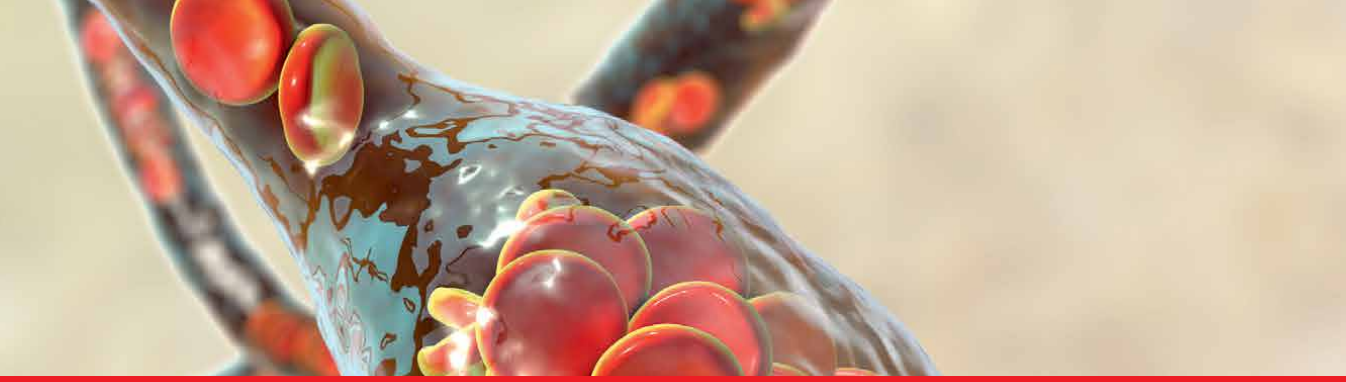


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Aortic Aneurysms

Screening, Diagnostics and Management

Edited by Reinhart Thomas Grundmann and Eike Sebastian Debus



Aortic Aneurysms - Screening, Diagnostics and Management

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Meet the editor



Dr. Reinhart T. Grundmann currently works as an independent medical expert. He is a professor of surgery at the University of Cologne and he has the qualification of general and vascular surgery. He is the former medical director of the B.Braun company, one of the leading healthcare solutions providers. In the last eight years, he has been working as the medical director of the Clinics Altotting-Burghausen, Germany. Dr. Grundmann was from 1992 until 2008 the managing director of the Zentralblatt fur Chirurgie and he is currently a member of the Editorial Board of World Journal of Gastrointestinal Surgery. He edited from 2001 to 2005 the Jahrbuch der Chirurgie- the book that provides information on the latest developments in surgery. Dr. Grundmann already published more than 260 scientific publications, including books and book chapters. His recent research interests lie in the field of efficiency and effectiveness in surgery. In this frame, he published workflows on liver surgery, gastric cancer, obesity surgery, and surgery for abdominal and carotid artery stenosis treatment.



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Preface

This Edited Volume *Aortic Aneurysms – Screening, Diagnostics and Management* is a collection of reviewed and relevant research chapters, concerning the developments within the Aortic Aneurysms field of study.

The book includes scholarly contributions by various authors and is edited by a group of experts pertinent to Medicine. Each contribution comes as a separate chapter complete in itself but directly related to the book's topics and objectives.

The target audience comprises scholars and specialists in the field.

IntechOpen Team

Chapter 1

Acute Aortic Occlusion

Amr Abdelghaffar Hanfy Mahmoud

Abstract

Acute aortic occlusion (AAO) is a life-threatening condition that leads to a sudden occlusion of the aorta and requires early diagnosis and treatment. The main etiology of acute aortic thrombosis has changed from embolic to thrombotic occlusion in succeeding decades. We carefully searched the PubMed, Embass, and Web of Science databases for relevant research reported on acute aortic occlusion, analyzed the included literature, and summarized it in this book chapter**.** After a review of the literature, the management and treatment of AAO are life-saving and should be conducted on an urgent base. It is advised to perform CTA to confirm the diagnosis. Reperfusion injury is a severe pathology that can cause the death of patients after the operation. Surgical reperfusion *via* transfemoral thrombectomy is the first approach for revascularization, while the extra-anatomical bypass is an alternative option for revascularization.

Keywords: acute aortic occlusion, acute aortic thrombosis, reperfusion syndrome, bilateral acute limb ischemia, extra-anatomical bypass

1. Introduction

Acute aortic thrombosis (AAT) or acute aortic occlusion (AAO) is a life-threatening condition that leads to a sudden occlusion of the aorta and requires early diagnosis and treatment. Sometimes it could be mistaken with a stroke. It is an urgent situation that needs immediate diagnosis and intervention due to its severity. But even with optimal surgical care, it has serious morbidity and mortality [1].

D. Crawford et al. reported 29 patients with AAO, the overall mortality rate was 34%, with a postprocedural mortality of 15% and a 30-day mortality rate of 24% [2]. Although the mortality rate in AAO patients is significant, Grip et al. reported an improvement in mortality rate over time in a study conducted on 693 cases over 21 years which represents the largest AAO study, 25.5% mortality in 1994–2000 versus 15.5% mortality in 2008–2014 [3].

2. Methods

We carefully searched the PubMed, Embass, and Web of Science databases for relevant research reported on acute aortic occlusion, analyzed the included literature, and summarized it in this book chapter.

3. Etiology

a. Embolism (AF, myocardial infarction), embolus lodging at the aortic bifurcation (saddle embolus).

b. Thrombosis on top of atherosclerosis.

c. Complication during AAA repair/trauma [2].

4. Risk factors

a. Atherosclerosis: Heart disease, smoking, diabetes mellites, and hyperlipidemia.

b. Thrombophilia and hypercoagulable state: The subtypes of thrombophilia associated with arterial thrombosis are elevated levels of C-reactive protein, homocysteine, and lipoprotein (a). Antiphospholipid antibodies are associated with both venous and arterial thrombosis [4].

c. Chronic inflammatory diseases (e.g., ulcerative colitis) [5].

The main etiology of acute aortic thrombosis has changed from embolic to thrombotic occlusion in succeeding decades. Dossa et al. reported a 40-year experience of AAOs between 1953 and 1993, 65% of cases were embolic and 35% were thrombotic; [6]. Surowiec et al. reported a study conducted on 33 patients between 1985 and 1997, showing 52% of AAOs to be thrombotic and 48% embolic [1]. Crawford et al. reported a study conducted on 29 patients between 2005 and 2013, 76% were thrombotic and 7% were embolic occlusion [2]. Grip et al. reported a study conducted on 693 cases of AAO between 1994 and 2014, 66.1% of cases were thrombosis of native arteries, 21.9% were saddle embolism, and 12% were occluded grafts or stents [3]. This condition may also be a result of improved prevention of cardioembolic events with anticoagulation for patients with atrial fibrillation and/or valvular heart disease and may reflect the progression of atherosclerotic disease among the population [2].

5. Pathophysiology: virchow's triad

Acute thrombosis in the arterial system is a relatively rare event. Virchow's triad traditionally explains pathophysiologic mechanisms leading to thrombosis, including hyper-coagulability, hemodynamic changes, and endothelial changes/injuries, such as atherosclerotic plaque. This pathogenic process results in the exposure of subendothelial cells and the release of procoagulant material, which mediates activation and aggregation of platelets. Ultimately, platelet accumulation and fibrin deposition produce an occlusive platelet-rich intravascular thrombus (**Figures 1** and **2**) [7].

5.1 Hemodynamic changes

- They are classified *during* periods of acute ischemia to lower limbs, kidneys, bowel, and effect on cardiac function and *after* restoration of circulation to vital organs.

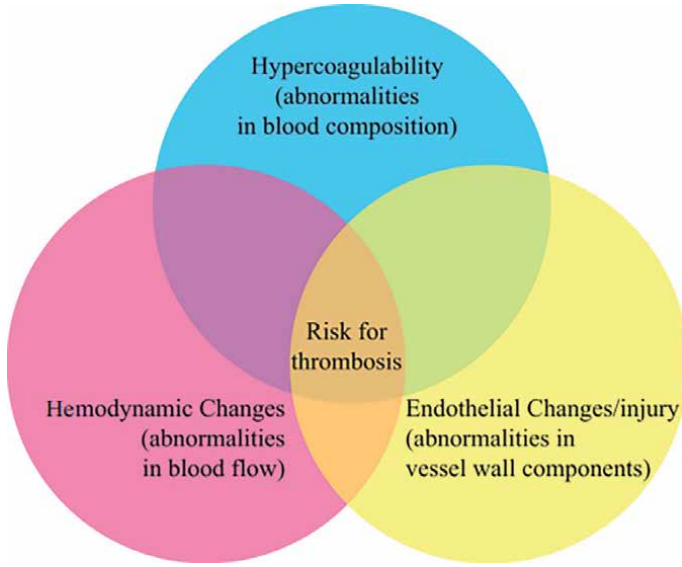


Figure 1.
Virchow's triad based on data from Wolberg et al. [7].

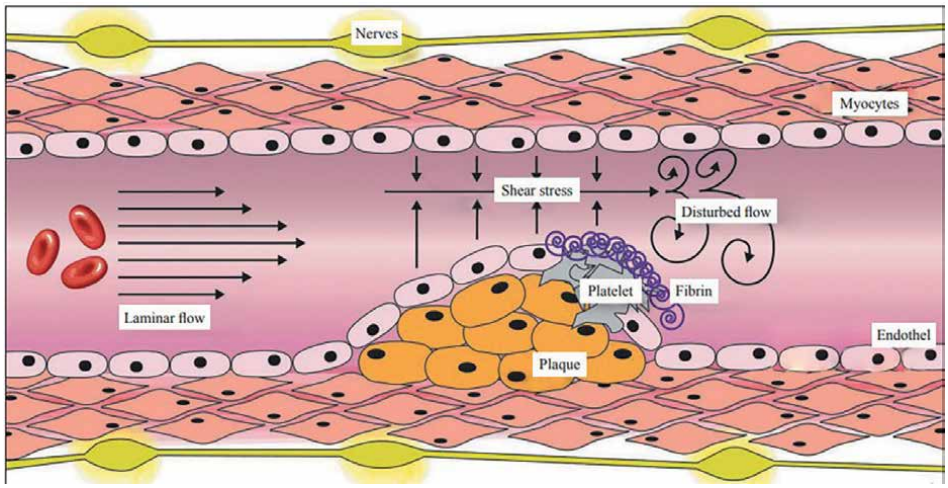


Figure 2.
Interplay between abnormalities in blood components, the vasculature, and blood flow contributes to the development of arterial thrombosis. Modified figure from Wolberg et al. [7].

- This is abbreviated as "*Ischemia-Reperfusion Injury syndrome*" or "*Myo nephropathic metabolic syndrome*."

The main trigger of this is a pathological activation of the immune system [8]. Activated immune cells such as neutrophils release proteolytic agents, for example, proteases and elastases as well as reactive oxygen species (ROS) that lead to severe cell damage [9]. If this cell damage aggravates organ failure results. Depending on the affected organ and the ischemic time, clinical signs can range from local injuries

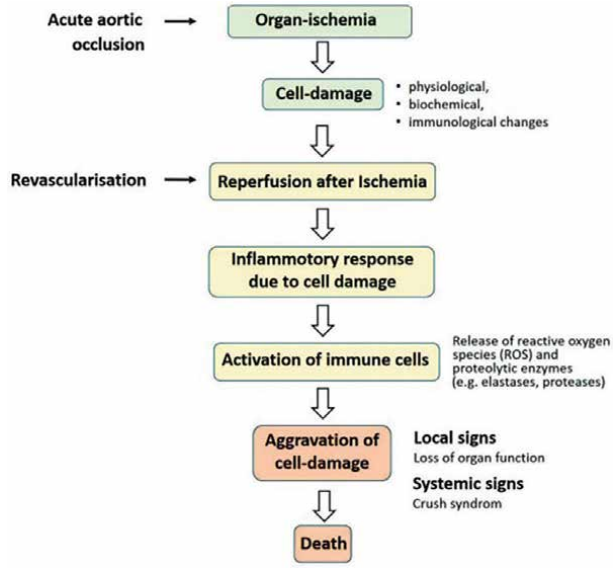


Figure 3.
Pathophysiology of reperfusion injury after acute ischemia, based on reviews from Eltzschig et al. [8] and Gillani et al. [9].

such as compartment syndrome due to limb ischemia to systemic signs like crush syndrome, which can lead to patient death, (**Figure 3**).

5.2 Acute aortic thrombosis effects on

5.2.1 Cardiovascular system

Acute aortic occlusion causes an increase in cardiac afterload, which increases mean arterial pressure, causing shifts in blood volume and increasing myocardial oxygen demand, which can lead to left ventricular failure and decompensation [10].

If the level of aortic occlusion is above the celiac artery, blood volume is shifted proximally to the heart (increasing preload), lungs, and intracranial compartment. In infra-celiac occlusion, the change in preload depends upon the tone of the splanchnic veins. If the splanchnic vascular tone is high, venous return to the heart increases. Alternatively, if the splanchnic venous tone is low, a decrease in preload occurs as blood volume shifts into the compliant splanchnic vasculature [10].

5.2.2 Respiratory system

Acute aortic occlusion causes increased pulmonary vascular resistance due to increased blood volume circulating through pulmonary vasculature. Accumulation of lymphocytes, c3a, c5a and thromboxane A2, mediate inflammation that causes non-cardiogenic pulmonary edema [11].

5.2.3 Renal system

Acute aortic occlusion results in decreased renal blood flow, reduced glomerular filtration rate (GFR), and, in some patients, the development of acute tubular necrosis [12]. In

supra-renal aortic occlusion, renal blood flow is reduced by 80 and by 45% during infra-renal occlusion. Increased levels of angiotensin II result in greater renal vasoconstriction, and endothelin may also contribute to renal hypoperfusion [12].

Aortic occlusion also causes a redistribution of blood flow away from the renal medulla, which is particularly susceptible to hypoxic injury [12]. Effects of neutrophil activation and mediators release contribute significantly to the occurrence of renal dysfunction [10]. The incidence of renal failure is approximately 13% after supra-renal aortic occlusion and 5% after infra-renal occlusion [12].

5.2.4 Spinal cord

The spinal cord is supplied by the anterior spinal artery, which supplies the anterior two-thirds of the cord, and by two posterior spinal arteries, which supply the posterior third of the cord. The spinal cord largely depends upon collateral blood supply from radicular arteries starting at the cervical level. The artery of Adamkiewicz or the arteria radicularis magna is the largest of these radicular vessels. In 75% of cases, this artery originates from the left side of the aorta and joins the anterior spinal artery between T8 and T12 [12]. The anterior spinal cord is at increased risk for ischemia when the level of the aortic occlusion is proximal to the origin of the artery of Adamkiewicz [12].

Hemodynamic hypo-perfusion of the spinal cord occurred due to thrombosis of feeding arteries or embolization. The degree of injury inflicted on the spinal cord correlates with the duration of limited blood flow, collateral circulation supplies the spinal cord, and neuronal metabolism. Pathophysiology of spinal cord ischemia is divided into two stages: direct ischemic changes and reperfusion injury. The ischemic injury cascade includes both direct and complement-mediated leukocyte activation, the endothelial cell production of adhesion molecules, vasoconstriction secondary to arachidonic acid metabolism, neuronal membrane injury, and spinal cord hyperperfusion and edema [13].

Reperfusion injury is a broad term that encompasses changes that occur following the ischemic event. A spectrum of injuries can occur. This is the most common etiology of delayed-onset paraplegia [14]. Severe prolonged ischemia can result in neuronal death and infarction with resultant immediate paraplegia or paraparesis. Mild ischemia of short duration may cause momentary neuronal dysfunction with a complete return of spinal cord function and no late sequelae. However, intermediate levels of ischemia—not so severe as to cause infarction yet severe enough to initiate reperfusion phenomena—may occur 1–5 days later as the injury cascade progresses. No immediate neuronal dysfunction but instead causes delayed-onset paraparesis or paraplegia [15].

5.2.5 Intestine

In particular, supra celiac/supra mesenteric aortic occlusion can lead to a significant reduction in blood flow to the intestine. Occlusive disease of the femoral arteries or the internal iliac arteries are risk factor for developing ischemic colitis.

Intestinal ischemia results in a spectrum of morphologic and functional alterations, ranging from minor changes in mucosal permeability to full-thickness tissue necrosis affecting the whole intestinal wall. The earliest physiological change, occurring after as little as 10–30 min of ischemia, is an increase in mucosal permeability followed by permanent cell damage that occurs within 3 hours, which is demarcated

by the loss of villus crypts. The resulting centrifugal tissue destruction starts from the mucosa to the submucosa and then to the muscularis. The crypt stem cells are irreversibly damaged and are usually complete within 24 hours after the ischemic insult [16].

Reperfusion gas plays a role in intestinal ischemia and it is medicated by reactive oxygen metabolites released from reperfused tissue which mediate microvascular and parenchymal injury. The relatively high concentrations of xanthine dehydrogenase in intestinal mucosal tissue are thought to be an important source of reactive oxygen metabolites in reperfused intestine [17]. Intestinal mucosal barrier dysfunction is an important consequence of intestinal reperfusion injury, which allows the translocation of bacteria and bacterial products (e.g., endotoxin) into the portal and systemic bloodstream [18].

6. Clinical picture

1. Cardiovascular: Hypertension, arrythmia, and myocadiac infarction (MI).

2. Respiratory: Non-cardiogenic pulmonary edema

3. Lower limb ischemia: Acute ischemia, critical limb ischemia, thrombo-embolism, and bilateral lower limb acute ischemia are the most common presentation in AAO cases [3].

4. CNS: Transient ischemic attack (TIA), spinal cord ischemia, and hemiplegia [4].

5. Renal: Hypertension, renal faultier, and metabolic acidosis. Flank pain, Hematuria, fever, and nausea/vomiting [19].

6. Intestine: Mesenteric ischemia, abdominal pain, melena, nausea, and vomiting [4].

Any patient presented with painful paresis or paraplegia with absent pulses in legs should risk suspecting of AAO [20].

7. Investigation

- Laboratory: Arterial blood gas (ABG), lactic acid, renal function, hepatic function, and CBC.

- Radiological: CT angiography with contrast (CTA) /MRA/ultrasound.

- Risk factors assessment: ECG, echo.

Computed tomography (CT) is the primary imaging method for detailed evaluation of AAO (**Figure 4**) [21]. Volumetric CT acquisition with three-dimensional analysis and multiplanar reconstruction is now the standard technique for evaluating the aorta [22]. If a CT is not available, ultrasound can be used for diagnosis (**Figure 5**) [23]. MR-angiography is due to the severity and the lack of time inappropriate as a primary diagnostic tool [21].



Figure 4.
Computed tomography angiography shows a complete thrombosis of the distal aorta below the inferior mesenteric artery, extending to common iliac arteries, based on a review from Kascwich et al. [21].

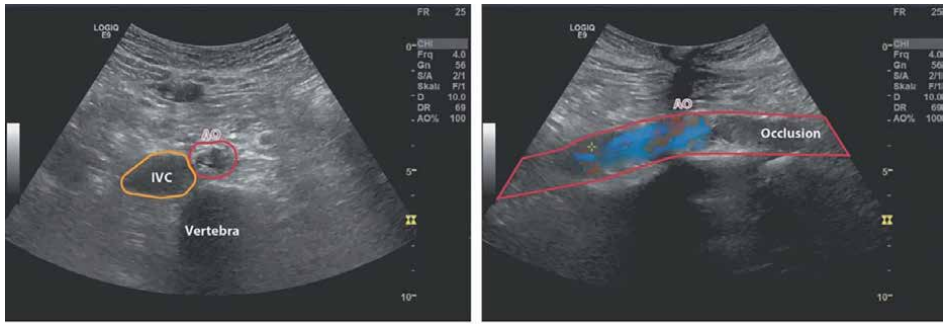


Figure 5.
Sonography of distal abdominal aortic occlusion. IVC: Inferior vena cava, AO: Abdominal aorta, based on a review from Kascwich et al. [21].

8. Therapy and management

Management and treatment of AAO are life-saving and should be conducted on an urgent base, this is an approach that was conducted based on data from (**Figure 6**) Crowford et al. and Singh et al. [2, 20].

- The general algorithm for diagnosis and management of these patients is to perform CTA to confirm the diagnosis.

- If the hospital has no facility for immediate surgical intervention, refer the patient.

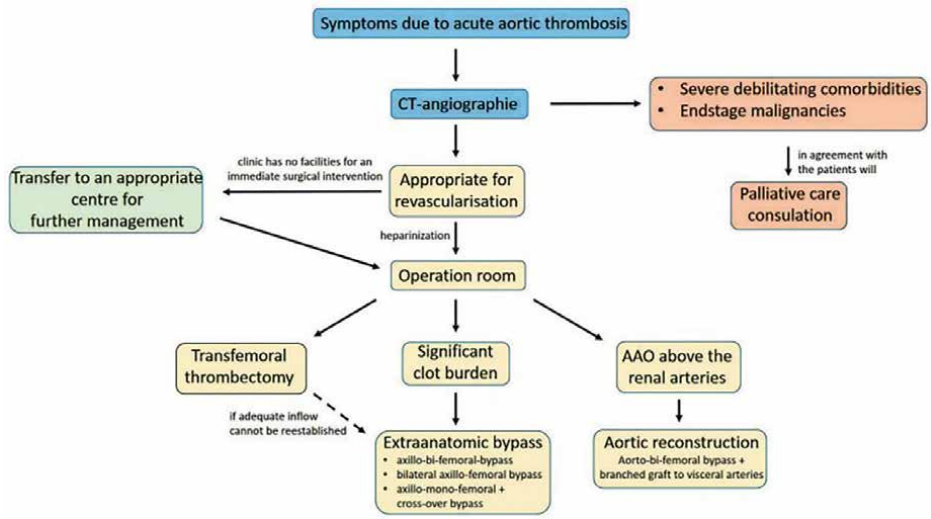


Figure 6.
Management of acute aortic thrombosis based on data from Crawford et al. [3] and Singh et al. [20].

- Palliative care consultation is considered in patients with severe end-stage malignancies or debilitating comorbidities.

- Patients fit for revascularization are then heparinized and taken to the operating room emergently.

- Trial of thrombectomy for infra-renal aortic occlusion/axillo-femoral bypass (extra-anatomical) is an alternative option after trial of femoral thrombectomy/embolectomy or in case of significant clot burden, it provides efficient revascularization with minimal physiologic impact and fit for elderly patients with advanced cardiac diseases.

- If CTA shows supra-renal aortic thrombosis and occlusion à aorto-bifemoral with branched graft to visceral arteries should be considered.

In previous studies, the most common line of treatment for acute aortic occlusion was bilateral trans-femoral thrombo-embolectomy, which has the advantage of avoidance of laparotomy and could be done under local anesthesia [1, 24, 25]. If trans-femoral thrombo-embolectomy failed to achieve full revascularization, aorto-bifem or aorto-bi-iliac graft bypass was suitable for surgical fit patients, while axillo-bifem graft bypass was suitable for surgical high-risk patients [1, 24, 25]. In a recent largest study in AAO reported by Grip et al. conducted on 693 patients, trans-femoral thrombo-embolectomy was done in 1/3 of cases only (31.9%), aorto-bifem or aorto-bi-iliac graft bypass had the same percentage of previous studies (almost 20%), and thrombolytic therapy often in combination with percutaneous transluminal angioplasty and/or stenting, represented 22.7% and stenting alone 6.3% of the procedures. Thrombolysis and endovascular interventions had emergent and upraised, thrombolytic therapy had an advantage in graft/stent thrombosis treatment when the ischemia time permits gradual reperfusion [26] and might be of value in a hypercoagulable state [27], but it carries more rate of reoperations in comparison to open surgery [3].

Endovascular stent implantation is a safe and long-term effective strategy for the treatment of infrarenal aortic occlusive disease, Tatiana et al. reported the long-term result of aortic stent placement in a study conducted on 34 patients between 1996 and 2014 with follow-up of 81 months. The mean estimated primary patency rate was 185.6 months (95% confidence interval: 161.3–209.8). There were six patients died during follow-up from non-procedure-related causes. Eight patients had a late recurrence of symptoms during follow-up. Two cases were due to aortic in-stent stenosis, five patients were due to PAD progression distal to the aorta, and one case was due to the progression of atherosclerotic lesion in the perirenal, non-stented part of the abdominal aorta [28].

A systematic review and meta-analysis aimed to assess the safety and efficacy of endovascular treatment for infra-renal aortic occlusion were reported by Fang et al., which collected recently published nine articles between 2000 and 2019 and included 220 patients. Nine articles consisting of 220 patients were included in this meta-analysis. Patients often had severe symptoms and many comorbidities. The overall technical success and periprocedural mortality were 95.64% (95% confidence interval [CI], 88.60%–99.42%) and 0.35% (95% CI, 0.00% to 2.33). Overall, primary patency was 93.53% (95% CI: 89.37%–97.68%) at 1 year, 78.96% (95% CI: 72.26%–84.96%) at 3 years, and 75.31% (95% CI: 66.42%–84.20%) at 5 years. Overall, secondary patency was 98.25% (95% CI: 95.50%–99.73%) at 1 year, 95.92% (95% CI: 89.25%–99.47%) at 3 years, and 94.02% (95% CI: 88.10%–98.00%) at 5 years. Periprocedural complications included vascular complications 11.35% mainly pseudoaneurysm, thromboses, hematoma, and dissections, and renal complications 1.25% [29].

The comparison between open and endovascular management of AAO as regards mortality and revascularization strategy has not been well studied. Grip et al. reported no differences in the frequencies of early complications when comparing open with endovascular surgery. In 67.1% of the cases, the revascularization procedure was performed without complication during the hospital stay. The most frequent complications were reocclusion (12.2%) and infection (8.5%) Compartment syndrome and subsequent fasciotomy were, however, more common after open surgery than after endovascular surgery [3].

Mohapatra et al. reported a retrospective single-center cohort study conducted on 65 patients who presented with AAO between 2006 and 2017. Whatever type of revascularization, the mortality rate was 27.7%, with risk factors, including aging, lower extremity motor deficit, elevated lactate level, and internal iliac artery occlusion. At least one complication was observed in 78.5, 21.5% required hemodialysis, and 15.4% had major amputations [30].

Sieber et al. reported a single-center retrospective cohort study, conducted on 74 patients with acute abdominal aortic occlusion between 2004 and 2019. Their average age was 64.5 years. 42% of the patients had undergone open transfemoral recanalization (including hybrid procedures), 35% had undergone open aortic surgery, 15% had undergone extra-anatomic bypass, and 5% were treated by endovascular methods alone. The overall mortality rate after 30 days was 23% and had decreased significantly during the past 8 years, from 54% (2004–2007) to 20% (2016–2019). The overall amputation and/or mortality rate after 6 months was 43%. Risk factors of increased overall amputation risk and mortality after 6 months include age > 64.5 years, atrial fibrillation, CK on admission >276 U/mL, acute limb ischemia (ALI): Rutherford I, IIa, Iib in comparison to III, and presence of cardiac or respiratory complications [31].

9. Conclusion

Acute aortic thrombosis is a rare life-threatening event that leads to sudden aortic occlusion. Hospital mortality and morbidity have not decreased over the last two decades and mid-term survival remains limited. Reperfusion injury is a severe pathology that can cause the death of patients after the operation. Surgical reperfusion *via* transfemoral thrombectomy is the first approach for revascularization, while the extra-anatomical bypass is an alternative option for revascularization.

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Conflict of interest

The authors declare no conflict of interest.

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Chapter 2

Open Repair of Abdominal Aortic Aneurysm (AAA)

Pedro Adolfo Mera Almonte

Abstract

Today, endovascular therapy is the recommended treatment modality for most aortic aneurysms and open surgery remains an essential treatment method for many patients. Long-term results obtained with endovascular therapy suggest that younger patients with a reasonably long life expectancy and low perioperative risk may benefit from open repair. Therefore, it is necessary to know both techniques for a comprehensive practice of aortic aneurysm surgery. A variable rate of RSO-related complications has been observed across studies. These complications, in order of appearance, are pulmonary (42%), cardiac (18%), renal (17%), ischemic colitis (9%), and wound complications (7%). Other less common but serious complications are postoperative end-organ ischemia, including colonic ischemia, acute lower extremity ischemia, or spinal ischemia. Historically, studies have shown that the benefit of EVAR in the early years decreases or could even be lost over time and therefore, EVAR could lead to a higher risk of rupture and reinterventions compared to open repair (OR) long-term. Under these considerations, the OR of AAA remains very important and should not be neglected in the endovascular era. The following chapter will show the strategy to develop an adequate selection of patients to undergo AAA, indications and contraindications.

Keywords: open AAA repair, indication for open repair, technical approach, complication, advantage/disadvantage

1. Introduction

The management of aortic aneurysms has undergone a drastic evolution in the last 30 years. The introduction of endovascular aneurysm repair with the use of stents caused a major paradigm shift regarding aortic aneurysm surgery. Although the technical implications of surgical treatment of aortic aneurysms may vary according to location and configuration, the surgical principles remain the same. In the era of endovascular repair of abdominal aortic aneurysms, open surgery continues to have a cavity, given that not all patients are candidates for endovascular procedures for anatomical reasons. Also, mention that many endovascular procedures require a conversion to open surgery [1].

One of the most important questions in the treatment of AAA should be: in which patient does open repair offer the greatest benefit? Within the recommendations in

the management of AAA, open repair may be the appropriate or preferred option in patients with a long-life expectancy and a reasonably low operative risk [2].

There are two classic routes for open AAA repair: the transperitoneal route and the retroperitoneal route. The transperitoneal technique is the method with which most surgeons are most familiar and allows for a wide intra-abdominal approach. The time from making the skin incision to placing the aortic clamp is shorter in the transperitoneal abortion. However, with this approach, there are related complications that can cause prolonged ileus and respiratory complications. To avoid or reduce the risk related to this approach, the retroperitoneal route is frequently adopted, which also offers better access to the aorta in its adrenal segment and supraceliac segment [3].

Despite the selectivity and optimization of the general status of the patient for open AAA repair, currently, it still has its periprocedural risks; post-repair complications remain unpredictable. However, this surgical option will have a place, both as a primary procedure and as surgery for complications related to EAVAR.

This chapter aims to present the generalities of the management of abdominal aortic aneurysm through open surgery, highlighting specific aspects such as indication, patient selection, surgical technique and approaches, complications, advantages, and disadvantages compared to endovascular methods, as well as treating situations special in highly complex aneurysms. Aspects such as the risk of open surgery and the preparation of the patient for this procedure will also be discussed.

2. Open repair of abdominal aortic aneurysm

2.1 The decision to operate

A good number of AAAs are asymptomatic and are only detected incidentally or when their significantly large diameter causes symptoms or has ruptured. Smaller AAAs will be easier to repair and should have slower AAA sac progression in the future, meaning the "repair threshold" can minimize short-term and long-term complications. However, AAA repair currently still has certain periprocedural risks, in some cases post-repair complications remain unpredictable.

Until now, an AAA requires repair if there are any AAA-related symptoms and, in case of asymptomatic, the AAA repair should be based on the initial diameter, annual growth rate, and estimated risk of rupture. For AAAs <40 mm, the risk of rupture is extremely low. Likewise, for 40–54 mm AAA, it reaches 1% per year. From this diameter, there is a very significant increase of almost 10% in the risk of rupture within 1 year in AAAs from 55 to 69 mm and a figure that exceeds 30% for AAA >70 mm [4–6]. So, 55 mm is the "danger threshold." Currently, asymptomatic AAA would be repaired if the maximum diameter was greater than 55 mm for men (50 mm for women), or if the growth rate exceeded 10 mm per year for an AAA of 40–55 mm [1, 3–5, 7, 8].

In general, indications for abdominal aortic aneurysm (AAA) repair include all symptomatic aneurysms regardless of size (presence of abdominal, back, or flank pain related to the aneurysm. Evidence of embolization, as well as eminence of rupture), aneurysm greater than 5.5 cm in men and greater than 5.0 cm in women. AAA of rapid growth, AAA in conjunction with other arterial diseases (especially iliac aneurysm), infected AAA, and complications after endovascular repair requiring conversion early or late to open AAA repair.

When explaining the surgery to the patient who has an unruptured AAA, the benefits and risks involved in this procedure in comparison with endovascular treatment must be detailed and specified. All this depends on your current and expected future health status and your life expectancy. These decisions must be made jointly between the patient and her doctor, considering the recommendations of other specialists (cardiologists, pneumologists, etc.) after evaluating the following factors:

- Shape, dimensions, and proximity to other vessels of the aneurysm.
- Life expectancy, age, comorbidities, fitness around the process.
- The risk of AAA rupture if not repaired.
- The short- and long-term benefits and risks, as well as other disadvantages of the procedure [8].

The risk of rupture is directly related to the morphology of the AAA (the saccular has a higher risk of rupture than the fusiform) and the histological, structural, and/or molecular characteristics. Until now, the parameters of the analysis of the biomechanical characteristics carried out with patterns and computational algorithms (wall stress, maximum rupture rate, wall stiffness) as well as the fused functional images have shown contradictory results to be able to predict AAA growth rate or probability of rupture [9, 10].

2.2 The choice of open repair

There are a series of relative contraindications for open surgical repair of AAA, such as hostile abdomen, obesity, cardiac pathologies, significant pulmonary pathologies, and a short-life expectancy. In short, open repair is contraindicated in patients in whom the potential risk of the procedure exceeds the risk of rupture, or this risk exceeds the benefit of the surgery.

Kevin Yei et al. [11] found that the mortality associated with open repair in a period of 6 years was significantly lower than in the endovascular technique (548 deaths [35.6%] vs. 608 deaths [41.2%]. Similarly, open surgery was associated with lower 6-year rupture rates (117 participants [5.8%] vs. 149 participants [8.3%]; HR, 0.76; 95% CI, 0.60–0.97; $P < 0.001$) as well as a lower re-intervention rate (190 participants [11.6%] vs. 267 participants [16.0%]; HR, 0.67; 95% CI, 0.55–0.80; $P < 0.001$). However, open repair, as is well known, was associated with significantly higher odds of dying within the next 30 days (OR, 3.56; 95% CI, 2.41–5.26; $P < 0.001$), as well as a higher rate of complications.

Georgios Loufopulus et al., published a meta-analysis, including 13,409 patients, with open surgery and 13,450 with endovascular repair. They demonstrated that open surgery has better long-term results, with a lower re-intervention rate over time [12].

A retrospective cohort study using health insurance data from Germany analyzed the results of EVAR vs. open surgery. Among 20,683 patients, 15,792 (76.4%) underwent EVAR and 4891 (23.6%) underwent OAR. Perioperative mortality was 1.9% and 5.9% for EVAR open repair, respectively ($P \leq 0.001$). A persistence of approximately 3 years in favor of early survival after endovascular repair was demonstrated (EVAR 82.3%, OAR 80.9%, $P = 0.021$). After this time, both survival curves were similar.

After 9 years, the estimated survival was 51.2% and 52.8% for EVAR and OAR, respectively (P = 0.102) [13].

Based on long-term data and following recent draft guidance from the National Institute for Health and Care Excellence, which proposes that patients should be offered repair, open surgical repair is appropriate, if the patient's condition is appropriate in terms of surgical risk and patient survival. These recommendations are based on data obtained from long-term data from randomized controlled trials. With EVAR, the odds are significantly lower for perioperative mortality as well as the risk of all-cause and aneurysm-related death within 6 months, but with additional follow-up, the combined risk estimates lean in favor of open surgery [14].

In this review (systematic review of outcome after EVAR vs. open aneurysm repair) [14], a total of 2983 patients were included in the quantitative synthesis. The meta-analysis found significantly lower odds of 30-day in-hospital mortality with EVAR. Reviewing long-term follow-up, they found no significant differences in all-cause mortality at any time between EVAR and open repair. At follow-up beyond 8 years, mortality was significantly greater after EVAR. Similarly, the risk of secondary intervention, aneurysm rupture, and death due to rupture was also predominant after EVAR.

The advantage in terms of early survival and lower perioperative mortality compared to open repair has been seen in many randomized trials. However, after a few years, this advantage is lost due to the increase in late mortality among patients undergoing endovascular therapy. This same pattern is repeated in large observational studies. If this behavior continued over time, open repair could become a superior strategy in patients selected as described. Long term, aneurysm-related mortality has been shown to be significantly lower in patients undergoing open surgery. The risk of subsequent interventions, aneurysm rupture, and death from rupture has also been significantly lower after open repair.

To date, it is known that the durability of an endoprosthesis is 10 years in accordance with the recommendation of the Food and Drug Administration (FDA), which means that for patients under 65 years of age, the rates of complications related to EVAR and subsequent re-interventions increase over time, leading to an increase in the cost of treatment.

