# Chapter 5
# Open Thoracoabdominal Aortic Aneurysm Repair

**Mark F. Conrad and Srihari K. Lella**

## Introduction

Aneurysms that simultaneously involve the thoracic and abdominal aorta and/or those that extend through the visceral aortic segment are referred to as thoracoabdominal aortic aneurysms (TAA). These are uncommon when compared to isolated infrarenal aortic aneurysms and comprise no more than 2–5% of the total spectrum of degenerative aortic aneurysms. However, the tendency toward aortic enlargement is strong in this population as up to 30% of the said patients will also develop an abdominal aortic aneurysm in their lifetime. The modern era of open surgical management of TAA has seen a shift from a straight clamp-and-sew approach to the addition of adjunctive measures aimed at reducing ischemia to the spinal cord, visceral vessels, and lower extremities and the potential for significant morbidity. Indeed, a number of surgical and non-surgical adjuncts (many discussed herein) intended to minimize distal ischemia and improve outcomes have been investigated, and our approach to these complex aneurysms has evolved over time. Despite improvements in operative strategies, open repair of TAA still carries a 5–10% risk of perioperative morbidity and mortality in the form of renal, respiratory, and spinal cord ischemic complications. Endovascular repair of TAA using modular grafts with branched and fenestrated technologies has been successful but is limited by anatomic considerations, and a lack of general availability as the procedure is only performed in select centers with individual device exemption protocols. Indeed,

M. F. Conrad (✉)
Vascular and Endovascular Surgery, St. Elizabeth's Hospital, Brighton, MA, USA
e-mail: Mark.conrad2@steward.org

S. K. Lella
Vascular and Endovascular Surgery Resident, Massachusetts General Hospital, Harvard Medical School, Boston, MA, USA

© The Author(s), under exclusive license to Springer Nature Switzerland AG 2023

S. S. Hans et al. (eds.), *Primary and Repeat Arterial Reconstructions*,
https://doi.org/10.1007/978-3-031-13897-3_5

despite advances in endovascular devices and techniques, there remains a cohort of patients with TAA who will require open repair, and this is unlikely to change in the foreseeable future.

## Initial Evaluation

### *Anatomic Classification*

TAA are classified according to the scheme originally devised by Crawford, which in the most basic terms considers whether the lesion is primarily a caudal extension of a descending thoracic aneurysm or a cephalad extension of a total abdominal aortic aneurysm (Fig. 5.1). This classification is especially useful in patients requiring operative repair since it has direct implications for both the technical conduct of operation and the incidence of operative complications, in particular, ischemic spinal cord injury (SCI). There is considerable variation in the operative approach required to manage different TAA lesions. For example, a type IV TAA can be repaired with the clamp-and-sew approach and should be accomplished with an expected morbidity and mortality that is similar to that of on open AAA repair. But the same cannot be said for the more extensive type II TAA lesions where the entire descending thoracic aorta is involved and repair is accomplished using distal aortic perfusion with atrial–femoral bypass.

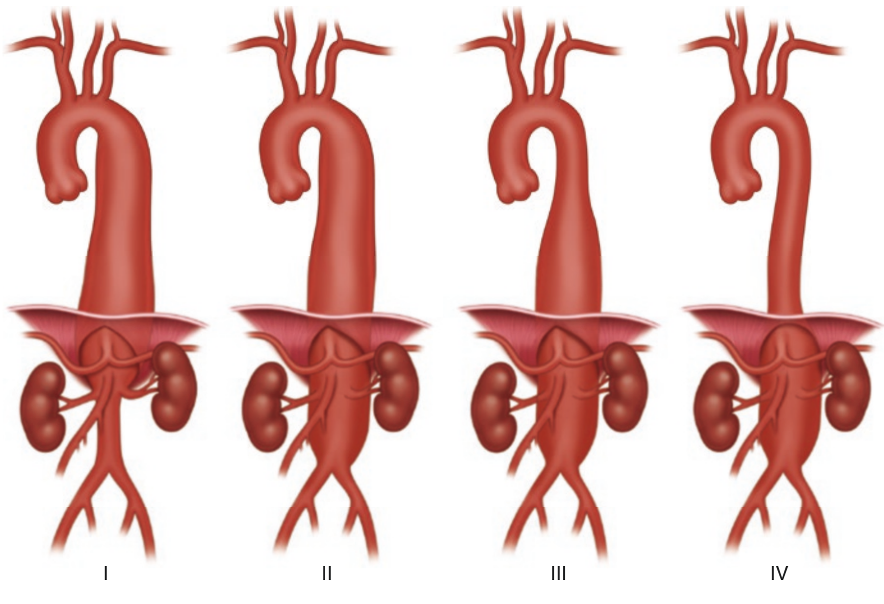


**Fig. 5.1** Crawford classification of the extent of thoracoabdominal aortic aneurysms

## *Natural History*

The expected natural history of TAA is progressive enlargement and eventual rupture regardless of etiology or location. Since thoracic aneurysms are uncommon when compared to AAA, fewer natural history studies are available. The general consensus is that the expected mean rate of growth for TAA is around 0.2 cm per year. This is accelerated in patients with dissections and connective tissue disorders such as Marfan syndrome. The size of the aorta at initial diagnosis has been shown to be an important predictor of future dilation, but there still remains substantial variation in individual aneurysm growth rates making prediction of future aortic size difficult. Population-based studies place the incidence of TAA at 5–6 per 100,000 people with a 5-year actuarial survival of 13% if left untreated and aneurysm rupture is identified as the cause of death in nearly 75% of untreated patients. Factors associated with increased risk of rupture include increasing aneurysm diameter, a rapid rate of expansion, the presence of chronic obstructive pulmonary disease (COPD), steroid use, female gender, advanced age, and the presence of renal insufficiency. Contemporary series indicate that the rupture risk is negligible in TAA less than 5 cm, equivalent to the risk of surgical morbidity in the 5–6 cm range, and it increases substantially at aneurysm diameters larger than 6 cm and/or growth rates of ≥10 mm per year. To wit, 6 cm is the surgical threshold for consideration of intervention in patients with degenerative TAA. For patients with TAA secondary to chronic dissection and/or those with Marfan syndrome, a 5.0–5.5 cm threshold is often used.

