Recoarctation resulting from patient growth in cases of stent implantation during childhood has been observed in several previous studies [49, 50, 52, 55] and has been a concern since the onset of the procedure [47]. However, this problem is not unique to stent implantation, since severe growth-induced recoarctation has also been observed following correction by balloon angioplasty or surgery [12]. Previous studies using experimental models of coarctation in animals have demonstrated that stents may be reexpanded [62]. In the latter study, Palmaz stents with a length of 30 mm implanted to a diameter of 10 mm could be radially expanded by approximately 4 mm. Unfortunately 29% (two of seven) of the animals experienced aortic rupture resulting in death after stent redilation [62]. Several studies conducted in humans have described successful expansion of stents following primary implantation on an individual basis, and a recent study was conducted to evaluate the efficacy of reexpansion for the serial treatment of coarctation [50, 53, 54]. In these studies, progressive expansion was able to restore the aorta to the diameter

obtained immediately after initial implantation. None of these studies have demonstrated that this technique can be used to account for somatic growth [50].

Several studies have documented the occurrence of aneurysms after stent implantation for treatment of coarctation [9, 26, 48, 54, 55]. Some of the aneurysms may be attributed to predilation with balloon angioplasty [26, 48, 54, 55]. In such cases the rate of aneurysm formation was approximately 6% [9, 26, 51]. Conversely, in cases where stent implantation was performed in the absence of predilation with balloon angioplasty, the rate of aneurysm formation was less than 1% [49, 52–54, 56]. These collective results suggest that primary stent implantation should be advocated to avoid the increased risk of aneurysms associated with balloon angioplasty. However, the prevalence of aneurysms following stent implantation may differ from that published as a result of variations in the definition of an aneurysm and questions as to the utility of imaging techniques for their assessment [9].

Other complications have been reported after stent implantation and include loss of femoral artery pulses and iliac artery bleeding [52, 55]. Improved delivery devices, lower-profile balloon–stent combinations and a trend toward primary stent implantation have reduced the frequency of these occurrences in recent years. Neurological complications, either transient ischemic attacks or cerebrovascular accidents, have been described with attempted balloon angioplasty or stent implantation [9]. Balloon rupture and partial embolization have also been an occasional occurrence during stent implantation primarily owing to resistant lesions and the sharp edges of the Palmaz stent [52]. As a result, some clinicians have suggested using high-pressure angioplasty balloons to minimize the potential for rupture and aortic damage during stent deployment or reexpansion [50, 52]. Newer balloon-in-balloon technology has reduced the incidence of balloon rupture, but has not gained widespread favor owing to the significantly larger sheaths required for stent delivery [63].

37.2.6 Indications for Stent Implantation

In addition to adult or near-adult-sized patients in whom stent placement is now becoming the treatment of choice, stent implantation may be especially practical for diffuse lesions where longer angioplasty balloons would be more likely to induce aneurysms and surgical repair would require the resection of a large portion of the aorta [64]. Similarly, older patients with longer coarctation segments, but modestly compromised aortic elasticity, may opt for stent implantation as an alternative to the insertion of an interposition graft or synthetic patch. Stents also have the ability to realign convoluted proximal and distal portions of the aorta that may be tortuous as a result of coarctation [55]. However, Harrison et al. [9] recently reported stent patient with a geometrically induced aortic obstruction that was complicated by aneurysm formation. The authors caution that surgery should be considered for these patients, or that stents should be gradually expanded over several catheterization procedures. Stent placement is also indicated following previous surgical repair or balloon angioplasty as repeating either treatment has met with marginal results [12, 13] and investigators have also used stents for palliative treatment when the risk of surgical repair was too great [45].

Isthmus and transverse arch hypoplasia are often present before stenting [55], but have also appeared with significant residual gradients after stenting of the primary coarctation region [52]. Successful stent implantation was recently reported in 29 coarctation patients presenting with aortic isthmus or transverse arch hypoplasia [55, 65]. In this study, concomitant stenting of the hypoplastic and coarctation regions was performed without short-term or intermediate-term complications. Immediate and follow-up angiographic images demonstrated that the aortic anatomy was hemodynamically advantageous after stent implantation [55]. This may prompt others to stent hypoplastic segments in future studies.

Contraindications for the use of stents in the treatment of coarctation are more controversial. Numerous case reports, first with balloon angioplasty and now with respect to stent implantation, have proclaimed or suggested that the use of such devices is efficacious despite the lack of long-term follow-up data. For example, the diameter of stents deployed to treat coarctation reported in the literature has ranged from 11 to 18 mm [9, 49, 54, 55, 58]. The typical diameter in an adult aorta is approximately 24 mm [66]. This disparity suggests that these stents will likely result in reports of recurrent aortic stenosis once long-term data are available. To our knowledge, no study conducted to date has expanded stents to account for progressive somatic growth in humans. As a result, additional studies properly designed to assess the chronic treatment of patients will be necessary to determine the ultimate utility of stents for the treatment of aortic coarctation. Moreover, there may be ramifications to this treatment as progressive expansion and inherent stent shortening may cause serious damage to the lumen of the aorta both circumferentially and longitudinally. Currently, a general consensus exists that surgery is preferred over stent implantation in neonates and infants as large sheaths and delivery catheters have the potential to cause occlusive femoral artery damage [49, 52], and somatic growth may cause recoarctation, prompting additional procedures [52, 55].

Long-term, randomized and prospective studies have not yet been conducted owing to the relatively recent application of this technology and scarcity of these cases at a single institution. The Congenital Cardiovas-

cular Interventional Study Consortium (CCISC), a concerted, multicenter registry is currently enrolling transcatheter and surgically patients. This will provide invaluable data about long-term morbidity and how treatment options may influence the overall outcomes.

Partial obstruction of peripheral vessels by stent struts may occur during and after stent implantation [9], but no adverse results have been reported in short-term or midterm follow-up studies. However, until long-term data are available, this situation should be avoided, if possible, to limit the potential restriction of blood flow to the carotid, subclavian, spinal and brachial arteries [67]. When partial obstruction of peripheral arteries is inevitable, expansion of obtrusive struts with subsequent balloon angioplasty catheters may be a viable option after coarctation relief is obtained.

A variety of anatomical diameters throughout the aorta have been referenced during stent implantation in an attempt to minimize aortic damage [51–53, 56]. Many investigators have selected stent deployment balloons with diameters equal to that of the transverse arch, but not exceeding that at the level of the diaphragm [33, 51, 56]. Still other studies have attempted to expand stents to a final diameter based on that of the stenosis [52, 53].

Although transcatheter techniques have revolutionized the treatment of coarctation, it is of concern that the practice of balloon angioplasty and stent implantation does not ubiquitously consider the compliance, pathology or functional integrity of the stenosed region prior to treatment. Preliminary evidence indicates that surgical correction or stent implantation for the treatment of coarctation may alter properties of the vascular wall [43, 50]. Collectively, these results strongly suggest that future procedures should work toward establishing noninvasive indices to determine the severity of vascular dysfunction within the region of the stenosis before treatment. Some investigators have suggested assessing stenosis compliance using the response of the vascular lesion to balloon predilation at 3 or 4 atm [58]. However, such invasive methods may predispose the region to aortic damage or embolization during stent implantation [49]. Nevertheless, implementation of novel pathological assessment tools prior to treatment may delineate which patients are more susceptible to aortic rupture, and should be referred for surgery.

Modest residual gradients persisting after correction for coarctation are an important indicator of future complications [33] and cause mild, but persistent stress on the left ventricle. Left ventricular end diastolic pressure (LVEDP) decreased 7 months after stent implantation in a recent study of 16 patients treated for mild residual or recurrent coarctation [58]. In this study, stent implantation was indicated and performed as a secondary treatment when inadequate pressure gradient relief was observed after balloon angioplasty. These results suggest that stent implantation may be superior to balloon angioplasty for eliminating these mild residual stenoses and for reducing LVEDP [58].

