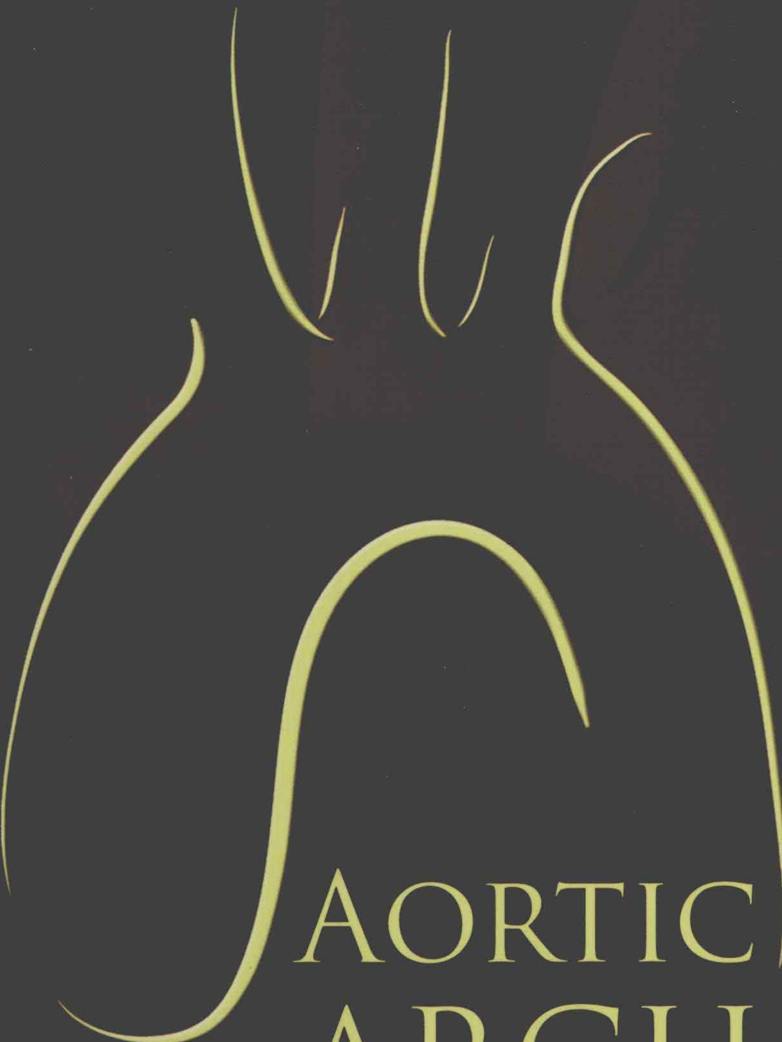

AORTIC ARCH SURGERY

PRINCIPLES, STRATEGIES AND OUTCOMES

EDITED BY
JOSEPH S. COSELLI, MD
SCOTT A. LEMAIRE, MD

WILEY-BLACKWELL

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Introduction

The first successful graft replacement of the aortic arch was reported in 1957 [1]. Over the past 50 years, advances in imaging technology, anesthetic management, extracorporeal circulation, surgical technique, and perioperative care have culminated in an armamentarium that now makes it possible to safely repair the aortic arch in the majority of patients. This armamentarium is the focus of this textbook, which is intended to serve as a comprehensive source of information on the available options for assessing and treating adult patients with aortic arch disease. Experts recruited from five continents have contributed detailed coverage of the general principles underlying aortic arch surgery, the numerous strategies for operative repair, and the outcomes of surgical treatment. We have encouraged the authors to explain the underlying rationale for the approaches they describe and to discuss the advantages and disadvantages of each technique relative to other available methods. While we hope that our emphasis on various technical aspects of surgical management will be particularly useful to thoracic and cardiovascular surgeons and trainees, we also believe that the book will be a valuable resource for cardiovascular anesthesiologists, perfusionists, neurologists, radiologists, and other healthcare professionals who have a special interest in treating patients with thoracic aortic disease.