Although EVAR should be considered the treatment modality of choice in most patients, it is very reasonable to consider OSR as an appropriate strategy in younger patients, at low surgical risk, and with a long-life expectancy. The median survival after elective AAA repair is approximately 9 years [14].

Table 1 shows a summary of several meta-analyses comparing elective endovascular aortic repair and open surgical repair of abdominal aortic aneurysms. For patients with a long-life expectancy, open surgical repair should always be considered the preferred treatment modality. Recommendation class IIa, level B [15].

3. Preparation for surgery

Prior to the surgical procedure, a careful and complete medical history should be obtained, and a strict examination and necessary laboratory tests performed. This analysis must include a complete blood count, creatinine levels, clotting times, and any laboratory tests deemed necessary. Evaluations, laboratories, and basic images

Author	Study type included	Recruitment period	Patients –*n*	Main findings
Powell et al.[471]	4 RCTs	1999–2008	2783	Lower all-cause mortality after EVAR within 6 months (3.3% vs. 5.3%, HR 0.61), thereafter no difference No difference in AAA-related mortality between 30 days and 3 years, thereafter higher in the EVAR group. Higher re-intervention rate after EVAR, but when taking laparotomy-based complications into account, as was done in the OVER trial, the difference was less significant.
Giannopoulos et al.[478]	5 RCT	1998–2008	2823	No difference in all-cause mortality or AAA-related mortality after 4–8 and > 8 years follow-up. Higher re-intervention rate after EVAR (29% vs. 15%)
Antoniou et al.[479]	7 RCT	1999–2011	2983	Lower all-cause mortality within 30 days (OR 0.36) and 6 months (HR 0.62) after EVAR Lower AAA-related mortality within 6 months after EVAR (HR 0.42), but higher after >8 years follow-up (HR 5.12). Higher re-intervention rate (HR 2.13), aneurysm rupture (OR 5.08) and death due to rupture (OR 3.57) after >8 years after EVAR
Bulder et al.[480]	4 RCT, 20 REG, 29 CS	1993–2015	189,022	Lower 30 days all-cause mortality after EVAR (1.2% vs. 3.2%), thereafter no difference.
Li et al.[481]	3 RCT, 68 CS	1999–2018	299,784	Higher all-cause mortality (OR 1.19), re-intervention (2.12), and secondary rupture rate (OR 2.47) after 5–9 years follow-up after EVAR No difference in all-cause mortality, but higher re-intervention rate (OR 2.47) and secondary rupture rate (OR 8.10) after EVAR after >10 years follow-up (up to 15 years).
Yokoyama et al.[482]	4 RCT, 7 PSS	1999–2016	106,243	Lower perioperative all-cause mortality after EVAR (RR 0.39), no difference between 0 and 2 years, higher between 2 and 6 years after EVAR (HR 1.15), and no difference between 6 and 10 years or ≥ 10 years.
Alothman et al.[483]	4 RCT, 12 CS	2004–2017	61,379	Lower perioperative all-cause mortality after EVAR (1.2% vs. 4.5%, thereafter no difference No difference in aneurysm-related mortality, higher rate of late aneurysm sac rupture after EVAR (1.8% vs. 0.4%) and of re-intervention (OR 1.94).

REG = registries; CS = cohort studies; PSS = propensity score matched studies; RCT = randomized controlled trial; EVAR = endovascular aneurysm repair; AAA = abdominal aortic aneurysm; HR = hazard ratio; OR = odds ratio; and OVER = the Open vs. Endovascular Repair of Abdominal Aortic Aneurysm trial.

Table 1.
Summary of meta-analysis comparing elective endovascular aortic repair and open surgical repair for abdominal aortic aneurysms [15].

provide information that allows estimating perioperative risk, as well as life expectancy after surgery (**Tables 2** and **3**).

Once you have decided in favor of open surgery, the next step is to identify any comorbid conditions that involve a risk factor that may increase the risk of complications and therefore decrease the chances of survival. To this end, a comprehensive cardiac evaluation is performed that is tailored to the patient's history, symptoms, and the results of preliminary screening tests (e.g., ECG and stress tests). In patients with coronary artery disease or a history of unstable angina, myocardial revascularization should be considered prior to surgery.

Because COPD is an independent predictor of operative mortality, lung function must be thoroughly evaluated, especially in patients' active smokers or with a history of tobacco use, through prompt evaluation by the pulmonologist and measurement of arterial blood gases in ambient air and lung function tests. In patients with abnormal test results, these anomalies must be corrected, and optimal lung function achieved.

Parameter	Points
Treatment	
EVAR	0
OAR (infrarenal)	2
OAR (suprarenal)	4
Aneurysm size, mm	
<65	0
≥65	2
Age, years	
≤75	0
>75	1
Gender	
Male	0
Female	1
Comorbidities	
Myocardial disease	1
Cerebrovascular disease	1
Chronic obstructive pulmonary disease	2
Laboratory value	
Creatinine, mg/dL	
<1.5	0
1.5 to <2	2
≥2	2

EVAR, endovascular aneurysm repair; OAR, open aneurysm repair.

Table 2.
Estimates to predict risk of mortality.

Points	Probability of mortality, %	Proposed risk designation
0	0.12	Low-risk group
1	0.20	
2	0.34	
3	0.59	
4	1.00	
5	1.71	Medium-risk group
6	2.91	
7	4.90	
8	8.14	High-risk group
9	13.2%	
10	20.75	
11	31.05	Prohibitive high-risk group
12	43.63	
13	57.10	
14	69.59	

Table 3.
Risk categories based on the model.

Antibiotics (usually cephalosporin, such as cefazolin, 1 g IV are given in the preoperative period) to reduce the risk of infection [16]. In the same way, the colon must be prepared so that it is clean and discharged using enemas. Adequate intravenous access will be placed, preferably a central venous catheter, through the right internal jugular vein and by controlling blood pressure through an arterial line. The placement of a nasogastric tube and placement of a Foley catheter to monitor urine output are routine for surgery.

For high-risk patients due to cardiac involvement, a Swan-Ganz catheter is recommended to assist with cardiac monitoring and volume assessment. Cardiovascular monitoring, central venous pressure, and arterial line monitoring are suggested for all patients. The use of transesophageal echocardiography is recommended in patients who are "at risk" of hemodynamic instability or in unstable patients to monitor both cardiac volume status and function; however, routine use does not influence clinical results [17, 18].

Units of compatible blood are reserved, and preparations are made for blood replacement postoperatively. Intraoperative use of a cell rescue machine for autotransfusion is recommended [2, 19]. To reduce the risk of coagulopathy, as well as to maintain optimal metabolic function, the patient's body temperature should be maintained at a normal level during the intervention. To prevent hypothermia, a warm, recirculating air blanket should be placed over the patient, and any intravenous fluids and blood should be warmed before administration. The skin is prepared from the nipples to the middle of the thigh.

3.1 Choice of anesthetic technique

Except in unusual circumstances, open aneurysm repair requires general anesthesia due to the need for relaxation of the abdominal wall musculature and the need for

extensive exposure to the aorta and its branches. Placement of monitoring lines is required before induction of anesthesia if these devices optimize the safety of induction. The use of analgesics through an epidural catheter is desirable as it reduces the required dose of anesthetic agents and is associated with a shorter time for extubating. In addition, it has been reported that there is a decrease in hemodynamic instability and cardiac ischemia [16, 19].

3.2 Graft selection and configuration

The graft configuration can be a straight or bifurcated tube. This depends on the configuration and extension of the aneurysm. Whenever the characteristics and extension of the aneurysm allow it, a tubular graft is preferable, this reduces surgical time, therefore less blood loss and a less demanding dissection and exposure with minimal risk of inadvertent injury to the ureter, iliac veins, and nerves.

When the aneurysm extends to the distant aorta and affects the iliac arteries, a bifurcated graft is used. Extension of the graft to the femoral arteries may be required depending on the affected iliac territory. In the latter case, attention should be paid to the risk of wound infection, thrombosis of the extremities, and formation of anastomotic aneurysms [20].

All graft materials currently used share similar characteristics regarding permeability, durability, resistance to infection, or risk of degeneration or dilation. In the case of polyester grafts, they include double coverage to reduce their porosity. Impregnation with silver or rifampicin is also used to improve resistance to infections [20–22].

4. Surgical approaches: nonruptured aneurysm

Approaches for open surgical repair include a transperitoneal (TP) or retroperitoneal (RP) approach. The RP approach is most frequently performed for complex AAAs (cAAAs), involving renal and viceral arteries [22]. TP access offers a better approach to the right iliac and right renal arteries and a comprehensive evaluation of the abdominal cavity and coexisting pathologies and may be more comfortable for surgeons trained in the midline (or transverse) laparotomy for general surgery. The absolute advantage of the RP approach is that it facilitates exposure of the suprarenal aorta and is ideal in the presence of a hostile abdomen or the repair of an inflammatory aneurysm or aneurysm related to a horseshoe kidney.

The RP approach is associated with lower perioperative mortality and morbidity rates when compared to the TP approach. Despite this, a decrease in the slippage of this pathway has been observed over time, even in thoracoabdominal adrenal/type IV aneurysms and repairs that require the use of supraceliac clamping. The RP route, whenever appropriate, is associated with better outcomes after open AAA repair [23]. It has been observed that the transperitoneal approach is associated with higher rates of late re-intervention and readmission, which must be considered when making surgical decisions (**Table 4**).

4.1 Transperitoneal approach

The incision begins from proximal to distal, taking as reference the xiphoid process at the upper end and is carried downwards, along the entire midline, except

	Transperitoneal	Retroperitoneal
Advantages	• Most rapid, greatest versatility • Provides widest access • Enables evaluation and treatment of concomitant intra-abdominal disease	• Avoids hostile abdomen • Facilitates suprarenal exposure and control • Potential reduction of postoperative ileus • Obesity • Inflammatory AAA • Horseshoe kidney
Disadvantages	• Longer postoperative ileus • Potential for greater fluid losses • Difficulty with exposure and control for suprarenal aneurysms • Higher incidence of incisional hernia	• Poor access to right renal and iliac arteries • Cannot evaluate intra-abdominal disease • Flank bulge

AAA, abdominal aortic aneurysm.
Adapted from Chaikof et al. [24].

Table 4.
Surgical approaches for open aneurysm repair.

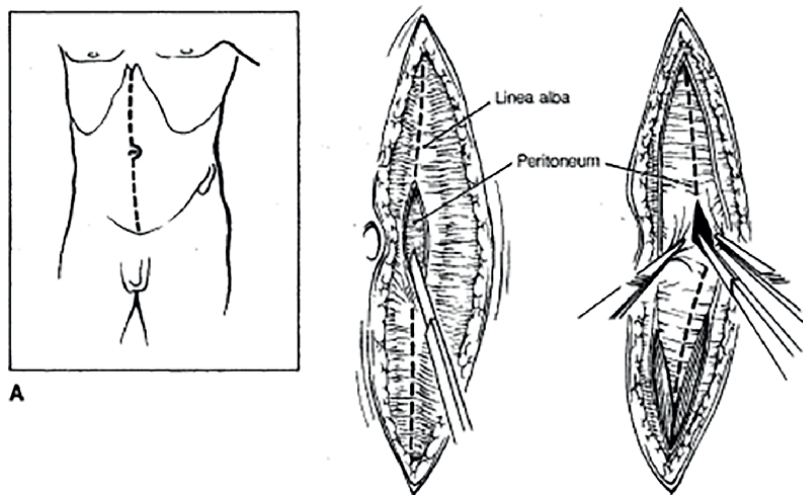


Figure 1.
The pre-peritoneal fat is separated, the peritoneum is exposed, and its two layers are opened.

for the navel, which is bordered, ending proximal to the pubic symphysis. The alba line opens in the supraumbilical segment, where it is wider. In the infraumbilical segment, the same procedure is followed, taking care not to involuntarily open the rectum sheath. The incision is taken toward the pubis. The pre-peritoneal fat is separated, the peritoneum is exposed, and its two layers are opened (**Figure 1**).

Upon entering the peritoneal cavity, the first step is to verify and explore the status of all intra-abdominal structures (stomach, gallbladder, liver, pancreas, colon, and small intestine), then proceed to expose the aorta. Likewise, the main visceral branches of the aorta are explored in search of possible associated vascular lesions, the presence of thrill, or decreased pulsation.

Next step, the small intestine is externalized toward the upper right part, and it is wrapped with wet compresses or dressings to prevent desiccation. Meticulous palpation allows recognition of the state of the upper and lower limits, as well as the condition and characteristics of the adjacent arteries and their walls, particularly the mesenteric, internal iliac, and external iliac arteries. Likewise, inappropriate and excessive manipulation of the aneurysm should be avoided until adequate proximal and distal control has been obtained, to minimize the possibility of embolization to the lower limb.

A longitudinal incision is made in the peritoneum that covers the aorta, taking as reference the root of the mesentery just to its left, and is directed in a proximal direction, bordering the left aspect of the fourth portion of the duodenum to the lower surface of the pancreas and, distally, toward both iliac arteries. Both ureters face both common iliac arteries and are protected. With special attention to sexually active men, it is important to perform a meticulous dissection around the aortic bifurcation and the left common iliac artery to reduce the risk of damage to the sympathetic nerves that run in front of this vessel. Once the ligament of Treitz is divided, the inferior mesenteric vein is identified, this can be ligated and divided if necessary (**Figure 2A** and **B**).

An important aspect is the relationship of the aorta with the left renal vein. This is usually in the anterior and marks the proximal limit of the aortic dissection. However, in juxtarenal or pararenal aneurysms, it may be necessary to dissect the renal vein to allow traction upward, thus to the neck of the aneurysm. Before performing this step, ligation and division of the left gonadal vein may be required. Sometimes, the left renal vein, despite its proximal traction, can affect the access to the neck of the aneurysm, with the consequent technical difficulty, in this case, it can be ligated and divided medial to its gonadal and adrenal tributaries (**Figure 3A** and **B**).

To obtain proximal control of the aorta, the anterior surface is first dissected just proximal to the "neck" of the aneurysm, remaining in this plane, it is advanced laterally and medially, bordering the circumference of the aorta toward the posterior

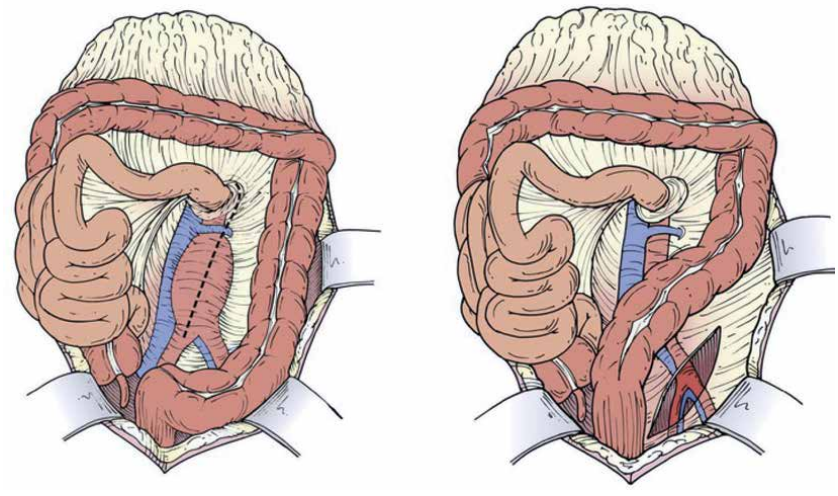


Figure 2.
A: exposure of the aorta through the opening of the posterior peritoneum, and B: approach to the left iliac artery, displacing the sigmoid colon medially and making an incision at the base of the posterior peritoneum. "Based on a chapter from the seventh edition by Brian G. Rubin and Gregorio A. Sicard."



Figure 3.
Mobilization of the left renal vein can be performed, by dividing its lateral branches (A) or by section close to the IVC (B).

surface. In general, it may not be necessary to encircle the aorta as the proximal clamp can be placed by palpating the aorta between the index finger and thumb. It is mandatory, prior to placing the clamp, to palpate both renal arteries and the mesenteric arteries. The pulses of both the superior and inferior mesenteric arteries should be palpated. If the inferior mesenteric artery is patent, a vascular clamp or an elastic vascular loop can be placed temporarily. This should be preserved for reimplantation, especially if the hypogastric arteries are occluded or may need to be sacrificed due to aneurysmal disease.

To expose the supraceliac segment of the aorta, the lesser omentum or gastrohepatic ligament is divided. The aorta is identified by palpation. The overlying right crus fibers of the diaphragm are then divided with electrocautery. If necessary, it is mobilized from the left lobe of the liver, dividing the left triangular and coronary ligaments, as well as the falciform ligament. Great care must be taken not to inadvertently injure the esophagus. The presence of a nasogastric tube helps identify it. Moving the esophagus to the left, the aorta is dissected on its anterior surface up to the level of the celiac axis, always taking special care not to affect the pancreas in this maneuver in the caudal direction.

The selection of the appropriate site for placement of the clamps for proximal and distal control, as well as the level of reconstruction, is done with the analysis of cross-sectional images of the aorta. The proximal extension of the aneurysm, iliac aneurysms, as well as concomitant stenotic or occlusive disease of the iliac arteries, renal arteries, and mesenteric arteries, any anatomical variants, the presence of calcium, thrombi, or atherosclerotic remains are evaluated. The structural integrity of the aortic wall is another important aspect to consider. Ideally, the clamp site should be relatively free of thrombi, atherosclerotic debris, or calcifications. Other considerations to consider are the presence of concomitant visceral branch disease and unusual venous anatomy. Whenever possible, the aortic clamp will be placed in the most distal position possible to avoid renal and visceral ischemia, but at the same time optimal anastomosis in the healthy aortic wall. For infrarenal aortic aneurysm repair, the clamp is placed immediately below the level of the lowest renal artery.

The graft anastomosis begins on the posterior wall below the level of the clamp. Efforts should be made to perform the proximal anastomosis in a healthy aortic wall,

in this way the risk of aneurysmal degeneration in the anastomosis area or above will be minimized [21]. Before aortic clamping, the hemodynamic status and urine production are confirmed, and systemic heparin is administered before proceeding with clamping. It is not strictly necessary to surround the vessels with silastic loops or cloth umbilical tape and increases the risk of injury to the posterior structures; however, it is customary for some surgeons to place this type of vascular control in case an accidental release of the vessel occurs. Gripper. Sufficient exposure to apply a clamp is mandatory. Special care must be taken not to injure or avulse closely related veins. Distal clamping is usually performed, thus avoiding embolization to the legs during proximal clamping (**Figure 3B**).

4.2 Aortic reconstruction

As already mentioned, the aneurysm is excluded using vascular clamps both distal and proximal to the sac. This opens longitudinally, and at its upper end, the incision is configured in a "T" shape to extend in this way to both side walls of the proximal neck.

The posterior wall of the aorta is not divided. All mural thrombi are evacuated, as well as remains of atheroma from the aneurysm wall. The orifices of the lumbar arteries are identified inside the sac on its posterior wall; this bleeding can be controlled by direct compression. The pad is slowly removed, the respective holes are closed with figure-8 suture ligatures. Once this has been controlled, the proximal anastomosis is initiated (**Figure 4C**).

The anastomosis begins in this way, from the inside on the posterior wall, the suture line, starting in the midline, must include the entire thickness of the posterior wall for greater strength, using #3-0 polypropylene suture with double needles. In the same way, the anterior half of the suture line is completed, with continuous stitches of full thickness. If the aortic wall is friable, Teflon or Dacron pads can be incorporated into the suture line. It is mandatory to perform a regulated and systematic anastomosis, observing and maintaining the curved path of the needle while suturing through the aortic wall and avoiding excessive tension while continuing each new suture placement.

After completing the proximal or superior aortic anastomosis, a vascular clamp is placed in the distal part of the graft and the aortic clamp is slowly released to confirm if there are leaks in the suture line, especially on its posterior surface, since its exposure is very difficult once the distal anastomosis is completed (**Figure 5**).

If there is no aneurysm of the iliac arteries, the inferior anastomosis can be performed in the distal aorta. For this, a straight tubular graft is used, which is sutured to the distal aorta at the level of the bifurcation, covering both orifices of the common iliac artery. If iliac artery aneurysms are present, an anterior incision can be made so that the ends of a bifurcated graft are anastomosed, below the ureters, in an oblique ellipse that includes the orifices of the internal and external iliac arteries. The configuration of the anastomosis can be end-to-end in the common iliac artery (**Figure 6**) [25].

Adequate patency of the extremities must be confirmed, observing rapid reflux; prior to completing the anastomoses of each iliac branch. If necessary and there is suspicion of distal embolization, embolectomy catheters (e.g., Fogarty) are used. Antegrade perfusion should be ensured in at least one of the internal iliac arteries to reduce the risk of left colonic ischemia. Once the first iliac anastomosis is completed, flow to that extremity must be restored [26].

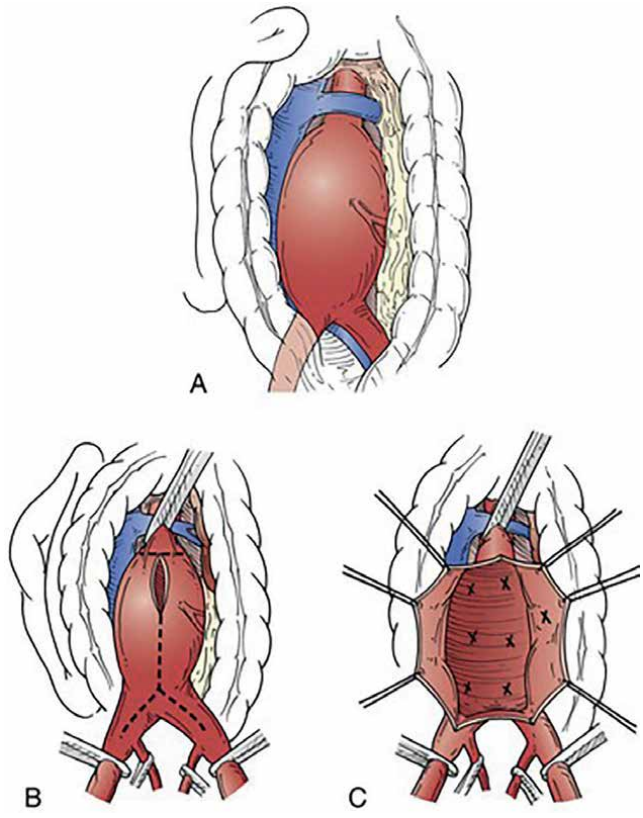


Figure 4.
A. The incision "T'," B. Figure 8 ligation to control bleeding from the emergency openings of the lumbar arterial branches, C.

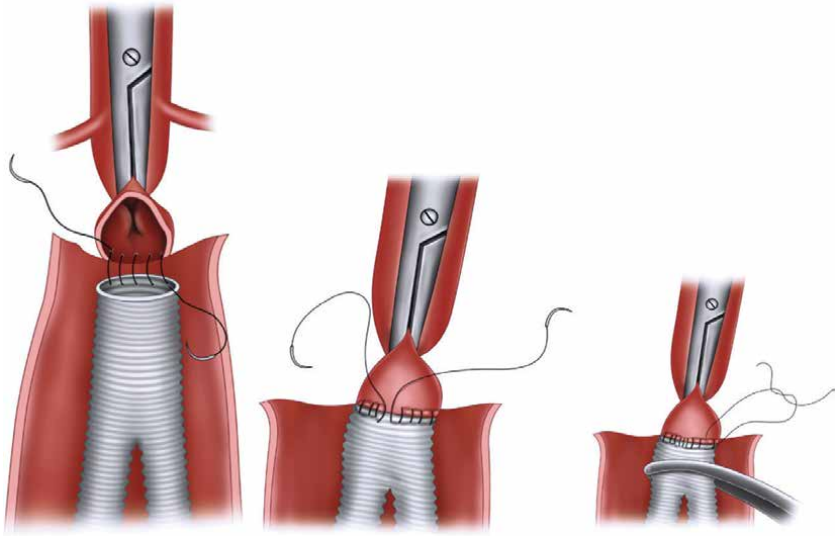


Figure 5.
Hans [25].

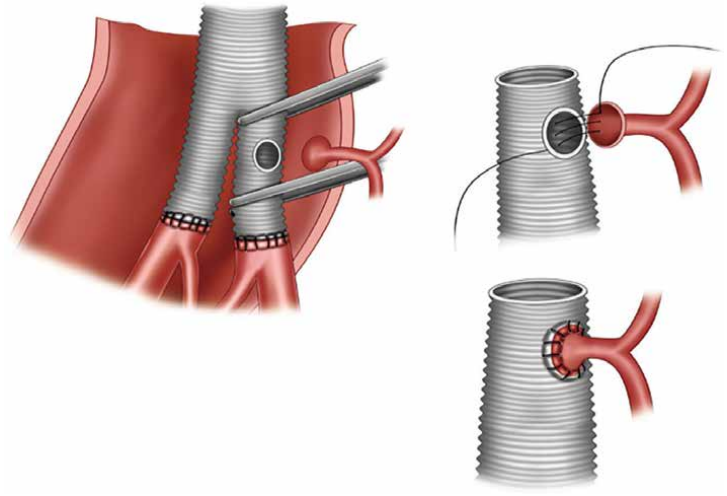


Figure 6.
Distal anastomosis and reimplantation to an aortic graft of IMA. Hans [25].

In patients with underlying celiac artery disease and SMA occlusive disease, especially if the IMA is large, reimplantation should be considered. Reimplantation in the aortic graft is performed with the Carrel patch technique in which a small button is dissected from the aortic wall in continuity with the IMA (**Figure 7**). The antegrade flow must be preserved toward at least one of the internal iliac arteries. This can be achieved through different configurations for anastomosis of the iliac

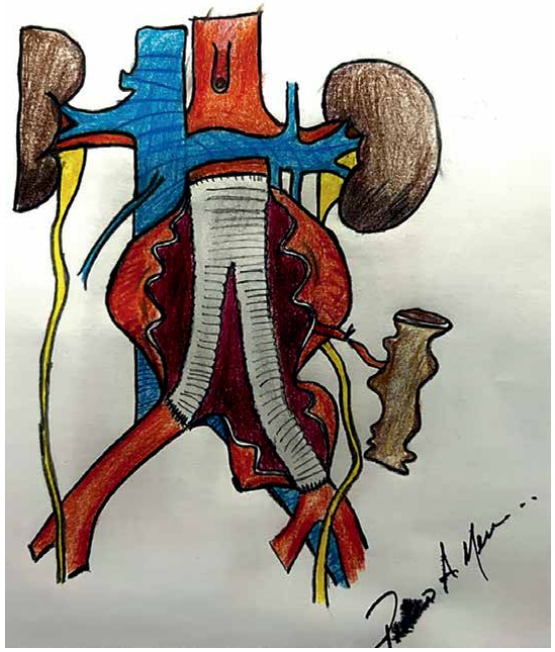


Figure 7.
Complete implantation of the aortic graft.

branches of the prosthesis: distal to the iliac bifurcation, performing an end-to-lateral anastomosis in the external iliac artery that allows the retrograde flow to the internal iliac artery, or with a graft of anastomosed bypass, separately to the internal iliac artery [21, 26].

Hypotension after release of the clamps is produced by reperfusion of the dilated distal arterial vascular bed and, concomitantly, a venous return of vasoactive substances and toxic products of anaerobic metabolism. This can be avoided by administering adequate intravenous fluids. When the aortic clamp is released, there is an immediate and significant reduction in the vascular resistance of the peripheral arterial bed. As blood is "sequestered" in previously ischemic tissues due to reperfusion hyperemia, central hypovolemia develops, further exacerbating hypotension. This hypovolemic event can be reduced by slowly and deliberately releasing the clamp while observing the blood pressure on the monitor and allowing flow to the internal iliac artery before the external iliac artery. This maneuver also allows diverting possible emboli toward the hypogastric circulation and not toward the legs.

4.3 Retroperitoneal approach

For the retroperitoneal approach, the patient is placed with the hips in a supine position and the thorax rotated medially so that the left chest is almost in an anterior position. The patient is placed in a modified right lateral decubitus position with the shoulders rotated at 70 degrees to the operating table. This allows us to easily perform groin approaches, if necessary, thus allowing access to both femoral arteries. The incision begins and extends from the eleventh left intercostal space, along the lateral edge of the rectus sheath, downward. The abdominal wall muscles and intercostal muscles are divided at the incision line and the extraperitoneal space is entered at the tip of the twelfth rib. The peritoneum together with the transversal fascia is separated from the muscles of the abdominal wall in the anterior part. The left psoas muscle is identified and the inferior part of the dissection, the peritoneal sac, and its contents are retracted anteriorly and medially. Once the retroperitoneal space is approached in the usual manner, the peritoneal sac is mobilized in a medial direction, thus allowing the entire abdominal aorta to be exposed. Aneurysm repair is then performed as described for the transabdominal approach (**Figures 8–10**) [23].

To improve the approach to the visceral and adrenal segment of the aorta and obtain an adequate supraceliac clamping site, the diaphragm should be divided at its left crus, and the aorta should be dissected bluntly along its anterior and posterior aspects. Care must be taken to avoid avulsion of any posteriorly running lumbar vessels. Caution should be used when attempting to surround the aorta or iliac veins, as this runs the risk of injuring the esophageal, cava, or iliac vein.

An adequate approach is made from the left flank to the left ICA and its bifurcation, but the right ICA can only be exposed in its proximal third. To improve the approach, the IMA is divided, and the peritoneal sac is mobilized medially. If it is not possible to safely clamp the right ICA, endovascular control can be performed with a Fogarty catheter or an occlusion catheter to prevent retrograde bleeding [23].

4.4 The arterial reconstruction

Once the heparin is administered and the supraceliac cross-clamp is performed, the aneurysmal sac is opened with a longitudinal arteriotomy from distal to the normal proximal aorta, after which the arteriotomy is transformed into a T-shaped



Figure 8.
The left flank incision for retroperitoneal incision. (A) Infrarenal AAA. (B) Juxtarenal AAA. Hans [25].

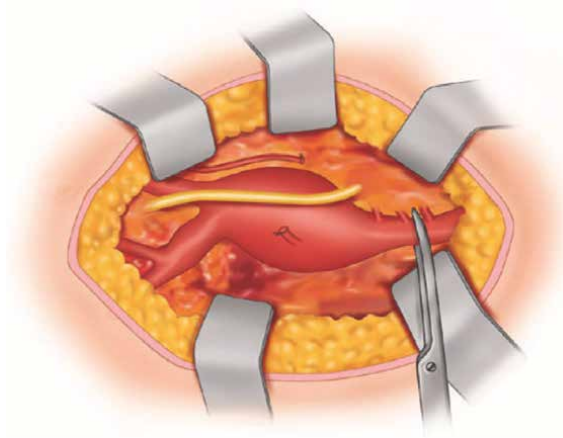


Figure 9.
Retroperitoneal exposure of AAA, the dissection plane posterior to the left kidney is outlined. Proximal aortic clamping is done above the superior mesenteric artery for pararenal AAA repair. Hans [25].

incision. The origin of the left renal artery must be identified, and the renal vein divided so that it is not damaged during the execution of this maneuver.

Once the proximal part of the aneurysm is opened, the celiac, SMA, and right renal arteries are identified from the inside. If any critical, significant stenosis is observed in preoperative angiography or during surgery, it can be treated with end-arterectomy or by placing an expandable balloon stent through the open aorta. The

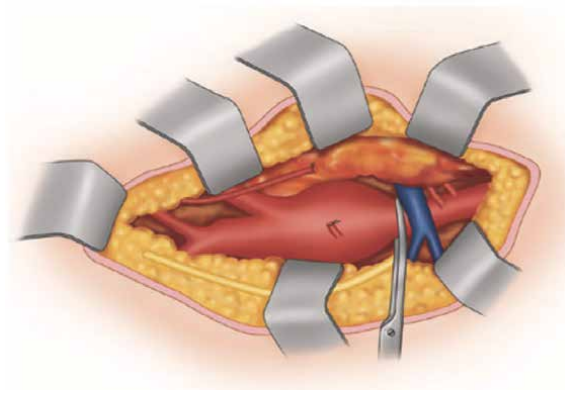


Figure 10.
Retroperitoneal exposure with the left kidney is the necessary technique in patients with retroaortic left renal vein. Hans [25].

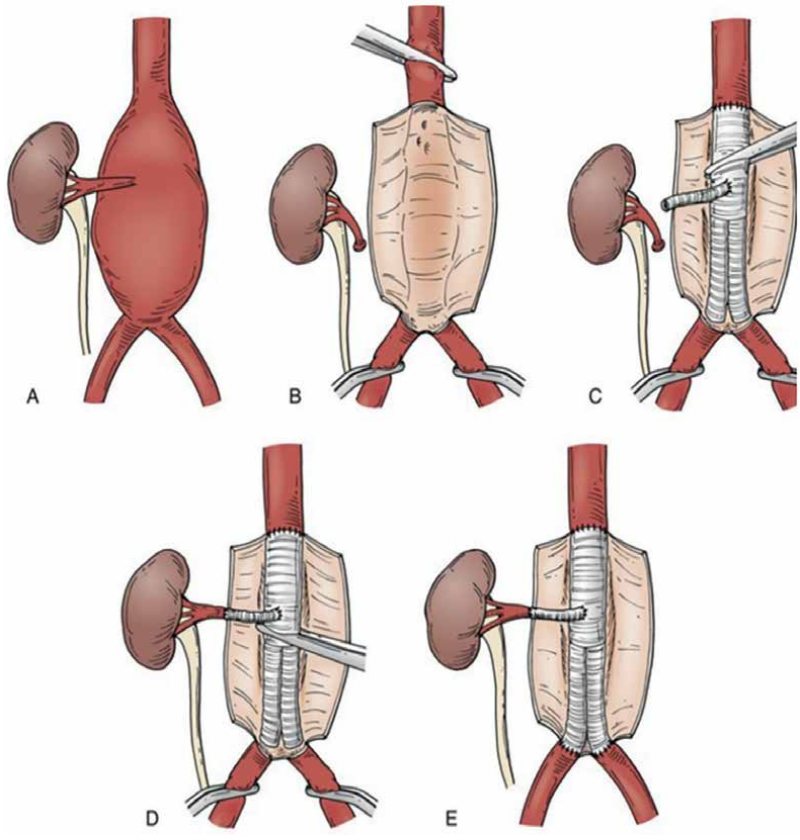


Figure 11.
Anastomosis with renal bypass. Clamping of the aorta and opening it in a T shape. Separation of the renal artery (A and B). Beveled proximal anastomosis toward the visceral segment and the right renal artery, the clamp is placed distal to the anastomosis (C). The left renal artery is bypassed with a pre sewn graft segment (D). The distal anastomoses are made, and the clamp (E) is removed. "Based on a chapter in the seventh edition by Brian G. Rubin and Gregorio A. Sicard."

proximal portion of the graft is cut in a bevel shape, and in this way, the celiac, SMA, and right renal arteries are reimplanted.

To perform the anastomosis, a continuous polypropylene suture will be used. A vascular clamp is placed in the proximal segment of the graft, distal to the suture, and the supraceliac clamp is removed so that the right kidney and viscera are perfused. The left kidney is revascularized by bypass with a segment of the graft. If a bypass is required, it can be fabricated as a side branch from the main graft before aortic cross-clamping, thus reducing left renal ischemia time and facilitating anastomosis. It is essential to minimize ischemia time in this area. Therefore, proper performance of the operation and attention to technique are essential (**Figure 11**).

5. Declamping

Hypotensive phenomena secondary to rapid reperfusion of the dilated distal arterial bed, coupled with the venous return of products of anaerobic metabolism, as well as vasoactive substances, is reduced by performing a regulated and controlled release of the aortic clamp. By performing rapid and deliberate unclamping, there is a significant and instantaneous reduction in peripheral vascular resistance.

As blood pools in previously ischemic tissues due to reperfusion hyperemia, central hypovolemia develops, further exacerbating hypotension. The effects of these changes are minimized by slowly releasing the clamp while observing the blood pressure on the monitor.