Although there are currently no FDA-approved stents designed to treat aortic coarctation, new designs that specifically consider somatic growth will likely be developed in the next decade. The Palmaz stent is currently the most popular choice for treatment of coarctation [68] and has recently been made available in 40- and 50-mm lengths. Studies have suggested that stent redilation of shorter Palmaz stents may be possible using animal models of aortic coarctation, but that this expansion is associated with appreciable reductions in stent length [63]. If long-term data prove that reexpansion of these stents is both necessary and possible in response to aortic growth, longer designs may ensure that foreshortening does not displace the stent from the localized region of the coarctation. Biodegradable stents may be the ideal choice for congenital stent implantation, but several technical limitations, including inadequate radial strength and small diameter sizes, prevent their application to coarctation at the present time [68]. In theory, these devices represent an important treatment option as their gradual degradation may provide the greatest chronic benefit during the growth of a patient.

37.3 Comparing Treatment Modalities

Comparisons between groups of patients treated with the various methods of coarctation repair have only recently emerged and should be interpreted within the constraints of their inherent limitations. Procedural details associated with balloon angioplasty and surgery have evolved from empirical evidence and revised techniques that have developed since the introduction of these procedures. In comparison, early case reports and studies with modest patient populations treated by stent implantation have only been conducted since 1991 [45], and the results are therefore biased by the relatively recent application of stents to the treatment of aortic coarctation. Fortunately, the short- and intermediate-term results of stent implantation for the treatment of coarctation in certain patient populations appear to be comparable to those obtained after surgery or balloon angioplasty [48, 52, 55].

In a recent retrospective study, comparisons were attempted between two treatment modalities despite significant differences in follow-up periods [24, 33]. The median ages for patients in the surgical and balloon angioplasty groups of one study were 0.63 and 5.8 years, respectively [24]. Immediate success rates were nearly equivalent for both techniques and they were comparable in their ability to reduce pressure gradients acutely at rest. However, recoarctation was modestly higher at follow-up for patients treated with balloon angioplasty

as compared with that for those treated surgically during infancy (7 versus 5.6%, respectively) [24].

Studies have indicated that mortality after balloon angioplasty and surgery increases with patient age at coarctation repair, and preliminary results after stent implantation suggest that procedural outcome is better if stent implantation is performed shortly after identifying the coarctation [22]. These findings suggest that favorable chronic results after any treatment to alleviate coarctation depend on recovery of previously depressed cardiac function after the procedure [58]. Conversely, the potential for recoarctation following balloon angioplasty or surgical correction for coarctation is greater when patients are treated during infancy. This finding may be explained by the local vascular morphology of the aorta within the region of the coarctation during this period [27, 28, 38] as 67–91% of patients with a patent ductus arteriosus developed recoarctation following balloon angioplasty for treatment of native coarctation [26, 38]. Comparisons between surgical and transcatheter treatments for coarctation are also complicated by different definitions of procedural success and inconsistencies in the extent of patient data reported in each study. Comparison of experiences during surgical repair of native coarctation and those after unsuccessful angioplasty in the absence or presence of transcatheter-induced aneurysms revealed no differences in procedural complications or outcome [69]. These findings suggest that prior balloon angioplasty will not preclude future successful surgical intervention for recoarctation. This may not be true, however, in the case of surgery after stent implantation. If further expansion of stents becomes necessary but is not possible, the removal of large portions of the aorta or the continued presence of the stent in the aortic wall may prove less beneficial when compared with initial surgical treatment of the coarctation.

37.4 Future Considerations for Transcatheter Treatment of Aortic Coarctation

37.4.1 Criteria for Successful Treatment

A universal standard for assessing the success of treatments for coarctation has not yet emerged. A residual pressure gradient of 20 mmHg or lower at rest has been the historical goal after transcatheter or surgical interventions [52, 70], though some clinicians define success as gradients ranging from 15 to 40 mmHg [27, 52, 71, 72]. Other clinicians have suggested treatment options based on functional flow charts of immediate-term results [33], while still others reference an average blood pressure percentile based on the patient's age [14]. Unfortunately, while pressure gradients represent fairly standardized guidelines suggesting when the severity of a coarctation warrants intervention, there are few experimental or physiological data supporting any of these guidelines and they remain the only parameter of "success" monitored. The current 20-mmHg guideline for intervention has evolved from the best possible results that were previously obtained, on average, by surgical repair or balloon angioplasty without the increased risk associated with additional procedures [67]. With the introduction of stent implantation, awareness of cardiac dysfunction that can result from modest residual gradients, and advances in computational tools to assess the ramifications of a particular treatment, the hemodynamic and physiological influence of various pressure gradients, including the putative 20-mmHg guideline, should be revisited.

Not surprisingly, coarctation causes increased blood pressure and fatigue during exercise and several studies have advocated exercise testing as an indication for recoarctation after surgical repair [5]. Pathological modifications resulting from increased afterload prior to the correction of a coarctation can persist even after surgical or transcatheter repair and are important risk factors for morbidity and mortality in adulthood. This finding is underscored by a study demonstrating that patients surgically treated for coarctation rely on anaerobic metabolism to a greater extent during exercise than age- and gender-matched controls [4]. Interestingly, previous studies have demonstrated that patients who are normotensive at rest after coarctation repair are often hypertensive during exercise [5]. These studies, combined with the premature life expectancies of patients with coarctation, suggest that the current means of assessing procedural success predominantly under resting conditions should be reassessed. To our knowledge, no studies have examined exercise-induced systolic pressure gradients after stent implantation. Although a previous porcine model demonstrated that aortic compliance and hemodynamics were unchanged shortly after stent implantation at rest [73], subtle differences unique to each treatment option at rest may be amplified during exercise conditions.

37.4.2 A New Paradigm for Treatment

Many of the risk factors for morbidity associated with coarctation can be attributed to abnormal hemodynamics throughout the aorta. The coarctation causes pre- and poststenotic dilatation that, in turn, reduces capacitance and leads to elevated pulse pressure in the ascending aorta. Pressure-wave amplification from the summation of normal incident waves and those reflected from the stenosis account for this increased pulse pressure and hypertension during rest and exer-

cise [74]. Subsequent perfusion of the coronary arteries during diastole is also compromised, resulting in decreased flow and an increase in precursors of coronary artery disease [75]. Reduced coronary artery perfusion and concomitant increases in afterload may also explain the high instance of indices associated with heart failure in these patients [58, 76]. Relief of these deleterious hemodynamics was observed following the alleviation of an experimental coarctation [74], suggesting that treatment strategies that optimize vascular hemodynamics may provide the greatest chronic benefit to patients.

Hypertension is the most frequent complication associated with repair of coarctation regardless of treatment modality. In a study of patients subjected to exercise testing approximately 20 years after treatment for coarctation by surgical repair, nearly 50% of patients were found to have ambulatory and exercise-induced hypertension, a finding that is commoner when treatment is obtained after 1 year of age [77]. Residual coarctation caused by scarring at the suture site or persistent aortic arch hypoplasia after treatment may contribute to this finding [5]. Although long-term data after stent implantation for coarctation are not yet available, it seems possible that the presence of a rigid stent in the compliant aorta may also cause hypertension. Persistent pathologic arterial modifications such as increased systemic vascular resistance, aortic stiffness, elevated left ventricular contractility [43, 78] and anatomical abnormalities of the transverse arch not unique to a particular treatment strategy are also thought to contribute to hypertension [79].

Coronary artery disease, cerebral aneurysms and stroke also occur despite "successful" coarctation repair, indicating that the current perception of success may be incorrect and the ongoing severity of treatment-specific hemodynamic alterations manifested in the aorta and coronary, head and neck vessels during ambulatory or exercise conditions may contribute to long-term morbidity. For example, studies conducted on canine coronary arteries have demonstrated that the compliance mismatch between a stent and a native vessel is masked during conditions of resting blood flow, and causes deleterious alterations in local flow patterns during maximum vasodilation [80]. Similarly, the coarctation causes drastic reductions in the capacitive function of the aorta and there are likely hemodynamic ramifications of the compliance mismatch caused not only by coarctation prior to surgical or catheter-based intervention at rest, but also during ambulation.

It is clear from the clinical literature that parametric alterations within a single treatment, or relying on the gradual empirical modification of these treatments, will only modestly increase the life expectancies of patients with aortic coarctation. Alternatively, more favorable long-term results may be possible by examining the origin of coarctation symptoms that emanate from alterations in vascular hemodynamics within the ascending aorta.