The aim of the first part, "General Principles," is to provide information that is essential to understanding aortic arch surgery, including how these operations have evolved over the past half-century, the anatomic considerations that affect choice of strategy, and the natural history data that are used to support treatment decisions. In the second part, "Imaging Techniques," our colleagues describe how each of the four major imaging modalities – aortography, computed tomography, magnetic resonance imaging, and echocardiography – can be used to evaluate patients with aortic arch disease. Each of these modalities has important strengths and limitations and must be considered in the context of institutional variations in availability and reliability. Although the book focuses on surgery in adult patients, images illustrating important aspects of congenital cardiovascular disease appear in this section wherever they may facilitate the reader's understanding of adult disease. The third part, "Strategies for Intraoperative Management and Neurologic Protection," is intended to present a detailed approach to anesthetic management and to describe the numerous options for obtaining aortic exposure and for monitoring and protecting the brain during arch repair. The relative merits of each technique are covered in detail. In the fourth part, "Options for Aortic Repair," our contributors provide detailed descriptions of several different approaches to aortic arch reconstruction. Parts III and IV comprise a virtual menu of management options that can be used when operating on the aortic arch; how various surgical teams select and apply these options when treating distinct conditions is the focus of the fifth part, "Surgical Treatment of Specific Problems." The sixth and final part addresses "Neurological Complications," the prevention of which has remained a major focus of investigation since the first arch replacement operations were performed more than 50 years ago. The aim of this part is to present our current understanding of the mechanisms, evaluation, and treatment of perioperative stroke and other forms of brain injury.

The rationale for a few of our editorial decisions deserves explanation. First, we have selectively included material on the evaluation and management of the neighboring ascending and descending thoracic aortic segments, because the aorta adjacent to the diseased arch is usually also affected and generally requires concomitant treatment during arch repair.

Second, although we have attempted to minimize overt repetition, we have allowed substantial overlap between various chapters to illustrate how different surgeons employ the numerous available options. Thus, varying approaches to several techniques – such as axillary artery cannulation, application of surgical adhesive, and the elephant trunk repair – are described throughout the book.

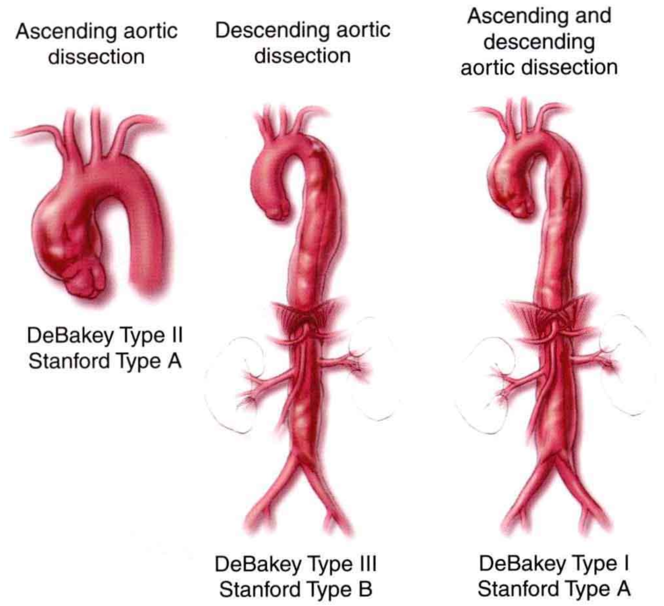

Figure 1 This simplified, descriptive classification scheme categorizes aortic dissection on the basis of the involvement of the ascending aorta, the descending aorta, or both. The corresponding traditional classifications are included for comparison. The primary limitation of the Stanford classification is that it is based solely on the presence (Type A) or absence (Type B) of ascending aortic involvement; it does not consistently provide information about distal aortic involvement, a factor that has important management and prognostic implications.

This practice has the added benefit of assuring that each chapter is able to stand alone and provide comprehensive coverage of its topic.

Finally, we have attempted to standardize terminology as much as possible throughout the book. The most notable example is the uniform approach to the classification of aortic dissection. The management and prognosis of aortic dissection are based on several important variables, including which segments of the aorta are involved. Borst and colleagues [2] have advocated using a simplified, descriptive classification of aortic dissection instead of the traditional DeBakey and Stanford classifications, both of which have important limitations; therefore, throughout the book, we have used a simple anatomic classification (Figure 1). Ascending dissection refers to any dissection involving the ascending aorta, regardless of whether or not it extends distally into the descending thoracic aorta. Likewise, descending dissection refers to any dissection involving the descending thoracic aorta, regardless of whether or not it involves the ascending aorta.