## *Clinical Presentation*

Although patients commonly present in an asymptomatic fashion with incidental detection during radiologic surveillance for other disease processes, symptoms referable to TAA do occur and should be evaluated in a timely manner. In addition to the acute onset of severe pain, which may be associated with aneurysm expansion, rupture, and/or acute dissection, large thoracic aneurysms may produce symptoms of back, epigastric, or flank pain related to either compression of local structures or chronic inflammatory changes of the mediastinal pleura. Unlike AAA where back pain usually indicates an acute event, the pain associated with thoracic aneurysms may be atypical or chronic in nature and the presence of even uncharacteristic pain is an independent risk factor of rupture and should be taken seriously. When the aneurysm erodes into the thoracolumbar spine or chest wall, complaints of chest and back pain can be prominent and, again, may be present for weeks or even months. The new onset of hoarseness can be related to a left recurrent laryngeal nerve palsy, while compression or erosion of the tracheobronchial tree or pulmonary parenchyma will produce a chronic cough, hemoptysis, dyspnea, or dysphagia lusoria. Perhaps related to reluctance to recommend operation because of the threat of surgical morbidity, up to 40% of thoracic aortic aneurysm patients will present with symptoms. This explains the higher incidence of patients treated for rupture when compared to AAA series. Our results are consistent with those available from a review of the literature indicating that some 25% of patients will be treated under urgent or emergent circumstances with approximately half of these presenting with a frank rupture. Unfortunately, we and others have demonstrated that such non-elective operations are associated with a significant increase in morbidity.

## *Diagnostic Imaging*

Accurate and complete radiographic evaluation is essential for precise operative planning with no equivocation in the surgeon's mind as to the proximal and distal extent of aortic resection. In contemporary practice, a dynamic, fine-cut, contrast-enhanced CT angiogram with or without helical reconstruction provides the physician with important information. This includes the qualitative assessment of the aorta at the proposed site of proximal cross-clamp, the location and patency of the visceral vessels, and the topography and location of the origins of the renal arteries and the adequacy of renal perfusion. Imaging will also identify the distal extent of the aneurysm and the status of the iliac vessels including the presence of occlusive disease in the pelvis that could decrease the efficacy of distal aortic perfusion.

Accurate assessment of the size of thoracic aortic aneurysms is contingent upon measurement in the appropriate perpendicular plane. When imaging a tortuous aorta or evaluating sections through the aortic arch or lower descending aorta, it is important to understand that individual axial images may section the aorta in a plane that is off axis. Such measurements result in an erroneous overestimation of aortic diameter and underscore the importance of personally viewing CT scans prior to initiation of therapy. One way to avoid this error is through three-dimensional reconstruction of the thoracic aorta with determination of the centerline of axis that ensures that any cross-sectional measurement will be perpendicular to the aortic axis. The quality of current CT scanners with three-dimensional reconstruction is exceptional, and in our practice, this has become the image modality of choice for the evaluation and treatment of thoracic aortic aneurysms.

## *Preoperative Evaluation*

The majority of patients who undergo TAA resection will have degenerative aneurysms, and as such, most will be around 70 years of age with a history of hypertension. A history of cigarette smoking with some form of COPD is common, and up to 25% of patients have severe disease with an FEV1 < 50% predicted.

Cerebrovascular disease is also common, and up to 30% of patients will have some degree of associated visceral or renovascular disease, which could add complexity to the visceral portion of the repair. Indeed, the presence of extreme preoperative azotemia (GFR <30) constitutes a relative contraindication to elective repair unless preoperative studies show that there is some potential for recovery of function with renal artery reconstruction as the mere presence of renal disease is a predictor of increased mortality.

Despite the firm literature base against routine preoperative cardiac testing, all patients should be evaluated with physiologic testing to assess perioperative myocardial ischemic potential. In addition, patients with a history or symptoms suggestive of heart failure should have an assessment of left ventricular function. While patients with significant impairments of pulmonary reserve can usually be detected on a historical basis alone, we routinely obtain preoperative pulmonary function studies. Preoperative consultation with a pulmonologist for optimization of bronchodilator therapy and pulmonary toilet is an important component in the management of patients with significant COPD. However, institution of preoperative steroid therapy with the intent of improving respiratory function is contraindicated since we have observed this maneuver to precipitate aneurysm rupture. Finally, advanced age is an important component only in as much as it is accompanied by overall fragility and impaired functional status.

## Surgical Treatment

### *Treatment Options*

Graft replacement by direct surgical approach is the current standard of care for TAA. Total endovascular repair continues to evolve but remains limited by a lack of commercial availability of branched/fenestrated grafts and anatomic considerations. The hybrid approach that combines visceral artery debranching with endovascular exclusion of the TAA has allowed surgeons who lack the resources to perform distal perfusion to offer TAA repair to their complex patients, but the reported results compare poorly with open repair at high-volume centers. Medical therapy is appropriate in patients who are frail and have prohibitive associated comorbid conditions or small aneurysms. This consists of aggressive blood pressure control with beta-blockade, which has been shown to decrease the rate of aortic dilation. The goal of antihypertensive therapy is to keep the systolic pressure at a low-normal range of 105–120 mmHg, and this often requires additional medications to maintain. Risk factor modification is another important aspect of patient education regarding TAA. Patients should be counseled regarding smoking cessation and given appropriate support to achieve this goal as elective open TAA repair should not be offered to someone who is actively smoking.