Researchers in the Cardiovascular Biomechanics Research Laboratory at Stanford University, in collaboration with Departments of Pediatric Cardiology and Cardiothoracic Surgery, are currently investigating a new paradigm to improve our understanding of the hemodynamic and physiologic conditions before and after treatment for coarctation. This research is based on the hypothesis that treatment strategies that optimize vascular hemodynamics at rest and during exercise will minimize known risk factors for long-term morbidity associated with aortic coarctation. Rather than modifying the technique of a given treatment or evaluating strategies based on the current standards for mortality, recoarctation, aneurysm formation and hypertension, treatment strategies could be scrutinized according to their ability to restore optimal hemodynamics in the ascending and descending aorta and head and neck vessels. A similar approach to treatment planning has previously been described for occlusive vascular disease in adults [81].

Through this interdisciplinary collaboration, computer models can be created from time-resolved 3D phase-contrast magnetic resonance imaging data obtained at rest and during lower limb exercise using a

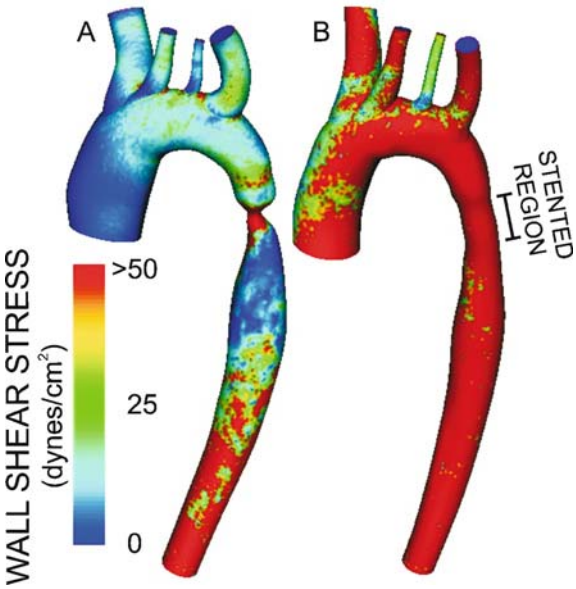

Fig. 37.3. Average wall shear stress (*WSS*) in a patient with coarctation of the aorta before (**a**) and after (**b**) stent implantation. Aortic coarctation causes ascending aortic dilation and pre- and poststenotic dilatation that is responsible for low WSS in the arch, ascending and descending aorta and branch arteries. Most of these low WSS regions are alleviated after stent implantation, but some areas of the aortic arch, branch vessels and anomalous vertebral artery remain and may be deleterious as low WSS is known to correlate with sites of atherogenesis and vascular inflammation

supine stationary ergometer. Treatment-specific alterations in vascular wall motion, indices of wall shear stress and pressure wave reflection and amplification manifested in the head and neck vessels and throughout the aorta can then be quantified and interpreted as surrogates of the potential for morbidity (Fig. 37.3). The results may reveal hemodynamic adaptations associated with the acceptable systolic pressure gradient of 20 mmHg and determine if treatment-specific guidelines may be more appropriate for minimizing morbidity. In addition, the simulations can reveal 3D spatial and temporal hemodynamic ramifications of compliance mismatch caused by the coarctation prior to intervention, and the surgical suture line or rigid stent afterward. This hemodynamic characterization process may be amenable to predicting which treatment strategies will be advantageous for a particular patient and to identifying deleterious processes that lead to morbidity decades before they are clinically apparent.

In the future, computational models may be used to determine which strategy will benefit the patient from a hemodynamic and physiologic perspective. If the development of these computational models based on patient-specific anatomy and physiology is successful, they may provide the potential to increase our scientific understanding of this problem and the various treatment options. In the long term, patient-specific modeling may provide clinicians with a resource to decrease disease- and procedure-related morbidity and mortality.

37.5 Summary

Balloon angioplasty and stent implantation are now widely accepted as treatment options for coarctation of the aorta. Both of these strategies, as well as surgical repair, have advantages and disadvantages in specific patient populations. In the future, changes in stent design and materials and better predictive models of appropriate candidates for endovascular treatment will optimize treatment outcomes. As additional long-term data regarding procedural success, morbidity and mortality become available and surgical and transcatheter techniques progress, management strategies will also continue to evolve. As always, close collaboration between surgeons and cardiologists will remain imperative.

References

1. Bobby JJ, Emami JM, Farmer RD, Newman CG. Operative survival and 40 year follow up of surgical repair of aortic coarctation. Br Heart J 1991; 65:271–276.
2. Rothman A. Coarctation of the aorta: an update. Curr Probl Pediatr 1998; 28:37–60.
3. Bouchart F, Dubar A, Tabley A, Litzler PY, Haas-Hubscher C, Redonnet M, Bessou JP, Soyer R. Coarctation of the aorta in adults: surgical results and long-term follow-up. Ann Thorac Surg 2000; 70:1483–1488.
4. Rhodes J, Geggel RL, Marx GR, Bevilacqua L, Dambach YB, Hijazi ZM. Excessive anaerobic metabolism during exercise after repair of aortic coarctation. J Pediatr 1997; 131:210–214.
5. Pelech AN, Kartodihardjo W, Balfe JA, Balfe JW, Olley PM, Leenen FH. Exercise in children before and after coarctectomy: hemodynamic, echocardiographic, and biochemical assessment. Am Heart J 1986; 112:1263–1270.
6. Moskowitz WB, Schieken RM, Mosteller M. Altered systolic and diastolic function in children after "successful" repair of coarctation of the aorta. Am Heart J 1990; 120:103–109.
7. Varma C, Benson LN, Butany J, McLaughlin PR. Aortic dissection after stent dilatation for coarctation of the aorta: a case report and literature review. Catheter Cardiovasc Interv 2003; 59:528–535.
8. Erbel R, Bednarczyk I, Pop T, Todt M, Henrichs KJ, Brunier A, Thelen M, Meyer J. Detection of dissection of the aortic intima and media after angioplasty of coarctation of the aorta. An angiographic, computer tomographic, and echocardiographic comparative study. Circulation 1990; 81:805–814.
9. Harrison DA, McLaughlin PR, Lazzam C, Connelly M, Benson LN. Endovascular stents in the management of coarctation of the aorta in the adolescent and adult: one year follow up. Heart 2001; 85:561–566.
10. Ovaert C, McCrindle BW, Nykanen D, MacDonald C, Freedom RM, Benson LN. Balloon angioplasty of native coarctation: clinical outcomes and predictors of success. J Am Coll Cardiol 2000; 35:988–996.
11. Toro-Salazar OH, Steinberger J, Thomas W, Rocchini AP, Carpenter B, Moller JH. Long-term follow-up of patients after coarctation of the aorta repair. Am J Cardiol 2002; 89:541–547.
12. Pollack P, Freed MD, Castaneda AR, Norwood WI. Reoperation for isthmic coarctation of the aorta: follow-up of 26 patients. Am J Cardiol 1983; 51:1690–1694.
13. Singer MI, Rowen M, Dorsey TJ. Transluminal aortic balloon angioplasty for coarctation of the aorta in the newborn. Am Heart J 1982; 103:131–132.
14. Rao PS, Najjar HN, Mardini MK, Solymar L, Thapar MK. Balloon angioplasty for coarctation of the aorta: immediate and long-term results. Am Heart J 1988; 115:657–664.
15. Fawzy ME, Dunn B, Galal O, Wilson N, Shaikh A, Sriram R, Duran CM. Balloon coarctation angioplasty in adolescents and adults: early and intermediate results. Am Heart J 1992; 124:167–171.
16. Yetman AT, Nykanen D, McCrindle BW, Sunnegardh J, Adatia I, Freedom RM, Benson L. Balloon angioplasty of recurrent coarctation: a 12-year review. J Am Coll Cardiol 1997; 30:811–816.
17. Koerselman J, de Vries H, Jaarsma W, Muyldermans L, Ernst JMPG, Plokker HWM. Balloon angioplasty of coarctation of the aorta: a safe alternative for surgery in adults: immediate and mid-term results. Catheter Cardiovasc Interv 2000; 50:28–33.
18. Gibbs JL. Treatment options for coarctation of the aorta. Heart 2000; 84:11–13.
19. Lock JE, Niemi T, Burke BA, Einzig S, Castaneda-Zuniga WR. Transcutaneous angioplasty of experimental aortic coarctation. Circulation 1982; 66:1280–1286.
20. Lock JE, Castaneda-Zuniga WR, Bass JL, Foker JE, Amplatz K, Anderson RW. Balloon dilation of excised aortic coarctations. Radiology 1982; 143:689–691.
21. Sohn S, Rothman A, Shiota T, Luk G, Tong A, Swensson RE, Sahn DJ. Acute and follow-up intravascular ultrasound findings after balloon dilation of coarctation of the aorta. Circulation 1994; 90:340–347.