We wish to conclude by expressing our gratitude to the many people whose efforts made completion of this book possible. We are especially indebted to our esteemed contributing authors, who generously shared their expertise while exhibiting extreme patience with the editorial process. We sincerely appreciate the efforts of the team at Blackwell Publishing, especially Steve Korn, who originated this project and who provided the vision and steadfast encouragement needed to keep it moving forward, and Beckie Brand, who patiently led the production process. Finally, we are eternally grateful to our staff at Baylor College of Medicine, including Stacey Carter, Marisa M. Jones, Susan Green, and Anne Laux for tirelessly providing invaluable organizational and editorial support; Scott Weldon for creating remarkable medical illustrations and assisting with figure editing; and Alan Stolz for contributing crucial administrative support.

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Part IV: Options for Aortic Repair

Part V: Surgical Treatment of Specific Problems

Part VI: Neurological Complications

I

GENERAL PRINCIPLES

1 Historical perspective – the evolution of aortic arch surgery

Denton A. Cooley, MD

Introduction

The challenges involved in aortic arch repair are such that the field of aortic arch surgery has existed for scarcely more than 60 years. However, the history of its foundations – the development of our understanding of aneurysms and aortic anatomy, and the rise of techniques and technology for cardiovascular surgery – can be measured in millennia.

Aneurysms from the ancient world to the nineteenth century: diagnosis and non-surgical treatment

It is clear that the ancient Egyptians suffered from aortic disease; signs of aortic atherosclerosis have been found in Egyptian mummies [1]. There is also evidence that the ancient Egyptians were aware of the existence of aneurysms, at least those of the peripheral type. The Ebers Papyrus (Figure 1.1), which was written in 1500 BC or earlier and is probably the most well-known ancient Egyptian medical document, appears to describe an aneurysm as '... a swelling of vessels ... it is hemispherical and grows under thy fingers at every going [i.e. it pulsates], but if separated from his body it cannot become big and not come out [i.e. diminish] ... it is a swelling of a vessel ... and it arises from injury to a vessel' [2]. However, ancient Egyptian physicians could do little to treat aneurysms or many other serious ailments, and their frequent frustration in the face of these conditions is revealed in another passage from the Ebers Papyrus: 'A suffering person is not to be left without help: go in to him, and do not abandon him' [3].

Ancient Asian civilizations may also have been aware of aneurysms. For example, in India, between 800 and 600 BC, Indian surgeon Sushruta described peripheral aneurysms in his work, *Samhita*, as localized, pulsatile swellings in blood vessels. Sushruta recommended treating these swellings with compression, cauterization, or excision [4].

In the second century AD, the Greek physician Galen wrote what some believe to be the first true description of an aneurysm: 'When the arteries are enlarged, the disease is called an aneurysm. ... If the aneurysm is injured, the blood gushes forth, and it is difficult to staunch it' [5]. (Because exact translations are not always available for medical terms in ancient languages, there is some debate as to whether the pre-Galenic texts discussed here really describe aneurysms and not some other disease. For example, the word translated as 'vessels' in the Ebers Papyrus is *metu*, which was used to refer not only to blood vessels but also to muscles, nerves, or any other long, thin body structure [4].) Also in the second century, the Greek surgeon Antyllus produced the first known writings on the causes of aneurysms. He distinguished between aneurysms caused by trauma and fusiform or cylindrical

Figure 1.1 A passage from the Ebers Papyrus, which may contain the first known record of aneurysmal disease. The manuscript appears to state that aneurysms should not be treated surgically, but only by incantation. It also repeatedly admonishes the physician not to abandon the patient.

aneurysms, as they are called today, caused by syphilis or other chronic diseases. Antyllus described treating these aneurysms with proximal and distal ligation and evacuation of the sac – a technique that remained the standard of care until the eighteenth century [6].