## *Renal and Spinal Cord Protection*

Outcomes of TAA repair are closely correlated with renal and spinal cord complications; accordingly, operative adjuncts to minimize these complications have been principal drivers of the technical conduct of the operation. Consistent with a firm literature base supporting regional hypothermic protection of the kidneys, our approach involves direct installation of renal preservation fluid (lactated Ringer's with 25 g of mannitol/L and 1 g/L methylprednisolone at 4 °C) into the renal ostium during ischemia. In type IV TAA, the left renal artery is transected prior to placing the proximal aortic clamp, and 250 mL of the renal cold solution is instilled into the artery followed by a continuous drip through a six French perfusion balloon-tipped catheter. Once the aorta is opened, renal cold is infused in the right renal artery through the ostium, which should be coursing down and away from the surgeon. In more complex TAA (type I–III), where distal perfusion is used, renal cold is given prior to the start of the visceral reconstruction. Experience has shown that such an infusion will result in a rapid decline of renal parenchymal temperature to 15 °C after the bolus infusion. During the continuous infusion, renal core temperatures remain in the 25 °C range as monitored by direct temperature probes in the renal cortex.

It is evident that most of the nuances, which drive the technical conduct of TAA repair, are directed toward the prevention of SCI, to wit, the abundance of adjuncts, which have been championed to minimize this dreaded complication. To date, only cerebrospinal fluid drainage is appropriately evidence based and used by most surgeons. Other adjuncts aimed at preserving spinal cord blood flow such as intercostal (IC) vessel reconstruction have been championed and/or routinely practiced despite its empiric nature and evidence base limited to retrospective studies including our own. The alternative position with specific respect to IC vessel reconstruction is that it is unnecessary (related to the collateral network) and expends cross-clamp time and blood turnover. Distal aortic perfusion via left atrial–femoral bypass used in conjunction with intraoperative motor-evoked potential (MEP) monitoring to dynamically assess spinal cord ischemia during the operation has replaced epidural cooling as our principal cord protective strategy in patients with more extensive TAA (type I–III). This is based upon a series of studies that used magnetic resonance imaging combined with intraoperative MEP to show that individual intercostal vessels were typically not critical for cord preservation and most collaterals that support the cord originated from the pelvis (i.e., hypogastric arteries); thus, preservation of continuous perfusion of the pelvis is logical and prudent. The addition of MEP monitoring affords the surgeon objective criteria to direct selective IC vessel reconstruction and thus replaces the subjective application of or routine posture toward intercostal vessel reimplantation. The use of MEP monitoring does mandate a departure from anesthetic techniques typically used in North America, and the technical requirements of such monitoring can only be satisfied by a dedicated team specialized in neurophysiology.

# Technical Components

## *Operative Exposure*

Irrespective of individual preferences concerning the technical components of the operation, the key to operative success remains the provision of broad, continuous exposure of the entire left posterolateral aspect of the thoracoabdominal aorta (Fig. 5.2). The patient is positioned on the table in the right lateral decubitus position. The location and extent of the thoracic portion of the incision are determined by the proximal extent of the aneurysm as the posterior portion of a standard posterolateral thoracotomy incision is only necessary for type I and type II aneurysms. We keep the thoracic portion of the incision low and have found that the fifth or sixth interspace with posterior division of the sixth or seventh rib provides adequate exposure for even the more proximal aneurysms (Fig. 5.3). The costal margin is divided at the level of the sixth interspace, and a self-retaining retractor system is placed in order to ensure continuous exposure of the entire operative field. A thoracoabdominal incision at the eighth interspace will usually provide adequate exposure for a type IV TAA, and a double lumen tube for deflation of the left lung is generally not necessary in these cases. The abdominal portion of the incision is not extended to the midline; rather, it is kept well lateral on the abdominal wall along

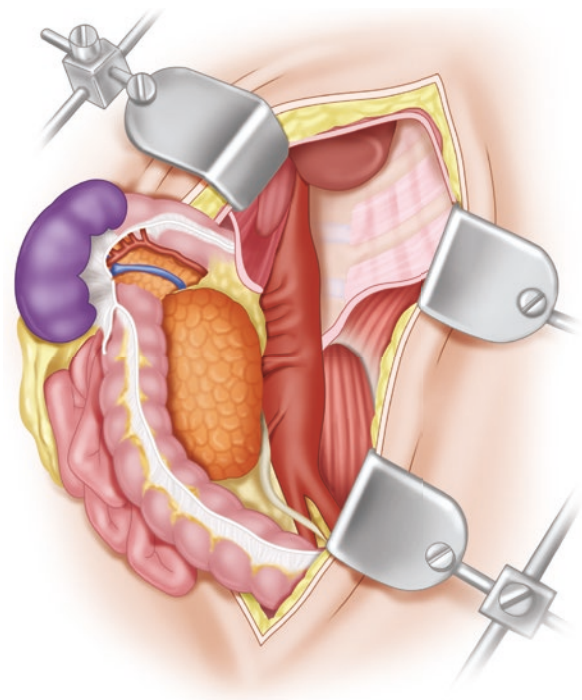

**Fig. 5.2** Exposure for TAA repair. Exposure of the left chest and abdomen through a thoracoabdominal incision with the left kidney, spleen, pancreas, and left colon reflected up. This exposes the entire left posterolateral aspect of the TAA