22. Hellenbrand WE, Allen HD, Golinko RJ, Hagler DJ, Lutin W, Kan J. Balloon angioplasty for aortic recoarctation: results of Valvuloplasty and Angioplasty of Congenital Anomalies Registry. Am J Cardiol 1990; 65:793–797.
23. Ovaert C, Benson LN, Nykanen D, Freedom RM. Transcatheter treatment of coarctation of the aorta: a review. Pediatr Cardiol 1998; 19:27–44.
24. Walhout RJ, Lekkerkerker JC, Oron GH, Bennink GB, Meijboom EJ. Comparison of surgical repair with balloon angioplasty for native coarctation in patients from 3 months to 16 years of age. Eur J Cardiothorac Surg 2004; 25:722–727.
25. Lababidi Z. Neonatal transluminal balloon coarctation angioplasty. Am Heart J 1983; 106:752–753.
26. Fletcher SE, Nihill MR, Grifka RG, O'Laughlin MP, Mullins CE. Balloon angioplasty of native coarctation of the aorta: midterm follow-up and prognostic factors. J Am Coll Cardiol 1995; 25:730–734.
27. Mendelsohn AM, Lloyd TR, Crowley DC, Sandhu SK, Kocis KC, Beekman RH 3rd. Late follow-up of balloon angioplasty in children with a native coarctation of the aorta. Am J Cardiol 1994; 74:696–700.
28. Rao PS, Galal O, Smith PA, Wilson AD. Five-to nine-year follow-up results of balloon angioplasty of native aortic coarctation in infants and children. J Am Coll Cardiol 1996; 27:462–470.
29. von Kodolitsch Y, Aydin MA, Koschyk DH, Loose R, Schalwat I, Karck M, Cremer J, Haverich A, Berger J, Meinertz T, Nienaber CA. Predictors of aneurysmal formation after surgical correction of aortic coarctation. J Am Coll Cardiol 2002; 39:617–624.
30. Patel HT, Madani A, Paris YM, Warner KG, Hijazi ZM. Balloon angioplasty of native coarctation of the aorta in infants and neonates: is it worth the hassle? Pediatr Cardiol 2001; 22:53–57.
31. Rao PS, Thapar MK, Galal O, Wilson AD. Follow-up results of balloon angioplasty of native coarctation in neonates and infants. Am Heart J 1990; 120:1310–1314.
32. Tyagi S, Arora R, Kaul UA, Sethi KK, Gambhir DS, Khalilullah M. Balloon angioplasty of native coarctation of the aorta in adolescents and young adults. Am Heart J 1992; 123:674–680.
33. Zabal C, Attie F, Rosas M, Buendia-Hernandez A, Garcia-Montes JA. The adult patient with native coarctation of the aorta: balloon angioplasty or primary stenting? Heart 2003; 89:77–83.
34. Rao PS, Thapar MK, Kutayli F, Carey P. Causes of recoarctation after balloon angioplasty of unoperated aortic coarctation. J Am Coll Cardiol 1989; 13:109–115.
35. Duke C, Qureshi SA. Aortic coarctation and recoarctation: to stent or not to stent? J Interv Cardiol 2001; 14:283–298.
36. Ino T, Ohkubo M, Akimoto K, Nishimoto K, Yabuta K, Kawasaki S, Watanabe M, Hosoda Y. Angiographic assessment of the stretch-recoil-gain relation after balloon coarctation angioplasty and its relation to late restenosis. Jpn Circ J 1996; 60:102–107.
37. Anjos R, Qureshi SA, Rosenthal E, Murdoch I, Hayes A, Parsons J, Baker EJ, Tynan M. Determinants of hemodynamic results of balloon dilation of aortic recoarctation. Am J Cardiol 1992; 69:665–671.
38. Park Y, Lucas VW, Sklansky MS, Kashani IA, Rothman A. Balloon angioplasty of native aortic coarctation in infants 3 months of age and younger. Am Heart J 1997; 134:917–923.
39. Weber HS, Cyran SE. Initial results and clinical follow-up after balloon angioplasty for native coarctation. Am J Cardiol 1999; 84:113–116.
40. Balaji S, Oommen R, Rees PG. Fatal aortic rupture during balloon dilatation of recoarctation. Br Heart J 1991; 65:100–101.
41. Rao PS, Waterman B. Relation of biophysical response of coarcted aortic segment to balloon dilatation with development of recoarctation following balloon angioplasty of native coarctation. Heart 1998; 79:407–411.
42. Xu J, Shiota T, Omoto R, Zhou X, Kyo S, Ishii M, Rice MJ, Sahn DJ. Intravascular ultrasound assessment of regional aortic wall stiffness, distensibility, and compliance in patients with coarctation of the aorta. Am Heart J 1997; 134:93–98.
43. Ong CM, Canter CE, Gutierrez FR, Sekarski DR, Goldring DR. Increased stiffness and persistent narrowing of the aorta after successful repair of coarctation of the aorta: relationship to left ventricular mass and blood pressure at rest and with exercise. Am Heart J 1992; 123:1594–1600.
44. Rosenthal E, Qureshi SA, Tynan M. Stent implantation for aortic recoarctation. Am Heart J 1995; 129:1220–1221.
45. O'Laughlin MP, Perry SB, Lock JE, Mullins CE. Use of endovascular stents in congenital heart disease. Circulation 1991; 83:1923–1939.
46. Pedulla DM, Grifka RG, Mullins CE, Allen D. Endovascular stent implantation for severe recoarctation of the aorta: case report with angiographic and 18-month clinical follow-up. Cathet Cardiovasc Diagn 1997; 40:311–314.
47. Redington AN, Hayes AM, Ho SY. Transcatheter stent implantation to treat aortic coarctation in infancy. Br Heart J 1993; 69:80–82.
48. Ledesma M, Alva C, Gomez FD, Sanchez-Soberanis A, Diaz y Diaz E, Benitez-Perez C, Herrera-Franco R, Arguero R, Feldman T. Results of stenting for aortic coarctation. Am J Cardiol 2001; 88:460–462.
49. Bulbul ZR, Bruckheimer E, Love JC, Fahey JT, Hellenbrand WE. Implantation of balloon-expandable stents for coarctation of the aorta: implantation data and short-term results. Cathet Cardiovasc Diagn 1996; 39:36–42.
50. Duke C, Rosenthal E, Qureshi SA. The efficacy and safety of stent redilation in congenital heart disease. Heart 2003; 89:905–912.
51. Ebeid MR, Prieto LR, Latson LA. Use of balloon-expandable stents for coarctation of the aorta: initial results and intermediate-term follow-up. J Am Coll Cardiol 1997; 30:1847–1852.
52. Hamdan MA, Maheshwari S, Fahey JT, Hellenbrand WE. Endovascular stents for coarctation of the aorta: initial results and intermediate-term follow-up. J Am Coll Cardiol 2001; 38:1518–1523.
53. Johnston TA, Grifka RG, Jones TK. Endovascular stents for treatment of coarctation of the aorta: acute results and follow-up experience. Catheter Cardiovasc Interv 2004; 62:499–505.
54. Magee AG, Brzezinska-Rajszys G, Qureshi SA, Rosenthal E, Zubrzycka M, Ksiazyk J, Tynan M. Stent implantation for aortic coarctation and recoarctation. Heart 1999; 82:600–606.
55. Suárez de Lezo J, Pan M, Romero M, Medina A, Segura J, Lafuente M, Pavlovic D, Hernandez E, Melian F, Espada J. Immediate and follow-up findings after stent treatment for severe coarctation of aorta. Am J Cardiol 1999; 83:400–406.
56. Thanopoulos BD, Hadjinikolaou L, Konstadopoulou GN, Tsaousis GS, Triposkiadis F, Spirou P. Stent treatment for coarctation of the aorta: intermediate term follow up and technical considerations. Heart 2000; 84:65–70.
57. Mullen MJ. Coarctation of the aorta in adults: do we need surgeons? Heart 2003; 89:3–5.
58. Marshall AC, Perry SB, Keane JF, Lock JE. Early results and medium-term follow-up of stent implantation for mild or recurrent aortic coarctation. Am Heart J 2000; 139:1054–1060.