6. Closure

For the transperitoneal route, one that achieves rigorous hemostasis, the aneurysm sac is closed over the graft using a continuous absorbable suture, to separate the graft from the rest of the contents of the abdominal cavity. The posterior peritoneum must

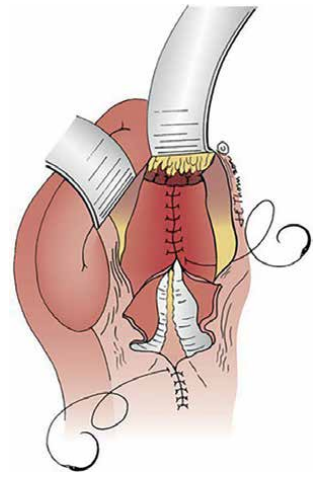


Figure 12.
Closure of the aneurysm sac over the graft and closure of the posterior peritoneum. "Based on a chapter from the seventh edition by Brian G. Rubin and Gregorio A. Sicard."

also be closed. Alternatively, if it is not possible to approximate the sac or retroperitoneum over the graft, the omentum can be used to cover the graft. It is essential and mandatory to keep the intestinal loops separated from the graft, thus avoiding the future formation of an aortoenteric fistula. Subsequently, the intestines are returned to their usual anatomical position and the anterior abdominal wall is closed according to the method preferred by the surgeon (**Figure 12**).

In the case of the retroperitoneal approach, the closure is as follows: Rigorous hemostasis is obtained, the separators are removed, and the peritoneal sac is returned to its usual anatomical configuration and position. Since the peritoneum is kept closed, the graft remains separate from the peritoneal contents and there is no need to close the aneurysm sac at the end of the repair.

If any opening occurs in the peritoneum, it should be closed with an absorbable suture. The operating table is returned to the neutral position to avoid tension on the wound and thus make closure more efficient, and the flank incision is closed in several layers. Wall closure can be performed in bloc or anatomical planes, according to the surgeon's preferences.

7. Complications and outcomes

Common postoperative complications can be classified into immediate, early, and late: OSR immediate complication: hemorrhage and myocardial infarction. Early complications of OSR: hemorrhage, ileus, ischemic colitis, myocardial infarction, pneumonia, renal failure, and wound infection. Late complication of OSR: incisional hernia number of complications after OSR varies between studies. The postoperative complication rates are pulmonary (42%), cardiac (18%), renal (17%), ischemic colitis (9%), and wound complications (7%). Postoperative end-organ ischemia, including postoperative colonic ischemia, acute lower extremity ischemia, or spinal ischemia, are rare but serious complications [20, 22].

Factors related to mortality after OSR have been reported to include surgeon experience and hospital volume of surgeries, elderly patients, severe comorbidities, as well as the morphology and proximal extension of the aneurysm. Symptomatic coronary heart disease, congestive heart failure, severe chronic lung disease, and advanced chronic kidney disease are also considered important predictors of mortality. The 30-day mortality from OSR in most large contemporary institutional reports has ranged between 1% and 4% [15, 20].

8. Conclusion

Abdominal aortic aneurysm repair is a life-saving procedure. The risk of death as a cause of AAA rupture reaches 90%, so elective repair of the abdominal aorta also plays a crucial role. As demonstrated by recent publications, robust and with a large population (see in the development of the chapter), open resection of abdominal aortic aneurysm continues to play an important role, which is demonstrated in its long-term results, especially in those patients with a good life expectancy, in those patients who do not have a favorable anatomy for endovascular exclusion and in those who have presented a complication associated with endovascular repair. It is important that training centers for vascular surgeons maintain training with this technique. Despite the advantages of endovascular procedures, open repair continues to have

precise indications and a leading role, with a significant improvement in short, medium, and long-term results.

Conflict of interest

The authors declare no conflict of interest.

Thanks

To my wife Cristina, for her advice, help, understanding and patience for every moment, activity, or project I carry out. Thanks to my teachers from the Angiology, Vascular, and Endovascular Surgery service at the National Medical Center on November 20 in Mexico City, for their support and constant interest in my development. To the members of the Dominican Society of Vascular and Endovascular Surgery. To my work team at Clinica Unión Médica del Norte.

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Chapter 3

Low-Cost Digital Tools for Endovascular Aortic Aneurysm Repair Sizing and Planning

Juan Carlos Gomez-Rodriguez

Abstract

Preoperative planning and appropriate device selection have been shown to significantly reduce the rate of type 1 endoleak and secondary re-intervention rates. Precise anatomical measurement for endovascular aortic repair (EVAR) planning and stent graft selection is critical to obtain favorable outcomes when there is a lack of 3D workstations, specialized software, or advanced image techniques like 3D fusion digital subtraction angiography (FDSA) and intravascular ultrasonography (IVUS). This chapter describes available methods to improve the sizing and planning technique using open-source and low-cost universally available digital tools that can be used to plan TEVAR, F/BEVAR, infrarenal EVAR, and covered endovascular reconstruction of the aortic bifurcation (CERAB) cases. These designing tools can help teams overcome technical limitations due to the lack of FDSA, IVUS, costly imaging workstations, or advanced vascular software, a typical scenario in many countries. Using the described digital toolkit to size, measure, and plan graft selection and procedure execution in complex aorta endovascular repair offers multiple advantages, such as quick availability, low costs, knowledge of patient anatomy, 3D modeling, and printing. 3D modeling can help the accuracy of fenestrations in back-table physician-modified cases, especially in urgent cases with complex anatomy. Vector design software has advantages such as layers, transparencies, and node-based tracing to enhance the process and improve visualization. This produces high-quality images with a 1:1 proportion that can be used in the OR and easily distributed to team members involved with patient care. This might prove most beneficial in developing countries where advanced imaging hardware and software are scarce and cost-prohibitive.

Keywords: aneurysm, EVAR, endovascular, repair, planning, sizing, 3D printing

1. Introduction

Precise perioperative planning is essential for short- and long-term outcomes after EVAR [1]. The study of images in the pre-operatory time takes the uttermost importance to ensure the adequate selection of patient candidates for EVAR, the endograft type and size, and even what patients are not suitable for endovascular approach and should be prepared for open repair [2].

First, obtaining a helical CTA with 0,5 to 1,5 mm thickness is recommended. To avoid contrast-induced nephropathy and radiation over-exposure, if an aneurysm is suspected, double contrast abdominal and pelvic 3 mm CT should be avoided, and a 0,5 to 1 mm CTA should be preferred for it facilitates ulterior image analysis. A single phase is usually sufficient for analysis, but delayed or non-contrast images can be acquired following specific indications.

Once the diagnosis is made and a good image set is obtained, a refined measuring method should be followed, considering specific general relative contraindications and morphologic vital characteristics.

1.1 General failure prediction

Identification of genetically triggered diseases and aortic infections should be treated by open abdominal aortic aneurysm repair (OAR) whenever possible, as well as in excessive risk of embolization associated with severe atherosclerotic disease or shaggy aortas.

1.2 Morphology

Several aspects should be carefully considered and precisely measured to decide whether to treat with EVAR appropriately. Even though prospective randomized trials have demonstrated that EVAR is associated with lower mortality, morbidity, blood loss, and faster recovery compared to surgical repair [3], several other studies have shown the association between inadequate anatomy and the development of endoleaks and sac expansion [3, 4], late failures can manifest even after 3 years of follow up and may require additional secondary interventions, leading to higher costs, risk of rupture, and mortality [5, 6].

1.3 Necks

Necks are the proximal aortic and distal iliac segments free of aneurysmatic disease; they ensure the grafts' adequate positioning and fabric sealing to the vessel and stent fixation. The graft's durability and stability depend on the device's active fixation but, most of all, on the radial force and friction to the arterial wall; because of this, precise measurements and defining unsuitable anatomies are crucial steps of EVAR planning.

1.3.1 Proximal neck

In an infrarenal aneurysm, the proximal neck is defined as the segment from immediately below the lowest renal artery to the beginning of the aortic dilation. Cylindrical necks have a difference of less than 15% between proximal and distal diameters; tapered and reverse tapered necks show more than 20% variation. Necks over 30% or reversed tapered are not suitable for EVAR. The minimum acceptable length of the proximal landing zone is 15, or 10 mm, when the device includes proximal fixation; nevertheless, the shorter the neck, the greater the risk of type Ia endoleaks. Taking the inner curve (shorter) length in angulated necks is recommended to avoid overestimating the landing zone [7].

Necks over 30–32 mm in diameter are more likely to be diseased, and due to cranial progression of the aneurysmal disease, they offer no durability to sealing.

They can develop type Ia endoleaks requiring additional interventions. Small neck diameters (under 18 mm) can lead to fabric corrugation and aortic rupture.

1.3.2 Angulation

The angulation between the aortic neck and the aneurysm should not exceed 60° except for those devices specifically designed to accommodate high angulations between 75 and 90°. The suprarenal angle is relevant when deploying bare-stent fixation mechanisms (i.e., free flow). Special attention must be paid to increasing the oversizing of the body of the graft in the proximal diameter due to the asymmetric oblique positioning that comes with the geometrical alteration of the angled neck deployment [8].

The presence of thrombus or calcifications should be assessed. Thrombus covering over 50% or two-thirds of the neck's circumference prevents ideal proximal sealing, with potential type 1a endoleaks evolution, and EVAR is not recommended.

The aortic bifurcation should also be measured, and it must be at least 20 mm in diameter for it must fit both iliac leg grafts to avoid compression that could lead to stenosis and thrombosis.

2. Planning and sizing digital tools

Now we provide insights into digital tools to process DICOM images and produce detailed plans to perform EVAR procedures, which are available at low or no cost. This chapter does not include details on Imaging 3D workstations or specialized vascular software packages for those that come with appropriate learning methods for the institutions that can afford such tools.

2.1 Medical imaging viewer: Horos™

Horos™ is an Open-Source Medical Image Viewer based upon the Osirix ™ and other open-source medical image libraries. As in Egyptian mythology, the son (Horus) is made out of the parts of the father (Osiris) and follows the latter in functions and capabilities. Even though it lacks FDA marking, the interface and functionality were mirrored entirely from its predecessor.

Horos™ was initially released in February 2015 and was intended to be a viewer for medical images in any modality in DICOM format. It can only be downloaded from www.horosproject.org. It is an open-source project and explicitly invites community involvement in improving and adding to its capabilities. Horos is designed to operate in Apple Macintosh OSX and will not run on Windows or Linux computers.

As mentioned above, a good quality CTA (containing between 600 and 1000 slices) can be processed in Horos™ in different ways, as multiplanar reformats, bidimensional (2D) and tridimensional (3D) multiplanar reconstruction (MPR), and curved MPR, minimal and maximal intensity projections and can produce 3D volume rendering and surface rendering suitable for 3D printing.

Each professional must know that there is no ideal processing modality but the precise indication for each use, that combined allows for identification of anatomy and image pathology analysis and corrected isometric views that permit sizing to be corrected beyond the scope of axial, coronal, or sagittal views alone.

2.1.1 Centerline

A tridimensional structure can be registered in an axial view in planes that are oblique to its axis, and measurements of lengths can be geometrically distorted, and over or unmeasured; Kanistar et al. in 2002 proposed a method of reformation in multiplanar sequences [9] now used by Horos™. Because acquisition in CT is based on tridimensional units called voxels (a portmanteau of "volume" and "element" as the 3D equivalent of a pixel [10]), images theoretically can be viewed in any angular plane.

A multiplanar reformatting or reconstruction (MPR) allows data from axial acquisition to be reformatted in different planes and be reconstructed simultaneously in three basic views (axial, coronal, and sagittal) to compensate for axial bias in distorted or curved structures as vessels (**Figure 1a–c**) [9].

The curved MPR allows the reconstruction of a dataset along a curved plane like a vessel. Horos™ has two curved MPR modalities called straightened and stretched. It is important to note that for EVAR planning, isometry (resolution along the X and Y axis) should be conserved, so reliable sizing should only be performed in stretched rendering in Horos™.

To obtain the 3D curved MPR render in Horos™, the user must define a curved path using sequential points that can be placed in any of the three orthogonal views. The smaller the slice intervals, the better the image quality of the rendered curve (**Figure 1d**).

In spatially complex scenarios, the vascular surgeon must decide to place each point of the curved path in the center of the vessel independently of the amount of lumen to achieve precise whole vessel measurement; this is especially important in severe vessel atherosclerosis or aortic dissections due to the reduced lumen and tortuous lumen anatomy that can change the geometry of the reformation.

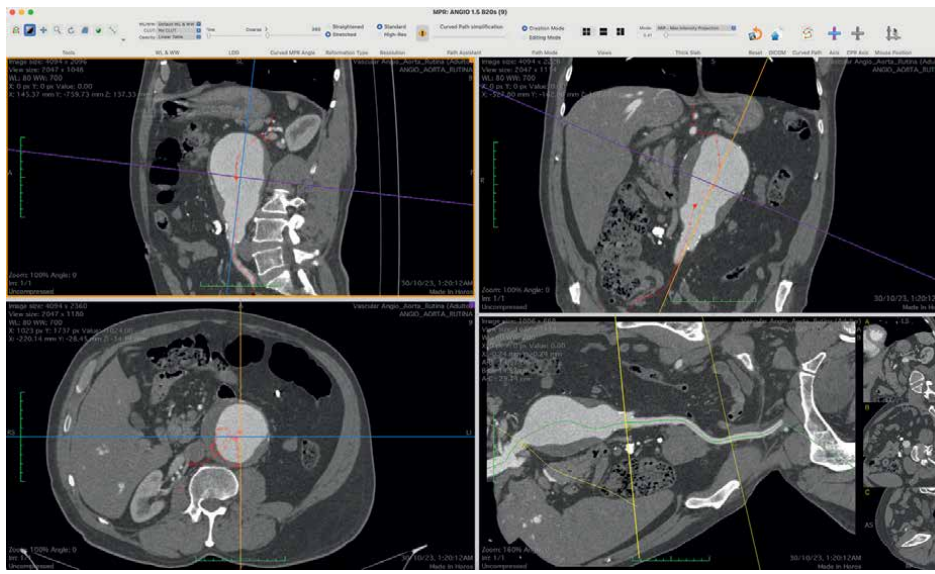


Figure 1.
Screenshot of Horos™ curved 3D multiplanar reconstruction (MPR) showing sagittal plane (a), coronal plane (b), axial plane (c), and stretched centerline lumen (CLL) reconstruction of a CTA.

Special attention must be paid to each proposed graft's Instructions for Use (IFU) due to the specifications of measurements made inner to inner (intima to intima/inner wall) pe. Gore™ Excluder or outer wall (adventitia to adventitia) pe. Cook™ Zenith or Medtronic™ Endurant. It is important to remember that under or overestimating even 2 mm in vessel size can result in fixation and sealing failure, favoring endoleaks or graft migration [2].

2.1.2 Maximum intensity projection (MIP)

A frequently used technique to visualize the aorta is the MIP, in which images display the voxel with maximum intensity in the view plane that faces the virtual camera. This method allows the visualization and assessment of contrast-enhanced structures, like vascular structures. This method should not be used for measurements because it lacks depth relations reliability (**Figure 2**) [10].

2.1.3 Segmentation

Shaded surface display (SSD) and volume rendering images are created by identifying structures of interest within the source data set based on their CT attenuation values, this process is called segmentation and has been used for surgical purposes since the nineties [11], however, their usage was limited to powerful workstations due to the amount of computer power required. Nowadays, the suitable computer power of CPU and GPU augmentation for tridimensional imaging computation and processing are widespread and usual in personal computers.

The organ segmentation can be performed by different methods like threshold or seed growth in 3D Slicer™; in Horos™ can be performed through the region of interest (ROI) method and even produce surface rendering that can be easily exported to STL files could be 3D printed. We prefer to use 3D Slicer for segmentation.



Figure 2.
Coronal view of a CTA with maximum intensity projection (MIP) setting of 37 representing 30,5 mm of voxel overlay.

2.1.4 Projection of C-arm angles

Horos™ can easily produce a tridimensional surface model of the vessels and registers the rotation of views in three planes: Cefalocaudal (S-I), laterolateral (L-R), and roll. The volume can be positioned (in 0° roll) to mimic the C-arm angulation and register the axes deviation in RAO (Right anterior oblique) and LAO (Left anterior oblique) or cranial/caudal degrees to obtain an optimal view of the main branch emergence to avoid too much parallax and prepare a precise deployment of the graft (**Figure 3**).

Alternatively, an angle calculation can be obtained in the orthogonal views of the three-dimensional MPR using the Horos™ measurement tools.

2.2 3D slicer

3D Slicer is an open-source platform developed at Harvard University in 2000 to analyze and display information derived from medical imaging and similar data sets. Such advanced software environments are used daily by researchers and clinicians and in many nonmedical applications [12]. Volumetric data can be semi-automatically segmented using the 3D Slicer's suite of editing tools. Effects such as thresholding, morphological operations (erosion, dilation), island removal (erasing small groupings of similar pixels), measuring the size of islands, cropping, and free-hand drawing of polygons, lines, or points can be applied to the data [13]. 3D Slicer has been used in several medical applications to plan and guide surgical procedures [14–17].

2.2.1 Creation of a 3D model using a CTA

We use the DICOM module to import the CTA data, and then after a short learning curve, a first-year fellow can produce an STL model of the aorta in less than 5 minutes using the Grow From Seeds effect. A millimetric slice CTA is essential to achieve good results, so institutional standardization should be assured.



Figure 3.
Horos™ 3D volume rendering using -soft tissue: Standard- preset, showing optimal angle view of the left internal iliac bifurcation. In the right lower corner, angulation data represents RAO 20,6° (L-R – 20.6) and CAU (S-I -17.3°) and is the optimal vessel visualization settings for the C-arm position.

An extension named SegmentEditorExtraEffects from Lasso, MacNeil, and Fedorov can be added to 3D slicer using the extension manager; this extension adds the Local Threshold effect, which adds the structure that is located at the selected position and has intensity values within the specified threshold range, this could be set visually or using a local histogram which in turn, represents voxel intensity distribution within a selected region of the image. Then, a segment is drawn within the aortic lumen using any of the three views on the screen; the histogram limits are then extended not far above and below the selected values, and with command + click, the selection is added to the actual segment, and then, show 3D is selected (**Figure 4**). It is important to remember that segmentation is made of a representation of the voxels creating the aortic lumen, so make sure to make the 3D model hollow using the segment and growing outwards. The vessels are cut to the ostial lumen level, and then the aorta is longitudinally cut so a stencil is created. This model is then exported to a STL file. The STL file itself is not usable by a 3D printer, so it needs to be processed with a slicer software like Ultimaker Cura™ (Geldermalsen, Netherlands) to prepare, transform, and position the model into the G-Code programming language to tell the printer the coordinates to make material deposition and build the model (**Figure 5**).

The Vascular Modeling Toolkit module, an extension developed by D. Haehn, has shown promise in improving the sizing and extraction of centerline vessels within 3D Slicer. However, for our applications, the most powerful feature of 3D Slicer is the capability to easily produce STL files of solid or hollow models of the aortic lumen for 3D printing based on the adjacency of similar voxels contained in a defined threshold (**Figure 6**). These models can facilitate planning showing angles, lengths, and relationships of visceral vessels to achieve canulation in complex endovascular aortic repairs successfully or to design homemade fenestrated devices in urgent cases [18].

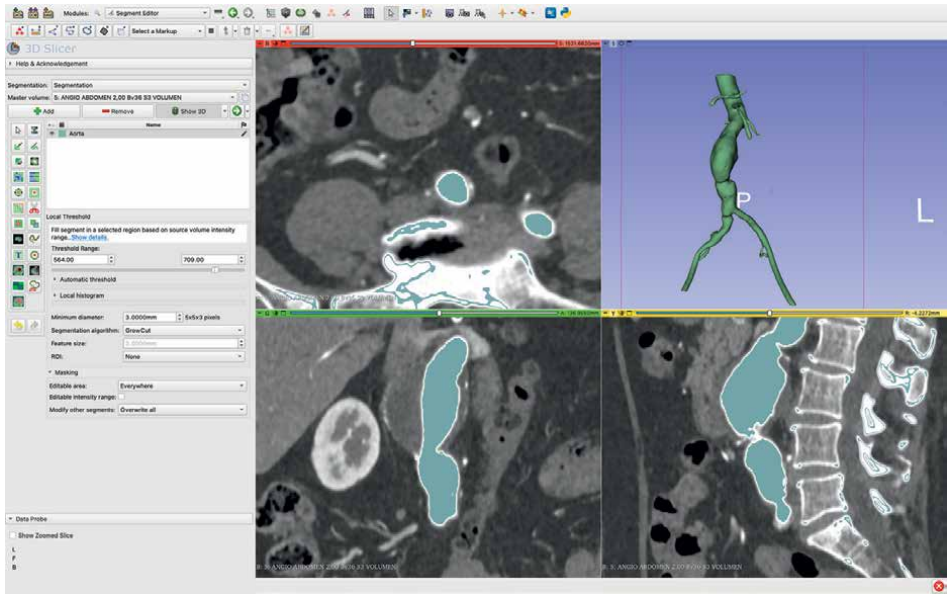


Figure 4.
Screenshot of 3D slicer segment editor showing the local threshold tool configuration menu (left column). The right upper view represents the three-dimensional view of the segmentation product, which in turn, represents the aortic lumen density values between 564 and 709 Hounsfield units.

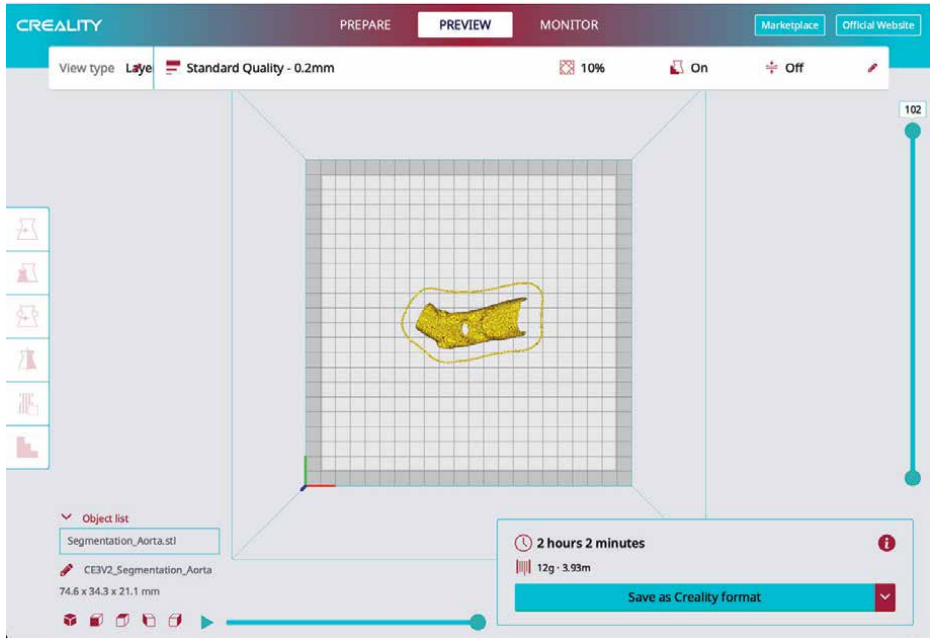


Figure 5.
Screenshot of Creality slicer with the sliced STL file of the aortic shell semi-cylinder representing the aortic vessels and ostia. Notice the production time and the simulated position on the 3D printer.

2.3 3D printers

The evolution of 3D printing technologies has allowed the commercial spread of printing devices to be available even for the home user. Previous experiences have shown that printed aortic phantoms are ideal for preoperative planning and device selection and to aid intraoperative performance [19, 20].

In the perioperative process, we use two printed models, one destined for patient education and engagement, planning and sizing, and anatomic familiarization of the surgical team, and one sterilized in hydrogen peroxide that is used in the operating room and manipulated during the procedure to achieve complete visualization of anatomy, angles, and spatial relations among vascular branches. Further development is required to generate models with optimal anatomical and fluoroscopic fidelity so procedures can optimally be simulated preoperatively (**Figure 7**).

2.3.1 3D printing for FEVAR

Due to the complexity of pararenal aneurysms, the use of physician-modified grafts can represent a solution for emergency cases and to solve the unavailability of certain types or sizes of endograft devices.

Millimeter precision sizing is paramount to avoid catastrophic complications in anatomically complex cases. The use of fenestration and scallops in the modifications depends on patient-specific anatomy, and those modifications are made based on two main measurements: Arc length from the anterior midline of the graft and distance from the proximal edge.

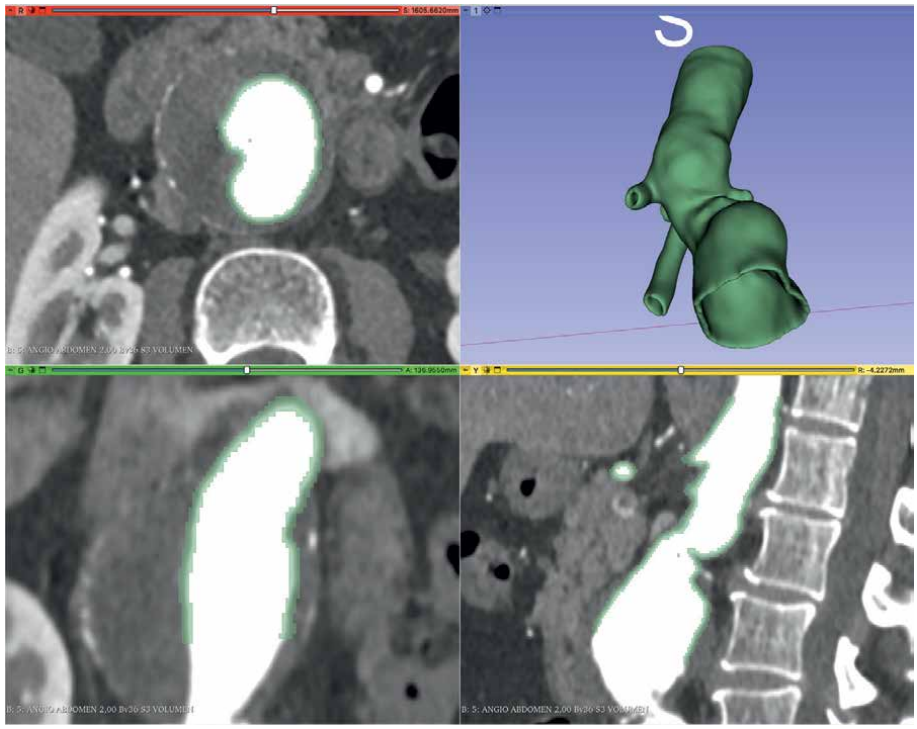


Figure 6.
Screenshot of 3D slicer segment editor showing the three planes and the segmentation 3D model hollowed out of the previously segmented lumen and cut to represent the visceral vessels' aortic level. Make hollow tool was set using the segment as the inside surface and with a shell thickness of 2 mm.

2.3.2 Arc length

AngioCT is usually obtained in the supine position and aortic position within the body, and the emergence of visceral vessels is represented as hourly marks. The distance between two points in the length of a section of a curve can be calculated if the radius is known using the formula:

$$Arc = 2\pi r\left(\frac{\theta}{360}\right) \tag{1}$$

The diameter should be measured using MPR of CTA images to obtain an aortic radius, and a good quality centerline should be produced using Horos. Aortic diameter should be obtained at the point that represents the center of the ostium of each visceral vessel. Our team calculates the ostium diameter based on arc length, measuring the degrees of the mentioned ostium's starting and endpoints. In cases where the graft is going to be free within the lumen due to abnormal aortic diameter, the graft's diameter is to be used instead of the aortic diameter.

The distances of the ostia from the edge of the graft and the distance from 12 O'clock in the graft are represented in the digital version of millimeter paper in a 1:1 ratio. This is the stencil for the fenestrations, which are thermally open in the graft textile with an ophthalmologic cautery (**Figure 8**).



Figure 7.
Polylactic acid (PLA) home-produced models based on STL files rendered out of a CTA in 3D slicer. At the left, visceral vessels stencil for fenestrations, and to the left, solid aortic model to familiarize with vessels ostia and directions to facilitate cannulation. A Creality™ ender V3 home 3D printer was used.

A hollow model of the aorta is then produced in 3D Slicer with the Hollow tool and a stencil modeled out of it, this is printed in PLA material in about 2 hours and sterilized in oxygen peroxide in one more hour.

Both tools, the stencil, and the millimeter paper ostial map, are used to confirm measurements before heat fenestration itself (**Figure 9**).

2.4 Drawings in EVAR planning and sizing

Traditionally, the vascular surgeon uses millimeters or regular paper and colored pencils to trace the aorta out of a computer screen with a less-than-ideal representation of measurements and proportions. Also, the lack of reproducibility or non-destructive modifying properties of these drawings was an obvious limitation in planning.

On the other hand, the prohibitive cost of available software packages for EVAR planning and sizing took us to the vector graphics path.

2.4.1 Vector graphics

Vector graphics were developed in an effort of MIT and IBM for the US Air Force to use in the computer-based predictive and preemptive system of air defense denominated SAGE (Semi Automated Ground Environment) [21]; Vector graphics are computer graphics images that are defined in terms of points on a Cartesian

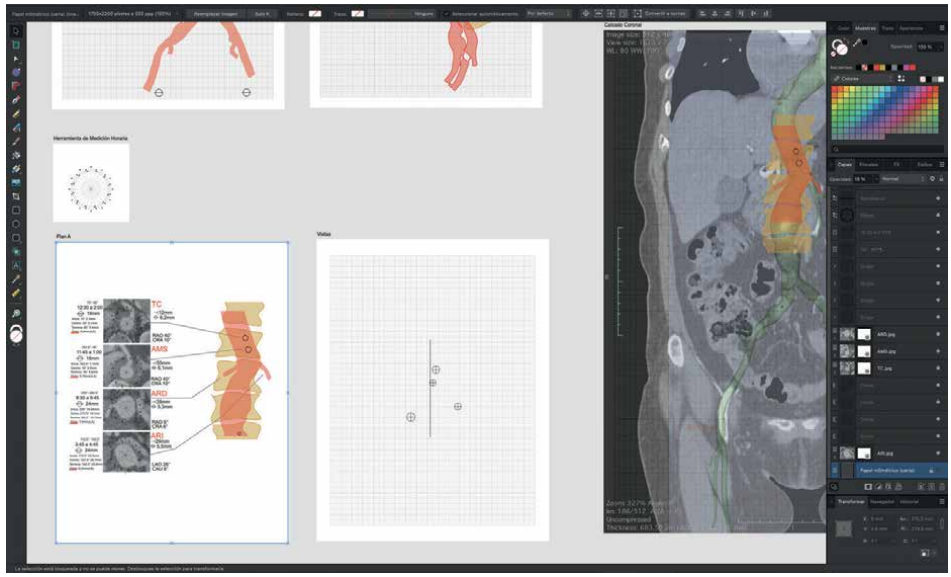


Figure 8.
Screenshot of affinity designer for mac interface with artboards showing visceral vessels measurement of diameters, arc lengths, and distances to the first branch. Angle measurements for arc length are measured with a digital representation of a transparent hour tool. To the right, the 1:1 DICOM coronal representation was used to trace anatomy and landmarks.

plane, which are connected by lines and curves to form polygons and other shapes. Vector graphics have a unique advantage over raster graphics in that the points, lines, and curves may be scaled up or down to any resolution with no aliasing. The points determine the direction of the vector path; each path may have various properties, including values for stroke color, shape, curve, thickness, and fill [22, 23].

Even though Adobe Illustrator is the industry standard, the prohibitive costs associated with subscription made us opt for Affinity Designer (Serif, UK), a low-cost, fully capable vector design software available for Windows, Mac, and iPad.

We use Affinity Designer™ for Mac to generate the planning drawings in 1:1 scale for infrarenal, thoracic, and thoracoabdominal aneurysms, using the software's capabilities like layers, transparencies, and tracing.

Several images from Horos™ are exported in coronal and sagittal views and create two artboards, matching the centimeter scale of Horos™ exported images with the millimeter paper in 1:1 scale to create scale images of the CTA and trace the features. In complex cases, we export a 3D Slicer segmentation with a ruler scale in both anterior and lateral views to match the CTA. Then, the transparency tool for images and the layers is used to progressively trace the shape of the aorta, the vertebrae, and the aneurismatic dilations or other relevant anatomy features with the pen tool (**Figure 10**).

Once the aorta is traced, two more artboards are created with the object representing the aorta, colored and in 1:1 scale on millimeter paper so the measurements obtained in Horos are put in place. One artboard is dedicated to measurements of lengths and angles, and one is for the proposed treatment.

The software's features allow us to represent transparent tools as the hourly measurement or Cook T-Branch fitting tools to be represented exactly as you could with physical ones, but with more precision and reproducibility (**Figure 11**).

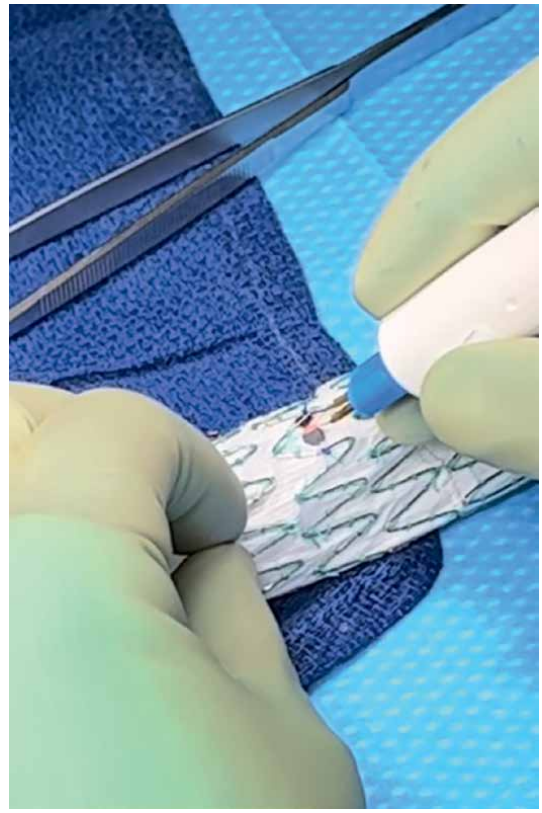


Figure 9.
Photography of a stent graft being modified. After precision measurement, an ophthalmologic cautery is used to thermally make the holes in the fabric.

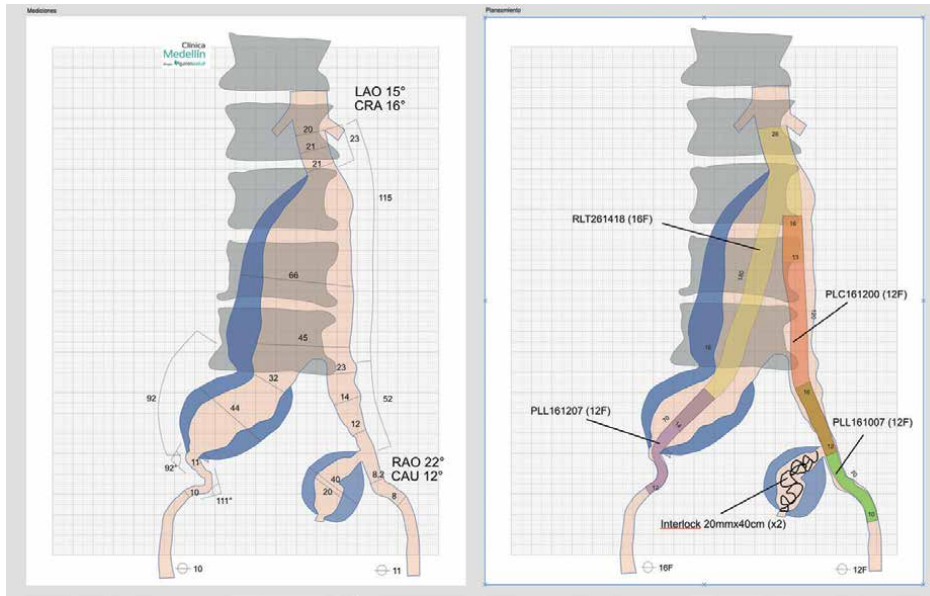


Figure 10.
Screenshot of affinity™ designer™ sizing and planning sheet of an infrarenal EVAR case.

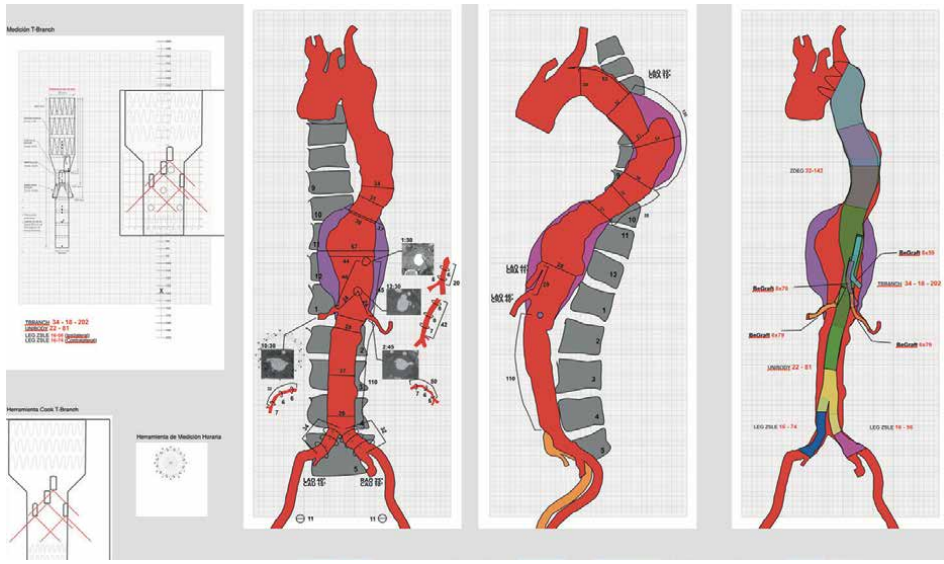


Figure 11.
Screenshot of affinity™ designer™ sizing and planning artboards for a cook™ T-branch™ case. Note the transparent tools to check the patient's anatomical suitability for the device and one to make angle measurements.