Aortic aneurysms do not appear to have been identified as such until the Renaissance era, when the dissection of corpses began to become an acceptable practice, at least in some circles. In 1542, prominent French physician Jean-Francois Fernel (who has been credited with, among other things, coining the terms 'physiology' and 'pathology') published his work *De Externis Corporis Affectibus*, in which he distinguished between 'external' aneurysms (i.e. aneurysms of the peripheral vasculature) and 'internal' ones (i.e. aneurysms of vessels within the chest and abdomen, including aortic arch aneurysms). Fernel's contemporary, University of Montpellier chancellor Antoine Saporta, described the pulsatility of aortic aneurysms, thus distinguishing them from tumors, and he also described the symptoms of fatal aortic rupture. Illustrations of aortic arch aneurysms in particular appeared in several books written in the sixteenth century and thereafter [4].

Between the sixteenth and nineteenth centuries, many theories were proposed about the genesis of aortic aneurysms, and some of these theories were later substantiated. For example, several prominent physicians and scientists suggested that syphilis played a causal role in many aortic aneurysms; in the seventeenth century, two Italians, anatomist Giovanni Lancisi and surgeon Marcus Aurelius Severinus, both described the weakening of vessel walls in syphilitic persons. This theory was substantiated in 1876, when Francis Welch published his series of post-mortem examinations of patients with or without aortic aneurysms. Of 53 patients with aneurysms, two-thirds had clear signs of syphilis, whereas all but one of the 106 non-syphilitic patients he examined had no aortic dilatation [7]. Although there was considerable resistance even to the discussion of this theory at the time, the notion that tertiary syphilis caused aortitis that led to the formation of aortic aneurysms eventually became commonly accepted. The discovery of penicillin in 1928 made syphilitic aneurysms a rarity.

Other useful theories about the origin of aneurysms were also introduced before the twentieth century. Fernel, in the 1600s, correctly theorized that fusiform or cylindrical aneurysms caused by degenerative disease resulted from the simultaneous dilatation of all layers of the artery, rather than the dilatation of individual layers as some of his contemporaries asserted. Also, Lancisi posited traumatic and congenital origins for some aneurysms. In the nineteenth century, another Italian anatomist, Antonio Scarpa, suggested atherosclerotic degeneration of vessels as a cause of some aortic aneurysms [4].

Awareness of aortic arch coarctation also arose in the eighteenth and nineteenth centuries. This problem was first described by Johann Friederich Meckel in 1750 and by Morgagni in 1760 (although Morgagni described it as a localized constriction of the descending aorta) [8,9]. However, it would be almost 200 years before any attempt at surgical intervention was made.

The advent of surgical treatment for aortic arch disease

For centuries, total bed rest, starvation, and dehydration were the standard treatment for aneurysms. External aneurysms were sometimes treated by direct compression with bandages, cauterization with hot irons, limb amputation, and ligature of parent arteries. Internal aneurysms, however, remained untreatable; sixteenth-century surgeon Ambrose Paré wrote that 'the aneurysms which happen in the internal parts are incurable' [10].

In the late eighteenth century, some physicians began to advocate treating aortic aneurysms by introducing heated needles into the sac to stimulate thrombosis. However, the results were unpredictable, and the technique fell out of favor for some time [11]. Then, in 1864, Charles Hewitt Moore of London's Middlesex Hospital introduced the technique of intrasaccular wiring, in which coils of fine wire were fed into the aneurysm in the hope that fibrous tissue would form around the wire and fill the aneurysmal sac (Figure 1.2). The technique worked in its first clinical use, but the patient later died of sepsis.

Subsequently, many other physicians tried similar techniques to treat aneurysms, sometimes inserting iron wire, watch springs, or horsehair into the aneurysmal sac,