59. Farb A, Weber DK, Kolodgie FD, Burke AP, Virmani R. Morphological predictors of restenosis after coronary stenting in humans. Circulation 2002; 105:2974–2980.
60. Schulz C, Herrmann RA, Beilharz C, Pasquantonio J, Alt E. Coronary stent symmetry and vascular injury determine experimental restenosis. Heart 2000; 83:462–467.
61. LaDisa JF Jr, Olson LE, Guler I, Hettrick DA, Audi SH, Kersten JR, Warltier DC, Pagel PS. Stent design properties and deployment ratio influence indexes of wall shear stress: a three-dimensional computational fluid dynamics investigation within a normal artery. J Appl Physiol 2004; 97:424–430.
62. Mendelsohn AM, Dorostkar PC, Moorehead CP, Lupinetti FM, Reynolds PI, Ludomirsky A, Lloyd TR, Heidelberger K, Beekman RH 3rd. Stent redilation in canine models of congenital heart disease: pulmonary artery stenosis and coarctation of the aorta. Cathet Cardiovasc Diagn 1996; 38:430–440.
63. Ing F. Stents: what's available to the pediatric interventional cardiologist? Catheter Cardiovasc Interv 2002; 53:374–386.
64. Thanopoulos BV, Triposkiadis F, Margetakis A, Mullins CE. Long segment coarctation of the thoracic aorta: treatment with multiple balloon-expandable stent implantation. Am Heart J 1997; 133:470–473.
65. Pihkala J, Pedra CA, Nykanen D, Benson LN. Implantation of endovascular stents for hypoplasia of the transverse aortic arch. Cardiol Young 2000; 10:3–7.
66. Perloff JK. Coarctation of the aorta. In: Clinical recognition of congenital heart disease. Saunders, Philadelphia. 2003. p. 113–143.
67. Rosenthal E. Stent implantation for aortic coarctation: the treatment of choice in adults? J Am Coll Cardiol 2001; 38:1524–1527.
68. Ebeid MR. Balloon expandable stents for coarctation of the aorta: review of current status and technical considerations. Images Pediatr Cardiol 2003; 15:25–41.
69. Minich LL, Beekman RH 3rd, Rocchini AP, Heidelberger K, Bove EL. Surgical repair is safe and effective after unsuccessful balloon angioplasty of native coarctation of the aorta. J Am Coll Cardiol 1992; 19:389–393.
70. van Heurn LWE, Wong CM, Spiegelhalter DJ, Sorensen K, de Lavel MR, Stark J, Elliott MJ. Surgical treatment of aortic coarctation in infants younger than three months: 1985 to 1990. Success of extended end-to-end arch aortoplasty. J Thorac Cardiovasc Surg 1994; 107:74–86.
71. Beekman RH 3rd, Rocchini AP, Behrendt DM, Bove EL, Dick M II, Crowley DC, Snider AR, Rosenthal A. Percutaneous balloon angioplasty for native coarctation of the aorta. J Am Coll Cardiol 1987; 10:1078–1084.
72. Cooper SG, Sullivan ID, Wren C. Treatment of recoarctation: balloon dilation angioplasty. J Am Coll Cardiol 1989; 14:413–419.
73. Pihkala J, Thyagarajan GK, Taylor GP, Nykanen D, Benson LN. The effect of implantation of aortic stents on compliance and blood flow. An experimental study in pigs. Cardiol Young 2001; 11:173–181.
74. O'Rourke MF, Cartmill TB. Influence of aortic coarctation on pulsatile hemodynamics in the proximal aorta. Circulation 1971; 44:281–292.
75. Malek AM, Alper SL, Izumo S. Hemodynamic shear stress and its role in atherosclerosis. JAMA 1999; 282:2035–2042.
76. Prisant LM, Mawulawde K, Kapoor D, Joe C. Coarctation of the aorta: a secondary cause of hypertension. J Clin Hypertens 2004; 6:347–350, 352.
77. Sigurdardottir LY, Helgason H. Exercise-induced hypertension after corrective surgery for coarctation of the aorta. Pediatr Cardiol 1996; 17:301–307.
78. Gardiner HM, Celermajer DS, Sorensen KE, Georgakopoulos D, Robinson J, Thomas O, Deanfield JE. Arterial reactivity is significantly impaired in normotensive young adults after successful repair of aortic coarctation in childhood. Circulation 1994; 89:1745–1750.
79. Weber HS, Cyran SE, Grzeszczak M, Myers JL, Gleason MM, Baylen BG. Discrepancies in aortic growth explain aortic arch gradients during exercise. J Am Coll Cardiol 1993; 21:1002–1007.
80. LaDisa JF Jr, Hettrick DA, Olson LE, Guler I, Gross ER, Kress TT, Kersten JR, Warltier DC, Pagel PS. Coronary stent implantation alters coronary artery hemodynamics and wall shear stress during maximal vasodilation. J Appl Physiol 2002; 93:1939–1946.
81. Taylor CA, Draney MT, Ku JP, Parker D, Steele BN, Wang K, Zarins CK. Predictive medicine: computational techniques in therapeutic decision-making. Comput Aided Surg 1999; 4:231–247.
82. Maheshwari S, Bruckheimer E, Fahey JT, Hellenbrand WE. Balloon angioplasty of postsurgical recoarctation in infants: the risk of restenosis and long-term follow-up. J Am Coll Cardiol 2000:35:209–213.
83. Fawzy ME, Sivanandam V, Galal O, Dunn B, Patel A, Rifai A, von Sinner W, Al Halees Z, Khan B. One- to ten-year follow-up results of balloon angioplasty of native coarctation of the aorta in adolescents and adults. J Am Coll Cardiol 1997; 30:1542–1546.
84. Huggon IC, Qureshi SA, Baker EJ, Tynan M. Effect of introducing balloon dilation of native aortic coarctation on overall outcome in infants and children. Am J Cardiol 1994; 73:799–807.
85. de Giovanni JV, Lip GY, Osman K, Mohan M, Islim IF, Gupta J, Watson RD, Singh SP. Percutaneous balloon dilatation of aortic coarctation in adults. Am J Cardiol 1996; 77:435–439.
86. Walhout RJ, Lekkerkerker JC, Ernst SM, Hutter PA, Plokker TH, Meijboom EJ. Angioplasty for coarctation in different aged patients. Am Heart J 2002; 144:180–186.

Current Multicentric Studies and Those to Plan for the Descending Thoracic Aortic Diseases

Hervé Rousseau, Jean Philippe Bolduc, Francis Joffre

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Contents

38.1 Introduction

Cardiovascular disease is the leading cause of death in most Western societies and is increasing steadily in many developing countries. Longer life expectancy, hypertension and the proliferation of modern noninvasive imaging modalities have contributed to the growing awareness of acute and chronic aortic syndromes. Despite recent developments in epidemiology, diagnostic and therapeutic modalities, there is still a lot of progress to be made to understand the spectrum of aortic syndromes and to define an optimal approach to managing aortic diseases.

In the 1990s, endovascular stent-graft treatment emerged as a new and less invasive method to treat abdominal aortic aneurysm. It soon led to the use of stent grafts in the treatment of thoracic aortic diseases, but their exact role remains approximate.

Although only midterm study results are now available, they indicate a better outcome compared with conventional surgery, especially in elderly patients with significant comorbidities such as pulmonary and renal insufficiency, coronary heart disease, hypertension and diabetes mellitus, where morbidity and mortality rates after an open surgical repair are as high as 50%. However, despite the good published results, endoluminal stent grafts are not risk-free: endoleaks, prosthesis dislocations, neurological complications, acute or late rupture of the aorta and side branch occlusions are described leading to therapy failure. Owing to the actual restrained number of patients treated by endovascular repair, the blur in the indications and the different types of devices used, it is nearly impossible to identify if the complications are device-, procedure- or patient-related and the exact place of this new therapy.