Furthermore, 3D images of volume rendering and visualization of anatomic features, branches, or other key pictures can be added to facilitate operative performance.

Artboards can be exported, printed, or distributed in several vector or raster formats at different resolutions and matching printers' and plotters' specifications.

One advantage of Affinity™ Designer™ is that the tracing process can be done easily on an iPad with an Apple Pencil naturally and fluidly. Still, graphic pen tablets like Intuos™ (Wacom, Saitama, JP) are affordable and used with any vector graphics software.

3. Conclusion

Many institutions with experienced teams and suitable facilities can perform aortic aneurysm repair. Still, their precision planning and sizing capabilities are limited because of the elevated costs of vascular imaging analysis software packages and workstations.

It has been demonstrated that three-dimensional analysis of CTA data is a better option than two-dimensional analysis, decreasing interobserver variability [23] and thus resulting in better device selection, and decreasing late complications as endoleaks.

The ability to produce and manipulate vector graphics, three-dimensional virtual models, and three-dimensional printed models is nowadays universally available for any health worker, and the decreasing costs of software and devices are currently making these technologies more affordable.

The process is relatively easy to learn and has the advantage of familiarizing the team with the complex details of a case anatomy and manipulating DICOM data which are essential skills for successful aortic repair programs.

The digital process is collaborative, reproducible, and precise. In some institutions, different team members can be assigned to different parts of the process, decrease case planning and sizing time, and maximize group effort.

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Chapter 4

Type B Aortic Dissection-Diagnosis, Treatment, and Management

Saqib Zia and George E. Mina

Abstract

Type B aortic dissections (TBADs) present a complex clinical challenge, characterized by diverse presentations and life-threatening complications. Aortic dissections involving the descending thoracic aorta are influenced by age, hypertension, smoking, and genetic factors. Clinical presentation varies, from asymptomatic to acute complications such as end-organ malperfusion or rupture, emphasizing the importance of timely diagnosis and intervention. Diagnostic evaluation involves clinical assessment and imaging modalities such as CT and MRI. Management strategies include medical therapy, endovascular intervention, and surgical repair, tailored to individual patient characteristics. Early and delayed complications, including aortic rupture, end-organ malperfusion and aortic event related mortality, necessitate regular surveillance. Future directions focus on refining risk stratification, optimizing therapy, and developing innovative interventions. Biomarkers and advanced imaging hold promise for improving outcomes.

Keywords: type B aortic dissection, malperfusion, thoracic endograft, trauma, branched devices

1. Introduction

Aortic dissection is the most common aortic catastrophe and a life-threatening condition characterized by the separation of the layers within the aortic wall, creating a false lumen through which blood can flow. Incidence of aortic dissection in hospital patients is ~3 per 100,000 per year and in general population is 6 per 100,000 per year. The peak incidence is between the age of 60–70 years and predominantly affects male patients (65%) [1].

This condition is often classified based on anatomical involvement, which helps guide treatment decisions and predict outcomes. The anatomic classification of aortic dissection typically includes the location and extent of the dissection, as well as any associated complications. Understanding these classifications is essential for clinicians managing patients with this complex condition.

1.1 Classification

The most widely used classification system for aortic dissection is the Stanford classification, which categorizes dissections into two main types: Type A and

Type B [2]. Type A dissections involve the ascending aorta, while Type B dissections are confined to the descending aorta distal to the left subclavian artery. This classification is based on the prognostic significance of involvement of the ascending aorta, as Type A dissections are associated with higher mortality rates and require emergent surgical intervention.

Another classification system commonly used for aortic dissections is the DeBakey classification, which further subdivides dissections based on the extent of aortic involvement [3]. Type I dissections involve the ascending aorta, arch, and descending aorta, while Type II dissections are confined to the ascending aorta. Type III dissections are limited to the descending aorta distal to the left subclavian artery. This classification provides additional information regarding the extent of the dissection and helps guide treatment decisions (**Figure 1**).

In addition to the Stanford and DeBakey classifications, aortic dissections can also be classified based on the Society for Vascular Surgery/Society of Thoracic Surgeons (SVS/STS) Aortic Dissection Classification System, which classifies dissection subtype according to zone location of primary entry and extent of the dissection. The aorta is split into sections 0–11 from proximal to distal (Section 0 is type A, sections 1–11 type B) and the dissection is classified from where the tear begins and to what extent it ends. For example a dissection that starts in section one and extends to section three can be labeled a $B_{1,3}$ dissection [4].

Aortic dissections can be further classified based on the presence of associated complications or variant forms. Dissections can be Complicated or Uncomplicated based on the presence of complications such as intramural hematoma, pseudoaneurysm formation, malperfusion or aortic rupture. Complications may necessitate additional treatment strategies and influence patient outcomes [5]. Variant forms of aortic dissection include penetrating aortic ulcers, intramural hematomas, and aortic intramural gas, each with unique pathophysiological mechanisms and clinical implications (**Figure 2**).

The anatomic classification of aortic dissection is clinically significant as it helps guide treatment decisions and predict outcomes. Type A dissections require emergent surgical intervention due to the risk of aortic rupture and cardiac tamponade. In contrast, Type B dissections can often be managed medically initially, with surgical

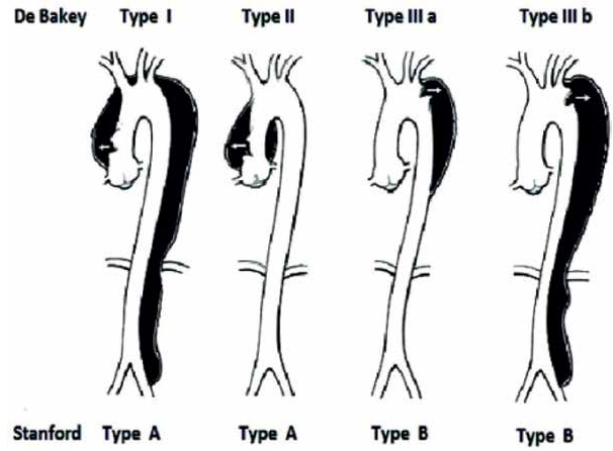


Figure 1.
DeBakey and Stanford aortic dissection classification systems.

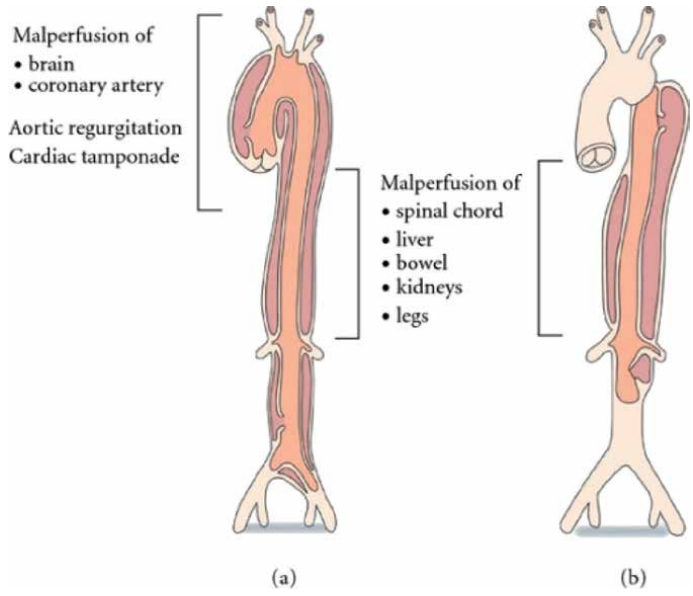


Figure 2.
Malperfusion syndromes based on the location of the dissection.

intervention reserved for complications such as malperfusion, rupture or ongoing pain despite optimal medical therapy. The extent of aortic involvement and the presence of associated complications influence the choice of treatment modalities and the prognosis of patients with aortic dissections.

Aortic dissections are also classified based on the duration of clinical onset into hyperacute dissections <24 hours, acute dissections within 14 days, subacute dissections between 14 days to 3 months and chronic dissections greater than 3 months. The duration of onset plays a key role in devising an appropriate management plan in addition to other important factors.

The anatomic classification and duration of onset of aortic dissection plays a crucial role in guiding treatment decisions and predicting outcomes. Understanding the location, extent, and associated complications of the dissection is essential for clinicians managing patients with this complex condition and provide valuable information that helps tailor treatment strategies to individual patient characteristics and optimize outcomes (**Table 1**) [4].

1.2 Etiology and risk factors

Aortic dissections have an incidence rate of 2–4 cases per 100,000 individuals with Type B Aortic Dissections (TBAD) accounting for 21% of those dissections [6]. The etiology of TBAD is multifactorial, involving a complex interplay of genetic predisposition, hemodynamic stress, and structural abnormalities of the aortic wall. While the exact cause remains elusive in many cases, several underlying mechanisms have been implicated in the pathogenesis of Type B dissections [7].

Several risk factors have been identified that increase the likelihood of developing TBAD. Elevated blood pressure is the most significant modifiable risk factor for TBAD, contributing to the mechanical stress and structural damage of the aortic wall. Cigarette smoking is associated with increased oxidative stress, endothelial

High-Risk Imaging Findings
Maximal aortic diameter > 40 mm
False-lumen diameter > 20–22 mm
Entry tear >10 mm
Entry tear on lesser curvature
Increase in total aortic diameter of >5 mm between serial imaging studies
Bloody pleural effusion
Imaging-only evidence of malperfusion
High-Risk Clinical Findings
Refractory hypertension despite >3 different classes of antihypertensive medications at maximal recommended or tolerated doses
Refractory pain persisting >12 h despite maximal recommended or tolerated doses
Need for readmission

Table 1.
High risk features of type B aortic dissection.

dysfunction, and inflammation, all of which contribute to the pathogenesis of aortic dissections [7]. Abnormal lipid metabolism, characterized by elevated levels of low-density lipoprotein (LDL) cholesterol and reduced levels of high-density lipoprotein (HDL) cholesterol, promotes the development of atherosclerosis which can weaken the integrity of the aortic wall.

Genetic factors play a significant role in the development of aortic dissections, with factors mutations in genes encoding structural proteins implicated in the pathogenesis of thoracic aortic diseases. Disorders such as Marfan syndrome, Ehlers-Danlos syndrome, and Loeys-Dietz syndrome are associated with mutations in genes encoding fibrillin-1 (FBN1), collagen, and transforming growth factor-beta (TGF-β) receptors, respectively [3]. These genetic mutations lead to abnormalities in the structure and function of the aortic wall, predisposing individuals to aortic dissections and are especially found in younger individuals with aortic dissection [8].

Chronic hemodynamic stress, particularly hypertension (whether physiologic or due to other factors such as cocaine use), is a well-established risk factor for the development of aortic dissections. Elevated blood pressure increases the mechanical forces exerted on the aortic wall, leading to endothelial damage, smooth muscle cell dysfunction, and structural remodeling. The increased shear stress and turbulence within the aorta promote the formation of intimal tears, which serve as the initial site of dissection [7].

Structural abnormalities of the aortic wall, such as atherosclerosis, cystic medial degeneration, and connective tissue disorders, predispose individuals to TBADs. Atherosclerosis, characterized by the accumulation of cholesterol-rich plaques within the arterial wall, weakens the integrity of the aortic wall and increases the risk of dissection. Cystic medial degeneration, characterized by fragmentation and loss of elastic fibers within the media of the aorta, is commonly observed in patients with thoracic aortic aneurysms and dissections [8].

Advanced age is a significant non-modifiable risk factor for TBAD, with the incidence increasing with age. Aging leads to structural changes in the aortic wall, including elastin fragmentation and collagen deposition, which contribute to the

weakening of the vessel wall. Men are at higher risk of developing TBAD compared to women, with a male-to-female ratio of approximately 2:1. This gender difference may be attributed to hormonal differences, genetic predisposition, and lifestyle factors [9].

A multitude of different factors affecting the risk profile of patients such genetic predisposition, hemodynamic stress, acquired, and inherited structural abnormalities of the aortic wall contribute to the pathogenesis of Type B dissections. Identification of modifiable and non-modifiable risk factors is crucial for risk stratification, preventive interventions, and optimization of patient outcomes.

2. Diagnosis and management of type B aortic dissection

2.1 Clinical presentation and diagnostic work up of type B aortic dissection

The hallmark symptom of TBAD is sudden-onset severe chest or back pain, which is often described as tearing, ripping, or stabbing in nature [2]. The pain may be localized to the chest, back, or abdomen and can radiate to the neck, shoulders, or arms. Patients may also experience migratory pain as the dissection propagates along the aortic wall.

In addition to pain, patients with TBAD may present with symptoms related to end-organ malperfusion. Malperfusion syndromes occur when the dissection obstructs blood flow to vital organs, leading to ischemia and dysfunction. Common manifestations of malperfusion include neurological deficits, such as stroke or transient ischemic attack (TIA), limb ischemia, renal failure, mesenteric ischemia, and spinal cord ischemia (**Figure 2**) [1].

On physical examination, patients with TBAD may exhibit signs of hemodynamic instability, including hypotension, tachycardia, and diaphoresis. Blood pressure discrepancies between the upper extremities, known as pulse deficits, are classic findings suggestive of aortic dissection. Hypertension may also be present, particularly in cases of acute pain or stress response.

Other physical findings may include murmurs suggestive of aortic regurgitation, diminished peripheral pulses, or focal neurological deficits indicative of cerebral or spinal cord ischemia. Signs of limb ischemia, such as pallor, coolness, or absent pulses, should prompt immediate evaluation for malperfusion syndromes.

The clinical presentation of TBAD can mimic various other conditions and "painless dissections" are not unheard of, necessitating clinicians to have a thorough differential diagnosis [10]. Common differentials include acute coronary syndrome (ACS), pulmonary embolism, musculoskeletal pain, and gastrointestinal disorders such as pancreatitis or peptic ulcer disease [5]. Clinicians must consider these differential diagnoses based on the patient's clinical presentation, risk factors, and physical examination findings [9].

The diagnosis of TBAD relies on a combination of clinical assessment, imaging studies, and laboratory investigations. Computed tomography angiography (CTA) is the imaging modality of choice for diagnosing aortic dissections, providing detailed anatomical information regarding the extent of the dissection, involvement of branch vessels, and the presence of complications such as intramural hematoma or aortic rupture [11]. Magnetic resonance imaging (MRI) may be utilized in patients with contraindications to iodinated contrast agents or in cases where CTA is inconclusive (**Figure 3**).

Laboratory investigations such as complete blood count (CBC), comprehensive metabolic panel (CMP), coagulation studies, and cardiac enzymes may be obtained to assess for end-organ dysfunction, electrolyte abnormalities, or myocardial injury.



Figure 3.
MRI of a type B aortic dissection. (1) descending aortic dissection (2) aortic isthmus.

Electrocardiography (ECG) and echocardiography may also be performed to evaluate for cardiac abnormalities or ischemic changes suggestive of ACS. This work up is important as it helps establish the extent and acuity of the dissection which effects the timeline and type of management.

TBAD presents with a diverse array of clinical manifestations, ranging from chest or back pain to end-organ malperfusion syndromes. Recognizing the clinical presentation of Type B dissections is critical for early diagnosis and prompt intervention to prevent adverse outcomes. A multidisciplinary approach involving clinical assessment, imaging studies, and laboratory investigations is essential for accurate diagnosis and optimal management of patients with TBAD.

2.2 Initial management

TBAD poses a significant clinical challenge due to its potential for catastrophic complications and high mortality rates. The initial management of TBAD is critical in stabilizing patients, controlling symptoms, and preventing disease progression.

2.2.1 Medical management

Medical management serves as the cornerstone of initial therapy for TBAD, aiming to reduce aortic wall stress, alleviate pain, and prevent complications. The key components of medical therapy include blood pressure control, pain management, and aggressive risk factor modification.

Aggressive blood pressure control is paramount in the management of TBAD to minimize shear forces on the aortic wall and prevent further propagation of the dissection. Beta-blockers are the first-line agents of choice, exerting their effects by reducing heart rate and blood pressure, thereby decreasing aortic wall stress. Intravenous beta-blockers such as labetalol or esmolol are often used initially, followed by oral beta-blockers for long-term management [12, 13]. Calcium channel blockers, such as diltiazem or verapamil, may be used as adjunctive therapy to further lower blood pressure and heart rate in patients who cannot tolerate beta-blockers or have contraindications to their use. Furthermore angiotensin converting enzyme (ACE) inhibitors or angiotensin receptor blocking (ARB) medications has shown to be beneficial for patients with connective tissue disorder associated with TBAD (**Figure 4**) [7].

Pain management is crucial in alleviating the severe chest or back pain associated with TBAD. Analgesics such as opioids or nonsteroidal anti-inflammatory drugs (NSAIDs) may be administered to provide symptomatic relief and improve patient comfort. However, caution must be exercised when administering NSAIDs in patients with aortic dissection due to the risk of exacerbating hypertension, renal hypoperfusion and promoting aortic wall stress.

Medical therapy also focuses on preventing complications associated with TBAD, such as malperfusion syndromes, aortic rupture, or pseudoaneurysm formation. Antiplatelet agents such as aspirin may be prescribed to reduce the risk of thromboembolic events, particularly in patients with atherosclerotic disease or concomitant coronary artery disease [5].

While medical therapy remains the mainstay of initial management for TBAD, surgical intervention may be warranted in select cases, particularly in patients with complicated dissections or persistent symptoms despite optimal medical therapy.

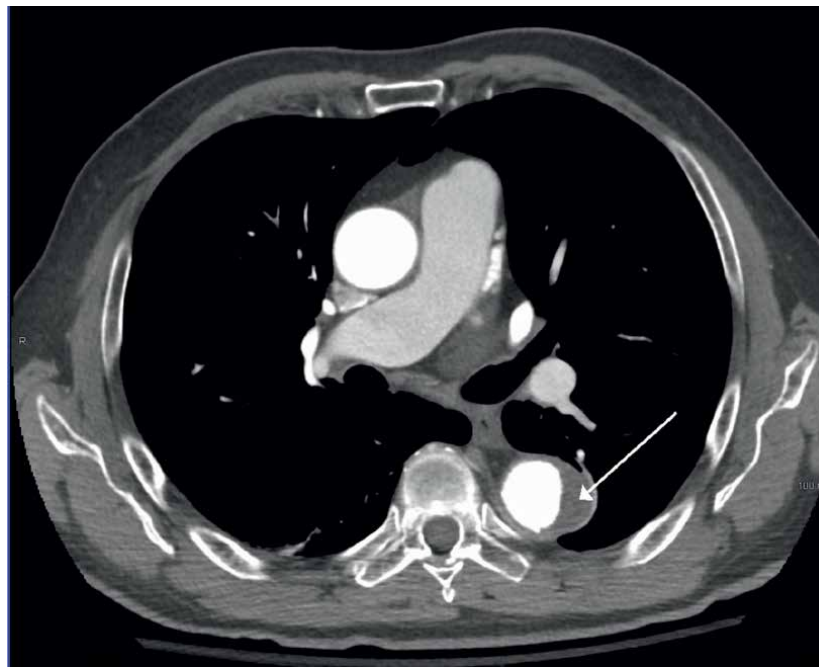


Figure 4.
CTA of stabilized false lumen after medical management.

Surgical options include open surgical repair, endovascular techniques or hybrid approaches, each with its own indications, advantages, and limitations.

2.2.2 Surgical management

The decision to pursue emergent surgical management in TBAD depends on several factors, including the clinical presentation, imaging findings, and hemodynamic stability of the patient.

Patients with complicated TBAD, such as those presenting with aortic rupture, malperfusion syndromes, or ongoing pain despite optimal medical therapy, may require emergent surgical intervention. Signs of hemodynamic instability, such as hypotension, tachycardia, or shock, warrant immediate evaluation for surgical management to prevent adverse outcomes.

There are two main types of surgical management for TBAD. They both aim to replace the dissected lumen of the aorta with a prosthetic graft, thereby excluding the false lumen from the circulation promoting the stabilization of the aortic wall, referred to as aortic remodeling.

Open surgical repair involves accessing the diseased aorta through an open approach and replacing it with a graft that is sewn into healthy aortic tissue.

This approach is typically reserved for patients with complicated Type B dissections, such as those with aortic rupture, malperfusion syndromes, or persistent pain refractory to medical therapy. Open surgical repair offers durable long-term outcomes but is associated with significant perioperative morbidity and mortality, particularly in elderly or high-risk patients when compared to endovascular techniques (**Figure 5**) [11, 13].

Endovascular techniques, such as thoracic endovascular aortic repair (TEVAR), have emerged as less invasive alternatives to open surgical repair for TBAD (**Figure 6**). TEVAR involves the placement of a stent graft within the true lumen of the aorta to exclude the false lumen and promote aortic remodeling. This minimally invasive approach offers favorable outcomes in terms of perioperative morbidity and mortality, reduced blood loss, and shorter hospital stays compared to open surgical

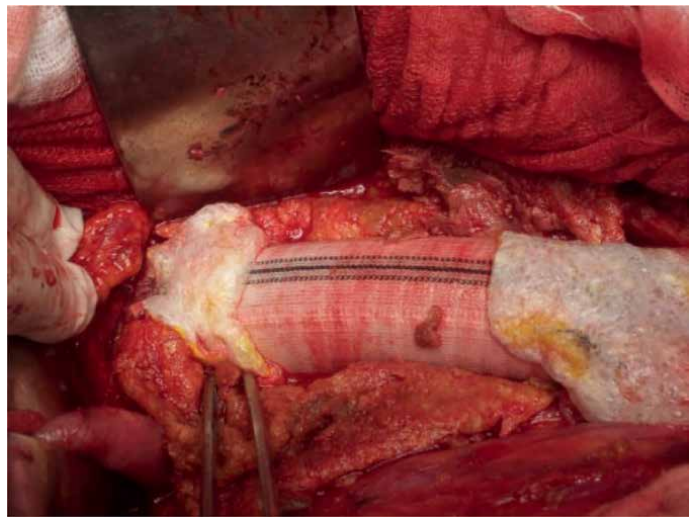


Figure 5.
Sewn aortic graft during open aortic repair.

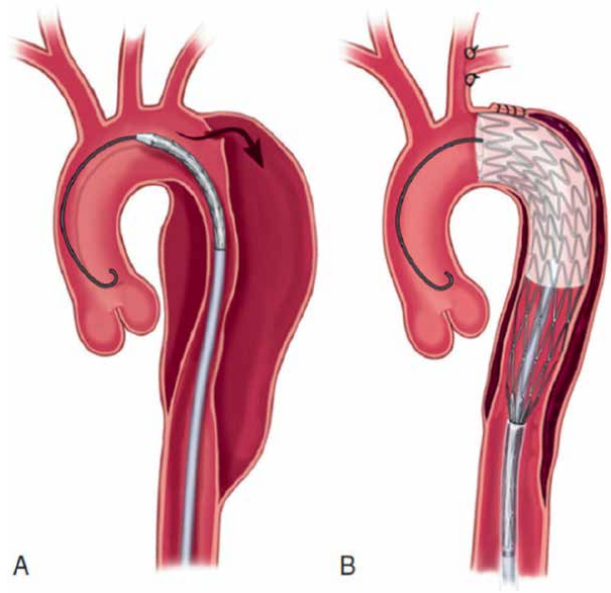


Figure 6.
Illustration of TEVAR deployment in endovascular TBAD repair.

repair [11, 12]. However, TEVAR may not be feasible in all cases, particularly in patients with complex aortic anatomy or extensive dissection involvement (**Figure 7**).

The hemodynamic stability of the patient and their imaging are key considerations in determining the timing of surgical intervention for TBAD. Imaging studies such as CTA or MRI play a crucial role in assessing the extent of the dissection, involvement of branch vessels, and the presence of complications such as intramural hematoma or pseudoaneurysm formation. Patients with evidence of aortic rupture, visceral malperfusion, or impending rupture on imaging may necessitate emergent surgical intervention to prevent catastrophic complications. Patients who are hemodynamically

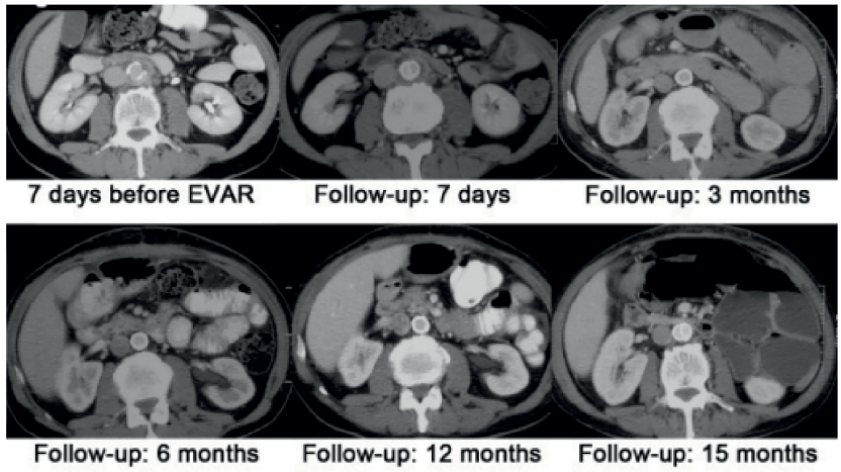


Figure 7.
Change of false lumen over time following endovascular repair.

unstable, with evidence of shock or end-organ dysfunction, require immediate surgical evaluation and intervention to restore perfusion and prevent further deterioration [2, 14, 15]. Studies have shown that uncomplicated patients with certain high-risk features also benefit from TEVAR to prevent early or late complications. High risk features include refractory pain or hypertension, bloody pleural effusion, aortic diameter >40 mm, radiographic only malperfusion, readmission, entry tear on lesser curvature of the arch and false lumen diameter >22 mm [1, 2].

The initial management of TBAD involves a multidisciplinary approach encompassing medical therapy, surgical intervention, and meticulous monitoring of patients' clinical status. While medical therapy remains the cornerstone of treatment, surgical management may be warranted in select cases, particularly in patients with complicated dissections or hemodynamic instability or with patients with high risk of complications. Criteria for emergent surgical management include the presence of complications such as aortic rupture or malperfusion syndromes, as well as evidence of hemodynamic instability on clinical examination and imaging studies.

2.3 Open versus endovascular management

One of the primary factors influencing the choice between open surgical repair and endovascular repair is the anatomy and extent of the dissection. Endovascular repair is often preferred in cases where the proximal entry tear is located within the descending thoracic aorta and the anatomy is suitable for stent graft deployment. Patients with suitable anatomy for TEVAR typically have an adequate "landing zone", defined as a healthy segment of the aorta proximal to the entry tear, which allows for secure stent graft fixation and sealing of the false lumen [16, 17].

In contrast, patients with complex or extensive dissections involving the arch vessels, proximal aorta, or visceral segment may not be suitable candidates for endovascular only repair due to the technical challenges and increased risk of complications. Open surgical repair may be preferred in these cases, as it allows for direct visualization and reconstruction of the aorta, including resection of the diseased segment and replacement with a prosthetic graft. In situations where the dissection affects major branch vessels or there is inadequate or unfavorable landing zone, hybrid approach with open surgical debranching to get adequate landing zone followed by TEVAR is a suitable option [15]. Example of such approach is carotid subclavian transposition or bypass to get adequate landing zone followed by TEVAR.

Patient characteristics and comorbidities play a crucial role in determining the feasibility and safety of both open surgical repair and endovascular repair. Endovascular repair may be favored in patients who are deemed high-risk surgical candidates due to advanced age, significant medical comorbidities, or frailty. TEVAR offers several advantages in this patient population, including reduced perioperative morbidity and mortality, shorter hospital stays, and faster recovery times compared to open surgical repair [12, 16].

Conversely, open surgical repair may be preferred in patients with anatomical considerations or comorbidities that preclude endovascular repair. These may include the presence of extensive aortic calcification, tortuous aortic anatomy, or previous aortic surgeries that limit the feasibility of endovascular stent graft deployment. Additionally, patients with connective tissue disorders such as Marfan syndrome or Ehlers-Danlos syndrome may benefit from open surgical repair to address underlying structural abnormalities and prevent disease recurrence [1].

The risk of complications, particularly endoleaks, is an important consideration in the choice between open surgical repair and endovascular repair. Endoleaks, defined

as persistent blood flow within the false lumen despite stent graft deployment, are a common complication of TEVAR and can lead to persistent or recurrent dissection, aneurysm expansion, or rupture [7, 14, 15, 18]. Because of this, timing of intervention for TBAD is very crucial when it comes to better outcomes. Studies have shown poor outcomes of TEVAR in uncomplicated patients when performed in hyperacute or acute phase as compared to the subacute or chronic phases. For this reason many suggest waiting at least 2 weeks, if a patient's clinical condition allows, to perform TEVAR for TBAD [1].

Patients with a high risk of endoleaks, such as those with extensive dissection involving branch vessels, complex aortic anatomy, or inadequate sealing of the proximal or distal landing zones, may be better suited for open or hybrid surgical repair. Surgical reconstruction allows for direct visualization and repair of the entry tear, elimination of the false lumen, and reinforcement of the aortic wall with a prosthetic graft, thereby reducing the risk of endoleaks and improving long-term outcomes [19].

Long-term durability and follow-up are important considerations in the choice between open surgical repair and endovascular repair. While TEVAR offers favorable perioperative outcomes and shorter recovery times, long-term durability remains a concern, particularly in younger patients with life expectancy beyond 10–15 years. Endovascular stent grafts may be prone to device-related complications such as migration, endoleaks, graft thrombosis, or graft infection, which necessitate ongoing surveillance and potential reintervention [18, 20].

Conversely, open surgical repair is associated with durable long-term outcomes and lower rates of reintervention compared to endovascular repair. Surgical reconstruction allows for complete removal of the diseased segment, replacement with a prosthetic graft, and elimination of the false lumen, thereby reducing the risk of disease recurrence and improving overall survival [15, 18, 20].

The decision between open surgical repair and endovascular repair of TBADs requires careful consideration of various factors, including anatomy and extent of dissection, patient characteristics and comorbidities, risk of complications, and long-term durability. Both treatment modalities offer advantages and limitations, and the choice should be tailored to individual patient needs, preferences, and risk profiles.

2.4 Long-term management

TBAD poses a significant challenge in long-term management due to its potential for complications and progressive aortic remodeling. The long-term management of TBAD focuses on preventing disease progression, managing associated complications, and optimizing cardiovascular health to improve patient outcomes. This chapter provides an overview of the key aspects of long-term management, including medical therapy, surveillance imaging, lifestyle modifications, and follow-up care, with reference to current evidence and guidelines.

Medical therapy plays a central role in the long-term management of TBAD, aiming to reduce aortic wall stress, control blood pressure, and prevent complications such as aneurysm expansion or rupture. The cornerstone of medical therapy includes the use of beta-blockers and other antihypertensive agents to maintain blood pressure within the target range and minimize shear forces on the aortic wall [1, 2].

Beta-blockers such as metoprolol, atenolol, or propranolol are the first-line agents of choice, exerting their effects by reducing heart rate, myocardial contractility, and blood pressure. These medications help to decrease aortic wall stress and shear forces, thereby reducing the risk of dissection propagation or rupture. In

addition to beta-blockers, other antihypertensive agents such as calcium channel blockers, angiotensin-converting enzyme (ACE) inhibitors, or angiotensin receptor blockers (ARBs) may be used as adjunctive therapy to achieve optimal blood pressure control [11, 12, 17].

Anticoagulation therapy may be considered in patients with TBAD complicated by thromboembolic events or evidence of intramural hematoma. However, the role of anticoagulation in the long-term management of uncomplicated Type B dissections remains controversial, with limited evidence to support its routine use. The decision to initiate anticoagulation should be individualized based on the patient's clinical presentation, underlying comorbidities, and risk of thromboembolic complications [1].

Regular surveillance imaging is essential in the long-term management of TBAD to monitor disease progression, assess for complications, and guide therapeutic decision-making. CTA or MRI is typically performed at regular intervals, such as 6 months to 1 year post-dissection, to evaluate the size of the aorta, the extent of dissection, and the presence of complications such as aneurysm formation, pseudoaneurysm, or endoleaks [7, 18, 19].

Serial imaging allows clinicians to track changes in aortic diameter, detect early signs of disease progression, and identify patients at increased risk of adverse outcomes. Patients with evidence of progressive aneurysmal dilation, expansion of the false lumen, or new-onset complications may require closer surveillance and consideration for intervention to prevent catastrophic complications such as aortic rupture or malperfusion syndromes [2].

Lifestyle modifications play a crucial role in the long-term management of TBAD, aiming to reduce cardiovascular risk factors, promote aortic health, and improve overall quality of life. Patients are advised to adopt heart-healthy habits, including smoking cessation, regular exercise, healthy diet, weight management, and stress reduction [3].

Smoking cessation is particularly important in patients with TBAD, as cigarette smoking exacerbates oxidative stress, endothelial dysfunction, and inflammation, all of which contribute to the progression of aortic disease. Regular exercise, such as walking, swimming, or cycling, helps to improve cardiovascular fitness, reduce blood pressure, and promote weight loss, thereby reducing the risk of disease progression and cardiovascular events [7, 21].

Regular follow-up care is essential in the long-term management of TBAD to monitor disease progression, assess treatment response, and address patient concerns. Patients should be followed closely by a multidisciplinary team of specialists, including cardiologists, vascular surgeons, and imaging experts, to ensure comprehensive care and coordination of services [3, 7, 9, 15].

Follow-up visits may include clinical evaluation, imaging studies, laboratory tests, medication adjustments, and patient education. Clinicians should assess for symptoms of disease progression or complications, such as chest or back pain, dyspnea, or neurological deficits, and perform regular physical examinations to detect signs of end-organ malperfusion or hemodynamic instability.

Patients should be educated about the signs and symptoms of aortic dissection recurrence or complications and instructed to seek immediate medical attention if they experience any concerning symptoms. In addition, patients should be counseled about the importance of medication adherence, lifestyle modifications, and regular surveillance imaging to optimize long-term outcomes and prevent adverse events.

The long-term management of TBAD requires a comprehensive and multidisciplinary approach, encompassing medical therapy, surveillance imaging, lifestyle

modifications, and follow-up care. By optimizing blood pressure control, monitoring disease progression, and promoting heart-healthy habits, clinicians can improve patient outcomes and reduce the risk of complications associated with TBAD.

2.5 Screening and prevention

TBAD remains a life-threatening condition with high morbidity and mortality rates, necessitating effective screening and preventive strategies to reduce the burden of disease. While the primary focus of management is often on acute presentation and treatment, efforts towards screening and prevention are essential to identify high-risk individuals, intervene early, and mitigate adverse outcomes. This chapter explores the screening and preventive measures for TBAD, incorporating evidence-based recommendations and guidelines.

Effective screening strategies for TBAD are crucial for identifying individuals at risk and facilitating early intervention. Screening may be targeted towards high-risk populations, including individuals with known risk factors such as connective tissue disorders, family history of aortic diseases, or aortic aneurysms. Additionally, screening may be indicated in patients with a history of hypertension, smoking, or previous aortic surgeries [7, 11, 15].

2.5.1 Screening

Screening for TBAD often involves imaging studies such as CTA, MRI, or transesophageal echocardiography (TEE). These modalities allow for visualization of the aortic anatomy, detection of aneurysmal dilation, and assessment of the integrity of the aortic wall. Imaging studies may be performed as part of routine surveillance in high-risk populations or in response to concerning symptoms suggestive of aortic dissection.

Clinical evaluation plays a vital role in screening for TBAD, with careful assessment of patients' medical history, physical examination findings, and presenting symptoms. Clinicians should maintain a high index of suspicion for aortic dissection in patients presenting with acute-onset severe chest or back pain, particularly in the presence of risk factors such as hypertension, connective tissue disorders, or family history of aortic diseases.