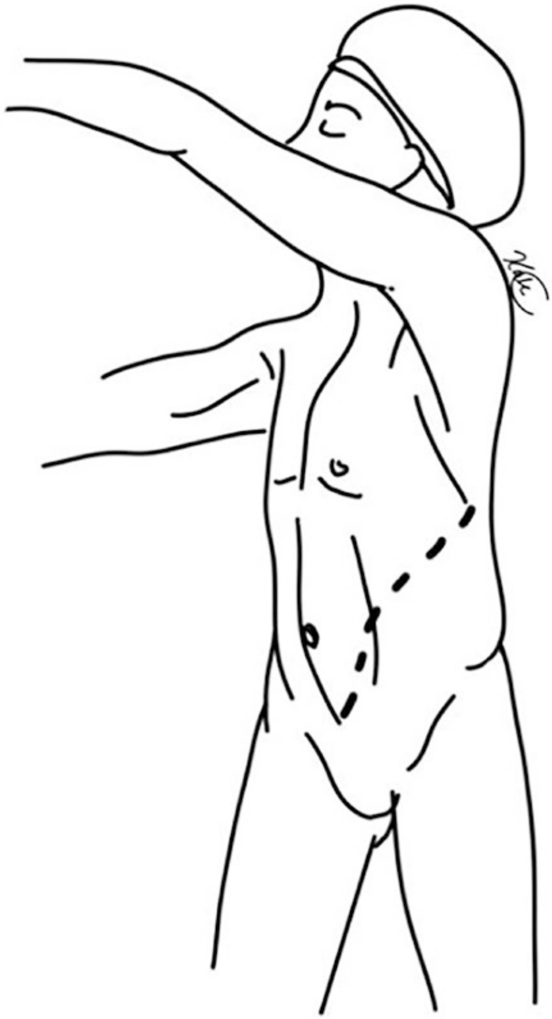

**Fig. 5.3** Positioning for TAA repair. The thoracoabdominal incision is made in the ninth–fifth interspace depending upon the proximal extent of dissection

the edge of the rectus. The advantage of this approach is that it allows the visceral contents to lie within the abdominal cavity, thus decreasing evaporative fluid and heat losses. The abdominal portion of the incision is transperitoneal allowing direct inspection and assessment of the visceral circulation when the case is completed.

Exposure of the left posterolateral aspect of the abdominal aorta is obtained by entering the plane posterior to the spleen, left kidney, and left colon. The abdominal contents are then reflected to the patient's right and the left ureter is identified and preserved under laparotomy pads (Fig. 5.4). The retroperitoneal fatty and lymphatic tissues overlying the aorta are transected with electrocautery, and the renal–lumbar vein that courses across the aorta is identified and divided. Located topographically

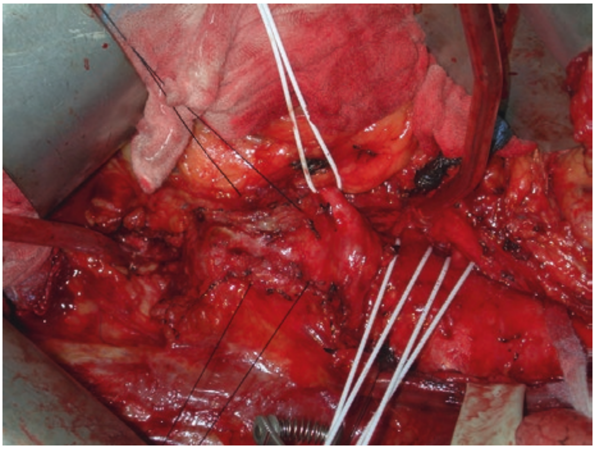

**Fig. 5.4** Operative photo of exposure of the visceral segment. The vessel loop at 12 o'clock is around the left renal artery and the two loops at 6 o'clock are around the superior mesenteric and celiac arteries

close to this vein is the left renal artery. Once identified, the left renal artery is dissected toward its origin on the aorta. This serves as a suitable point to initiate the cephalad and caudal division of the retroperitoneal tissues over the aorta inferiorly and division of the median arcuate ligament and diaphragmatic crura superiorly.

There are several methods by which the incision in the diaphragm may be managed. The quickest and simplest method that affords excellent exposure is direct radial division of the diaphragm from underneath the costal margin to the aortic hiatus. This approach, however, will irrevocably paralyze the left hemidiaphragm and ultimately contribute to postoperative respiratory embarrassment. A second approach involves the circumferential division of the diaphragm through its muscular portion leaving a few centimeters attached laterally to the chest wall. There is benefit to preserving the phrenic innervation to the left hemidiaphragm by dividing only a portion lateral to the phrenic nerve insertion and then taking down the muscular fibers of the aortic hiatus. A large Penrose drain can be passed around the diaphragm pedicle and used to retract superiorly and inferiorly as needed during the reconstruction. We have applied this method liberally, particularly in patients with evidence of preoperative pulmonary compromise (Fig. 5.5).

## *Dissection of Left Pleural Space*

After deflation of the left lung, the thoracic component of the dissection is typically straightforward. Electrocautery is used to divide the mediastinal pleura over the aneurysm and proximal aorta. For type I and type II aneurysms, proximal control of the aorta in the region of the left subclavian artery origin is necessary. Further mobility of the vagus nerve is gained by dividing it distal to the origin of the left

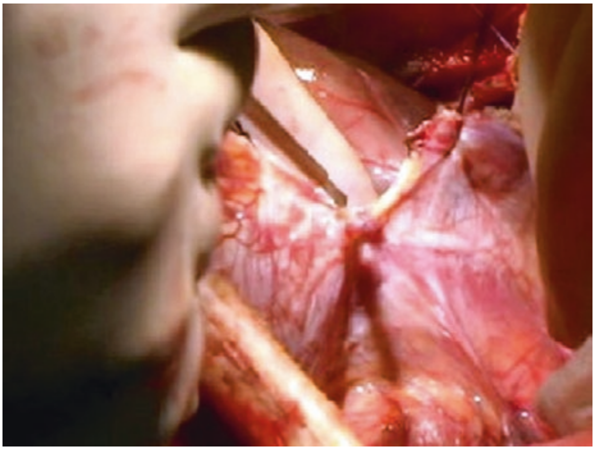

**Fig. 5.5** Diaphragm management during extensive thoracoabdominal repair. Radial division provides rapid, direct, and uncompromised aortic exposure but causes left hemidiaphragm paralysis