Nevertheless, we will attempt, in this chapter, to discuss the ongoing studies and the need for future studies to better understand and treat the various thoracic aortic pathologies.

38.2 Descending Thoracic Aortic Aneurysms

Aneurysms of the thoracic aorta represent a potentially life-threatening situation. Surgical resection and interposition with a vascular prosthesis have long been considered the standard treatment despite the substantial risks of the procedure. The use of an endovascular stent graft to treat thoracic aortic aneurysms emerged a decade ago propelled by the desire to reduce surgical risks and induce remodeling of the diseased aorta by initiating a natural healing process after exclusion and depressurization of the aneurismal sac.

So far, all prospective studies and registers have shown that the stent-graft technique has better immediate results compared with classic open surgery, with lower 30-day morbidity–mortality and paraplegia rates. In midterm studies, the complication rates are, however, not negligible and habitually consist of secondary leaks which can mostly be treated intravascularly [1, 2, 3]. Compared with stent-graft abdominal aortic aneurysm repair, complications of thoracic treatment differ considerably. Abdominal complications mostly relate to changes in aneurysmal volume after successful exclusion, which result in device distortions, kinks or modular disconnections. At the thoracic level, as only one tubular device is needed in most patients, the risks of type III leaks, kinks, disconnections or thromboses are

either eliminated or greatly reduced. Furthermore, the diameter reduction after complete aneurysm exclusion is probably less than in the abdomen combined with the use of an oversized device (at least 10% more than the normal aortic diameter) and this reduces risks even more. Nevertheless, the most frequent thoracic complications are type°I endoleaks that occur at aortic and graft junctions allowing the aneurysmal sac to remain pressurized. They are more frequent because degenerative thoracic aortic disease is usually more diffuse than abdominal disease; thus, progression of the malady at attachment sites is more likely. To avoid this problem, we recommend the placement of longer stent grafts covering healthy aorta up to the visceral arteries. Type II endoleaks, except from the left subclavian artery, are rare. If two or more grafts are used, type III endoleaks can arise at junctions, requiring insertion of another stent-graft segment. This complication is greatly reduced when we systematically overlap a long segment of the grafts. Finally, pseudoaneurysms and intimal perforations at distal implementation sites have been reported secondary to stent-graft erosions [4]. Complete long-standing studies are still needed to determine the incidence of these complications and their long-term effects.

The question of intentional exclusion of the left subclavian artery is still unanswered. In patients with a very short neck between the left subclavian artery and the aneurysm requiring coverage of the former, different treatment attitudes have been described; left subclavian transposition or bypass either systematically before stent-graft insertion or only if the patient has ischemic neurological or left arm symptoms after occlusion. Left subclavian artery coverage is routinely done without complication in many centers [5, 6]. Nevertheless, it should be kept in mind that it is crucial to evaluate the vertebral arteries before occluding the left subclavian artery to prevent ischemic symptoms in cases of stenotic vertebral arteries or absence of collateral pathways between the two as observed in up to 6% of cases.

As devices improve, better results should be observed in the future. Therefore, requests to place endografts in patients with small lesions, in which the risk of rupture is extremely low, should be more frequent. It will be important to resist these demands until further data prove otherwise. So, as far as we are concerned, we recommend that endograft use should be limited to patients who truly exhibit surgical indications.

38.3 Dissection

Despite the frequency of acute aortic dissection, there are few large series published on the outcomes of dissections and most are long retrospective multicenter studies confounded by inconsistent methods of treatment and data collection. The IRAD study, a prospective multicenter registry has now been created to address some of these concerns. This study [7, 8] provides better understanding of the clinical profile and outcomes of patients with acute type B aortic dissection, helping clinicians in early risk stratification and decision-making. Unfortunately, there is an inherent selection bias because the study results are mainly based on data from tertiary referral centers that may not necessarily be extrapolated to the general population. Even though the IRAD study is a step forward, to better evaluate survival predictors, prospective studies are still needed mainly because the actual registry does not regroup homogeneous patients with similar risk factors whose outcomes could be rigorously compared nor does it take into consideration factors such as nonfatal morbidity, quality of life and cost effectiveness.

Actual consensus exists regarding the need for emergency surgical treatment of patients with acute Stanford type A aortic dissection. The optimal treatment strategy for Stanford type B dissection remains controversial [9–12]. Most groups today reserve the surgical replacement of the descending aorta for patients with aortic rupture, organ ischemia, refractory pain, uncontrolled hypertension, false lumen dilatation or other life-threatening conditions. Other teams have advocated early surgery for young and good operative candidates irrespective of the presence of complications [13], arguing that if the surgery is successful, these individuals would be at lower risk of late dissection-related aortic complications. Finally, f percutaneous interventional techniques, i.e., fenestration and stent-graft repair to correct ischemic complications related to thoraco-abdominal malperfusion, have become a valuable adjunct to both medical and surgical therapy, but their role is still debated.

For type B dissections with complications, percutaneous stent-graft placement seems to be superior to surgery on short-term follow-up [14–19]. Recently, it was shown that percutaneous stent-graft treatment has an early mortality rate of 16% among patients with acute Stanford type B aortic dissections associated with life-threatening complications [16]. If treated surgically, i.e., an emergency thoracotomy, these patients would be facing an early mortality risk of 40%. The rate was said to be 60–70% if treated medically [11, 14, 15] The effectiveness of stent-graft treatment in patients with complicated acute type B aortic dissections must however still be confirmed by long-term prospective randomized trials. Such a study was started in early 2003 but regrettably had to be stopped after the intentional retrieval of the Gore device after cases of nitinol wire fractures.

In cases of acute type B dissection without complications, medical treatment was long the only accepted treatment until stent grafts were used successfully [17], complicating the decision-making process. The INSTEAD study was started in Europe in 2002 to compare medical and stent-graft treatment in patients with un-

complicated acute type B aortic dissections. The aim of this multicenter randomized controlled clinical trial is to evaluate the 1-year outcomes, including complication rates and quality of life, of patients with type B dissection treated either percutaneously or medically. Early results can be expected in 2005.

Other concerns include the timing of the intervention and the length of coverage necessary to exclude the false lumen.

38.3.1 Timing of Treatment

Stent-graft placement could become, in the near future, the standard treatment for most cases of complicated or uncomplicated aortic dissection mostly because the operative mortality rate approaches 70% if we wait for complications to occur. Another argument in favor of early endovascular treatment is the evolution of aortic morphology with time following dissection. In acute type B dissections, an isolated tear is more frequent and usually no thrombus is present in the false lumen, while in chronic dissections multiple entry and exit points are seen along the aorta associated with thrombus formation enlarging the vessel diameter. Therefore, delaying treatment could increase implantation failure rate or make the intervention no longer possible [20–22].

38.3.2 Length of Coverage

An unanswered technical question concerns the length of aortic coverage necessary to achieve dissection healing. The key is to cover the proximal entry site to reduce pressure in the false lumen and consequently shrink the total aortic diameter and improve flow in the true lumen expanding the later, resolving ischemic complications or malperfusion syndromes. Given our results and those of others, it seems that complete thrombosis of the false lumen is necessary to reduce the overall aortic diameter and protect against subsequent aneurismal dilatation and rupture [23, 24]. So, from these results combined with the fact that the risks of neurological paraplegic complications are particularly low in dissections treated by stent grafts, one can suggest covering a long part of the descending aorta above the diaphragm at the time of initial implantation to exclude all entry points feeding the false lumen. Adjunctive measures to achieve complete thrombosis of the false lumen such as use of coils or glue have also been described. Again, long-term controlled trials are needed to categorically guide our future therapeutic strategies.

38.4 Trauma

Despite advances in surgical and reanimation techniques, surgery is still associated with significant morbidity and mortality rates ranging between 8 and 15% depending on whether circulatory assistance to maintain satisfactory perfusion of the distal aorta is used or not [25]. The postoperative paraplegia rate without circulatory assistance can be as high as 19% and increases significantly when the aorta is clamped for more than 30 min [26]. With circulatory assistance, the rate is about 2% [25] However, the systemic anticoagulation required for the extracorporeal circulation is often undesirable in traumatic patients with multiple fractures and/or parenchymal or cerebral lesions.