Genetic testing may be considered in individuals with suspected hereditary connective tissue disorders associated with an increased risk of aortic dissection, such as Marfan syndrome, Ehlers-Danlos syndrome, or Loeys-Dietz syndrome. Genetic testing allows for the identification of underlying genetic mutations, enabling targeted screening and surveillance of at-risk family members.

2.5.2 Prevention

Preventive measures for TBAD focus on reducing modifiable risk factors, optimizing cardiovascular health, and implementing lifestyle modifications to mitigate the risk of disease development and progression. While certain risk factors such as genetic predisposition cannot be modified, interventions targeting hypertension, smoking, and atherosclerotic disease may help reduce the overall burden of TBAD [7]. Lifestyle modifications such as dietary sodium restriction, regular exercise, weight management, and medication adherence are essential components of hypertension management, aiming to reduce blood pressure and prevent aortic wall stress.

Cigarette smoking is strongly associated with the development and progression of aortic dissection, underscoring the importance of smoking cessation as a preventive measure. Smoking cessation counseling, nicotine replacement therapy, and pharmacotherapy may be utilized to support individuals in quitting smoking and reducing their risk of aortic dissection. Dyslipidemia and atherosclerotic disease contribute to the pathogenesis of TBAD, highlighting the need for lipid management to reduce cardiovascular risk. Statins are recommended as first-line therapy for lowering LDL cholesterol levels and reducing the risk of atherosclerotic plaque formation, thereby mitigating the risk of aortic dissection and other cardiovascular events [2].

Screening and prevention strategies play a crucial role in mitigating the burden of TBAD by identifying high-risk individuals, facilitating early intervention, and reducing modifiable risk factors. Effective screening modalities, including imaging studies and clinical evaluation, enable early detection of aortic dissection, while preventive measures such as blood pressure control, smoking cessation, and lifestyle modifications help reduce the risk of disease development and progression. By implementing comprehensive screening and prevention strategies, clinicians can optimize patient outcomes and reduce the overall burden of TBAD.

2.6 Future directions of treatment and management

The management of TBAD has evolved significantly over the past decades, leading to improved outcomes and reduced mortality rates. However, challenges remain in optimizing treatment strategies, reducing complications, and enhancing long-term survival for patients with aortic dissections.

While endovascular approaches have grown in popularity in recent decades, hybrid procedures combining open surgical repair with endovascular techniques may represent the future direction in the management of complex aortic dissections. These hybrid approaches allow for tailored treatment strategies, combining the advantages of open surgical repair for proximal aortic pathology with the less invasive nature of endovascular stent grafting for distal disease [2, 18, 22].

Future research may focus on targeted pharmacotherapy for aortic dissections, aiming to mitigate aortic wall stress, reduce inflammation, and promote aortic remodeling. Novel agents targeting specific pathways implicated in aortic pathology, such as matrix metalloproteinases (MMPs), transforming growth factor-beta (TGF-β), or endothelin-1 (ET-1), may offer potential therapeutic benefits [2, 9].

The advent of personalized medicine may also revolutionize the management of aortic dissections by tailoring treatment strategies to individual patient characteristics, genetic profiles, and disease phenotypes. Genetic testing, biomarker analysis, and advanced imaging modalities may help identify patients at increased risk of disease progression or complications, enabling targeted interventions and personalized therapy regimens [7].

Biological therapies, such as stem cell therapy, gene therapy, or tissue engineering, may hold promise for the treatment of aortic dissections by promoting tissue regeneration, enhancing vascular healing, and preventing disease progression. Stem cell-based approaches offer the potential for repair and regeneration of damaged vascular tissues, while gene therapy may target specific molecular pathways involved in aortic remodeling and repair [7].

Ongoing developments in device innovations, including bioresorbable stent grafts, drug-eluting stents, branched endografts or tissue-engineered scaffolds, may revolutionize the field of aortic surgery by offering durable and biocompatible solutions

for aortic repair. These innovative devices aim to improve long-term outcomes, reduce the risk of device-related complications, and enhance vascular healing and remodeling [8].

The future of treatment and management for aortic dissections holds promising prospects for advancements in surgical techniques, medical therapy, imaging modalities, and innovative interventions. By embracing technological innovations, personalized medicine approaches, and multidisciplinary collaborations, clinicians and researchers can continue to improve outcomes, reduce complications, and enhance the quality of life for patients with aortic dissections.

3. Conclusions

In conclusion, the management of TBADs represents a multifaceted clinical challenge that requires a comprehensive understanding of its anatomy, pathophysiology, clinical presentation, diagnostic evaluation, and management strategies.

Anatomy and pathophysiology elucidate the underlying mechanisms driving aortic aneurysm formation, including chronic hemodynamic stress, inflammation, and genetic predispositions. Risk factors such as age, hypertension, smoking, and connective tissue disorders play significant roles in predisposing individuals to aortic aneurysms, underscoring the importance of preventive measures and risk factor modification.

Clinical presentation varies widely, ranging from asymptomatic to life-threatening complications such as aortic dissection or rupture. Early recognition and prompt intervention are crucial for mitigating adverse outcomes and improving patient prognosis. Diagnostic evaluation relies on a combination of clinical assessment and advanced imaging modalities, allowing for accurate anatomical delineation and assessment of disease severity.

Management strategies encompass medical therapy, endovascular intervention, and surgical repair, tailored to individual patient characteristics and the presence of complications. Medical therapy aims to control hypertension and reduce the risk of aortic expansion, while endovascular techniques offer minimally invasive alternatives to open surgical repair, particularly in high-risk patients or those with complex anatomy.

Future directions in the management of TBADs focus on refining risk stratification, optimizing medical therapy, and developing innovative interventions. Biomarkers and advanced imaging modalities hold promise for improving risk prediction and prognostication, while novel endovascular devices and techniques offer potential for enhanced outcomes and reduced complications.

Ultimately, the management of TBADs requires a multidisciplinary approach informed by current evidence and ongoing research. By addressing the complexities of this condition comprehensively, clinicians can optimize patient care, improve outcomes, and enhance the quality of life for individuals with TBADs.

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Conflict of interest

The authors declare no conflict of interest.

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Chapter 5

Physician-Modified Stent Grafts for the Treatment of Juxtarenal and Pararenal Abdominal Aortic Aneurysms

Arkadiusz Kazimierczak and Paweł Rynio

Abstract

This chapter pertains to the utilization of physician-modified stent grafts (PMSG) as a treatment option for complex aortic aneurysms, specifically focusing on juxtrarenal and pararenal abdominal aortic aneurysms. PMSG, which can be used immediately, is advantageous in emergencies and specific anatomical conditions. The text emphasizes the importance of using PMSG for specific indications and the necessity of familiarity with supporting technologies, such as the 3D-printed template. The text delves into the indications for PMSG implantation as well as the various stent-graft platforms that can be modified and their respective technical data. Methods of stent-graft modification are also presented. Finally, the PMSG results are discussed.

Keywords: PMSG, pararenal aortic aneurysm, fenestrated endovascular aortic repair, physician-modified stent grafts, FEVAR, custom-made devices, juxtrarenal aortic aneurysm, 3D printed template, 3D printing

1. Introduction

The management of complex aortic aneurysms presents significant challenges, particularly when anatomical intricacies require tailored solutions. Among these evolving strategies, physician-modified stent grafts (PMSG) have emerged as a viable option for patients requiring personalized endovascular repair. Unlike custom-made devices, which entail prolonged production times of approximately 12 weeks, PMSG offers immediate readiness by leveraging existing standard stent grafts. This unique advantage has positioned PMSG as a recommended alternative in emergencies, as endorsed by the current European Society for Vascular Surgery (ESVS) guidelines [1].

The development of fenestrated PMSG may be attributed to the research conducted by Sang Joon Kim and Jae Hyung Park, who successfully performed two cases of fenestrated endovascular aortic repair (FEVAR) [2]. In each of these cases, the endograft was modified to include a single fenestration: the first for the inferior mesenteric artery and the second for the renal artery. Anderson's groundbreaking

work involved aligning the fenestration with the target artery by employing a balloon-expandable stent [3]. Unflacker's 2006 series marked the first application of PMSG based on the available stent-graft platforms [4]. Subsequent publications have underscored the high interest in PMSG for thoracoabdominal and pararenal aneurysms.

2. Indication for PMSG implantation

Fenestrated PMSG can be used in emergency settings for the treatment of juxtrarenal and pararenal abdominal aortic aneurysms [5]. For these patients, a fenestrated endograft may be preferred over a branched endograft because it covers a shorter segment of the thoracic aorta. The length of thoracic aorta coverage is correlated with the risk of developing paraplegia due to occlusion of the intercostal arteries that supply the spine [6].

The bridging stents used during FEVAR are shorter than those used during BEVAR. The length of the bridging stent has been shown to affect the long-term patency. Moreover, the take-off angle of the target vessel is crucial. The arteries that are horizontal or upward may cause the branch stent to kink and occlude during follow-up. The bridging stent of the fenestrated endograft seems to be less influenced by the direction of the target artery. These hypotheses were supported by a series of stented renal arteries, where a higher occlusion rate was reported for BEVAR than for FEVAR [7]. Another advantage of FEVAR is that the fenestrations can be potentially cannulated using femoral access, while the classic BEVAR requires upper access.

Although FEVAR has some potential advantages over BEVAR technology in the treatment of juxtrarenal and pararenal aortic aneurysms, specific anatomical requirements must be met to ensure long-term durability. The fenestration sealing can be achieved if the stent graft is opposed to the aortic wall. The maximum acceptable distance between the orifice of the target vessel and the stent-graft fabric is 5 mm. Therefore, a careful examination of the diameter of the visceral aortic lumen must be performed and compared to the available stent-graft diameter that is intended to be a platform for modification. When planning to use fenestrated PMSG, one should look for at least 2 cm of relatively healthy aorta for a sealing zone, which is usually found proximally to the celiac trunk. Durable results can be achieved if the landing zone wall is parallel and has minimal or no thrombus or calcifications. The maximum aortic diameter should allow for at least 10% of oversizing of the planned endograft for modification.

The clinical indications for PMSG use were already briefly mentioned, and they include ruptured, symptomatic, and giant aneurysms. Although sometimes there are possibilities to use the off-the-shelf BEVAR device outside the instructions for use in these patients, there will always be patients with some anatomical features that would require a customized solution. Such a situation could occur in a patient with an additional third renal artery larger than 4 mm or separate orifices of the hepatic and splenic arteries that need separate fenestrations or branches (**Figure 1**).

The economic aspect of PMSG is also essential in some countries around the world. PMSG is based on a relatively cheap standard stent graft, so it might be preferred in cases of reimbursement limitations from the national health service. In regions with limited access to other advanced stent-graft platforms, PMSG promptly provides suitable solutions.

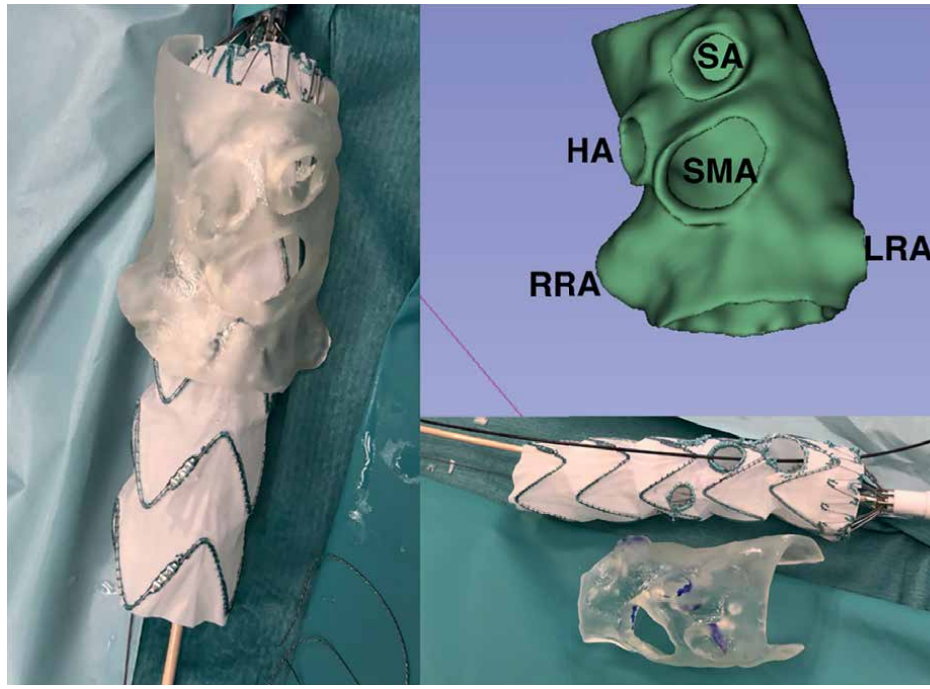


Figure 1.
Separate orifice of hepatic and splenic arteries in ruptured juxtarenal abdominal aortic aneurysm.

While regulatory constraints limit the elective use of PMSG owing to deviations from standard instructions for use, it remains a valuable tool in specific indications and emergency scenarios. The utilization of cutting-edge technologies, such as 3D-printed aortic templates, significantly increases the feasibility of PMSG.

3. Platforms for stent-graft modification

3.1 Management of stent-graft selection

The management of complex abdominal aortic aneurysms often involves adapting commercially available stent grafts as platforms for tailored interventions. These stent grafts, including both thoracic and abdominal, serve as foundational structures upon which surgeons create patient-specific fenestrations based on the intricate vascular anatomy. Decision-making in this context should prioritize considerations such as aneurysm extent, iliac artery morphology, the number and dimensions of planned fenestrations, and the necessity for a repositioning system. However, paramount to successful outcomes is the surgeon's familiarity with the specific stent graft being employed. Proficiency in recognizing the fluoroscopic appearance of the endograft, understanding radiopaque markers, and mastering deployment techniques is essential. Before embarking on physician-led modifications, a thorough grasp of standard implantation procedures is mandatory.

Thoracic stent grafts characterized by larger delivery systems, afford sufficient space for multiple fenestrations and ancillary tools, including preloaded wires and repositioning systems. These adjuncts enhance the surgeon's ability to manipulate

partially deployed stent grafts, while preloaded guidewires facilitate rapid cannulation of the fenestration. The utilization of a four-fenestrated device allows for effective sealing proximal to the celiac trunk, ensuring a robust sealing zone. Such a design becomes indispensable when aneurysmatic involvement extends to the renal artery level or when mesenteric arteries are closely juxtaposed.

The evolution of fenestrated endovascular aneurysm repair (FEVAR) technology has underscored the durability of four-fenestrated endografts [8]. However, thoracic endografts exhibit a limitation—their delivery system diameter—which may pose challenges in cases involving narrowed, tortuous, and calcified iliac arteries. In complex abdominal aneurysms, these endografts often necessitate a distal bifurcated component. The connection between these components can give rise to complications, including endoleaks or distal endograft migration.

In contrast to their thoracic counterparts, abdominal stent grafts feature smaller-diameter sheaths. This design choice allows for greater flexibility when dealing with variations in iliac artery morphology. The reduced sheath size also translates to fewer endograft modifications fitted within the delivery system.

Considering the type of stent graft, one should think about the following factor: the amount of space between stents to fit the constellation of fenestrations. This factor varies between stent-graft types owing to different stent-spring periods and inter-stent distances. The preferred fenestrations are strut-free, as the stent strut crossing the fenestration could compromise the surgical results, enhancing the difficulty of cannulating and stenting the target vessel. External compression could lead to bridging stent failure during follow-up. Surgeons must carefully assess and address these considerations to optimize patient outcomes and long-term endograft durability.

3.2 Technical characterization of platforms for modification

3.2.1 Medtronic devices (Dublin, Ireland)

The Medtronic Endurant series comprises three stent-graft models: Endurant, Endurant II, and Endurant IIs. These devices share common features that contribute to their clinical efficacy. The fabric is woven from high-quality polyester, and the stents are meticulously constructed from nitinol, a shape-memory alloy known for its flexibility and resilience. Endurant devices utilize M-stents, providing excellent radial force and conformability, however, they limit available fabric space for placing fenestrations. The hydrophilic-coated delivery system ensures smooth deployment, and the transparent sheath facilitates resheathing and precise fenestration orientation outside the patient's body. Endurant II/IIs have an outer profile of 18/20 Fr, making them suitable for most iliac arteries. However, the smaller sheath diameter reduces the number of fenestrations and ancillary tools that surgeons can accommodate.

The Medtronic Valiant Captivia stent-graft system was primarily designed for thoracic applications. Unlike abdominal counterparts, the proximal component of Valiant Captivia incorporates a free-flow stent without hooks. Valiant Captivia employs Z-stents characterized by significant gaps that accommodate multiple fenestrations. The controlled deployment mechanism ensures precise placement, while the transparent sheath aids in resheathing and stent-graft positioning outside the patient's body. Valiant Captivia comes in sizes 22/24/25 Fr, allowing for several modifications to fit inside the delivery system. Four reinforced fenestration, one preloaded 0.035-inch guidewire and a diameter-reducing system can be loaded.

Surgeons should prefer devices without proximal free-flow components when extending modified Valiant grafts with a distal bifurcated stent graft. Positioning the free flow below the renal fenestration reduces overlap between covered segments. Proximal bare stents often feature hooks that may inadvertently damage the fabric of the proximal module. Awareness of this limitation is crucial during device selection. The Gore Excluder, a distal device, remains the preferred choice for fenestrated repair due to its design—infrarenal fixation. Surgeons can resheath Medtronic devices using silicon loops, crimping devices, or manual techniques.

3.2.2 Cook devices (Cook Medical, Bloomington, IN)

These devices include the Flex [9, 10], Alpha thoracic [11], and TX2 [11]. These devices are constructed with a fabric made of woven polyester, while the stents themselves are crafted from either stainless steel or nitinol. The profiles of outer diameter delivery systems are 7.1–8.5 mm, 6.0–7.7 mm, and 7.7–8.5 mm, respectively, for Flex, Alpha, and TX2. The Zenith Flex is a bifurcated component, and Alpha thoracic and TX2 are tubular. The delivery system features a hydrophilic coating and a deployment mechanism based on pulling away the sheath. All devices share a Z-stent design; however, the Alpha thoracic nitinol stents have wider spacing between the struts. Tight spacing of stainless-steel stents may necessitate stent dislocation or bending to accommodate a strut-free fenestration [11]. The TX2 is designed without a proximal bare stent, while the fixation hooks are positioned on the first covered stent row, a configuration also found in the Alpha thoracic stent. Sometimes, they may limit the ability to resheath and, therefore, should be cut out in advance [11]. Alternatively, the TX2 dissection device could be used as it has no hooks or barbs. For the treatment of juxtarenal abdominal aortic aneurysms, thoracic fenestrated endografts require a distal bifurcated component. To address this, the modified Cook flex is used with an excised proximal uncovered stent. Within the Cook endograft family, the trigger wire can be retrieved from the inner cannula and used as a reducing-diameter wire, facilitating easier vessel cannulation. The Cook thoracic endografts offer ample space inside the delivery sheath, allowing for the fitting of several fenestrations and preloaded wires. Loading into the sheath is accomplished using silicon loops.

3.2.3 Gore excluder C3 (W.L. Gore & Associates, Flagstaff, AZ, USA)

The excluder has a modular design with a proximal bifurcated component and infrarenal fixation with barbs. The fabric is made of expanded PTFE and the stents are made of nitinol. The stent springs have small gaps between each other, limiting the strut-free fenestration design. The delivery system's outer diameter ranges from 16 to 18 Fr and allows for the repositioning of the device, which may be beneficial during the positioning of fenestration with respect to the target vessel. The device allows for up to two fenestration designs and a scallop or two 0.014′ preloaded guidewires [12, 13]. Fenestrations can be cannulated and stented either through the contralateral gate or *via* the brachial approach. Device deployment involves pulling out the deployment knob and releasing the device from the leading to the trailing edge. Repacking necessitates using an additional 20 Fr DrySeal sheath with an excised hemostatic valve, which constrains the device during delivery through a 22 Fr DrySeal sheath [13].

3.2.4 Terumo medical (Tokyo, Japan)

The Terumo devices include the Treo stent graft. This stent graft features a trimodular design, consisting of a proximal bifurcated component and two distal iliac legs. Its skeleton is made of nitinol, and the fabric is woven polyester. The trunk features a proximal uncovered stent with hooks. The proximal clasp, in conjunction with the delivery system, provides a strong connection that allows for substantial rotation during fenestration alignment to the target vessel. The length of the trunk varies from 50 mm to 90 mm. Longer trunks may be beneficial in anatomies with longer distances between target ostia. The Treo stent design provides ample space for placing a fenestration constellation due to the wide stent spacing and long inter-stent distances [14]. The outer diameter of the delivery system ranges from 18 to 19 Fr. While this is sufficient for accommodating four reinforced fenestrations, it may not be enough for ancillary tools like preloaded wires and a reducing diameter system.

3.3 Advantages and disadvantages of platform for stent-graft modification

Each platform has its own advantages and disadvantages, which are summarized in **Table 1**.

4. Designing physician-modified endograft

4.1 Designing fenestrations position based on CT scans

CT scans provide essential information about the position of the target vessel ostia, which is crucial for stent-graft personalization. All measurements should originate from the central point of the vessel ostium. In this context, the superior mesenteric artery (SMA) serves as the reference point for all measurements. Lengths between SMA and the target vessels should be measured along the centerline of the aorta.

The SMA clock or angle position plays a critical role in determining the arc lengths of both renal arteries and the celiac trunk. At the level of a specific artery, the length of a curve measured along the aortic outline—from the SMA clock position to the center of the measured artery—represents the arc length. However, this measured arc length needs adjustment to account for the planned stent graft oversizing at the given aortic level. This adjustment can be calculated using the following proportion (math formula (1)):

$$LDl / d \tag{1}$$

where L represents the adjusted arc length; D is the stent graft diameter; l denotes the measured arc length; d corresponds to the aortic diameter.

4.2 Designing fenestrations position with the aid of 3D printed aortic template

While the determination of fenestration positions based on CT scans is feasible, the practical challenge lies in translating this information to the stent graft during surgical intervention. Stent grafts, characterized by metallic struts, inherently impede the ideal placement of fenestrations. Ideally, these fenestrations should be devoid

Platform	Pros	Cons
Cook Zenith Flex	• Bifurcated design • Spacious delivery system allowing for the accommodation of several fenestrations, preloaded wires and reducing diameter system • Trigger wire, which can be used to create a reducing-diameter system	• High profile • Small space for fenestrations design due to high frequency of stent strut period • Short delivery system
Cook TX2	• Spacious delivery system allowing for the accommodation of several fenestrations, preloaded wires, and reducing diameter system • Trigger wire, which can be used to create a reducing-diameter system	• Tubular design • High profile • Barbs impeding resheathing • Small space for fenestrations design due to high frequency of stent strut period
Cook Alpha thoracic	• Spacious delivery system allowing for the accommodation of several fenestrations, preloaded wires, and reducing diameter system • Fair spacing between stent struts	• Tubular design • Intermediate profile • Barbs impeding resheathing
Gore Excluder	• Low profile • Repositioning system • Bifurcated design	• Difficult to resheath, requiring additional sheaths • Small space for fenestrations design due to close inter-stent distances and high frequency of stent strut period • Allows for up to two fenestrations design • ePTFE may be more prone to tearing during the modification process
Medtronic Endurant	• Low profile • Bifurcated design • Transparent sheath	• Limited space inside the delivery system limiting the number of fenestrations • Small space for fenestrations design due to closely placed stent rows and M-stent configuration • Lack of repositioning system and stage delivery
Medtronic Valiant Captivia	• Spacious delivery system allowing for the accommodation of several fenestrations, preloaded wires and reducing diameter system • Fair spacing between stent struts • Transparent sheath • Easy to resheath	• High profile • Lack of distal clasp
Treo Terumo	• Low profile • Bifurcated design • Fair spacing between stent struts • Firm free-flow clasp, allowing for stent-graft twist, creating some space for cannulation	• Lack of repositioning system and stage delivery

Table 1.
Advantages and disadvantages of stent grafts as platforms for modifications.

of strut interference. However, as the number of fenestrations increases, the task of identifying a position that circumvents strut obstruction becomes progressively intricate.

To address this clinical challenge, we propose the utilization of a 3D-printed aortic template. This innovative tool faithfully reproduces the intricate internal anatomy of the patient. By superimposing the template directly onto the stent graft, one can discern optimal locations for fenestrations between the stents. Notably, this method significantly enhances target vessel alignment with the corresponding fenestrations [15].

Furthermore, the application of 3D printing technology to stent graft modifications offers several compelling advantages. First, it mitigates interobserver variability, thereby promoting standardization. Second, the 3D-printed aortic models serve as a valuable quality control measure for the creation of patient-specific stent grafts. These models can be reapplied to the prepared fenestrated endograft, allowing meticulous verification of the stent graft's anatomical fitness.

4.3 Manufacturing the 3D printed aortic template

The process of creating a 3D-printed aortic template commences with the segmentation of the aorta and its side branches. This segmentation involves extracting the relevant structures from the background. While manual segmentation remains an option, leveraging appropriate software tools can significantly expedite this process, rendering it semiautomated. Notably, several software packages, such as Mimics (Materialize NV, Leuven, Belgium), Osirix (Pixmeo SARL, Switzerland), and 3D Slicer (3D Slicer community, headquartered in Boston, USA), offer specialized segmentation tools. The output of this step is an STL (stereolithography) file, which subsequently undergoes further modeling to achieve specific functionality after 3D printing.

We incorporate an artificial wall outside the aortic lumen in designing the aortic template. Ideally, this wall possesses a thickness of 1.5 mm. Additionally, the side branches are meticulously excised, leaving short vessel stumps—approximately 5 mm in length. Optionally, the posterior wall of the aorta can be removed, creating a model that serves as an overlay applied directly onto the stent graft.

The choice of 3D printing technology plays a pivotal role. The two most common methods are fused deposition modeling (FDM) and stereolithography (SLA). For our purposes, SLA is particularly advantageous due to its ability to produce transparent models. Furthermore, 3D printers typically come equipped with dedicated software for model orientation within the build chamber and for designing necessary supports. The printing time varies based on the volume and geometrical complexity of the 3D model. However, for a visceral aorta template, the printing duration typically falls within the range from 5 to 6 hours [16].

Postprocessing follows the completion of printing. This step involves removing any support structures. In the case of SLA technology, the model is rinsed in isopropyl alcohol.

Sterilization is imperative before deployment in the operating theater. Various in-hospital sterilization methods effectively eliminate pathogens. These include steam sterilization at 121°C for 30 minutes, ethylene oxide gas sterilization, and hydrogen peroxide plasma sterilization [17]. However, careful evaluation of the build material is essential to ensure it remains undistorted under high-temperature sterilization methods, such as hot steam. Fortunately, biocompatible materials approved for sterilization are readily available in the market.

5. Methods of stent-graft modification

When modifying stent grafts, several techniques come into play.

5.1 Selection between reinforced fenestration, mini-cuffs, and directional branches

The choice depends on the diameter between the aortic wall and the stent graft. Reinforced fenestration is the preferred option if this distance is between 0 and 5 mm. It ensures complete wall apposition. Mini-cuff modification may be more relevant for distances between 5 and 10 mm. When the distance exceeds 10 mm, directional branches become necessary. However, it is worth noting that mini-cuffs and directional branches are less commonly used nowadays due to the availability of off-the-shelf branched endografts. Therefore, reinforced fenestrations should be the primary focus.

5.2 Creating the fenestration

Develop the fenestration by carefully creating holes in the stent-graft sheathing using low-temperature surgical cautery. It is important to consider safety measures, such as having a sterile saline syringe readily available to the assisting physician to flush any potential flames that may occur (refer to **Figure 2A**). The fenestration should be about 1 millimeter smaller than the intended size since it typically expands after reinforcement of the edge.

5.3 Reinforcing the fenestration edge

For reinforcing fenestrations, consider using a double nitinol loop obtained from a snare device, such as the EnSnare 18-30 (MeritMedical, USA), which offers four loops, each suitable for reinforcing four fenestrations. To reinforce a fenestration, suture the nitinol wire alongside the coil (used for radiopaque marking the edge) using a 4.0 Ethibond suture. Be sure to remove any cloth-activating fibers before suturing the embolization coil into the edge. The first suture line serves as a tack, keeping the coil and snare wire adapted to the fenestration edge, while the second, thicker suture line completes the reinforcement (refer to **Figure 2B** for visual guidance).

5.4 Radiopaque markers for fenestrations

If an embolization coil was used to reinforce the fenestration edges, radiopaque markers are not necessary. The embolization coil itself is highly visible in fluoroscopy (see **Figure 2C**). A practical tip: gently extend the coil and pinch the fibers to remove any remaining cloth-activating material. Alternatively, the radiopaque markers are added in the corners at the circumference of the fenestration. All described maneuvers must be done in a sterile environment by the physician equipped with a double pair of sterile gloves.

5.5 Diameter-reducing system

A diameter-reducing wire creates space for catheter manipulation and adjusts for any fenestration misalignment. A 0.018-inch V Control wire (Boston Scientific, USA) is usually used for this purpose. The optimal location for it is along the suture

line of the stent-graft fabric (**Figure 2A**). The puncture site of the delivery sheet to introduce the diameter-reducing wire is determined by measuring the length of the stent-graft with the free-flow stent plus 5 mm (**Figure 3D**). More distal puncture is not recommended due to the risk of blood leakage through the puncture hole, which might be exposed outside the artery during the procedure after stent-graft deployment. This might be overcome by using a large-size introducer sheath. Diameter reduction is achieved along the PMSG by a number of Z stents selected for crimping. Typically, four Z stents are involved (**Figure 3A**). The first loop (Prolene 4.0) is stitched around the stent strut and then placed around the V 18 control wire. The second loop is stitched to the opposite Z stent and then routed around the first Prolene loop (**Figure 3B** and **C**). Some platforms do not require a diameter-reducing wire. According to B. Starnes' experience, strong bare stent holding from the top and contralateral leg cannulation supporting the endograft from below are sufficient to allow twisting of the endograft, which reduces the size and enables safe adjustment of the fenestrations [14].

5.6 Preloaded guidewires

Preloaded wires are used through fenestrations to facilitate catheterization via the brachial/axillary approach. They can be made of soft Terumo 0.035-inch guidewire or other types (e.g., 0.014 or 0.018). The puncture site of the delivery sheet can be located opposite to the diameter-reducing 0.018 wire exit on the same level or up to 5 mm distally.

5.7 Stent-graft resheathing

Resheathing can be achieved by using 1–0 silk ties to sequentially collapse the Z stents (**Figure 4A**) or by using a crimper device, which is more comfortable, faster, and less prone to fabric twisting (**Figure 4B**). A crimper device can be obtained from the set for transcatheter aortic valve implantation.

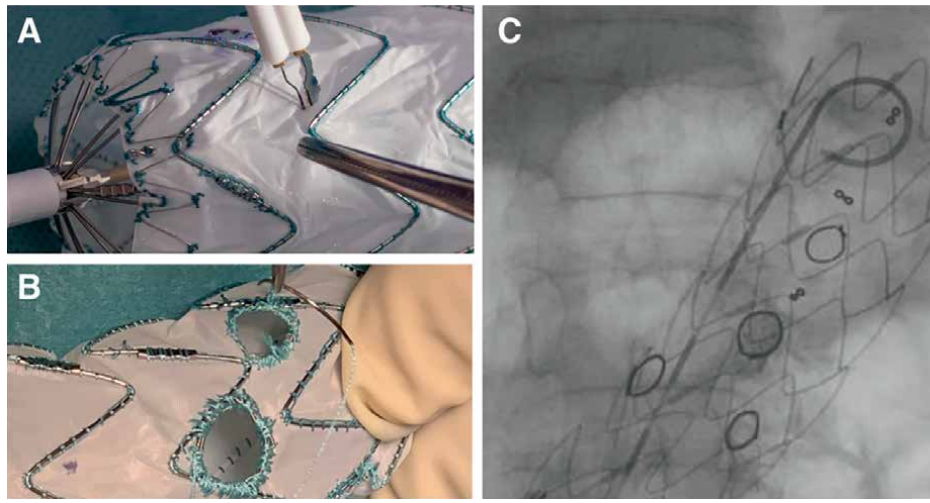


Figure 2.
Preparation of the reinforced fenestrations.

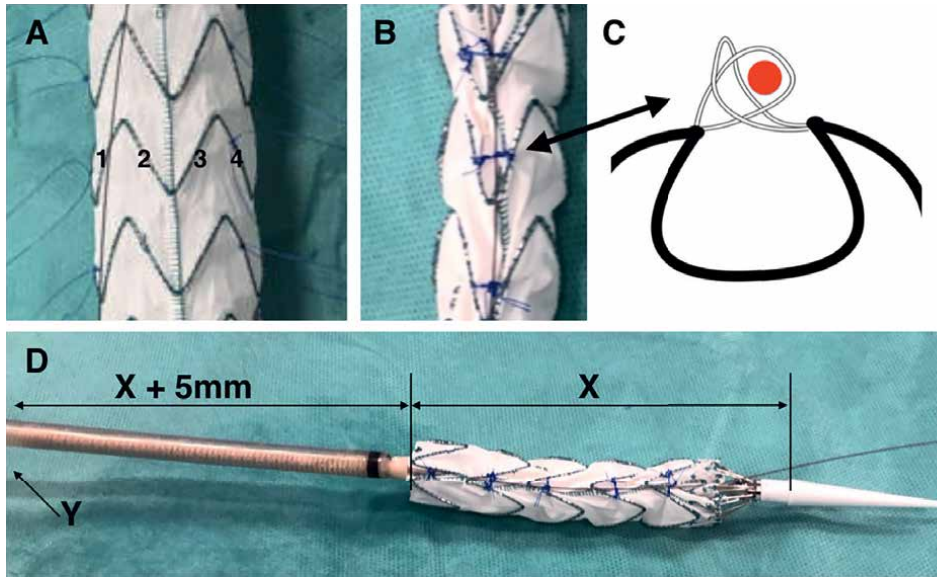


Figure 3.
Diameter reducing wire.

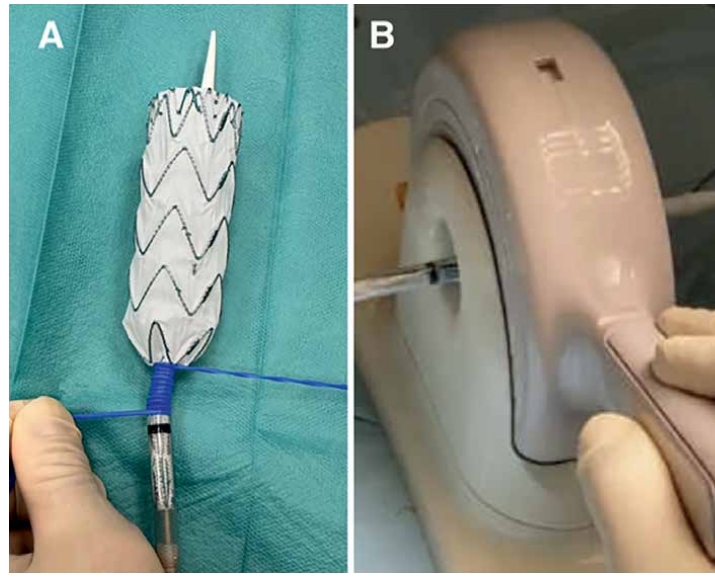


Figure 4.
Re-sheathing of the stent graft.

6. Surgical techniques of physician-modified stent-graft implantation

6.1 Anesthesia and access

The choice of anesthesia depends on the planned access sites. The procedure can be performed under general or spinal anesthesia. The patient should be positioned

in a supine position, with the arms abducted. The operator can select either percutaneous or surgical access based on their preference, experience, and the quality of the femoral arteries. The access can be either bilateral or unilateral, depending on the stent-graft configuration and the target arteries. For cannulation from above, the operator should expose the axillary artery. The distal segment of the axillary artery, typically located in the axilla, can accommodate up to a 12 Fr sheath. For larger or dual sheath access (e.g., two 7 Fr sheaths), the operator may need to expose the middle segment of the axillary artery. Alternatively, the operator can use both axillary arteries. The sheaths should be compatible with the bridging stents in size and allow for smooth delivery and manipulation of the devices.

6.2 Stent-graft deployment

The deployment of a stent graft during fenestrated endovascular aneurysm repair (FEVAR) is a meticulously guided process. Here are the key steps involved:

6.2.1 Fluoroscopic guidance

- The procedure is performed under fluoroscopic guidance, utilizing a combination of anteroposterior and oblique views.
- Contrast injections or road-mapping techniques enhance visualization during stent-graft deployment.
- It is suggested to employ cone beam computed tomography at the end of the procedure to evaluate the bridging stent structure's status.