recurrent nerve, which should be identified and preserved. Should more proximal control be necessary, the ligamentum arteriosum is divided on the underside of the aortic arch. Care must be taken to keep the dissection directly on the aortic arch in order to avoid injuring the left main pulmonary artery. When degenerative aneurysm is the underlying pathology, dissection in this area is usually straightforward. However, in patients with chronic dissection, the prior inflammation from the dissecting process makes exposure more difficult. The aorta is surrounded with a vessel tape on either side of the left subclavian artery depending on the proximal extent of the aneurysm. Blunt dissection on the posterior aspect of the aorta is used to clear sufficient normal aorta to allow placement of the cross-clamp while maintaining adequate length of the aorta for an accurate proximal aortic anastomosis. External control of the left subclavian artery is desirable but not mandatory as intraluminal balloon control can be obtained if the aortic clamp is placed proximal to the left subclavian artery. During the thoracic portion of the dissection, the left inferior pulmonary vein is isolated in cases where atrial–femoral bypass is used; a 4-0 Prolene purse-string suture is used to introduce the venous cannula, which in our experience need not be larger than 19 French.

## *Clamp and Sew Versus Atrial–Femoral Bypass*

In contemporary practice, the clamp-and-sew technique with adjuncts to minimize warm ischemic time is the best way to approach type IV TAA. The technique of distal perfusion through atrial–femoral bypass via a centripetal, motorized pump is the simplest form of distal perfusion and requires no or low doses of systemic heparin to function. Conversely, cardiopulmonary bypass using a femoral vein to femoral artery technique requires an in-line oxygenator and full pump doses of heparin making it less desirable given the extensive dissection required to complete TAA repair. Most surgeons have adopted the liberal use of atrial–femoral bypass for extent I–III TAA. We prefer to continuously perfuse the mesenteric circulation during reconstruction of the visceral aortic segment. This can be accomplished with either a Y-connection from the atrial–femoral bypass circuit or in-line mesenteric shunting from the proximal graft after completion of the proximal anastomosis (Fig. 5.6).

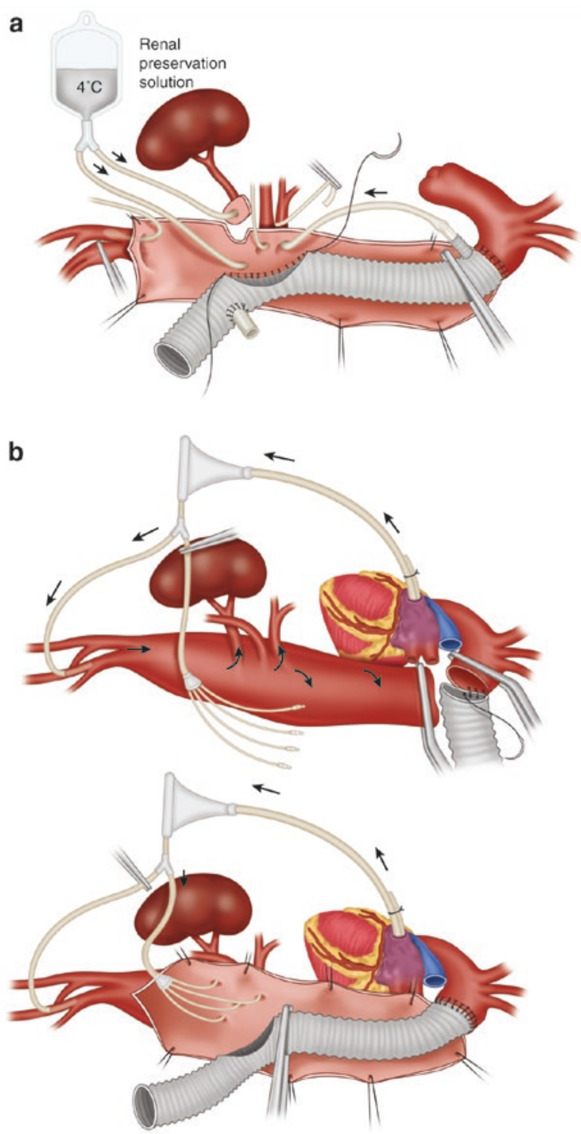


**Fig. 5.6** Approaches to operative conduct of thoracoabdominal aneurysm repair. (**a**) Clamp-and-sew technique with associated adjuncts of mesenteric shunting, renal cold perfusion, and epidural cooling (not shown). (**b**) Distal perfusion (left heart bypass) using the heparin-impregnated Bio-Medicus pump where perfusion distal to the proximal cross-clamp is initially maintained via the femoral artery and then by multiple perfusion catheters once reconstruction proceeds distally

## *Clamping Sequence and Proximal Anastomosis*

Next, the aortic prosthesis is prepared by attaching a 6 mm polytetrafluoroethylene (PTFE) sidearm graft that will serve as the conduit for left renal artery reconstruction. An additional sidearm graft of 10 mm PTFE may be placed proximally to provide inflow for the in-line mesenteric shunt. For most aneurysms, a Dacron prosthesis is the preferred conduit. However, a PTFE conduit is used to repair mycotic aneurysms because of its decreased susceptibility to infection.

Atrial–femoral bypass is initiated by cannulation of the left atrium through the left inferior pulmonary vein and the arterial return is via the left common femoral artery. Flows are initially adjusted to maintain distal mean perfusion pressures of at least 60–70 mmHg; any deterioration in MEP should prompt either an increase in the stimulus intensity or an increase in distal perfusion pressures. A sudden drop in MEP amplitude (occurring within 2–10 min) or a sustained progressive drop (within 10–40 min) of >75% from baseline is considered significant and should be addressed. The clamping sequence is begun in close cooperation with the anesthesia team. Efforts are made to place the first sequential clamp so as to allow lower intercostal and visceral retrograde perfusion.