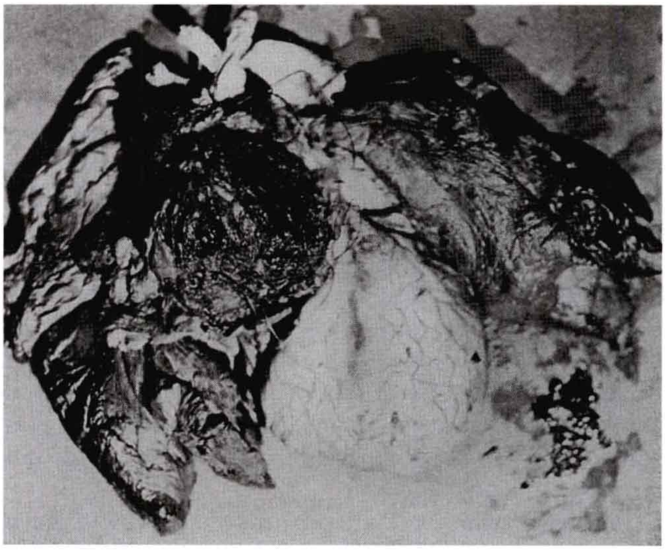

Figure 1.2 Specimen of sacciform aortic aneurysm removed after insertion of wire to promote thrombus formation and, thereby, to prevent rupture.

but rupture was not always prevented (Figure 1.3), and patients' life expectancies after these procedures could usually be measured in days, weeks, or months [12]. A particularly notable variant of this treatment method was tried by Duncan and Fraser, who in 1867 reported on their effort to obliterate a patient's thoracic aortic aneurysm by stimulating thrombosis within it with electrolysis delivered via a 13-cm needle. The aneurysm continued to expand after the treatment, however, and the patient died of hemorrhage 2 months later [13]. In 1879, Corradi combined Moore's intrasaccular wiring technique with electrolysis to create what became known as the Moore–Corradi method of electrothrombosis, variations of which were widely experimented with for many years afterward.

Open aortic surgery finally began to emerge in the early nineteenth century. In 1817, Sir Astley Cooper treated a 38-year-old man with a left external iliac aneurysm by placing a silk ligature on the abdominal aorta, which he had exposed via a transperitoneal incision – something Cooper had tried in a cadaver just two days earlier [14,15]. The patient lived for only 48 hours after the surgery, but Cooper's willingness to attempt such a difficult procedure impressed many of his colleagues, and he was eventually elected President of the College of Surgeons. (In his highly successful surgical practice, Cooper also became known for performing autopsies on his surgical patients whenever possible in order to learn from them.) Nonetheless, for the next 100 years, no patient would survive any attempt at aortic ligature. In 1902, Theodore Tuffier had brief success when he ligated the base of a saccular aneurysm of the aortic arch in an attempt to remove it, but ischemic necrosis developed and the patient died of hemorrhage two weeks later [16].

In 1888, American surgeon Rudolf Matas developed the concept of endoaneurysmorrhaphy: opening the aneurysmal sac and using sutures to narrow the lumen from within, thereby removing the aneurysm while leaving blood flow intact [17,18]. Matas also had the idea of temporarily occluding large vessels during surgery to determine the consequences that permanent occlusion of these vessels might have; this test later became common surgical practice [19]. The findings from these occlusive tests made it clear that Matas' original procedure could not be used in the aorta or other major arteries without the risk of serious ischemic complications, so Matas developed a new endoaneurysmorrhaphy procedure in which the aneurysmal tissue was removed and a channel was created in the remaining, healthy tissue to allow blood flow [20]. This innovative procedure constituted a leap forward for aneurysm surgery, and a modified form of this technique is still commonly used today.

Nonetheless, before the twentieth century, most aneurysm surgeries ended in the death of the patient – if not from technical failures, then from post-operative infection. Marginally greater success was achieved in the middle of the last century with attempts to repair aneurysms by wrapping cellophane or other plastic films around the aneurysm to stimulate periarterial fibrosis and, thereby, to occlude the aneurysmal vessel (Figure 1.4). This method was first applied by Harrison and Chandy [21] to treat a subclavian artery aneurysm, and later by Poppe and De Oliviera [22] to repair syphilitic aneurysms of the thoracic aorta. These methods were successful in some instances, including the first successful repairs of blunt aortic arch injuries [23], but the outcome was too often unpredictable.