6.2.2 Stent-graft delivery

- A super stiff guidewire is essential for advancing the stent graft.
- The guidewire tip should be positioned within the aortic arch.
- During advancement, all fenestrations must be carefully observed.
- Special attention is given to detecting any posterior rotation of the stent graft.

6.2.3 Fenestration markers and positioning

- The stent graft is advanced until the renal artery fenestration markers align with the level of the second lumbar vertebra.
- A side view confirms the anterior position of the fenestrations for the superior mesenteric artery (SMA) and celiac trunk (CT).

6.2.4 Digital subtraction angiography (DSA)

- DSA is performed to identify the renal artery level precisely.

- DSA should be performed in an angulation corresponding to the SMA angle position.
- The view corresponding to the SMA angle/hour position ensures that the SMA fenestration remains centrally aligned during deployment.
- The stent graft must be meticulously positioned with respect to the renal fenestration(s).

6.2.5 Deployment technique

- The specific deployment method varies based on the stent-graft platform.
- Typically, the stent graft is released from the sheath.
- Gradual unsheathing allows for precise fenestration release and subsequent cannulation.
- This method enhances endograft maneuverability and creates additional space below the fenestration level.

6.2.6 Sheath and tie system

- While the sheath is completely removed, a diameter-reduced tie system permits controlled rotation and movement.
- This flexibility is crucial in case of any fenestration misalignment.

6.2.7 Vessel cannulation

- Vessel access can be achieved *via* the femoral artery, axillary artery, or both.
- The stent graft should remain partially crimped until all fenestrations and target vessels are successfully cannulated.
- Sheaths with balloon-expandable stents should be meticulously placed in all target arteries.
- This strategic maneuver significantly reduces the risk of inadvertent decannulation during subsequent steps.
- Reintroducing a sheath to the target vessel after full endograft opening can be exceptionally challenging and should be avoided whenever possible.
- Stent-graft ballooning and distal component implantation
- Following the stent-graft delivery system removal, the stent graft is meticulously ballooned using a semi-compliant balloon.

- Distal components are implanted based on the specific configuration of the fenestrated part.

- In cases involving tubular fenestrated endografts, additional aorto-iliac bifurcated modules, and subsequent iliac limbs may be required.

6.2.8 Bridging stents and fenestration alignment

- Bridging stents are deployed within the target arteries, with stent lengths typically ranging between 20 and 30 mm. Shorter stents are believed to offer better patency.

- The proximal end stent should be positioned approximately 5 mm inside the aorta, followed by postflaring with a balloon.

- The 10 × 20 mm balloon is used to flare stents with diameters less than 8 mm, while 9 and 10 mm stents are flared with a 12 × 20 mm balloon.

- In the case distal bifurcated endograft is going to be deployed, all balloon-expandable stent cannulated from femoral access should be deployed in advance.

6.2.9 Challenging cannulation strategies

- Difficult target vessel cannulation can be overcome using the "swallow technique," where a balloon is alternately inflated and deflated within the target artery while advancing the sheath.

- Continuous verification of fenestration alignment with the corresponding target vessel is essential.

- Upward-going target arteries are more accessible from femoral access, while downward-going arteries are better accessed *via* the axillary route.

- A steerable sheath provides valuable support during cannulation and stent advancement, enhancing procedural success.

7. Results

Melo et al. performed a systematic review and meta-analysis of 29 studies involving 654 patients who underwent endovascular repair of complex abdominal aortic aneurysm with physician-modified endografts [18]. The pooled results showed that PMSG was associated with low rates of 30-day mortality (1.6%), postoperative rupture (0%), and paraplegia (1.1%). The technical success was 99.4%. The incidence of endoleak type I or III during follow-up was 5.4%, and the reintervention rate was 2.2%. The target vessel patency was 95.2%, and the overall mortality was 10.6% during the range of follow-up of 5–38 months reported by studies. The authors concluded that PMSG is a feasible and effective option for complex abdominal aortic treatment, with acceptable short- and mid-term outcomes. However, they also acknowledged the low quality of the included studies, the lack of standardization in the PMSG technique

and reporting, and the heterogeneity of the patient population and outcomes, which limit the generalizability and reliability of the results. Therefore, they recommended the need for well-designed randomized controlled trials (RCTs) to establish the real position of PMSG technology. A randomized controlled trial of this nature is currently underway in Poland and is being spearheaded by the authors of this chapter. However, the results of the study will not be available until 2027.

Smith et al. compared the outcomes of endovascular repair of type IV thoracoabdominal aortic aneurysm (TAAA IV) with physician-modified stent grafts and parallel grafts (PG), using a retrospective cohort from the vascular quality initiative (VQI) registry [19]. The study included 451 patients who underwent PMSG (n = 261) or PG (n = 190) between 2012 and 2020. The study demonstrated improved survival at 1 year with PMSG (84% vs. 78%, $p = 0.08$), as well as freedom from aneurysm- or procedure-related mortality (94% vs. 88%, $p = 0.02$). The rate of major adverse cardiovascular events (MACE) was significantly lower with PMSG (5.8% vs. 17.4%, $p < 0.01$), as well as any complication (23.4% vs. 36.3%, $p = 0.003$). There were some differences in the perioperative rates of type I endoleak (2.7% vs. 6.3%, $p = 0.1$), type IA endoleak (1.2% vs. 21.6%, $p = 0.01$), type IC endoleak (5.4% vs. 3.7% $p = 0.7$), or type III endoleak (24.7% vs. 8.1%, $p = 0.05$) between PMSG and PG. The authors suggested that PMSG may offer better outcomes than PG for TAAA IV repair, especially in terms of survival and MACE. However, they also recognized the limitations of their study, such as the retrospective design, the potential selection bias, the confounding factors, and the lack of long-term follow-up, which may affect the validity and applicability of the findings. Therefore, they also called for more RCTs to compare PMSG and PG for TAAA IV treatment.

Conflict of interest

Arkadiusz Kazimierczak is a proctor for Terumo Medical.
Paweł Rynio is a proctor for Medtronic.

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Chapter 6

Endovascular Management of Thoraco-Abdominal Aortic Aneurysms

Fernando Motta and Mark A. Farber

Abstract

Aortic aneurysm affects a significant part of the world's population. Traditional open surgery is considered safe, effective, and durable. However, some patients are considered not fit for such repair, especially when considering aneurysms that involve the thoracoabdominal aortic segment. The advent of the endovascular technique has gained great acceptance and, as evidence accumulated, it has shifted the paradigm for the treatment of TAAA. This chapter will address several aspects of the endovascular treatment of TAAA using devices with fenestration and directional branches, including aspects of the decision-making process, pre-operative planning, device implantation, intra-operative imaging, and the current evidence regarding outcomes.

Keywords: aortic aneurysm, open repair, endovascular, fenestrated, branched, outcomes

1. Introduction

The aortic aneurysm affects approximately 1.4% of the United States population between 50 and 84 years old [1]. The incidence is higher among smokers, patients with dyslipidemia, hypertension, and connective tissue disorders such as Marfan, Loeys-Dietz and Ehlers-Danlos Syndrome. The most feared complication is the aortic rupture, with associated mortality reaching more than 90%. To prevent rupture and associated mortality, surgical repair is recommended when the aneurysm reaches 55 mm diameter for infra-renal and descending thoracic aorta. For thoraco-abdominal aortic aneurysms, the recommendation for repair is ≥60 mm but also considerably reasonable when the diameter is >55 mm in patients with features associated with increased risk of rupture and if the procedure is performed in experienced centers [2]. The mentioned criteria do not apply to patients with connective tissue disorders. Similarly, for aneurysms with a saccular morphology, which has an unpredictable natural course, the repair is recommended regardless of its diameter at the time of diagnosis.

The aortic aneurysm open repair is safe, effective, and durable. However, is associated mortality and morbidity are not insignificant, and the complications increase proportionally with the complexity of the repair. Even in centers highly experienced

and with a high volume of thoraco-abdominal open repairs, the perioperative mortality ranges from 7.5–19% [3]. The associated morbidity can also be significant, such as renal failure requiring dialysis (5.7%), spinal cord ischemia (9.6%), respiratory failure (25%), and prolonged hospital stay. These numbers are even higher in the population older than 50 years old [4].

Since the advent of endovascular therapy for infra-renal aortic aneurysms, interest has risen to treat patients with aneurysms extending proximally into the visceral segment of the aorta (involving the renal arteries, superior mesenteric artery [SMA], and celiac artery [CA]). Inspired by the group in Australia, where the first implant of a fenestrated endograft occurred, surgeons around the world embraced the concept and were responsible for the technique dissemination and paved the way for most of what is available today regarding patient-specific fenestrated/branched endovascular repair of complex aortic aneurysm (F/BEVAR). Data in the literature from many countries have been accumulated demonstrating not only the safety and efficacy of these repairs but also outstanding mid- and long-term outcomes [5–10].

This chapter will delineate basic concepts of F/BEVAR repair of complex aortic aneurysm (juxta-, para-renal, and thoraco-abdominal [TAAA]) including definitions, planning the device, devices currently available, implantation technique, for potential pitfalls and strategy to prevent them, as well as the current literature data regarding early and late outcomes of these repairs. More specific aspects are beyond the scope of this chapter, and the reader is encouraged to search for sources dedicated to the endovascular repair of aortic aneurysms [11].

2. Decision-making and preoperative planning

2.1 Definitions and decision-making rationale

For a better understanding of the upcoming technical aspects, important concepts need to be mentioned. Fenestration (**Figure 1**) is when a hole is made in the device to align with the origin of the intended target vessel. It can be built in different sizes (see the specific description of devices in further sessions). During the early experience, the fenestrations were not reinforced and had struts that crossed it. It evolved with reinforcement of the fenestration with nitinol ring and suture of polyester suture, with some gold markers around the fenestration to facilitate the visualization during the operation. It is ideal for when the aortic lumen is small (<25 mm diameter) and requires more precise deployment of the endograft to avoid misalignment. Usually requires a covered stent to bridge between the endograft and the target vessel. The directional branch (**Figure 2**) is a component sewn into the aortic endograft as a cuff, allowing more overlap with the bridging stent. The branch can have different configurations (external, inner branch, diamond-shaped) and is ideal for aortas with large lumens. For this reason, the deployment is not required to be as precise as for fenestrations, but in some instances, are associated with lower long-term stent patency (discussed in more detail at the outcomes session).

One of the key points in vascular surgery is appropriate patient selection. This concept is even more appropriate when referring to F/BEVAR for the treatment of aortic aneurysms, not only from the general risk factors but also regarding the patient's anatomy to determine if they are a candidate for endovascular repair. Some anatomic details preclude the endovascular treatment of aortic aneurysms using F/BEVAR grafts, and some others make the repair more challenging although not

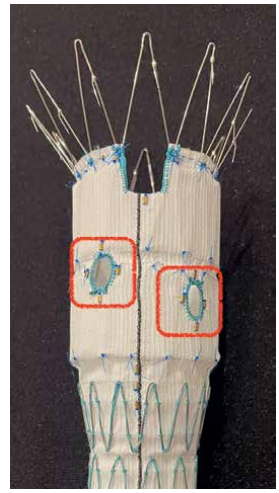


Figure 1.
The figure demonstrates the aspect of a fenestration, reinforced with polyester suture and golden marks to facilitate the cannulation under fluoroscopy.



Figure 2.
The figure demonstrates the features of directional branch. This specific one has a downward orientation, but it can have different configurations (see text). Image courtesy of Dr. Mark Farber.

considered prohibitive. First, is important to assess the patient's general health and functional status. It is very common for patients with aortic aneurysms to have multiple comorbidities, making them high-risk candidates or even not candidates for repair at all. It has been our practice to offer repair, if anatomic criteria allow, for patients with a life expectancy of at least 2–3 years.

From the anatomy standpoint, some aspects need to be considered. The presence of excessive thrombus burden into the aorta increases the risk of embolic complications during the procedure, such as to lumbar arteries (and possible spinal cord ischemia), to visceral arteries (and risk of renal failure and or mesenteric ischemia) and lower extremities. It has been demonstrated that the thrombus burden during F/BEVAR is associated with a higher risk of solid organ infarction, renal function deterioration, and a longer time to resume oral diet [12]. The aorto-iliac tortuosity is also a factor to be considered because might cause difficulties for the device to track into position and decrease the ability to move and or rotate the device during vessel cannulation. However, is rare that the vessel's tortuosity plays an isolated role as a contra-indication for F/BEVAR. Regarding the visceral vessels, the renal arteries are the ones with more often anatomical challenges. From the diameter standpoint, usually, F/BEVAR is not offered for patients with renal arteries smaller than 4 mm in diameter (small stents tend to have lower patency rates). Also, patients with multiple renal arteries are considered at high risk for F/BEVAR because the need for covering multiple accessory renal arteries can cause prohibitive worsening of renal function, especially for patients with already preoperative chronic kidney disease (CKD). The access arteries need to be evaluated as well. Although some low-profile devices can be built in an 18 Fr system, most devices' profile varies between 20 and 22 Fr. Therefore, at least a 7 mm iliac artery diameter is required to accommodate the devices. When facing small size iliac arteries, one alternative is to create conduits. Several different modalities can be used, such as open ilio-femoral bypass conduit, temporary iliac conduit (anastomosis at the iliac artery with retroperitoneal access and exteriorized through a groin's counter incision, and then removed at the end of the case) usually using a 10 mm diameter dacron graft. Alternatively, endoconduitis with covered stent Viabahn (W.L Gore) can be created (crack and pave technique [13]. Regardless of the conduit's modality chosen, it is crucial to try to preserve the hypogastric artery patency, since it decreases the risk of spinal cord ischemia associated with complex endovascular aortic repair.

2.2 Pre-operative planning

The planning for the F/BEVAR repair starts with a detailed assessment of the entire aorta from the aortic valve down to the femoral arteries. To facilitate that, besides looking at the regular views, we use TeraRecon software (InTuition, San Mateo, CA), which creates not only 3-D images from the aorta but also allows us to perform an analysis of the center line of flow of the aorta and its branches, eliminating the tortuosity and allowing precise measurements (**Figure 3**). Currently, there is more than one software used for F/BEVAR planning.

Considering that the patient has appropriate anatomy for F/BEVAR, the first step is to choose the proximal sealing zone. It is recommended that at least 2 cm of sealing in a healthy segment of aorta, with a parallel wall free from calcium and thrombus. However, it has been more common to incorporate more visceral branches to provide a more stable and durable repair. Mastracci et al., published data from the Cleveland Clinic in the U.S. demonstrating an increasing rate of type Ia endoleaks when only renal arteries were incorporated compared to when mesenteric vessels were also included in the repair [7]. The number of intercostal arteries covered by the intended device should also be taken into account since it can directly impact the risk of spinal cord ischemia following F/BEVAR. Once

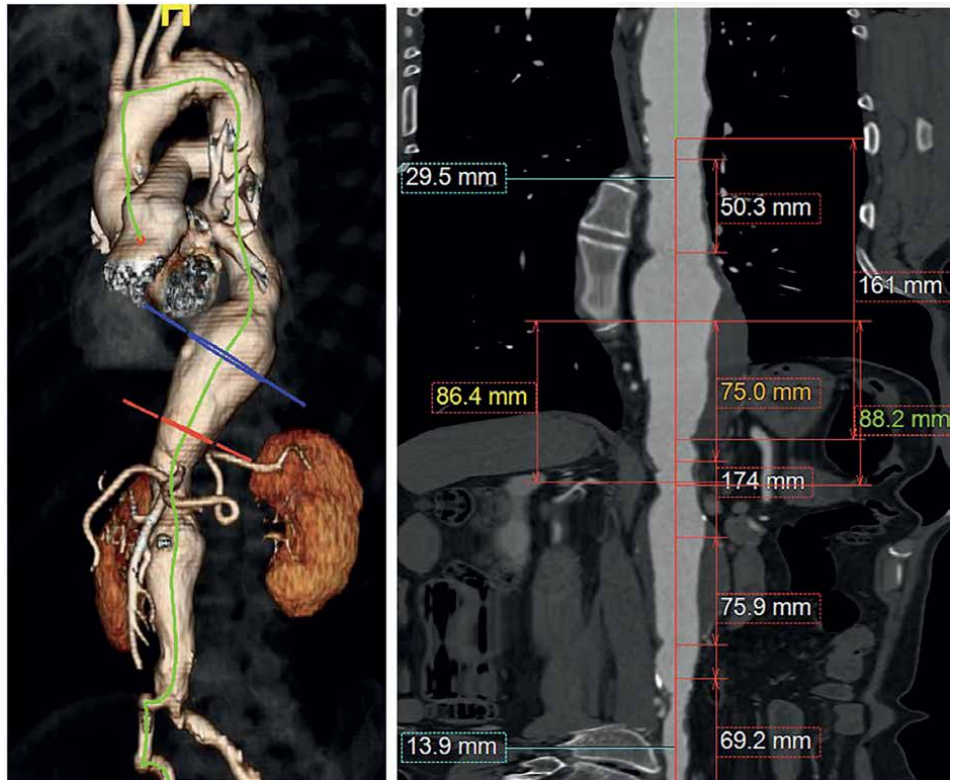


Figure 3.
The figure demonstrates the 3D reconstruction software with the centerline flow used for planning of patient-specific manufactures F/BEVAR.

the proximal neck has been defined, the next step is to determine the distance of the center of each visceral vessel to the edge of the fenestrated (when planning to design fenestrations) (**Figure 4**). This step is slightly different when planning of directional branch. In the later, we mark the distance between the edge of the device and 15 mm proximal to the origin of the vessel. The goal is to create a space between the bottom of the directional branch and the target vessel origin, thus creating more space to work with the catheter and wires to select the vessel. Next, using a combination of centerline and axial view, you determine what clock position each visceral vessel comes off the aorta (**Figure 4**). After these measurements have been made, you can decide if the anatomy is appropriate for an off-the-shelf device or if it will require a patient-specific graft company manufactured device. Then you transfer the measurements in a specific form for each endograft (**Figure 5**). Regarding each visceral artery, information about the diameter and the distance at where its first branch originates is important to choose the appropriate diameter and length of the covered bridging stent.

2.2.1 Devices designs

Fenestrated-branched devices are classified either as off-the-shelf (OTS) or patient-specific company manufactured to fit the patient's anatomy. While OTS can be readily available, thus allowing the use in urgent/emergent settings,

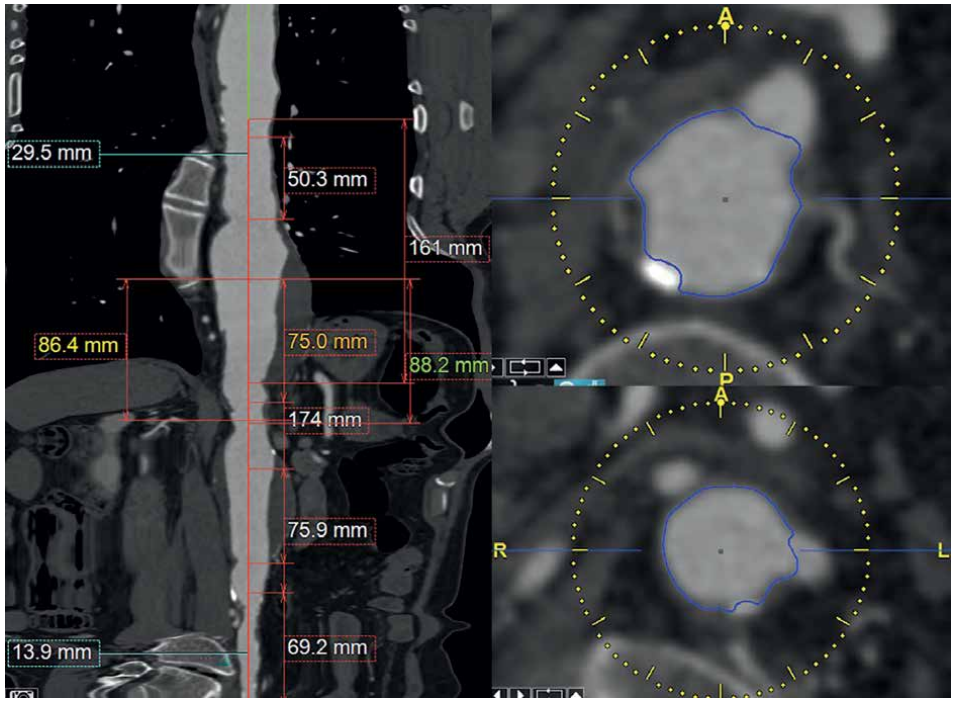


Figure 4.
The figure illustrates using the centerline of flow and clock position during planning for patient-specific F/BEVAR.

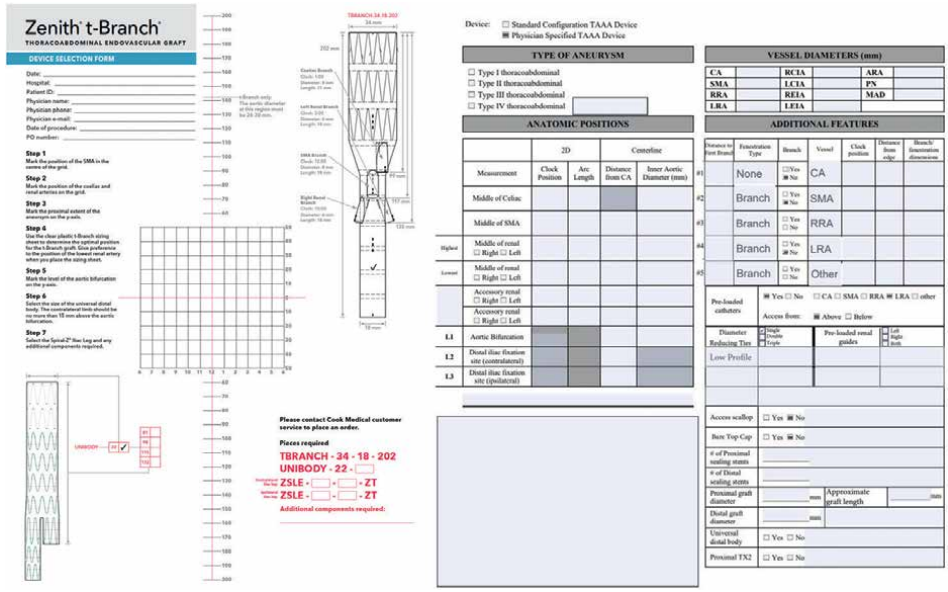


Figure 5.
This figure shows different planning forms for off-the-shelf (OTS) devices (5.A cook t-branch) and patient-specific manufacture device (5.b). T-branch form reproduced with permission of cook medical.

patient-specific manufactured devices require not insignificant time to be produced, which makes them unsuitable to be used in urgent situations. In the USA, OTS endografts are not available for commercial use (except one device recently approved by the FDA, see in the following session), but only in centers with authorization for investigational use. Although progress has been made with the development of OTS devices, still a significant number of patients are not suitable for those devices and require patient-specific devices.

2.2.1.1 Off-the-shelf device

2.2.1.1.1 Gore thoracoabdominal branch endoprosthesis - TAMBE

The Excluder thoracoabdominal branch endoprosthesis (TAMBE; Gore & Associates) is a modular, multi-component system composed of a multi-branch stent graft, bifurcated component, and iliac limb extension. The endograft was designed for repairing aneurysms that extend into the visceral segment of the aorta, with branches to incorporate the renal and mesenteric arteries. It is based on Gore's core technology, with a nitinol stent frame, conformable expanded polytetrafluoroethylene technology, and four portals for placing the Viabahn VBX bridging stent grafts (**Figure 6**). Target vessel stenting is achieved through a 12-F axillary sheath and all branches have preloaded wires, eliminating the need for branch portal catheterization. The TAMBE clinical trial evaluated the device's safety and effectiveness in type I to IV TAAAs and pararenal aneurysms and had recently been approved by the FDA for commercial use in the United States.

2.2.1.1.2 Zenith thoracoabdominal endovascular graft – t-branch (cook medical)

This is a tapered woven polyester stent graft sutured to a stainless-steel Z-stent exoskeleton. The device contains four 18-mm long branches that are positioned on predefined locations of the visceral vessels. The device's proximal diameter measures 34 mm and the distal diameter 18 mm, with a length of 202 mm. The celiac artery and SMA branches are each 8 mm in diameter and located at the 1 and 12 o'clock positions, respectively. The right and left renal artery branches are each 6 mm in diameter and positioned at the 10 and 3 o'clock positions, respectively. (**Figure 7**). The delivery system is a 22-Fr introducer with a low-profile fabric version of the device available in an 18-Fr delivery system. The device is available for commercial use in Europe but not in the United States.

2.2.1.1.3 Zenith p-branch endovascular graft (cook medical)

This device is designed to treat aneurysms that terminate at least 4 mm below the superior mesenteric artery (SMA). This device uses the Zenith Fenestrated platform (Cook Medical) and is composed of polyethylene terephthalate fabric with a proximal stainless-steel, uncovered, barbed supraceliac stent, followed by a series of nitinol Z-stents that incorporate a scallop for the celiac artery, an 8-mm strut-free fenestration for the SMA, and two renal pivot fenestrations The two pivot fenestrations for the renal arteries allow catheterization of the renal arteries that fall within 15 mm of the outer diameter. Two configurations incorporate different distances between the renal fenestrations (**Figure 8**). The device incorporates a pre-load wire system across the renal fenestrations, facilitating the catheterization of the fenestrations and renal arteries.



Figure 6.
The Gore excluder Thoracoabdominal branched Endoprosthesis (TAMBE). Picture is courtesy of W.L Gore.



Figure 7.
The cook off-the-shelf t-branch. Courtesy of Dr. Mark Farber.

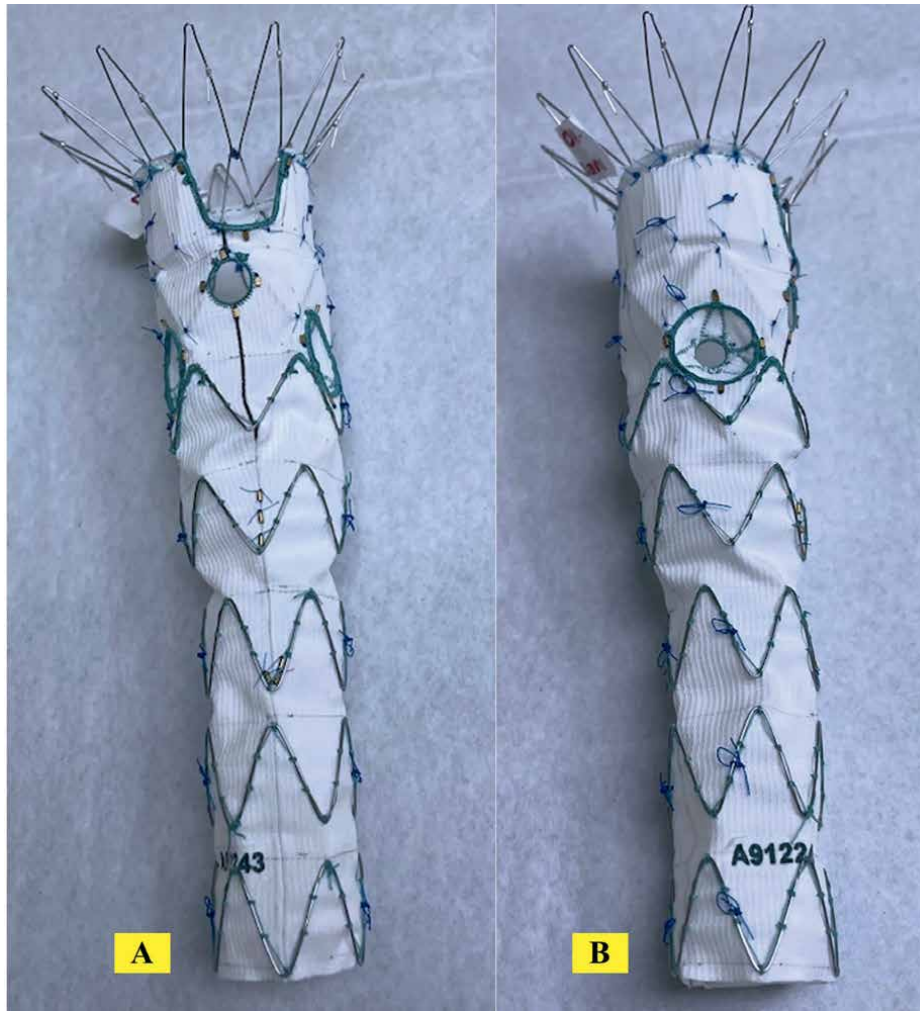


Figure 8.
The cook off-the-shelf p-branch. Courtesy of Dr. Mark Farber.

2.2.1.2 Patient-specific company manufactured devices

2.2.1.2.1 Cook zenith fenestrated device (Zfen)

The ZFen (**Figure 9**) is designed to treat juxta-renal aortic aneurysm with at least 4 mm neck length below the lowest renal artery. It is composed of a proximal fenestrated component, a bifurcated universal component, and a contralateral iliac limb extension. The modules are constructed of full-thickness woven polyester fabric sewn to self-expanding stainless-steel Cook-Z stents with polyester and polypropylene suture. The modules are fully stented. The FDA-approved version of the fenestrated component has a supra-graft bare metal stent and is custom-made to fit the patient's anatomy with up to three components. The components can be either scallops (usually to the SMA), small fenestrations, or large fenestration. The small fenestrations are usually designed for renal arteries and are reinforced, having two configurations

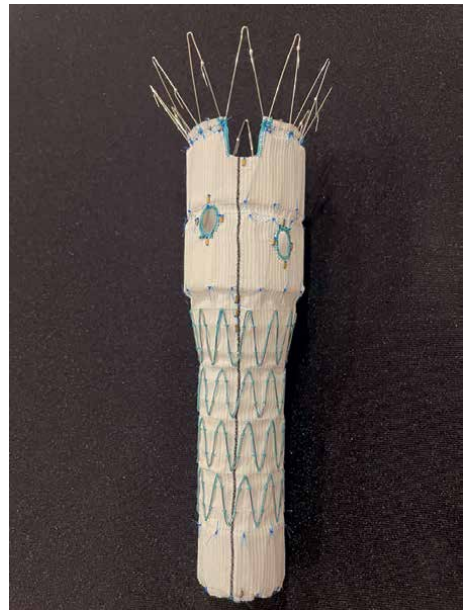


Figure 9.
Example of the cook ZFen commercial available in the United States, with 2 small fenestrations for the renal arteries and a scallop for the superior mesenteric artery (SMA).

of either 6 × 6 mm or 8 × 8 mm, without stent struts across it, and can be stented. The large fenestration measures 8–12 mm in diameter and due to having struts across it, it is not recommended to stent the visceral vessel (most designed to incorporate the SMA). The device is intended to treat the aorta with a maximum sealing zone diameter of 31 mm (maximum device diameter is 36 mm).

2.2.1.2.2 Other cook patient-specific company manufactured fenestrated/branched endografts

In the United States, the only commercially available fenestrated graft is the Cook Zfen described above. For patients whose anatomy does not fit for Zfen, an F/BEVAR with a patient-specific design is required to be implanted in centers authorized by the FDA under a physician-sponsored investigational device exemption (PS-IDE). Centers in the US with IDE trials use the Cook Zenith platform to build patient-specific devices with features not available in the ZFen. The main advantage of these devices is the ability to specifically fit the patient's anatomy and the possibility to incorporate some adjuncts to the delivery system, such as pre-loaded wires and/or catheters to the fenestrations/branches, facilitating vessel cannulation during the repair. Also, it is possible to design devices that use both fenestrations and directional branches, in many different configurations (**Figure 10**).

2.2.1.2.3 Terumo fenestrated anaconda device

The fenestrated Anaconda endograft (Terumo/Vascutek, Renfrewshire, Scotland) is a patient-specific device for individual patient use and is based on the Anaconda AAA endograft system. The system is a trimodular and consists of

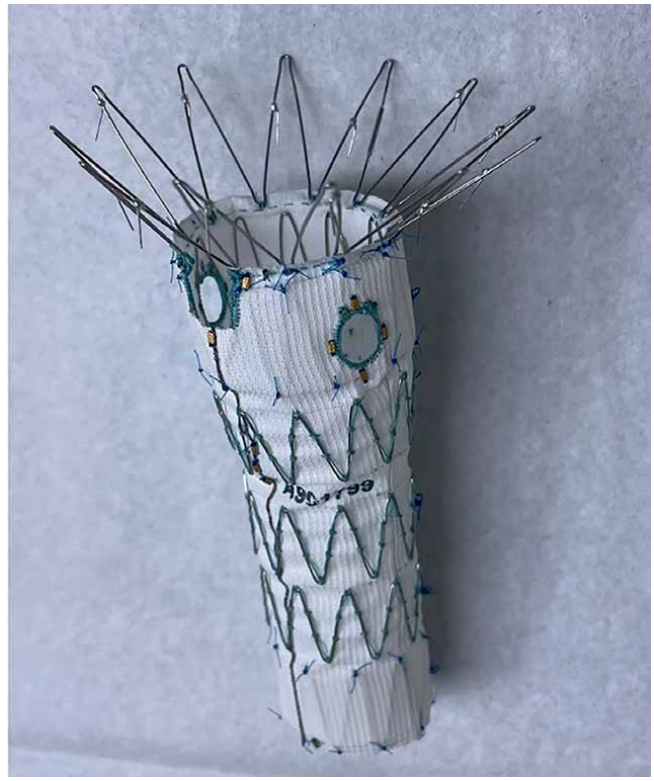


Figure 10.
Example of a patient-specific manufactures F/BEVAR device. Courtesy of Dr.Mark Farber.

a dual proximal ring stent with a maximum of four fixation hooks (variable with the device configuration), an unsupported part of the graft body that facilitates the nitinol-reinforced fenestrations, and a distal ringed stent. The device allows designs with up to four fenestrations. Also, the addition of an augmented valley (comparable to a scallop) and a bifurcated or tube design add further possibilities to treat AAAs with a various range of anatomy. The augmented valley is designed to facilitate vessel cannulation from the brachial access. The main device introducer profile is 20F or 23F, depending on the device's proximal diameter. This device has several unique features. It can be repositioned after full deployment, allowing for accurate deployment and easy repositioning of the endograft body and its fenestrations. Also, because the fenestrations are placed in the unsupported region, it maximizes the area available and potentially allows for easier alignment and subsequent cannulation of target vessels [14].

2.2.1.2.4 Terumo custom-made TREO device

Recently published the early results using a novel low-profile custom-made-fenestrated device based on the infra-renal TREO platform (TERUMO Aortic, Bolton Medical Inc., USA) in Europe [15]. The device is built with self-expanding nitinol stents sutured to woven polyester fabric. There are platinum-iridium markers applied for better fluoroscopic visualization. The fenestrations are reinforced nitinol rings sutured around the fenestration. The fenestrated endograft allows to build-up to 5

fenestrations. The length of coverage proximal to the celiac is 23–25 mm above the celiac trunk, which is adjustable to a minimum of 9 mm. In the design, there will be 3 main regions in the body part that are fully circumferentially reduced by reducing ties, which provides around 33% diameter reduction. The custom-made fenestrated TREO® endograft is a bifurcated endograft with a maximum length of 160 mm, instead of a tube graft.

2.2.2 Bridging stents

To bridge the gap between the fenestration/branch and the target vessel intended to be incorporated, there are different several options for covered stents. They can be balloon-expandable or self-expandable, with a choice between stents being mostly at the surgeons' preference. Below are the stents most used by the authors.

2.2.2.1 iCast (Maquet, Wayne, NJ)

Also known as V12 covered stent, it consists of a stainless-steel alloy, encapsulated in two layers of polytetrafluoroethylene (PTFE). The inner layer prevents the struts from being in contact with the lumen and it is mounted on a balloon that has golden marks on it to facilitate the visualization. In the USA, it is available in diameter from 5 to 10 mm and length from 16 to 59 mm in a 0.035″ system. It required a 6- or 7-Fr system for delivery. There are two options in terms of catheter length (80 or 120 cm). The iCast cover stent carries the precision in deployment characteristic of balloon-expandable stents but lacks flexibility. Stent fractures with iCast are extremely rare. This stent is chosen by the authors as a bridging stent for fenestrations.

2.2.2.2 Bentley BeGraft stent (Bentley, Hechingen, Germany)

This balloon expandable stent has been used in Europe and the UK during F/BEVAR and is currently in study in the USA during the ZFEN plus trial (NCT04875429). Also compatible with a 0.035″ system, the stent consists of Chromium-Cobalt alloy covered with PTFE. It is available in diameters ranging from 5 to 10 mm and has different length options (18, 22, 28, 38, and 58 mm). A 6 Fr delivery sheath is used for stents up to 8 mm diameter and a 7 Fr system for larger balloons (9- and 10 mm diameter). There are also two options for catheter working lengths (70 or 120 cm).