In cases where the entire descending thoracic aorta is resected, proximal intercostal vessel orifices between $T_4$ and $T_8$ typically vigorously backbleed and those are rapidly oversewn. Intercostal vessels in the critical $T_9$ to $L_1$ aortic segment are evaluated for potential reimplantation, usually guided by changes in MEP signals. These vessels are controlled with balloon occlusion catheters to prevent ongoing backbleeding and also to prevent the negative "sump" effect on net spinal cord perfusion that can result from these vessel orifices when exposed only to atmospheric pressure. Unless there are prompt, significant changes in MEP, we defer any intercostal reconstruction to later stages of the operation. Next, the proximal aortic neck is prepared for reconstruction. Circumferential division of the aorta avoids the late complication of suture line esophageal erosion and permits the use of circumferential Teflon felt wrap if the aorta is particularly fragile and or/dissected. After completion of the proximal anastomosis, a clamp is placed on the main aortic graft distal to the mesenteric shunt sidearm (if present). The clamp is moved to the distal sequential clamp position and the visceral aortic segment is opened.

## *Renal/Visceral Artery Reconstruction*

Visceral and renal artery reconstruction is carried out next. Orificial endarterectomy should be performed when significant occlusive lesions of the right renal and superior mesenteric arteries exist. This involves incising the diseased intima and media and developing a proper endarterectomy plane that can be verified by noting the pinkish color of the inner adventitia. In cases where aortic endarterectomy is required, the superior mesenteric and celiac arteries should be dissected sufficiently to facilitate countertraction from the external side of the vessel if necessary. This, however, is not possible with the right renal artery. In the event that the calcified end of the obstructing plaque does not feather nicely, sharp excision under direct vision is the best way to end the endarterectomy plane.

The most common method of visceral and renal artery reconstruction that has been employed in the majority of our cases is a single inclusion button that encompasses the origins of the celiac, superior mesenteric, and right renal arteries. If the aneurysm is excessively large in the visceral aortic segment, the wide separation of the visceral/renal ostia may necessitate individual inclusion button anastomoses for each vessel. Alternatively, the superior mesenteric artery and right renal artery can be reimplanted as a single inclusion while reconstruction of the celiac trunk is deferred until later. The aortic graft is placed under tension and an elliptical side island is excised from the main aortic graft. This ellipse usually begins on the lateral aspect of the graft and spirals posteriorly in the region of the right renal artery reconstruction. With the graft under tension, it is possible to complete the posterior portion of the anastomosis using single bites of the suture passing through both the aorta and the Dacron graft. Suture bites are taken close to the origin of the visceral vessels in order to avoid leaving excess aneurysmal aortic wall. As the posterior aspect of this suture line continues around the inferior border of the right renal artery, it is important to ensure that the lumen is not compromised. This can be accomplished by placing a 12F perfusion catheter in the artery and gently agitating it up and down, or more recently, we have used a 6 × 15 or 6 × 18 balloon expandable stent to ensure that the suture line does not compromise right renal artery flow. The stent is placed under direct vision after the proximal suture line is beyond the orifice of the artery (Fig. 5.7). Just prior to completion of this suture line, backbleeding and patency of the celiac, superior mesenteric, and right renal arteries are verified and the in-line mesenteric shunt is clamped and removed. A single flush of the proximal aortic cross-clamp is performed in order to ensure that no clot or debris has built up in the graft.

Reconstruction of the left renal artery is now accomplished with a separate sidearm graft of a 6 mm PTFE. This provides a direct deliberate anastomosis in end-to-end fashion while allowing flexibility to deal with the spectrum of occlusive lesions, multiple renal arteries, and other wrinkles that may be encountered. It is important to orient this sidearm graft so that it will not kink when the left renal artery is returned to its anatomic position. Some surgeons advocate the use of a single inclusion button that contains the renal arteries and the visceral vessels. This often requires the inclusion of too great an area of the native, aneurysmal aorta, unless the aneurysm is small in the visceral artery segment. A single, pristine left renal artery and orifice may be directly reimplanted, and the clamp is then advanced to a position inferior to the origin of the left renal artery graft prior to completing the distal aortic anastomosis.