In 1951, while speaking at the annual meeting of the Southern Surgical Society, Denton Cooley and Michael DeBakey of Houston became the first surgeons to advocate the direct surgical removal of aortic aneurysms [24]. In the cases they presented, saccular aneurysms of the thoracic aorta, including the aortic arch, had been

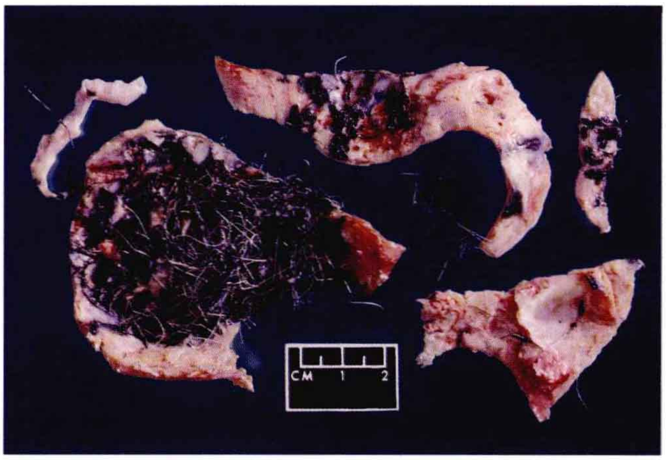

Figure 1.3 Post-mortem specimen of aneurysm of ascending aorta, which ruptured despite extensive introduction of steel wire.

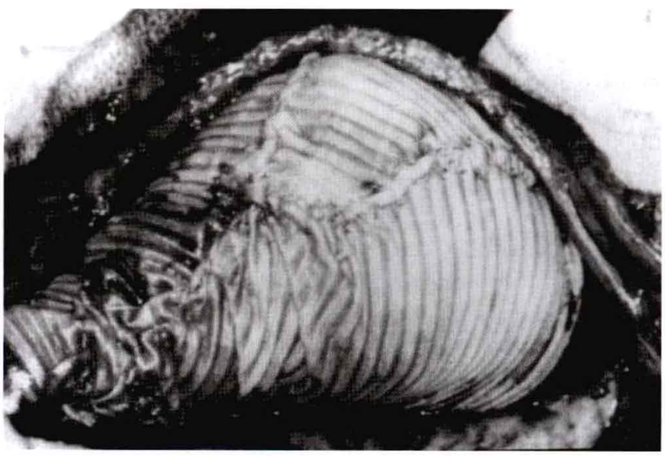

Figure 1.4 Treatment of an aneurysm by wrapping it in plastic film to induce fibrosis.