2.2.2.3 Gore balloon-expandable Viabahn VBX (WL Gore, Flagstaff, AZ)

This stent was specifically designed to work as a bridging stent during the repair of TAAA using the Gore TAMBE device. The stent is composed of independent nitinol stents externally attached to a PTFE layer. The VBX maintains the characteristics of balloon expandable stents (precise deployment) combined with the flexibility of the self-expandable Viabahn stent graft. The VBX is available in diameters from 5 to 11 mm and lengths 15, 19, 29, 39, 59 and 79 mm. It requires a 0.035″ system and is delivered on a 6 to 8 Fr sheath. The authors have moved away from self-expandable stents and the VBX has become the author's stent choice as a bridging stent for directional branches. The authors compared the performance of VBX to self-expandable stents for directional branches, and the VBX demonstrated similar results [16].

3. Technical aspects of device implantation

This session will discuss some technical aspects of treating complex aortic aneurysms with F/BEVAR. The following description is derived mostly from using devices that have the Cook platform. When addressing juxta-renal aneurysm, most of the time it can be repaired with the commercially available Cook Zfen device. As discussed previously, this device has some limitations and cannot be used for more complex aneurysms (para-renal, supra-renal, or TAAA). The authors will also describe techniques related to the use of patient-specific company manufactured F/BEVAR endografts used under a PS-IDE trial. Although we are not specifically addressing the deployment technique of all the fenestrated/branched devices, several points discussed here can be translated into the planning and implantation of other F/BEVAR devices.

We start with a detailed review of the patient's CT scan days before the procedure. This step is paramount to verify the initial strategy, review access sites, identify likely challenges during the case, and plan to address those in advance. The routine is to keep the 3D reconstruction of the CT scan next to the fluoroscopy screen to allow review of the images as needed during the procedure. This is also the time to check our inventory and make sure all the necessary materials are available.

It is our practice to admit the patient the night before to administer gentle hydration with normal saline solution and review pre-operative tests. Even for patients with CKD, it has not been the author's practice to administer sodium bicarbonate or n-acetyl cysteine pre-operatively. Patients taking beta-blockers are instructed to continue the medication; however, those taking either vasodilators or ACE inhibitors/ARBs are asked to hold medication for 24 hours before surgery to avoid perioperative hypotension. We routinely instruct to hold novel anticoagulants for at least 3 days and clopidogrel 5–7 days before surgery, while it is recommended to continue aspirin during the perioperative period.

Due to the complexity of F/BEVAR repairs, the surgeon and the team must recognize the importance of minimizing the use of contrast and decreasing radiation exposure. We have routinely used diluted contrast (30–50%) and performed small hand injections as needed. Although some centers have routinely performed cone beam CT scans at the end of the procedure, the author's choice is to perform a completed non-contrast dyna CT scan to evaluate the integrity of the devices. The use of fusion overlay images, which allow identification of the target vessel's origin and aorta layout, has contributed significantly to decreasing the use of contrast and radiation exposure. Although some surgeons prefer to pre-catheterize one or more target vessels to adjust the overlay images, has been our preference to use intravascular ultrasound (IVUS). It is also important to keep in mind the "as low as reasonably achievable (ALARA)" principles to keep the radiation dose as low as possible (fluoroscopy frame rate 7.5 fps or less, use of digital zoon, high table position, avoid excessive angulation of the image intensifier, minimize the amount of digital subtraction angiogram [DSA], etc). New technologies have emerged as an alternative to fluoroscopy during aortic interventions. An example is the intra-operative system (IOPS) that uses sensor-equipped catheters and wires coupled with a fiducial tracking patch and capital equipment. This creates a magnetic field that fused with a preoperative CT scan is capable of generating fluoroscopy-free images in multiple projections (**Figure 11**) [17]. Another example of an alternative imaging system is the fiber optic real shape (FORS) technology platform, which consists of equipment that sends laser light through a multicore optical fiber integrated into specially designed guidewires and catheters [18].

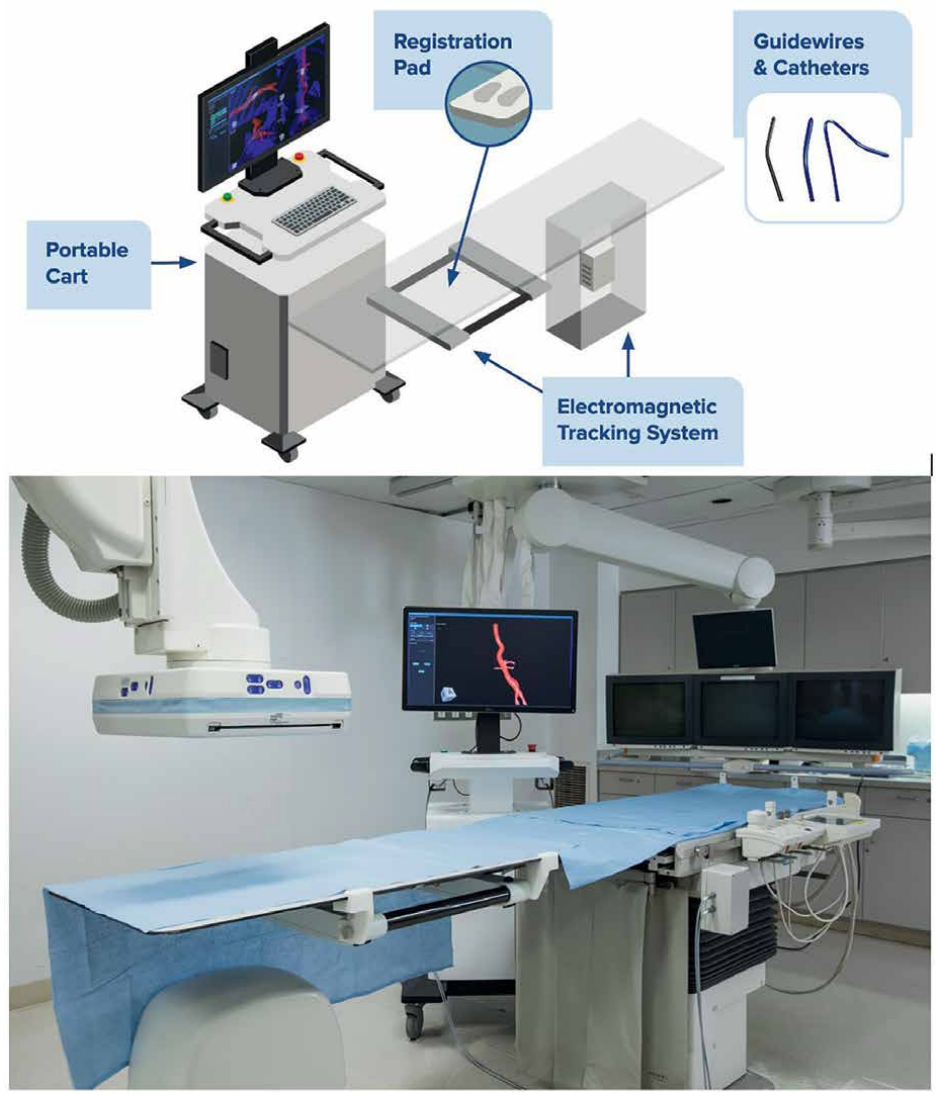


Figure 11.
The picture illustrates the intra-operative positioning system (IOPS). Reproduced with permission of centerline biomedical.

The surgery is performed under general anesthesia. For those who require prophylactic lumbar drain placement, it is performed 12 hours before surgery and kept clamped until the procedure is started and it is allowed to drain about 25 ccs into the operating room to keep intracranial pressure (ICP) between 8 and 12 cm H_2O and verify if the drain is functioning appropriately. We have also used near-infrared spectrometry (NIRS) as an adjunct to monitor para-spinal muscle perfusion as an indirect measurement of spinal cord perfusion in patients receiving lumbar drain. Patients are placed in a supine position with the left arm extended 90 degrees and the right arm tucked at the side. Before the patient is prepped, a fusion overlay system is obtained using fluoroscopy and a patient CT scan (**Figure 12**). Both groins and the left arm are prepped in a sterile fashion, with the left arm and upper chest left exposed if

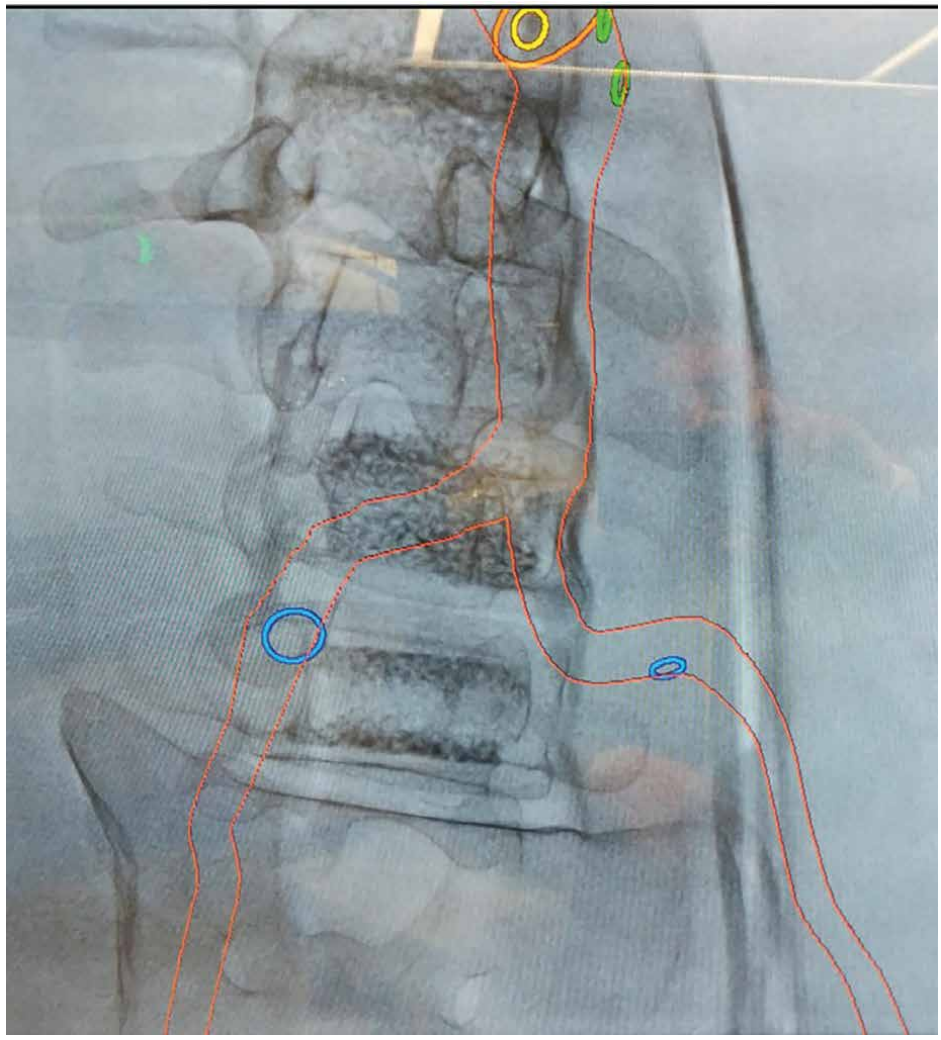


Figure 12.
The picture exemplifies of overlay used during complex aortic repairs.

we anticipate brachial/axillary artery access. The preferred access has been bilateral femoral percutaneous. Although during the initial experience, the upper extremities were used often, the authors have preferred to avoid this approach as much as possible, especially with the recent advances in the ancillary tools such as steerable sheaths allowing to overcome some challenging related to target vessel angulations.

When evaluating the femoral arteries for percutaneous access, it is important to recognize potential situations prone to failure of percutaneous access. Among those, high femoral bifurcation, small vessel diameter, and circumferential calcifications are the most common indications for open exposure, as well as when ilio-femoral conduit is necessary. In the latter, the authors prefer to create the ilio-femoral conduit a few weeks in advance and surgically expose the conduit on the day of the endovascular repair.

For percutaneous access, visualize the femoral artery using ultrasound and determine the ideal spot for access, preferentially 1–2 cm above the bifurcation, and make

sure to access the artery at 12 o'clock position, using an 18 G micro puncture needle, to avoid misplacement of the closure device. At this moment, we make a small incision in the skin large enough to accommodate the large bore sheaths. Then a micro wire is advanced, and a 5 Fr micro sheath is advanced into the external iliac artery. The micro-wire is exchanged to a Bentson wire (Cook Medical, Bloomington, IN) 0.035″ and advanced into the abdominal aorta. As an alternative, a glide wire can be used in situations of severe tortuosity or disease precluding advancing the Bentson wire. The 5 Fr micro sheath is then exchanged for a 6Fr hemostatic sheath in preparation for the closure device. It is the author's preference to use the pre-closure technique utilizing two Proglide Perclose (Abbott) devices, the first deployed at 10 o'clock and the second at 2 o'clock. Once the closure devices have been deployed, an 8 Fr × 25 cm hemostatic introducer sheath is advanced into the abdominal aorta over the wire. The same steps are performed on the contralateral side. A Kumpe catheter is advanced into the ascending aorta and exchanged the Bentson wire for a double curved Landerquist wire (Cook Medical, Bloomington, IN) in the side chosen to be the primary side for the fenestrated device. At this moment, we use an IVUS catheter to locate the target vessel's origins and adjust the overlay marks. Another option to adjust the overlay is to pre-catheterize one of the target vessels to match with the overlay. After this step, we upsize the contralateral 8 Fr sheath to an 18–20 Fr DrySeal sheath (W.L Gore, Flagstaff, AZ) through which 6–7 Fr Sheaths will be used for cannulation of target vessels. The authors have avoided pre-cannulation of target vessels as much as possible to minimize the risk of complication; however, this step might still be necessary in some situations, like vessel stenosis, when it is crucial to keep access to the vessel. Before inserting the fenestrated device, we confirm the orientation under fluoroscopy outside the patient's body. For the commercially available Cook Zfen device, after being inserted and positioned, the device is partially deployed (due to the presence of reducing diameter ties) and initially slightly higher position than the intended vessel. Next, from the contralateral side, usually, a combination of 6–7 Fr Ansel 1 high-flex sheath, VanSchie 4 catheter, and glide wire is used to cannulate the renal fenestrations and the renal arteries. Once it is confirmed the catheter is into the renal artery with a small amount of contrast angiography, the glide wire is exchanged to a Rosen Wire (Cook Medical), and the Ansel sheath advanced into the renal artery. Next, over the Rosen wire is inserted the chosen bridging stent, usually iCast covered stents for fenestration. The same steps are repeated to the contralateral renal artery. We do not routinely cannulate the SMA, for which we selectively place the stent, depending on some criteria after the full deployment of the device. The device is then fully deployed removing the diameter-reducing ties. Next, the endograft is gently molded with an aortic balloon, and is the author's preference to use the Coda aortic balloon (Cook Medical). The Ansel 1 sheaths are pulled exposing the bridging stents, which are deployed with the care of allow 3–5 mm inside the aorta. The stents are flared using a 9 or 10-mm angioplasty balloon and 200 mcg of Nitroglycerin is administered in each renal artery to avoid vasospasm. Before removing the balloon and the wires from the renal arteries, we insert the universal bifurcated distal piece while keeping the balloon inflated into the renal stents, to protect it. The bifurcated piece is deployed, wires and catheter removed from renal arteries and the procedure is completed with insertion and deployment of iliac extension limbs.

There are some modifications regarding the steps for when we are performing a complete four-vessel fenestrated repair. At the initial experience, it was common the need for upper extremity access to incorporate some of the target vessels, most commonly the celiac artery and the SMA. Under the PS-IDE trial in the USA, the Cook

fenestrated device can be customized with a preloaded catheter inserted through a modified bi-port handle at the main delivery system. The preloaded catheter is configurated from inside the device and exits at the renal fenestration (also can be preloaded into different fenestration if needed). Contralateral site access is then used to incorporate the CA and SMA. With these systems, the steps are slightly different. After the device is inserted and placed at the desired position, the fenestrated device is deployed about 2–3 stents. The preloaded catheters are then advanced, and a Rosen wire is inserted into the proximal aorta. Next, a 6Fr × 90 cm shuttle is inserted in each bi-port until exits through the renal fenestration, and the Rosen wire is exchanged for a 0.014″, which will secure the sheath in place as a "buddy wire". Next, using a combination of catheter and glide wire, each target vessel is selected, and the catheter advanced into the vessel, which is confirmed with angiography. Once it is confirmed, the glide wire is exchanged for a Rosen wire, the 0.014″ wire is removed, the shuttle sheath is advanced into the vessels, and the bridging stents are inserted and positioned. After this is completed, the remaining fenestrated graft is unsheathed and is accessed from the contralateral side. The SMA is commonly cannulated using a VanSchie 4 catheter and glide wire, which is exchanged for a Rosen wire, and then a 7Fr Ansel 1 sheath is advanced. The bridging stent is inserted, and the steps are repeated for the celiac artery. After all target vessels have been cannulated and secured with sheaths in place, the reducing diameter ties are removed, and the device is fully deployed. With the pre-loaded catheter system, the inner cannula cannot be completely removed before the pull of the sheaths that are inserted into the biport. The option is then the pull the inner cannula into the fenestrated delivery system, deploy the renal bridging stents (and flared with 9 mm balloon), followed by removing the sheaths, balloons, and wire from renal arteries, and completely removing the fenestrated delivery system. Before inserting the distal bifurcated device, the SMA and CA artery bridging stents are deployed and flared in standard fashion. At this moment, we analyze the path of the main Lunderquist wire at the primary side to determine which visceral stent is more at risk of being damaged during the insertion of the bifurcated aortic component. To decrease this risk of stent damage, the authors have frequently requested the bifurcated component to be built with a short "nose" inner cannula. The Wires and balloons are then removed from CA and SMA stents and those are used to protect whichever stent is needed. The bifurcated device is then inserted and deployed. The remaining wire and balloon are removed, and the repair is completed in standard fashion with iliac limb extensions. The bifurcated aortic component and the iliac limbs are molded with an aortic balloon.

Regarding the target vessel incorporation using directional branches, in the past, the authors have used upper extremity access due to the down-going design of directional branches. More recently, with the development of novel ancillary tools, most of the procedures can be performed with exclusively femoral access. We use a 16 Fr Aptus sheath (Medtronic), the same device utilized to deliver Endoanchors (Medtronic), as the main component. This steerable sheath provides enough support to allow the covered stent to track from the femoral access into the target vessel. Inside the Aptus sheath, we use an 8- or 9-Fr shuttle sheath as a coaxial system to provide more support. The Aptus sheath is then shaped and engaged into the proximal aspect of the directional branch. At this point, usually, a combination of Kumpe catheter and glide wire is used to select the target vessel. Again, once the catheter is advanced and confirmed into the vessels, a Rosen wire is advanced, and the shuttle sheath is advanced as distal as possible into the vessel. A marked catheter is then used to determine the length of the bridging stent. As mentioned previously, the author's

preference has been to use the Gore VBX stent. Besides the already mentioned characteristic, due to its extreme attachment to the balloon during the manufacturing process, it possesses the advantage of being able to advance without needing protection by the sheath (as other balloon expandable stents do). The above-described technique has been used by the authors for branch cannulation during repair using the Cook t-Branch device as well.

The authors elected to perform a non-contrast dyna CT scan when there was some concern regarding the integrity of any of the visceral stents. After that step, the sheaths are removed and the proglides are tied down.

4. Outcomes

As described before, although the durability of open repair for complex aortic aneurysms has been demonstrated, a significant part of the population is considered to high risk and not suitable for it. Since the first fenestrated repair more than two decades ago, the technique has disseminated and today is the method of choice for patients without connective tissue disorders and with aortic aneurysms involving the visceral vessels (renal and mesenteric arteries). A recent guideline from the American Heart Association (AHA) stated that F/BEVAR should be considered for patients with TAAA (elective and stable ruptured) and suitable anatomy if performed in centers with experience [2]. When comparing the endovascular approach to open surgery several variables are important, including mortality, length of hospital stay, and major complications. Also, some aspects specific to endovascular repair are crucial, especially related to the long-term durability of the visceral stents, which have an impact not only on the organ function but also the incidence of endoleaks, which can ultimately impact the risk of aneurysm rupture and death. The analysis of reinterventions following endovascular aortic repair is also very appropriate, more so for repair where the number of device components increases.

The first clinical trial in the USA that allowed a commercial fenestrated device for juxta-renal aortic aneurysm was published in 2009 by Greenberg et al., and in their first 30 patients in 5 centers demonstrated no aortic-related death in the first 30 days and no aortic rupture or aortic-related death in 24 months of follow up period [19]. Many other surgeons embraced this new vision and developed aortic programs dedicated to complex aortic aneurysm repair, with outstanding results. The authors published their results for the first 150 patients treated with F/BEVAR for TAAA I-IV and demonstrated 30-day mortality of 2.7% in a population with a mean age of 71 years old and an average of 3.8 fenestration/branch per repair. The technical success was 98.6% and vessel patency of 99.8% (525 out of 526 fenestration/branches). The most common complication was respiratory (7%), followed by acute renal injury (4.7%, with no patient requiring long-term dialysis), and 2.7% paraplegia [20]. In the USA also, Oderich et al., published the experience of the Mayo Clinic and, in 127 patients treated with F/BEVAR, technical success was achieved in 99.6% and there was no 30-day mortality, need for dialysis, no aortic ruptures or conversion to open repair. The good early results continue to be reproduced in many centers across the USA and Europe, demonstrating low mortality, less blood loss, short hospital stays, and low rates of major adverse events [8, 21–23]. One of the most feared and devasting complications related to complex aortic repair is the occurrence of paraplegia, which has a minimal relation to the extension of the aortic coverage [10]. For TAAA I-III, data demonstrated that performing in a staged fashion decreases the risk of spinal cord

ischemia (SCI) significantly. O'Callaghan and colleagues demonstrated a decreased incidence of SCI from 37.5 to 11.1% when performing the procedure in a staged fashion in patients with type II TAAA [24]. Dias-Neto also demonstrated the crucial aspect of stating endovascular repair for types I-III TAAA. This multicenter analysis showed a decrease in 30-day death/permanent SCI from 14–6% when performing in a staging fashion [25]. To prevent this complication, a lumbar drain has been advocated to allow decrease the pressure in the central nervous system and improve the perfusion pressure to the spinal cord. However, the risks associated with the lumbar drain are not insignificant and some centers have moved from prophylactic use and only as a rescue procedure when SCI occurs. Recently, Marcondes et al. published their experience with 541 patients treated for TAAA I-III with F/BEVAR and without prophylactic spinal drainage and concluded that there was low mortality and low rates of permanent paraplegia (2%). SCI occurred in 8% of patients (2% permanent), and rescue treatment improved symptoms in 73%. This is special important when considering that, contrary to the general concept of increased mortality with any degree of SCI, only permanent paraplegia has this association. This was demonstrated by Aucoin et al. Reviewing the data of the US-Aortic Research Consortium (US-ARC), in 1641 patients treated with F/BEVAR, the 5-year survival for patients with no SCI and those who developed paraparesis was the same [26]. It is important to note that when opting to use only rescue lumbar drains after F/BEVAR, time is paramount to the patient's recovery and the surgeon should understand the reality and logistics of the institution to guarantee a lumbar drain can be inserted in an expedited manner when needed.

The target vessel stents long-term patency rates have also been extensively studied with good results. The final 5-year results of the US Zfen trial showed primary and secondary renal target patency was 82.7 and 95.7%, respectively [6]. Of all visceral vessels, the renal artery stents remain though as the ones with more incidence of loss of patency compared to SMA and CA artery stents, and with fenestrations demonstrating better patency than directional branches. Mastracci et al. reported the 12-year experience of the Cleveland Clinic Foundation, which reported 2% of renal primary patency loss among 1134 fenestrations. More recently Tenorio et al., compared to results between reno-mesenteric stents between fenestrations and directions branches. Among 3155 target vessels, at 5-year follow up the primary patency was 94 and 83% for fenestration and directional branches, respectively. Similar difference for secondary patency, with fenestrations having 97% and branches 89% at the same follow-up period. No difference in type Ic or IIIc endoleak was observed between fenestration and branches. One factor that seems to be associated with more angulation and loss of patency for branches is renal arteries' upgoing angle [27]. The use of self-expandable stents seemed to be related to better outcomes in this cohort, which is different from the study published by the authors regarding the performance of Viabahn VBX in directional branches, where they found similar results between both stents [16]. Regarding the occurrence of endoleaks related to fenestration, Chait et al. studied the gap distance between the fenestration and the aortic wall and found that a gap >5 mm decreased the freedom from target vessel instability from 93–84% in 5-year follow-up [28]. Endovascular aortic repair has often raised concerns regarding long-term re-intervention rates, especially for F/BEVAR, where the number of device components is higher. However, not all re-interventions carry the same risk. Zetterval et al., studying the US-ARC data identified that, during 5-year follow-up, among 1681 patients treated with F/BEVAR freedom from reintervention was 59% [29]. However, the majority were percutaneous, minor, and of low magnitude. High-magnitude

operations were required for 19% of the patients. The mortality from the secondary interventions was <1%. Secondary interventions were associated with improved long-term survival (HR, 0.6; 95% confidence interval [CI], 0.5–0.7). High magnitude and open secondary interventions were not associated with improved survival, while percutaneous and minor secondary interventions were. Regarding aneurysm-related survival, low-magnitude secondary interventions were found to improve survival, and high-magnitude secondary interventions and open-secondary interventions were associated with increased mortality.

5. Conclusion

The endovascular repair for complex aortic aneurysms (juxta-para-renal and thoraco-abdominal) has significantly evolved over more than two decades. Advancements in devices, ancillary tools, creation of dedicated aortic centers with better perioperative care have significantly improved outcomes. Some aspects are still in constant improvement, especially concerning preservations of target vessels patency, rates of endoleaks, and consequently the need to decrease secondary interventions. However, most re-interventions are minor and when appropriately addressed, result in improved survival. Despite the difficulties that this complex aortic repair currently faces, the aortic aneurysm rupture rate and aortic-related mortality remain extremely low. However, those intending to treat this complex pathology should seek appropriate training and build a dedicated aortic team. Current data are very encouraging but highlight the importance of close, lifelong surveillance of the population treated with F/BEVAR.

Conflict of interest

Fernando Motta: none.

Mark Farber: W.L Gore: consulting, clinical trial support; Getinge: consulting; Cook Medical: research support, clinical trial support; ViTTA: consulting, clinical trial support; Centerline Biomedical: stock options, clinical trial support.

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Chapter 7

Management of Thoracoabdominal Aortic Aneurysms

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Abstract

Thoracoabdominal aortic aneurysms (TAAA) represent a unique pathology that is associated with significant mortality if left untreated. TAAA most commonly present in combination with multiple comorbidities of the heart, kidneys, and peripheral vascular systems. Optimal treatment of TAAA remains a complex challenge, with ultimate success requiring a coordinated effort from a multidisciplinary team. This chapter provides a comprehensive approach to the diagnosis and management of TAAA, as well as insight into the recent surgical paradigms and advances in organ protection, spotlighting the latest surgical outcomes and the evolution of techniques that have markedly improved patient care in this complex field.

Keywords: thoracoabdominal aortic aneurysms, TAAA, CSF drainage, endovascular, aortic surgery, Crawford classification

1. Introduction

A landmark in aortic surgery was achieved by Etheredge and colleagues in 1955 with the first successful repair of a thoracoabdominal aortic aneurysm (TAAA) using a homograft tube [1]. The following year, another groundbreaking development was achieved when DeBakey and his team employed a Dacron tube graft for the replacement of the descending thoracic aorta and infrarenal abdominal aorta [2]. Later, Crawford and associates introduced a method subsequently known as the clamp-and-go technique. This approach encapsulated three basic principles of aortic surgery: the inclusion technique; the utilization of a Dacron tube graft as a conduit; and reimplantation of visceral and renal arteries [3].

Historically, TAAA repair necessitated rapid execution to mitigate prolonged organ ischemia. Over time, TAAA surgery has been transformed with the use of adjuncts aimed at enhancing organ protection and improving overall outcomes. As a result, the surgical outcomes for TAAA repair have improved dramatically, ensuring favorable long-term survival compared to the untreated cohort (**Figure 1**). These pioneering efforts have significantly shaped the landscape of aortic surgery, providing a robust framework for the management and surgical correction of complex aortic aneurysms. However, further enhancements of these surgical outcomes remain.

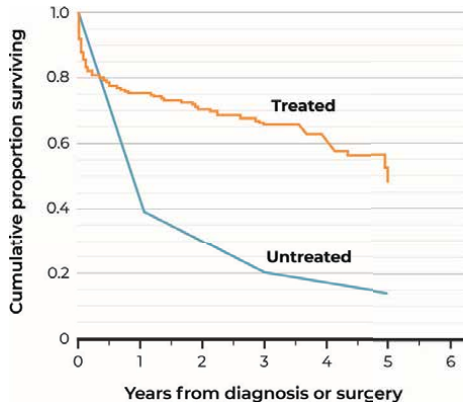


Figure 1.
Thoracoabdominal aortic aneurysm: comparison of survival rates in untreated patients versus surgically treated patients.

2. Natural history

Aortic aneurysm disease remains a significant cause of death in the United States. Advancement in diagnostic imaging modalities, aging population, and overall heightened awareness all contribute to an apparent increase in the prevalence of aortic aneurysms. Nevertheless, the annual repair rate of TAAAs, which involve both the thoracic and abdominal aorta, is less than 1000 cases, compared to approximately 50,000 repairs for infrarenal abdominal aortic aneurysms. The prevalence of abdominal aortic aneurysms is estimated to range from 2.3% to 10.7%, with this variation contingent upon the demographic characteristics of the studied population and the criteria defining aneurysm size [4, 5]. On the other hand, the incidence rate of TAAAs is approximately 10.4 cases per 100,000 person-years [6]. Furthermore, the average age of patients diagnosed with TAAA ranges from 59 to 69 years, exhibiting a male-to-female predominance ratio ranging from 2:1 to 4:1 [7]. Aneurysm disease occurs in more than one part of the aorta in approximately 20% of cases. The so-called "mega" aorta is an "extensive" aortic aneurysm involving the ascending, transverse arch, and entire thoracoabdominal aorta.

Less than 40% of individuals with untreated TAAA survive more than 5 years, with the majority of these deaths attributable to aneurysm rupture [3]. Studies focusing on TAAAs have demonstrated an increased likelihood of rupture in aneurysms exceeding 5 cm in diameter, with the risk of rupture escalating in proportion to the size of the aneurysm [8, 9]. The median diameter at which TAAAs typically rupture is approximately 7 cm [10]. Aneurysms that are 8 cm or larger carry an 80% risk of rupturing within a year of their diagnosis [11]. The lifetime risk of rupture for any untreated aortic aneurysm is estimated to be between 75 and 80%. The average rate of growth for TAAAs is noted to be between 0.10 and 0.42 cm annually, with aneurysms larger than 5 cm exhibiting an exponential increase in growth rate [12, 13].

3. Pathogenesis

An aortic aneurysm is delineated as a localized or diffuse enlargement exceeding 50% of the normal diameter of the aorta. Predominantly, TAAAs are of a

degenerative nature, sharing similar pathologies with the more frequently encountered infrarenal abdominal aortic aneurysms. Historically, arteriosclerosis has been implicated in the etiology of aortic aneurysm formation. Nonetheless, arteriosclerosis predominantly influences the intimal layer, often leading to occlusive disease, whereas aneurysm pathogenesis typically involves the medial and adventitial layers. From a histological perspective, degenerative aortic aneurysms are characterized by medial thinning, disruption of smooth muscle cells and elastin, infiltration by inflammatory cells, and neovascularization [14–16]. A consistent histological feature is a chronic inflammatory infiltrate in the aneurysm wall's outer layer, comprising macrophages, T cells, and B cells. The extent of this inflammation varies, and the catalyst for cellular migration remains elusive. These inflammatory cells, particularly macrophages, secrete proteases and elastase, which contribute to the degradation of the aortic wall. Elastin degradation products may further act as chemotactic agents, attracting additional inflammatory cells [14]. The role of matrix metalloproteinases (MMPs), particularly elastases such as MMP2, MMP9, and MMP12, in the development of aortic aneurysms, has been corroborated by both clinical and experimental research. These elastases have been identified in increased concentrations in the tissue of aortic aneurysms, suggesting their significant involvement in aneurysm pathogenesis [14, 17–19].

Approximately 25% of TAAAs are associated with chronic aortic dissection. An estimated 20–40% of patients will develop aneurysms in the thoracoabdominal aorta within 2–5 years following acute aortic dissection [20–22]. There is a notable familial aggregation in aortic dissections, as evidenced by the fact that up to 20% of individuals with ascending thoracic aortic aneurysms—a precursor to aortic dissections—have at least one first-degree relative similarly afflicted [23–25]. Marfan syndrome, typified by a constellation of skeletal, ocular, and cardiovascular anomalies, stands as the predominant hereditary connective tissue disorder associated with aortic aneurysm and dissection. This syndrome manifests globally at an incidence rate of approximately 1 in 5000–10,000 individuals. The aortic dilatation noted in Marfan patients is often attributed to mutations in the fibrillin-1 protein, which is encoded by the FBN1 gene. Several other genetic syndromes predisposing individuals to TAAA and dissection have been recognized, including Loeys-Dietz syndrome, Ehlers-Danlos syndrome, Turner syndrome, and polycystic kidney disease [26–28]. To date, four genes have been identified as contributing to familial thoracic aortic aneurysms and dissections, accounting for approximately 20% of these familial conditions. Mutations in the smooth muscle isoform of alpha-actin, encoded by the ACTA2 gene, are implicated in about 15% of familial aortic diseases [29]. Other genes, each accountable for less than 2% of cases, include MYH11, TGFBR2, and TGFBR1 [30–32].

Other rare causes of thoracic aortic disease are inflammatory diseases, such as Takayasu arteritis, Behçet disease, and giant cell arteritis [33]. Infection from *Staphylococcus aureus*, *Staphylococcus epidermidis*, Salmonella, and Streptococcus species, can cause primary infected aortic aneurysms [34, 35]. A false aneurysm can develop due to trauma or at the site of surgical anastomoses.

4. Clinical presentations

Many patients with aneurysms are asymptomatic. Patients with TAAA may present with chronic back pain, although discomfort may also be experienced in the chest, flank, or epigastrium. Acute changes in pain characteristics and intensity may

be indicative of rapid expansion or imminent rupture of the aorta. Hoarseness, a consequence of vocal cord paralysis due to compression of the left recurrent laryngeal or vagus nerves, and dyspnea secondary to compression on the tracheobronchial tree, may be observed in patients with large proximal descending thoracic aortic aneurysms [36].

Direct erosion of the aneurysm into the adjacent tracheobronchial tree or esophagus can cause life-threatening hemorrhaging, presenting as massive hemoptysis or hematemesis, respectively. In rare instances, paraplegia or paraparesis may arise in patients with TAAAs, due to acute occlusion of intercostal or spinal arteries, a scenario typically associated with acute aortic dissection or thromboembolism [37]. While most aneurysms exhibit varying degrees of mural thrombus, distal embolization resulting in acute mesenteric, renal, or lower extremity ischemia is relatively rare.

Rupture is estimated to be the initial clinical manifestation in approximately 5% of TAAA cases [38]. The sudden onset of pain with hypotension is a critical indicator of a ruptured aneurysm. Patients with ruptured TAAA, who make it to the hospital alive usually have ruptured TAAA contained within the pleural or retroperitoneal space, and may present hours and days after the onset of free rupture, which is associated with severe hypotension and often results in instant death and prehospital mortality.

5. Classifications

The Crawford classification and its modified version are used to categorize TAAAs based on their anatomical location and extent. These classifications are crucial for planning surgical interventions and understanding the prognosis of patients with TAAAs. The original Crawford classification divides TAAAs into four types, based on the segments of the aorta affected [3]:

- Extent I: involves the descending thoracic aorta from just distal to the left subclavian artery down to the abdominal aorta above the renal arteries.
- Extent II: involves the descending thoracic aorta from just distal to the left subclavian artery and extending into the abdominal aorta, including the segment where the renal arteries originate, or extending down to the aortic bifurcation.
- Extent III: originates in the descending thoracic aorta from distal to the sixth rib and extends into the abdominal aorta, including the segment where the renal arteries originate, or extending down to the aortic bifurcation.
- Extent IV: starts from the level of the twelfth rib to the aortic bifurcation.