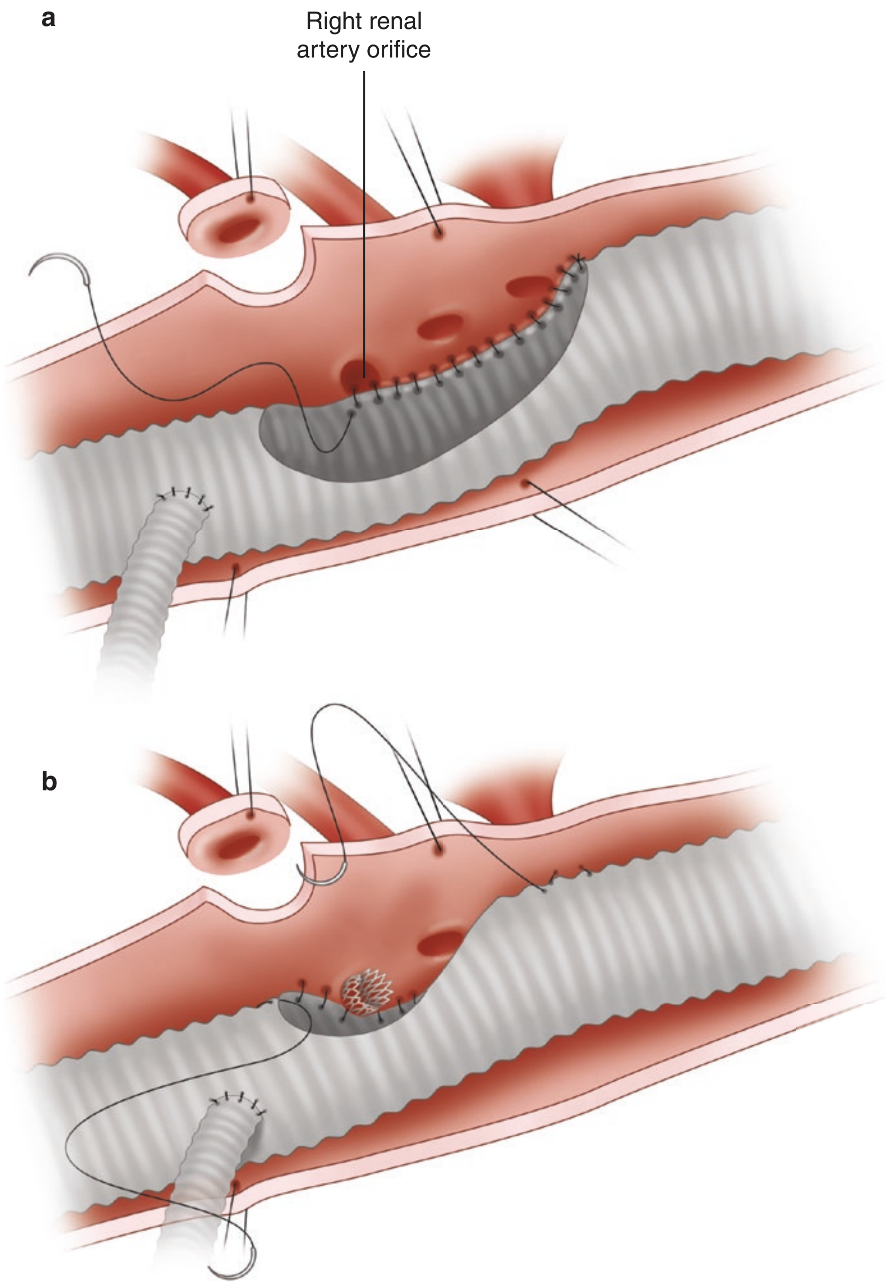


**Fig. 5.7** (**a**) Creation of visceral button inclusion anastomosis of the celiac axis, SMA, and right renal artery and 6 mm PTFE sidearm bypass for left renal artery reconstruction. When performing this, we use a 12F perfusion catheter as a stent of sorts in the right renal artery to prevent compromise of its orifice as the anastomosis is carried around these arterial origins. (**b**) Deployment of balloon-expandable stent into the right renal orifice to either treat occlusive lesions or prevent encroachment by the suture line, which should be placed immediately at or into the vessel ostia

## *Reconstruction of Intercostal Vessels*

The next step in the operation involves the intercostal vessels in the $T_9$ to $L_1$ segment. If there have been no MEP changes during the operation, the occlusion balloons are removed and the remaining intercostals are oversewn with silk sutures. If, however, reconstruction is desired, it can usually be accomplished through an inclusion button anastomosis. Other methods of intercostal vessel revascularization include the attachment of additional short sidearm grafts to the main aortic graft, or in cases where the vessel origin is rotated superiorly and to the patient's left side, implantation to the main aortic graft using Carrel patches of the aorta that contain the intercostal vessels may be feasible (Fig. 5.8).

## *Distal Anastomosis*

We make every effort to perform tube type of reconstructions to the aortic bifurcation unless there is gross aneurysmal disease of the proximal common iliac arteries. Extending the reconstruction to separate iliac artery reconstructions or, indeed, tunneling to an aortofemoral graft configuration is only performed when no other

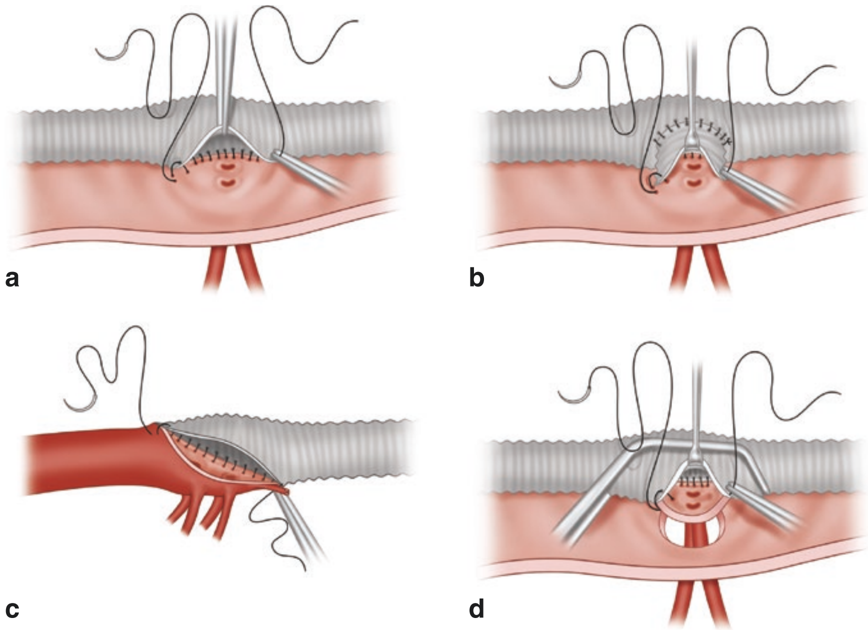


**Fig. 5.8** Methods of management of critical intercostal arteries. (**a**) Inclusion button anastomosis. (**b**) Separate sidearm graft. (**c**) Beveled anastomosis preservation when possible. (**d**) Carrell patch mobilization and direct reimplantation into the graft

technical alternative exists. After reestablishment of flow to the lower extremities and verification of adequate lower extremity perfusion by intraoperative pulse volume recordings, Doppler signals in the left renal, celiac, and superior mesenteric vessels are checked in addition to palpation of the superior mesenteric artery pulse in the root of the mesentery.