In the last 10 years, several studies showed, for stable and nonbleeding lesions, that surgical mortality after aortic injury can be significantly reduced when surgical repair is deliberately delayed [27–29]. These studies support the fact that free rupture of a contained acute traumatic tear of the thoracic aorta is unlikely to occur under proper blood pressure control. Therefore, it appears safe to allow patients who suffered a major trauma to be stabilized, undergo other emergent operations if needed and then have elective repair of the aortic tear. Although this attitude is justified by objective data, it is not entirely risk-free because as many as 4% of patients awaiting surgery might die of a ruptured aorta usually within 1 week of the traumatic injury [30].

More recently, the advent of the endovascular stent-graft technology has provided a less invasive alternative to thoracic aortic injury treatment. This substitute to open thoracic aortic replacement is attractive for several reasons but one of its main advantages is the possibility to avoid heparin use when necessary, decreasing hemorrhagic complications related to associated lesions if present.

Although some authors reserve endovascular treatment for patients for whom standard surgery is contraindicated [31], one might raise the issue of extending the indication to all patients with traumatic injury of the thoracic aorta. Our current experience, as that of others, has shown encouraging results of the endovascular technique compared with those for conventional surgery [31–41]. The benefits of aortic endoprosthesis in terms of morbidity and mortality by far outweigh those of classic surgery by thoracotomy. Our comparative study with similar lesions and severity scores (ISS) confirms that stent-graft therapy is an advantageous alternative to conventional open surgery. The mortality and the paraplegia rates were 21 and 7%, respectively, for the 35 patients surgically treated compared with 0% for the 29 patients treated with a stent graft [41]. With a mean follow-up of 46 months, we did not observe any aneurysm expansion or rupture. Complete healing of the aortic wall without any residual pseudoaneurysm

and total shrinking of the aorta over the stent graft were seen in all cases.

However, controversy remains regarding the best method of management. Studies must be carried out to determine the precise place of endovascular treatment in the management of acute rupture of the thoracic aorta. An ideal study would compare the outcomes of patients of similar health status subjected to conventional surgical intervention, to stent-graft placement or to medical treatment. Unfortunately, such a prospective study is not feasible for ethical reasons; patients incapable of undergoing conventional surgery for any reason should of course not be operated. Additionally, since a small number of patients receive treatment in each center, even a multicenter randomized study comparing the two treatment methods is illusive. A prospective registry evaluating patients considered unfit for surgical intervention because of comorbidities treated with or without stent-graft placement would best assess the effect of the endovascular strategy compared with that of medical treatment. In order to do so, we suggest the creation of an international registry similar to the one for aortic dissections to compile the results of endovascular treatment and consequently help to define its indications.

As a whole, we can actually consider that endovascular stent-graft treatment of the aorta is a less invasive strategy for most of the thoracic aortic diseases, particularly in patients with comorbidities; however, large prospective studies for the complete evaluation of this new therapeutic option are still needed.

References

1. Dake MD, Miller DC, Semba CP, et al. Transluminal placement of endovascular stent-grafts for the treatment of descending thoracic aortic aneurysms. N Engl J Med 1994; 331:1729–1734.
2. Dake MD, Miller DC, Mitchell RS. The "first generation" of endovascular stent-grafts for patients with aneurysms of the descending thoracic aorta. J Thorac Cardiovasc Surg. 1998; 116:689–703.
3. Greenberg RK, Resch T, Nyman U, et al. Endovascular repair of descending thoracic aortic aneurysms: an early experience with intermediate-term follow-up. J Vasc Surg 2000; 31:147–156.
4. Ninomiya M, Takamoto S, Kotsuka Y, et al. Stent-graft-induced intimal injury one year after surgery. J Thorac Cardiovasc Surg 2002; 123:371–372.
5. Hausegger KA, Oberwalder P, Tiesenhausen K, et al. Intentional left subclavian artery occlusion by thoracic aortic stent-grafts without surgical transposition. J Endovasc Ther 2001; 8:472–476.
6. Rehders TC, Petzsch M, Ince H, et al. Intentional occlusion of the left subclavian artery during stent-graft implantation in the thoracic aorta: risk and relevance. J Endovasc Ther 2004; 11:659–666.
7. Hagan P, Nienaber CA, Isselbacher EM, et al. The International Registry of acute aortic dissection (IRAD): new insights into an old disease. JAMA 2000; 283:897–903.
8. Suzuki T, Mehta RH, Ince H, et al. Clinical profiles and outcomes of acute type B aortic dissection in the current era: lessons from the International Registry of Aortic Dissection (IRAD) Circulation 2003; 108:II312.
9. Svensson LG, Crawford ES, Hess KR, Coselli JS, Safi HJ. Dissection of the aorta and dissecting aortic aneurysms: improving early and long-term surgical results. Circulation 1990; 82:(Suppl IV):IV24–38.
10. Da Gama D. The surgical management of aortic dissection: from uniformity to diversity, a continuous challenge. J Cardiovasc Surg 1991; 32:141–153.
11. Glower DD, Fann JI, Speier RH, et al. Comparison of medical and surgical therapy for uncomplicated descending aortic dissection. Circulation 1990; 82:(Suppl IV):IV39–46.
12. Miller DC. The continuing dilemma concerning medical vs surgical management of patients with acute type B dissection. Semin Thorac Cardiovasc Surg 1993; 5:33–46.
13. Umana J, Lai D, Mitchell RS, Moore K, et al. Is medical therapy still the optimal treatment strategy for patients with acute type B aortic dissections? J Thorac Cardiovasc Surg 2002; 124:896–910.
14. Miller DC. Acute dissection of the descending aorta. Chest Surg Clin North Am 1992; 2:347–348.
15. Fann JI, Smith JA, Miller DC, Mitchell RS, et al. Surgical management of aortic dissection during a 30-year period. Circulation 1995; 92:113–121.
16. Dake MD, Kato N, Mitchell RS, et al. Endovascular stent-graft placement for the treatment of acute aortic dissection. N Engl J Med 1999; 340:1546–1552.
17. Nienaber CA, Fattori R, Lund G, et al. Nonsurgical reconstruction of thoracic aortic dissection by stent-graft placement. N Engl J Med 1999; 340:1539–1545.
18. Palma JH, Souza JAM, Alves CMR, Carvalho AC, Buffolo E. Self-expandable aortic stent-grafts for treatment of descending aortic dissections. Ann Thorac Surg 2002; 73:1138–1142.
19. Lopera J, Patino JH, Urbina C, et al. Endovascular treatment of complicated type-B aortic dissection with stent-grafts: midterm results. J Vasc Interv Radiol 2003; 14:195–203.
20. Kato N, Matsuda T, Kaneko M, et al. Outcomes of stent graft treatment of false lumen in aortic dissection. Circulation 1998; 98:II305–312.
21. Kato N, Hirano T, Shimono T, et al. Treatment of chronic aortic dissection by transluminal endovascular stent-graft placement: preliminary results. J Vasc Interv Radiol 2001; 12:835–840.
22. Shimono T, Kato N, Yasuda F, et al. transluminal stent graft placement for the treatments of acute onset and chronic aortic dissection. Circulation 2002; 106:I241.
23. Gaxotte V, Thony F, Rousseau H, et al. Mid-term results of aortic diameter outcomes after thoracic stent graft implantation for aortic dissection: a multicenter study. J Endovasc Ther. In press 2005.
24. Sueyoshi E, Sakamoto I, Hayashi K, Yamaguchi T, Imada T. Growth rate of aortic diameter in patients with type B aortic dissection during the chronic phase. Circulation 2004; 110(11 Suppl 1):II256–261.
25. Jahromi AS, Kazemi K, Safar HA, Doobay D, Cina CS. Traumatic rupture of the thoracic aorta: cohort study and systematic review. J Vasc Surg 2001; 34:1029–1034.
26. Von Oppell UO, Dunne TT, DeGroot MK, et al. Traumatic aortic rupture: 20-year meta-analysis of mortality and risk of paraplegia. Ann Thorac Surg 1994; 58:585–593.
27. Stulz P, Reymond MA, Bertschmann W, et al. Decision-making aspects in the timing of surgical intervention in aortic rupture. Eur J Cardiothorac Surg 1991; 5:623–627.
28. Kipfer B, Leupi F, Schuepbach P, et al. Traumatic rupture of the thoracic aorta: immediate or delayed surgical repair? Eur J Cardiothorac Surg 1994; 8:30–33.