The modified Crawford classification, also known as the Safi classification, expands the original system to better categorize the aneurysms based on their anatomical extent and to aid in surgical planning. It introduces one additional type: Extent V, which involves the descending thoracic aorta distal to the sixth rib down to the level just above the renal arteries, without extending into the segment where the renal arteries originate (**Figure 2**).

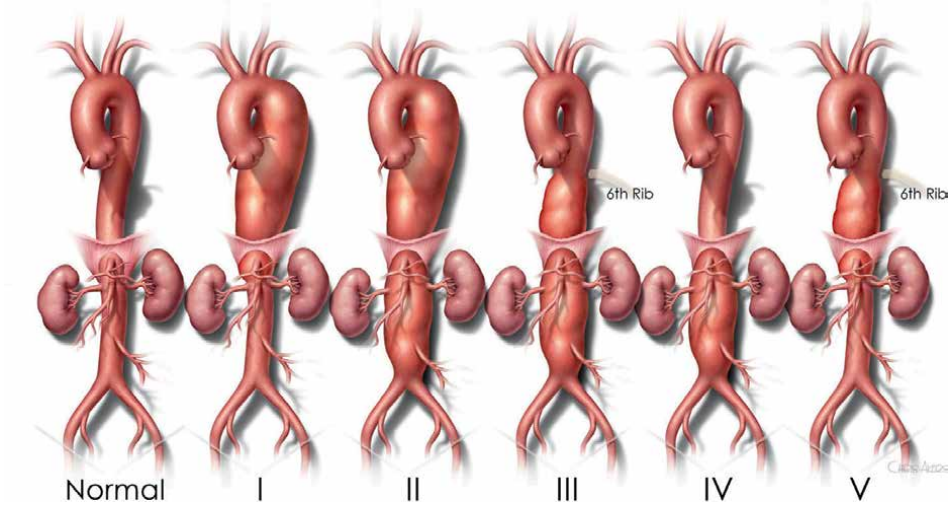


Figure 2.
Thoracoabdominal aortic aneurysm classification. Extent I, distal to the left subclavian artery to above the renal arteries. Extent II, distal to the left subclavian artery to below the renal arteries. Extent III, from the sixth intercostal space to below the renal arteries. Extent IV, the twelfth intercostal space to the iliac bifurcation (total abdominal aortic aneurysm). Extent V, below the sixth intercostal space to just above the renal arteries.

These classifications are essential for determining the surgical approach, which can range from open repair to endovascular procedures, and for predicting potential complications and substantial surgical risks associated with the aneurysm extent.

6. Imaging

The diagnosis of TAAA is achieved through various imaging techniques, with computed tomography angiography (CTA) being the gold standard. In scenarios of compromised renal function, intravenous iodinated contrast can be omitted, as it is not essential for the basic sizing of TAAA. CTA facilitates measurements of the aortic diameter from the ascending segment to its bifurcation across different levels. The reformatted coronal/sagittal views or three-dimensional reconstructions offer supplementary information for surgical planning, such as clamp sites.

Magnetic resonance angiography (MRA) has gained widespread acceptance as a screening modality for aortic diseases and their branches. The primary advantage of MRA over CTA lies in its non-reliance on intravenous iodinated contrast, rendering it safer for individuals with renal impairment. Moreover, MRA circumvents the exposure to radiation associated with CT, making it preferable for patients requiring sequential monitoring. The downside of MRA is longer imaging acquisition time (not amenable for people with claustrophobia), lower spatial resolution, and higher cost compared to CTA. Furthermore, CT exhibits a greater efficacy in evaluation for calcification and intramural thrombus compared to MRA.

Intravascular ultrasound has emerged as a significant diagnostic tool for thoracic aortic disease, offering detailed insights into intraluminal relationships, particularly in aortic dissection during endovascular aortic repair. Epiaortic ultrasound is helpful in deciding where to cannulate or clamp patients with atheromatous plaque and elephant trunk.

7. Surgical indications

The surgical indications of TAAA are determined by the balance of surgical risks and the expected adverse events. Guidelines suggest optimal treatment options for each condition [39–41]. American Heart Association (AHA) guidelines in 2022 recommend open surgical repair for TAAA when the diameter is ≧ 6.0 cm. As a class IIa recommendation, open repair is reasonable when the diameter is ≧ 5.5 cm and the repair is performed by experienced surgeons in a multidisciplinary aortic team. Open repair is also reasonable in patients who have features associated with an increased risk of rupture, including rapid growth ≧ 0.5 cm/year, symptomatic aneurysm, significant change in aneurysm appearance, and saccular aneurysm or presence of penetrating atherosclerotic ulcers.

Patients who have ruptured aneurysm are indicated for emergent/urgent surgical repair due to its lethal nature. In patients with acute type B dissection, interventions should be recommended when patients have organ malperfusion, the progression of dissection, aneurysm expansion, or uncontrolled hypertension (complicated type B dissection).

8. Preoperative evaluation

The initial consultation with TAAA patients primarily emphasizes a comprehensive history and physical examination aimed at identifying comorbid conditions, given the aneurysm typically presents with minimal symptoms or physical manifestations. The delineation of the aneurysm's scope is accomplished through imaging modalities. Subsequent assessments focus on evaluating associated risk factors, with the inclusion of consultations from cardiologists, pulmonologists, or nephrologists, as necessary, for a more refined risk stratification.

Ischemic heart disease emerges as a prevalent condition within this patient cohort, representing the leading mortality cause among those afflicted with TAAA. Transesophageal echocardiogram (TEE) serves as a pivotal tool for accurate cardiac function assessment. In cases of critically narrowed coronary artery disease, coronary artery revascularization via percutaneous interventions, such as balloon angioplasty or stenting, or surgical bypass, might be indicated prior to undertaking TAAA surgery. However, the imminent risk of aneurysmal rupture must be judiciously balanced against the coronary intervention risks and the potential delay introduced by such procedures.

9. Operative techniques

The patient is first placed in the supine position on the operating table. Following the induction of general anesthesia, endotracheal intubation is established utilizing a double-lumen tube to facilitate selective ventilation of a single lung during the procedure. A sheath is inserted into the internal jugular vein, and a pulmonary balloon-tipped catheter is navigated into the pulmonary artery for cardiac monitoring and rapid infusion. Large bore peripheral venous lines are placed for the administration of fluids and blood products. Temperature probes are positioned in the nasopharynx and bladder. Electrodes for electroencephalographic monitoring and motor and somatosensory evoked potentials are fixed for assessing the functionality of the central nervous system

and spinal cord, respectively (**Figure 3**). Subsequently, the patient is repositioned into a right lateral decubitus posture and a lumbar catheter is inserted into the third or fourth lumbar interspace for the monitoring and drainage of cerebrospinal fluid (CSF), maintaining the CSF pressure at or below 10 mmHg (**Figure 4**). The patient is then adjusted to a modified right lateral decubitus position, with a slight rotation of the hips to provide access to both groin areas. The surgical area is then sterilized and draped.

The incision is tailored to accommodate the extent of the aneurysm (**Figure 5**). A comprehensive thoracoabdominal incision is commenced posteriorly between the tip of the scapula and the spinous process, arcing along the sixth intercostal space to the costal cartilage, and then extending obliquely toward the umbilicus. The latissimus dorsi muscle is sectioned, and the insertion of the serratus anterior muscle is mobilized. Deflation of the left lung permits entry into the left thoracic cavity, which is typically required for extents II, III, and IV TAAAs. A modified thoracoabdominal incision, similar in initiation but terminating at the costal cartilage, offers optimal exposure for surgeries involving the descending thoracic aorta, particularly for extents I and V TAAAs, in which the aneurysm concludes above the renal arteries.

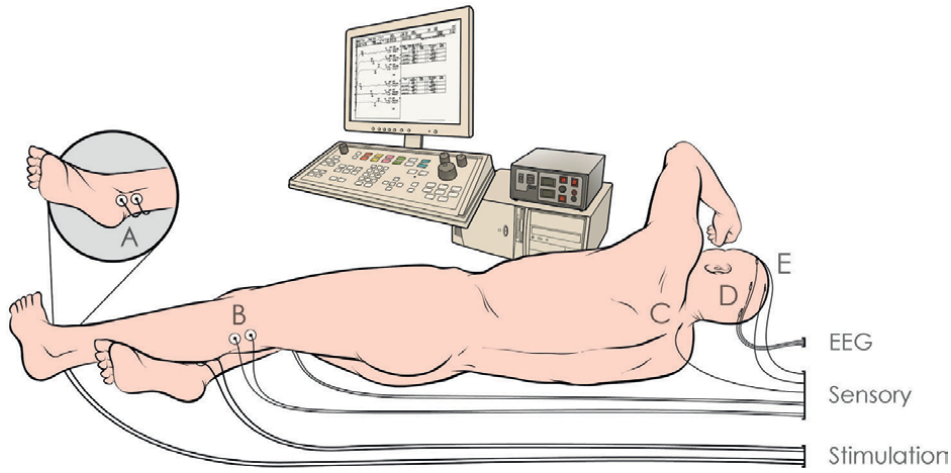


Figure 3.
Somatosensory and motor evoked potentials are recorded at three sites: the popliteal fossa (A, B), C5 (C) and the vertex (D).

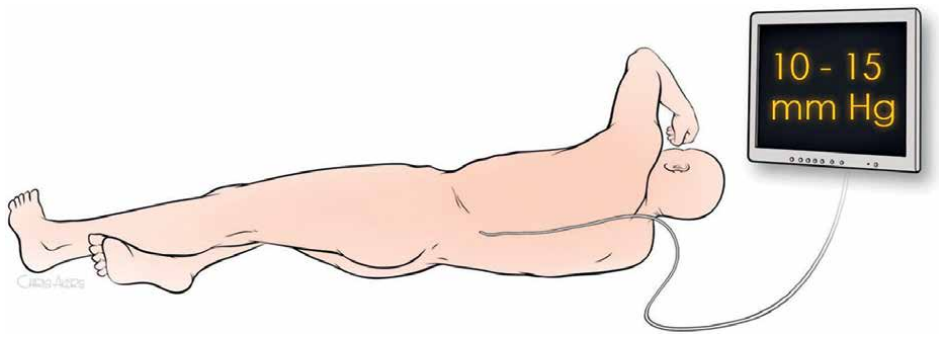


Figure 4.
Placement of the lumbar catheter in the third or fourth lumbar space to provide cerebrospinal fluid drainage and pressure monitoring.

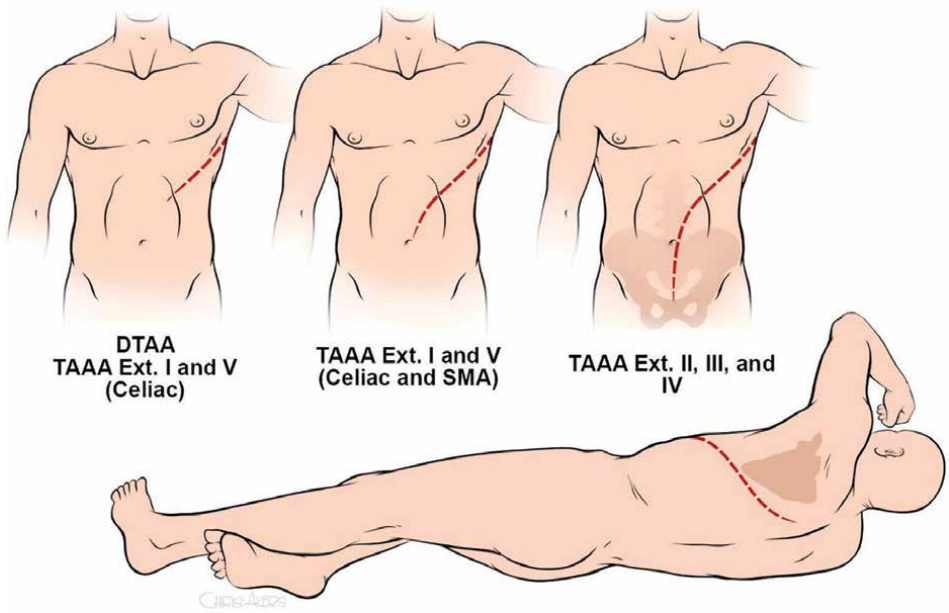


Figure 5.
Tailoring of thoracoabdominal incisions for aneurysm extent. DTAA = descending thoracic aortic aneurysms; TAAA = thoracoabdominal aortic aneurysm; SMA = superior mesenteric artery.

A self-retaining retractor is deployed to ensure uninterrupted exposure of the thoracic and abdominal regions during the operation.

Dissection is initiated at the lung hilum level, proceeding cephalad to the proximal descending thoracic aorta. The ligamentum arteriosum is identified and sectioned, with caution to avert damage to the left recurrent laryngeal nerve. The distal extent of the abdominal aneurysm is evaluated. The diaphragm's muscular component alone is divided, ensuring preservation of the left phrenic nerve (**Figure 6**). A retroperitoneal approach is then established, facilitating the medial visceral rotation of the spleen, bowel, and left kidney to the right side of the abdominal aorta. Anticoagulation is achieved with intravenous heparin (0.5–1 mg/kg body weight) in anticipation of distal aortic perfusion. An incision in the pericardium, posterior to the left phrenic nerve, permits direct observation of the pulmonary veins and left atrium. Cannulation is performed on the left inferior pulmonary vein. A centrifugal pump, equipped with an inline heat exchanger, is connected to the outflow cannula, and arterial inflow is established through the left common femoral artery via a Dacron graft sutured in an end-to-side manner, or through the descending thoracic aorta, if the femoral artery is not accessible, to commence distal aortic perfusion (**Figure 7**).

Protective clamps are positioned on the proximal segment of the descending thoracic aorta, immediately beyond the left subclavian artery and at the mid-thoracic region. In scenarios in which the aneurysm's initial segment is in close proximity to the left subclavian artery, the aortic segment lying between the left common and left subclavian arteries is subjected to clamping. The left subclavian artery undergoes individual clamping. Due to the risk associated with the graft-esophageal fistulas, the proximal anastomosis no longer employs the inclusion technique. Instead, the aorta is sectioned to detach it from the underlying esophagus (**Figure 8A**). A preference is shown for a woven Dacron graft, which has been treated with collagen or gelatin,

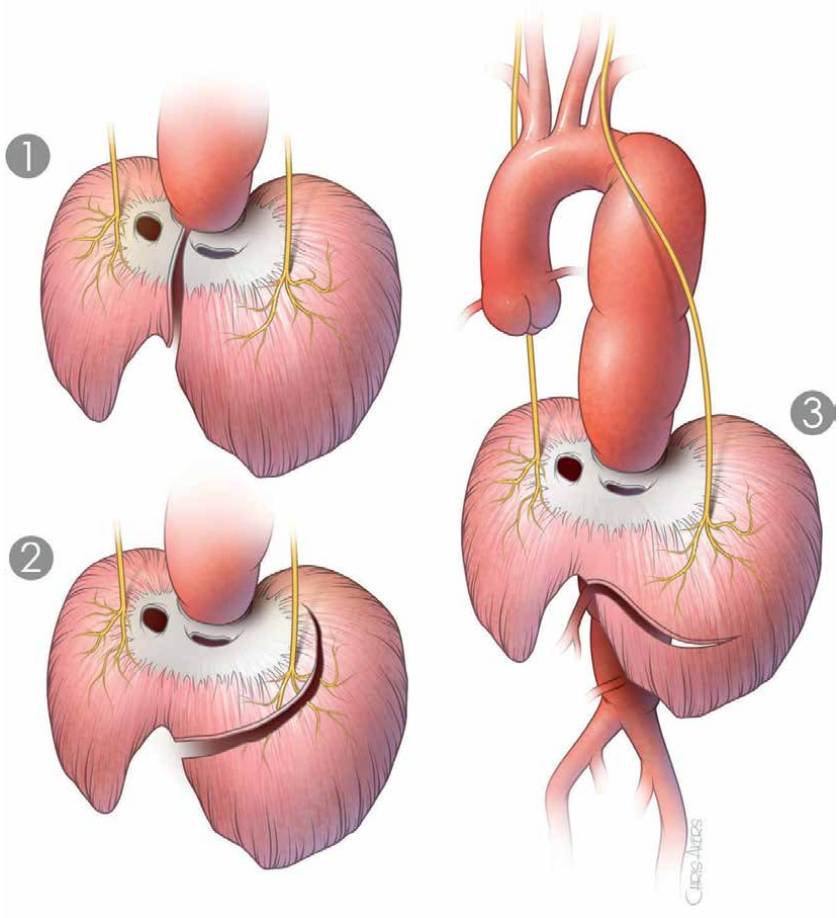


Figure 6.
In previous surgical practice, the diaphragm (1) was divided (2). Currently, only the muscular portion of the diaphragm is cut (3).

for the purpose of replacement. This graft is then sutured directly to the descending thoracic aorta in an end-to-end manner, employing a continuous 2-0 or 3-0 monofilament polypropylene suture. The integrity of the anastomosis is verified for any signs of hemorrhage. If needed, reinforced pledgeted sutures are placed for additional security. A sequential clamping method is implemented across all TAAAs. Upon the completion of the proximal anastomosis, the clamp on the mid-descending aorta is relocated distally toward the abdominal aorta at the level of the celiac axis to facilitate the reattachment of intercostal arteries, specifically those between the T8-T12 levels, except in circumstances involving occluded arteries, a significantly calcified aorta, or an acute aortic dissection. This process is conducted under the guidance of neuromonitoring techniques, such as motor and somatosensory evoked potentials. The absence of alterations in the neuromonitoring data pertaining to spinal cord function permits the team to proceed with distal anastomosis prior to reattaching the intercostal arteries without the risk of spinal cord damage. The distal clamp is then advanced to the infrarenal aorta, the abdominal aorta is incised, and the graft is threaded through the aortic hiatus. The celiac, superior mesenteric, and renal

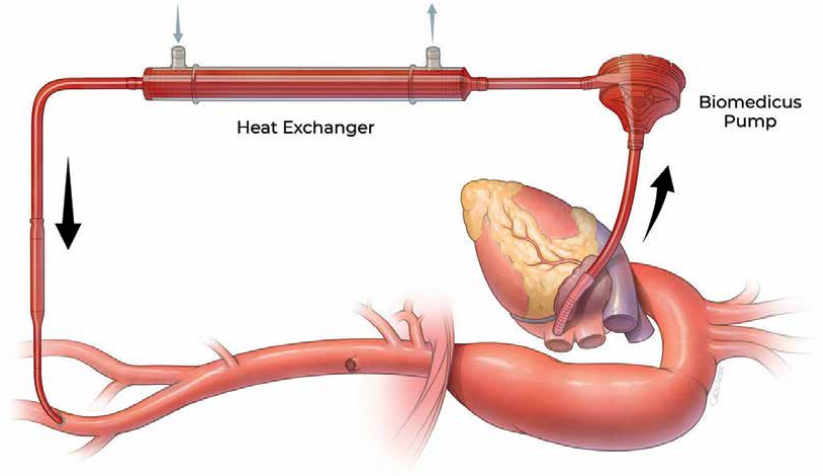


Figure 7.
Distal aortic perfusion from the left inferior pulmonary vein to the left common femoral artery.

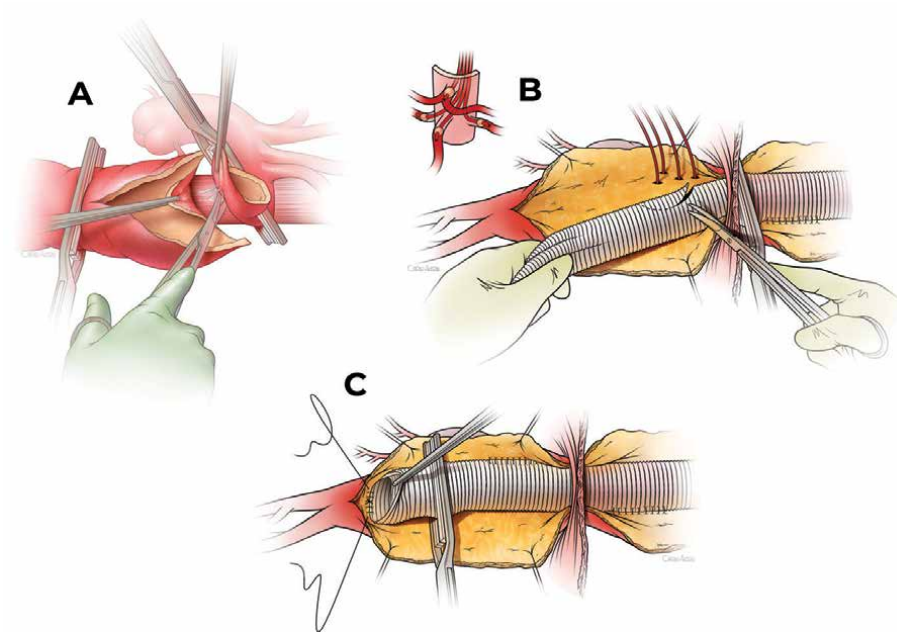


Figure 8.
Sequential clamping and graft replacement. Padded clamps are placed on the proximal and mid-distal descending thoracic aorta. A: the proximal part of the aneurysm is opened. The aortic neck is completely transected and separated from the esophagus. The proximal anastomosis is fashioned. Subsequently, the patent lower intercostal arteries are reattached via an elliptical hole in the graft. B: the proximal clamp is then moved onto the graft to restore pulsatile flow to the intercostal arteries, and the graft is pulled through the hiatus into the abdomen. The distal clamp is reapplied onto the infrarenal aorta. The remainder of the aneurysm is opened. Balloon-tipped catheters are inserted into the celiac, superior mesenteric, and renal arteries to permit perfusion. C: an elliptical hole is made in the graft for reimplantation of the visceral and renal arteries.

arteries are identified and cannulated for perfusion using balloon-tipped catheters of either 9- or 12-Fr, chosen based on the ostia's dimensions (**Figure 8B**). The delivery of cold perfusate at 4°C to the visceral organs is adjusted based on the proximal aortic

pressure, maintained within a range of 300–600 mL/min. The renal temperature is closely monitored and maintained at an approximate 15°C. Typically, visceral vessels are reattached employing the inclusion technique. Following the completion of this anastomosis, the proximal clamp is advanced beyond the visceral patch, restoring pulsatile circulation to the visceral organs and kidneys. The terminal graft anastomosis is finalized at the aortic bifurcation. Generally, an island patch is utilized for the reattachment of the celiac, superior mesenteric, and both renal arteries. In instances in which either the right or left renal artery is situated at a considerable distance from the other arteries, a separate interposition bypass graft is necessitated for its reattachment.

For patients diagnosed with connective tissue disease (e.g., Marfan syndrome), or those younger than 60 years, the use of a visceral patch is discontinued, due to the elevated risk of recurrent patch aneurysms. Instead, a commercially available woven Dacron graft with side-arm grafts measuring 10 mm and 12 mm is employed for the independent attachment of the celiac, superior mesenteric, and left and right renal arteries. Should intercostal reattachment be executed, reinstating pulsatile blood flow to the reattached intercostal arteries, an end graft or loop graft has superseded the island patch for the reattachment of intercostal arteries (**Figure 8C**).

The patient is gradually withdrawn from partial bypass as the core body or nasopharyngeal temperature reaches 36°C. Protamine sulfate is administered in a dosage of 1 mg per 1 mg of heparin used, and both the atrial and femoral cannula are removed. Following the achievement of hemostasis, two or three 36-Fr chest tubes are placed within the left pleural cavity. The diaphragm is sutured together using a running 1-0 polypropylene stitch. The left lung is re-expanded. The surgical incision is closed following standard procedures. The patient is then placed in the supine position and a single-lumen endotracheal tube is exchanged for the double-lumen tube. If the vocal cords are swollen, the double-lumen tube is kept in place until the swelling resolves. The patient is then transferred to the intensive care unit (ICU).

10. Postoperative management

Efforts are made to expedite the patient's awakening to assess neurological function. Most patients are candidates for extubation within a few hours postadmission to the ICU. Replacement of blood loss is generously undertaken and maintain hemoglobin above 8–9 g/dL. The patient's systolic arterial pressure is maintained within the range of 130–160 mmHg to ensure sufficient perfusion of organs, with particular attention to the spinal cord. CSF pressure is measured and drained with a maximum of 15 mL/h to maintain a pressure of 10 mmHg or below. The goal is to wean the patient from mechanical ventilation by the first day following surgery. Resumption of an oral diet is advised upon the patient's extubation.

Following recovery from anesthesia, neurological evaluation is performed hourly to detect potential delayed neurological deficits. Indicators of concern for such deficits include unstable arterial blood pressure, hypoxemia, low hemoglobin levels (below 10 g/dL), or elevated CSF pressure (exceeding 15 mmHg). CSF drainage is terminated on the third day after surgery if the patient remains neurologically intact. The duration of ICU stay typically ranges from 3 to 4 days, contingent upon the patient's neurological and pulmonary status, after which the patient is transferred to a telemetry unit. Initiation of physical therapy begins in the ICU and is maintained throughout the duration of the hospital stay.

Annual CT scans are advocated to monitor for the emergence of new aneurysms or the formation of graft-related pseudoaneurysms. The interval of follow-up visits or CT scans is adjusted based on the etiology of TAAA. For instance, patients with residual unoperated aortic dissection, connective tissue disorders (such as Marfan syndrome), a familial history of aortic aneurysms, or concurrent aneurysms may require more frequent surveillance.

11. Surgical outcomes

Mortality rates for patients undergoing TAAA repair and descending thoracic aortic aneurysms fluctuate significantly, observed within a range of 4–21% [9, 42–44]. This variation in outcomes can be attributed to the diversity within the patient demographics and the varying levels of expertise among the medical teams. According to aggregated data collected by the authors over the period from January 1991 to July 2012, a cohort of 1511 individuals underwent procedures for the repair of TAAA and descending thoracic aortic aneurysms. Within this group, males constituted 64%, with a median age of 67 years, and ages ranging from 8 to 91 years. Notably, approximately 7% of these surgeries were conducted as emergency interventions in response to either free or contained ruptures of the TAAA or descending thoracic aortic aneurysms. The current data indicate that the 30-day postoperative mortality rate is roughly 15%. However, in patients demonstrating normal renal function, as evidenced by a glomerular filtration rate greater than 90 mL/min/1.73 m^2, the early mortality rate is significantly lower, recorded at 5.9%. Multivariable analysis has facilitated the identification of advanced age, renal failure, and paraplegia as significant predictors of mortality risk [45]. Despite these risks, it is noteworthy that approximately 70% of patients experience recovery from TAAA surgeries without encountering severe postoperative complications [46]. The 5-year survival rate post-TAAA repair is estimated between 60% and 70%. Further analysis has illuminated several factors that negatively impact long-term survival, including advanced age, the presence of extent II TAAA, renal failure, the requirement for emergency surgical intervention, cerebrovascular disease, and active tobacco smoking [45].

11.1 Neurological outcomes

The occurrence of postoperative neurologic deficits constitutes the most severe complication following TAAA repair. Cross-clamping the descending thoracic aorta precipitates immediate ischemia of the spinal cord, primarily due to the abrupt cessation of perfusion to this region coupled with a consequent rise in CSF pressure. Historically, in the era characterized by the "cross-clamp-and-go" approach, the duration of clamp application emerged as the principal determinant of neurologic deficits. The current strategy for mitigating such risks includes enhancing spinal cord perfusion pressure directly through distal aortic perfusion and indirectly by minimizing CSF pressure to 10 mmHg or below. Evidence from both animal and human studies has substantiated that the drainage of CSF effectively lowers CSF pressure, thereby, facilitating improved perfusion of the spinal cord during periods of aortic cross-clamping [45, 47, 48].

In this comprehensive analysis, adjunctive strategies comprising distal aortic perfusion and CSF drainage, along with moderate hypothermia, were employed in 76% of the patient cohort, totaling 1155 out of 1511 patients. The implementation of these combined adjunctive measures has been correlated with a substantial 44% reduction

in the likelihood of neurologic deficits across all extents of aneurysm. Specifically, the overall incidence of neurologic deficits in patients not receiving adjunctive care was documented at 4.5%, compared to a reduced rate of 2.5% in those who did. Despite the duration of aortic cross-clamp application continuing to be a significant indicator of paraplegia risk, the introduction of adjunctive measures has effectively extended ischemic tolerance. For patients with high-risk extent II aneurysms, the employment of these adjuncts decreased the incidence of neurological deficits from 30% to 9% at an average aortic cross-clamp duration of 75 minutes (**Figure 9**). When analyzing all aneurysm extents collectively and excluding cases without adjunctive measures, the use of adjuncts has significantly lowered neurologic deficit rates to a range of 1–5%, simultaneously enhancing tolerance to clamp times.

Since 1991, the adjunctive use of distal aortic perfusion, CSF drainage, and reimplantation of segmental arteries has been a standard practice for patients undergoing elective TAAA repair. Among a subset of 1004 patients, immediate postoperative neurologic deficits, including paraplegia or paraparesis upon emergence from anesthesia, were observed in 2.4% of patients treated with adjuncts, compared to 6.8% of those without [45]. This strategic combination has effectively reduced the cumulative incidence of neurologic deficits to 3.3% for TAAA repairs. Historically, the repair of extent II TAAAs was associated with the highest rate of neurologic deficits, reaching 30–40% in the pre-adjunct era. With the introduction of adjunctive measures, the incidence of immediate neurologic deficits for extent II TAAA repairs has been reduced to 7.2%. In addition to aneurysm extent, other perioperative risk factors for immediate neurologic deficits include advanced age, emergency surgery, renal dysfunction, active tobacco use, and cerebrovascular disease. The combined application of intraoperative distal aortic perfusion and perioperative CSF drainage effectively prevents 1 neurologic deficit in every 20 cases across all patient groups, and 1 in 5 for patients with extent II TAAA.

The advancements in protective measures for the spinal cord during TAAA repair have significantly reduced the occurrence of neurologic complications, thereby highlighting the emergence of delayed onset neurologic deficit (DND) as a pivotal clinical concern (**Figure 10**). The precise mechanisms contributing to the development of DND remain elusive. It is hypothesized that DND following TAAA repair may be attributed to a "second hit" phenomenon. While intraoperative adjuncts are

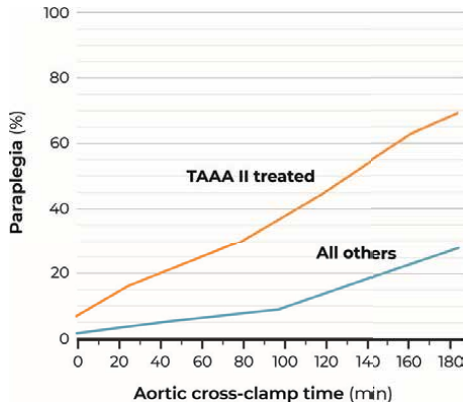


Figure 9.
In extent II aneurysms, the probability of developing neurologic deficits increases with increasing clamp time, but the use of adjunct distal aortic perfusion and CSF drainage reduces the chances of neurologic deficit by prolonging ischemic tolerance.

effective in safeguarding the spinal cord and diminishing the incidence of immediate neurologic deficits, the spinal cord continues to be susceptible to injury in the early postoperative phase. Potential additional ischemic events, triggered by hemodynamic fluctuations, any elevation in CSF pressure, or a combination of both, may serve as the "second hit" leading to DND. Consequently, in instances of DND development, CSF is actively drained to mitigate the compartment pressure.

To enhance postoperative spinal cord perfusion and oxygenation, strategies involve maintaining the mean arterial pressure above 90–100 mmHg, ensuring hemoglobin levels exceed 10 mg/dL, and sustaining a cardiac index above 2.0 L/min/m^2. Upon the onset of DND, interventions aimed at augmenting spinal cord perfusion are promptly implemented. CSF pressure is reduced to below 10 mmHg. For individuals diagnosed with DND, CSF drainage is maintained for a minimum duration of 72 hours. Employing this comprehensive management strategy for DND has resulted in a noted improvement in neurologic function in 57% of affected patients [49]. Specifically, functional recovery was observed in 75% of patients when the CSF drain was intact at the time DND was identified, compared to a 43% recovery rate in patients requiring CSF drain reinsertion subsequent to DND manifestation.

11.2 Renal failure

Acute postoperative renal failure is characterized by a daily increase in serum creatinine levels by 1 mg/dL over two consecutive days or the necessity for hemodialysis intervention. The incidence of acute renal failure among patients undergoing TAAA repairs is reported between 5% and 40%, correlating with mortality rates reaching up to 70% [50]. The prognosis for long-term survival among patients undergoing hemodialysis is notably poor. Known predictors for acute postoperative renal failure include preexisting chronic renal insufficiency and ruptured aneurysms. While it has been posited that patients with extensive Type II TAAA are at elevated risk for postoperative renal failure, the extent of TAAA has not been definitively proven as a significant prognostic factor and the high incidence of postoperative renal failure remains a significant concern. The search for an optimal renal protection strategy continues to be of paramount importance.

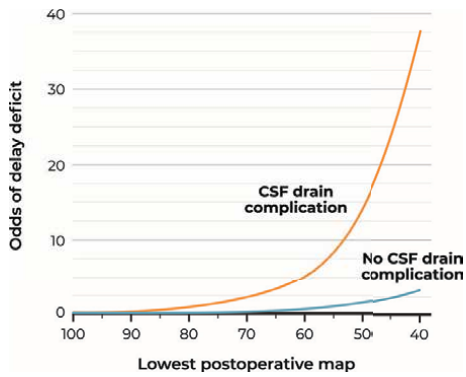


Figure 10.
Odds of delayed neurologic deficit by lowest postoperative mean arterial blood pressure, with or without cerebrospinal fluid drain complication. Odds are referenced to one. For example, a patient with a mean arterial blood pressure of 40 mmHg and a cerebrospinal fluid drain complication would have 40:1 odds of delayed neurologic deficit.

11.3 Endovascular repair

Since the inaugural success of thoracic stent graft repair documented in 1994 [51], the endovascular treatment of thoracic aortic diseases has rapidly advanced. The first device, developed by WL Gore in Flagstaff, AZ, was the initial thoracic aortic device to be granted approval by the United States Food and Drug Administration in 2005. Endovascular therapy offers the advantages of reduced morbidity and mortality when contrasted with traditional open surgical approaches. The endovascular management of TAAA necessitates the revascularization of visceral and renal vessels and is presently conducted via three distinct methodologies: hybrid repair; employment of parallel grafts; and utilization of bespoke branched and fenestrated devices.

The hybrid method integrates open debranching of the aorta with the subsequent endovascular exclusion of the aneurysmal segment, involving the bypass of visceral and renal arteries from an iliac artery. This approach circumvents the need for open thoracotomy, aortic cross-clamping, and single-lung ventilation [52–54]. Despite its technical feasibility, the associated risks of morbidity and mortality are significantly high. Recent scholarly works have indicated no substantial difference in outcomes between hybrid and open TAAA repairs, suggesting that the application of hybrid repair may be confined to individuals ineligible for open repair or other endovascular techniques due to anatomical constraints or the urgency of the situation [55–57].

An alternative strategy involves the use of parallel grafts, also known as chimneys, periscopes, or snorkels (collectively referred to as CHIMPS), to maintain perfusion to branch vessels. This method has been prominently advocated by Lobato et al. in Brazil, demonstrating a high rate of technical success and primary patency with a relatively low mortality rate [58]. The advantages of parallel stent grafts include their modularity and adaptability to diverse anatomical configurations, making them particularly beneficial for patients with challenging vessel characteristics. However, this technique is not without drawbacks, such as the potential for endoleaks through the gutters, which may lead to aneurysm sac pressurization. A recent systematic review of the chimney graft technique included 75 patients and a total of 96 branches, with a reported 98.9% early success rate with a perioperative mortality rate of 4% [59].

Total endovascular repair of TAAA, employing custom-made branched and/or fenestrated devices, represents the culmination of these approaches. Significant series and multicenter prospective studies have reported varying rates of perioperative mortality (2.5–12.5%) and complications, underscoring the need for continued innovation to enhance outcomes [60, 61]. The largest series by Dias-Neto et al. on their experience with 1947 patients reported a perioperative mortality and/or permanent paraplegia rate occurred in 14% of the single-stage approach and 6% of multi-stage approach [62].

Despite considerable advancements, the evolution of endovascular technologies for TAAA repair persists, with the future likely to see the development of modular, off-the-shelf devices capable of accommodating a broad spectrum of clinical scenarios.

Disclosures

Dr. Estrera is a consultant for WL Gore, CryoLife, Edwards Lifesciences, and Terumo Aortic. The other authors have no conflicts of interest. No outside funding was provided for this report.

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