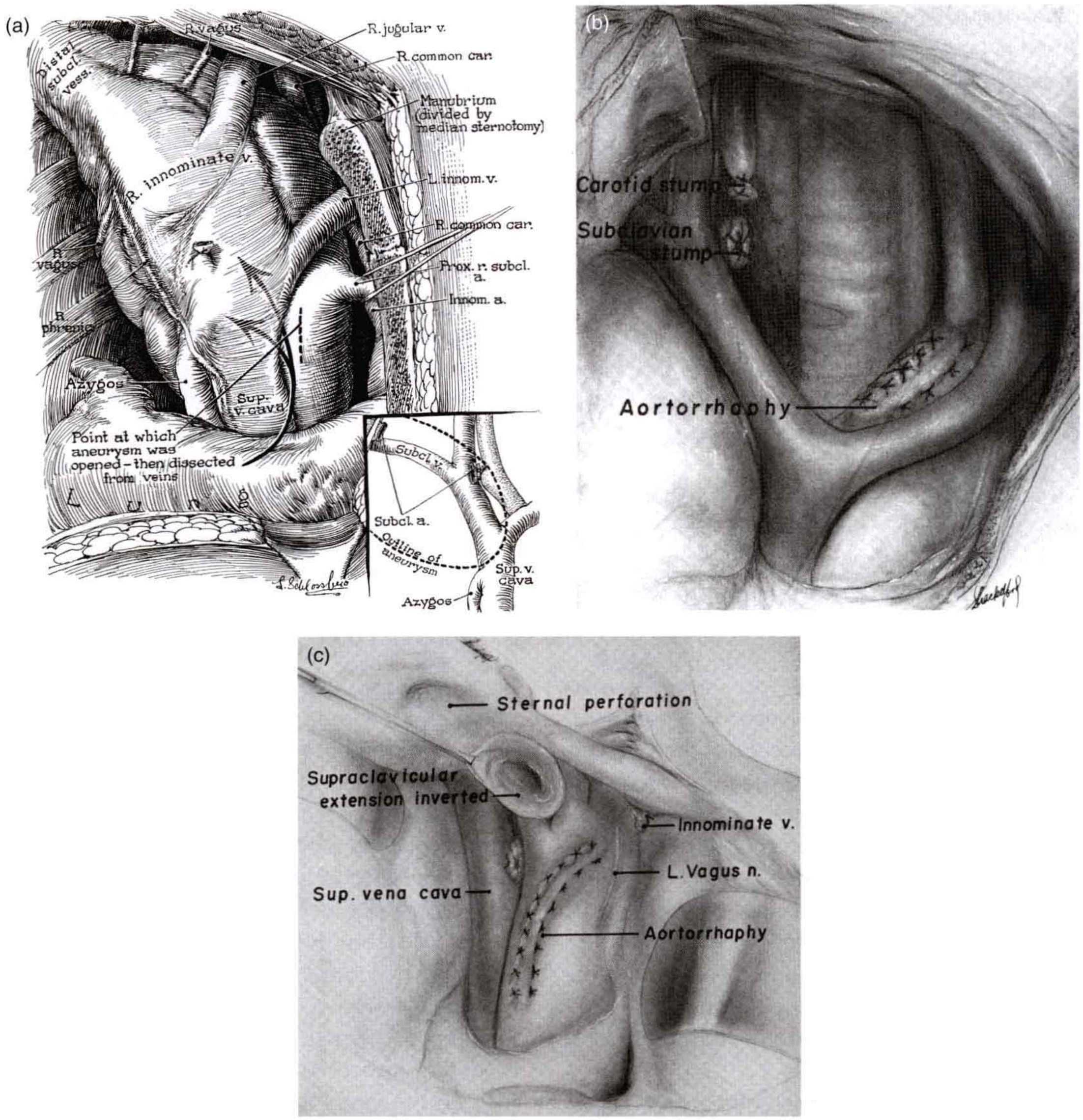

Figure 1.5 Drawings of three procedures performed by Cooley and DeBakey [24] in the early 1950s to repair aneurysms involving the aortic arch or its branches by clamping, excision, and aortic repair. (a) Repair of a subclavian artery aneurysm. a. = artery; car. = carotid; innom. = innominate; L. = left; Prox. = proximal; R. = right; subcl. = subclavian; sup. = superior; v. = vena/vein; vess. = vessel. (b) A completed repair of an aneurysm of the innominate artery and the adjacent portion of the aortic arch. Although the repair required the sacrifice of the right common carotid and subclavian arteries, the patient made a full recovery. (c) Repair of an aneurysm of the ascending aorta and the transverse arch. L. = left; n. = nerve; Sup. = superior. Reproduced with permission from [24].

successfully clamped, excised, and oversewn, so that the aneurysm was removed while aortic continuity was restored (Figure 1.5). In 1953, Bahnson [25] reported repairing several saccular aortic arch aneurysms, including one of traumatic origin. Impressively for the time, six of his eight patients survived.

The surgical repair of aortic coarctation also became a reality during the middle of the century. In the 1940s, surgical luminaries Alfred Blalock [26] and Robert Gross [27] each used animal models to develop techniques for the surgical repair of coarctation. These were put into practice in 1944 by Clarence Crafoord of the Karolinska Institute [28], who used end-to-end anastomosis to repair aortic coarctation in a 12-year-old boy. By 1956, Wright, Clagett, and colleagues had performed 10 coarctation repairs in adult patients [29].

The introduction of aortic grafts

Although the clamp-and-sew technique was very effective for treating localized sacciform aneurysms, these aneurysms were most commonly caused by tertiary syphilis, which, by the 1950s, was becoming increasingly rare. As a result, Fusiform and extensive sacciform aneurysms represented a greater proportion of the aortic aneurysms in need of treatment. Repairing these would require adequate graft materials to replace the substantial segments of the aorta that had to be excised.

In the early 1900s, Alexis Carrel and Charles Claude Guthrie [30,31] had conducted animal experiments in which homografts were used for aortic replacement. (This was part of the transplant research that would eventually win Carrel the Nobel Prize in medicine.) Gross and Hufnagel [27] had continued this line of research in the 1930s and 1940s in animal models of coarctation of the aorta, and Gross eventually used preserved homografts to repair aortic coarctation in human beings [32].