29. Maggisano R, Nathens A„ Alexandrova N. Traumatic rupture of the thoracic aorta: should one always operate immediately? Ann Vasc Surg 1995; 9:44–52.
30. Langanay T, Verhoye JP, Corbineau H, Agnino A, Derieux T, Menestret P, et al. Surgical treatment of acute traumatic rupture of the thoracic aorta: timing reappraisal. Eur J Cardiothorac Surg 2002; 21:282–287
31. Marty-Ané CH, Berthet JP, Branchereau P, Mary H, Alric P. Endovascular repair for acute traumatic rupture of the thoracic aorta. Ann Thorac Surg 2003; 75:1803–1807.
32. Melnitchouk S, Pfammatter T, Kadner A, Dave H, Witzke H, Trentz O, et al. Emergency stent-graft placement for hemorrhage control in thoracic aortic rupture. Eur J Cardiothorac Surg 2004; 25:1032–1038.
33. Thompson CS, Rodriguez JA, Damaia VG, DiMugno L, Shafique S, Olsen D, et al. Acute traumatic rupture of the aorta treated with endoluminal stent grafts. J Trauma 2002; 52:1173–1177.
34. Orend KH, Pamler R, Kapfer X, Liewald F, Gorich J, Sunder-Plassman L. Endovascular repair of traumatic descending aortic transection. J Endovasc Ther 2002; 9:573–578.
35. Lachat M, Pfammatter T, Witzke H, et al. Acute traumatic aortic rupture: early stent-graft repair. Eur J Cardiothorac Surg 2002; 26:959–963.
36. Orford VP, Atkinson NR, Thomson K, Milne PY, Campbell WA, Roberts A, et al. Blunt traumatic aortic transection. Ann Thorac Surg 2003; 75100–75111.
37. Daenen G, Maleux G, Daenens K, Fourneau I, Nevelsteen A. Thoracic aorta endoprosthesis: the final countdown for open surgery after traumatic aortic rupture. Ann Vasc Surg 2003; 17:185–191.
38. Scheinert D, Krakenberg H, Schmidt A, Gummert JF, Nitzsche S, Braunlich S, et al. Endoluminal stent-graft placement for acute rupture of the descending thoracic aorta. Eur Heart J 2004; 8:694–700.
39. Iannelli G, Piscione F, Di Tommaso L, Monaco M, Chiariello M, and Spampinato N. Thoracic aortic emergencies: impact of endovascular surgery. Ann Thorac Surg 2004; 77:591–596.
40. Amabile P, Collart F, Gariboldi V, Rollet G, Bartoli JM, Piquet P. Surgical versus endovascular treatment of traumatic thoracic aortic rupture. J Vasc Surg 2004; 40:873–879.
41. Rousseau H, Dambrin C, Marcheix B, Richeux L, Mazerolles M, Cron C, Watkinson A, Mugniot A, Soula P, Chabbert V, Canevet G, Roux D, Massabuau P, Meites G, Tran Van T, Otal P. Acute traumatic aortic rupture: a comparison of surgical or stent-graft repair. J Thorac Cardiovasc Surg 2005; 129:1050–1055.

Ten Years to Come

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In the management of thoracic aorta lesions, in contrast to that of those of the abdominal aorta, endovascular techniques were immediately considered not as a substitute, but rather as an adjunct to surgical techniques whose specific morbidity (spinal, pulmonary and renal) is still important.

Indeed, when stent-grafts came to be used to treat abdominal aorta aneurysms, the surgical technique was associated with a very acceptable morbidity rate, close to 5%, and to a perioperative mortality mainly related to myocardial infarction. The initial enthusiasm for this new technique was directly related to this significant reduction of perioperative mortality owing to the minimal invasivity and to the absence of aortic clamping. Today, this is weighted by the uncertainty about midterm and long-term durability of the aneurysm sack exclusion, and, as an effect, by the quality of the treatment, not to mention the rather unbalanced cost-efficacy ratio due to follow-up imaging studies and to the management of late complications.

The situation is quite different at the thoracic level. Ten years have passed since the first stent-graft was deployed to treat an aortic lesion. The feasibility of this technique is now well demonstrated and accepted, this book having been written to state it. Regarding the thoracic aorta, the benefit of the stent-graft became progressively obvious in acute diseases (complicated type B dissection, aortic rupture, etc.) with the idea of bridging a gap, to stabilize, if not definitely manage a situation too delicate for surgery, without hindering delayed intervention. Evidently, to deploy is not to cure, and the current concept of stent-grafts allows us in a minimally invasive way, well suited to an emergency, to quickly and safely blind an intimal tear or to restore the continuity of a ruptured aortic wall. The absence of endothelization with current stent-grafts does not allow us, today, to foresee the durability of the treatment, making unavoidable a continuous follow-up. On the other hand, the late results in degenerative aneurisms and chronic type B dissections are less convincing, such as the results of abdominal aorta aneurysm endovascular repair.

Thoracic aortic stent-grafts were not as frantically marketed as abdominal ones, and were initially limited to three types: the first-generation Stanford homemade stent-grafts and two industrially made ones, Medtronic's Talent and Gore's Excluder. This allowed relatively homogeneous international registers to be built up, avoiding the potential bias due to excessively different devices. This controlled maturity allows past experience to be taken into account for clinical evaluation research to develop new concepts, such as a better fitting to arch lesions or related to stent coating.

Feasibility studies reported in the literature mainly regarded four disorders: degenerative aneurysms, type B dissections, ulcers and hematomas, and isthmus rupture. After 10 years the first midterm results have now been published and it seems crucial for us to insist on the need for evaluation studies based not any more on the feasibility of the stent-graft concept, but rather on the results related to each pathology, defining two main groups: acute and chronic diseases, and separating the results by pathology.

- Dissection
  - Type A vs type B
  - Complicated vs not complicated
- Aneurysms
  - Degenerative
  - Posttraumatic pseudoaneurysms
  - Suturing false aneurysms
  - Mycotic aneurysms
- Aortic rupture
  - Isthmus
  - Descending aorta
- Hematomas and penetrating ulcers

In this decade of endovascular progress which brought about a new look at the physiopatholgy of dissection, ulcers and hematomas, we also must insist on the fantastic complementary advances in diagnostic imaging. The wider availability of multislice computed tomography scanner angiography has dramatically decreased the risk of misdiagnosed posttraumatic aortic rupture, thus lowering to nearly zero the likelihood of pseudoaneurysms in the future. Again, these acute disorders represent, in our opinion, the best application field for

endovascular procedures, with greater likelihood of expected benefit. Research in imaging remains vital for future advances in endovascular techniques, with two essential techniques driven by clinical requirements: lesion modelization and virtual angioscopy.

On a more practical point of view, real improvements have been made in delivery devices. For technical reasons, stent-grafts used to be relatively short, making it necessary to deploy several interconnected segments to bridge long lesions. Now, to avoid late endoleaks due to migration of segments, the trend is to use longer stent-grafts, especially for degenerative aneurysms. With the increase of coverage length, the risk of paraplegia becomes greater, and bypassing of the supra-aortic trunks (especially the left subclavian artery) could become necessary more frequently in the future.

To sum up, this new trend in the treatment of aortic pathologies focuses the major interests of a multidisciplinary approach, knowledge sharing and training in both surgery and diagnostic and interventional imaging. This synergy is necessary for the optimal choice of surgical or interventional strategies. This cooperative management leads us to consider hybrid training, which will impose itself on the future generations of physicians.

Randomized controlled studies will probably be difficult to build up owing to the low incidence of the various diseases, but prospective multicentric studies, complying with guidelines still to be defined, are the necessary evaluation tools for the next 10 years.

Thanks to the cooperation of all the authors of this book, to whom we are deeply and sincerely grateful, our wish is to promote this challenging spirit of partnership between surgery and interventional radiology driven by the rapid evolution of treatments of aortic pathologies.

To describe which routes must be followed was the primary reason for which this work was undertaken. Thank you for having read it.

Subject Index