Graft repairs of aortic arch aneurysms were particularly challenging, partly because there were few reliable ways to prevent ischemic damage during the period of interrupted blood flow that such repairs required. Schafer and Hardin, in 1951 [33], were the first to attempt to use a homograft to repair an aneurysm of the aortic arch. The patient died of ventricular fibrillation immediately after the placement of 4 temporary polyethylene shunts intended to maintain cerebral and distal perfusion during the procedure. Two years later, Stranahan [34] repaired a syphilitic aortic arch aneurysm with a xenograft while a temporary shunt maintained blood flow between the ascending and descending aorta. The patient survived the procedure and had no apparent neurological deficit upon awakening but died shortly afterward from hemorrhagic complications of a left pneumonectomy that had been performed concomitantly with the aneurysm repair. In a similar procedure in 1955, Cooley and DeBakey [35] repaired an aortic arch aneurysm using prosthetic graft replacement and an ascending-to-descending aortic shunt, which included side branches to the carotid arteries. Nonetheless, even this shunting scheme did not prevent cerebral ischemia, and the patient died 6 days after the procedure. The next year, however, this Houston group successfully used a homograft to repair a fusiform aneurysm of the proximal aortic arch, which they did while the patient was on cardiopulmonary bypass (CPB) [36].

It eventually became apparent that homografts had limited life spans. Attempts were made to preserve graft tissue through freeze-drying, but the durability of such grafts was found to be highly variable [37]. Therefore, starting in the 1950s, many different synthetic materials were examined as potential alternatives, including nylon, Vinyon N® (a synthetic fiber made from polyvinyl chloride), Teflon®, and Dacron® (polyester) [38–41]. It was found that nylon and Vinyon N deteriorated too rapidly, and Teflon, although durable, did not bond well with human tissue [42]. Dacron, therefore, became the material of choice.

The choice of fabric was not the only concern. Grafts made from fabrics whose weave was too porous had reduced durability and were associated with slower healing and increased risks of serious intra-operative bleeding and infection. This problem was addressed by weaving the material tightly and impregnating it with collagen, gelatin, fibrin, or similar substances to seal the interstices. In 1981, Cooley and colleagues reported another method of sealing woven Dacron grafts in which each graft was soaked in the patient's own plasma and then placed in a steam autoclave, thereby filling the interstices of the graft material with coagulated protein [43]. This measure substantially reduced post-operative mortality and bleeding complications [44], and it inspired many subsequent improvements in commercially manufactured grafts.

Protection against ischemic injury

Of equal importance as the development of graft materials to the evolution of aortic arch surgery was the introduction of measures to protect the central nervous system and the vital organs against ischemic injury. Temporary shunts could be used in some cases, but doing so added considerable time to the procedure, and, as noted above, the shunts did not always provide adequate protection. Additionally, surgery on aneurysms (especially fusiform aneurysms) in critical parts of the aorta, including the transverse arch, required temporary circulatory arrest while the repair was completed. Therefore, preventing this type of injury during cardiac, coronary, or aortic surgery would require some means of perfusing the vital organs and of reducing their metabolic requirements.

Cardiopulmonary bypass

In the early years of cardiovascular surgery, some clinicians experimented with cross-circulation, in which the heart and lungs of a 'donor' would circulate and oxygenate the patient's blood while the patient's own heart and lungs were disconnected from the circulation [45]. This cumbersome and potentially hazardous technique was abandoned after the introduction of effective mechanical pump oxygenators. The first of these devices was designed by John Gibbon of Jefferson Medical College. After more than a decade of work on the device, Gibbon put it to the clinical test in 1953, using it to support 4 patients during open-heart procedures to repair congenital cardiac defects [46]. Only 1 patient survived, however, and Gibbon abandoned his work on the pump. The device was later simplified and improved upon by DeWall and Lillehei [47], who added a bubble oxygenation system with a defoaming coil to return the blood to a purely liquid state.

With the advent of CPB came considerable debate about cannulation schemes and direction of blood flow. Crawford and colleagues [48] used antegrade perfusion in an aortic arch repair, a technique that came to be commonly used in the 1960s and thereafter. Retrograde cerebral perfusion through the superior vena cava, first used by Mills and Ochsner [49] in 1980 to treat a massive air