### *Postoperative Care*

Postoperatively, patients should be monitored in an intensive care unit (ICU) setting. It is important to limit hemodynamic shifts as these can contribute to complications such as renal failure and spinal cord ischemia. Blood pressure parameters should be tailored to the patient with the goal of maintaining adequate perfusion to preserve urine output, cardiac function, and spinal cord perfusion. Oxygen delivery is important in the early phase of recovery, and we rarely extubate patients in the early postoperative period. It they have stabilized overnight, we will pull the tube in the morning. It is important to monitor the hematocrit for signs of ongoing bleeding and all coagulation disorders should be aggressively corrected with the appropriate products. We typically support intravascular volume with fresh frozen plasma (FFP) infusions for the initial 12 h after the operation. CSF drainage is arbitrarily continued for 48 h postoperatively, and the drain is then capped for 24 h of observation prior to removal. Discontinuation of some preoperative antihypertensive medications may be necessary to maintain the relative hypertension necessary to avoid delayed SCI.

## Results of Treatment and Complications

### *Operative Mortality*

The operative mortality after TAA ranges from 8% to 16% in large clinical series. Preoperative patient characteristics influence the patient's outcome regardless of the conduct of the operation. In a recent update of our experience with type I–III TAA, a 30-day mortality was 4.4% for elective TAA repaired with atrial–femoral bypass and MEP monitoring. As the number of co-morbid conditions increases so does the overall operative risk, and individual series have reported that preoperative coronary artery disease, COPD, and renal insufficiency contribute to postoperative organ-specific complications and increased mortality. The influence of TAA extent is often (and appropriately) emphasized as having a dominant effect on, in particular, spinal cord ischemia. In particular, perioperative death after type IV TAA repair should mirror that of infrarenal repair. To wit, in our recent published experience, the 30-day mortality for type IV TAA repaired with the clamp-and-sew method was 2.8%.

## Renal Failure

We have traditionally defined postoperative renal failure as a doubling of the baseline serum creatinine level or an absolute postoperative creatinine level of >3.0 mg/dL. Minimizing renal ischemic times, the use of cold perfusate, avoidance of intraoperative hypotension, and a posture of aggressive treatment of stenotic lesions with either bypass or open stent placement are all strategies used to avoid postoperative renal insufficiency. Most cases are self-limited. We reserve dialysis for patients that need it for specific clinic indications such as volume overload, hyperkalemia, or acidosis. When needed, continuous venovenous hemodialysis is our preferred method as it provides for a smoother hemodynamic course than conventional hemodialysis. For those patients who continue to require dialysis, conventional hemodialysis is instituted once the patient is out of the intensive care unit and out of the window of risk for spinal cord ischemia. In our experience, and that of others, preoperative renal insufficiency is the most powerful predictor for the development of postoperative renal failure, and postoperative renal dysfunction remains independently associated with short- and long-term survival.

## Respiratory Complications

Although most clinical series emphasize spinal cord and renal complications, respiratory failure is the single most common complication after TAA repair. Indeed, if strict criteria are used, up to 40% of patients will suffer some type of respiratory complication. Contributing factors include paralysis of the left hemidiaphragm and the pain associated with an extensive chest wall incision that impedes pulmonary toilet. Accordingly, a diaphragm-sparing technique is applied when possible in contemporary practice. For patients that fail extubation, we favor early placement of a tracheostomy, although this procedure has been needed in less than 10% of patients. A slow wean from ventilatory support, often planned to proceed over several days, is appropriate management in patients with extensive TAA resection, particularly those with baseline pulmonary insufficiency.

## Spinal Cord Ischemia

Since the first descriptions of TAA repair, SCI has been the most feared and devastating nonfatal complication associated with TAA reconstruction. The pathogenesis of spinal cord injury after aortic replacement is likely multifactorial but ultimately results from an ischemic insult caused by temporary or permanent interruption of the spinal cord blood supply. SCI manifests along a clinical spectrum from complete flaccid paraplegia to varying degrees of temporary or permanent paraparesis, and the degree of SCI directly predicts long-term survival after TAA repair. Patients with incomplete deficits typically made a reasonable or complete functional outcome and have a long-term survival that is similar to those without SCI. However, patients with an SCID I score (flaccid paralysis) rarely live beyond the first year. The most common predictors of SCI after TAA repair include extent I and II aneurysms and urgency of operation. While a majority of cases of SCI are detected in the immediate postoperative period, there is a trend toward an increase in delayed paralysis in recent series.

### *Late Outcomes*

While some studies report significant continued mortality throughout the first year after operation (up to 30%), these reports include centers where the perioperative mortality approached 19%. It is, therefore, difficult to put these data into context with data from centers where the perioperative mortality is 5–8%. We found the late survival in our patients was identical to that from a population-based study of patients who underwent elective AAA. In addition, late aortic events occur in about 10% of patients, but few of these are graft related. Graft-related complications include occlusion of visceral vessel reconstructions, graft infections (including aortoesophageal fistulas), and the appearance of inclusion patch aneurysms and are rare in our experience. Most late aortic events are the result of native aneurysmal disease in remote (or noncontiguous) aortic segments. These data indicate that the substantial resource investment required to bring these patients through successful operation and recovery is an appropriate expenditure of such resources. With improvement of perioperative outcomes, the focus of long-term follow-up has shifted to examination of the impact of TAA repair on functional outcome. Several reports have emerged validating that a majority of operative survivors return to their preoperative independent living status.

## Further Reading

Acher CW, Wynn M. A modern theory of paraplegia in the treatment of aneurysms of the thoracoabdominal aorta: an analysis of technique specific observed/expected ratios for paralysis. J Vasc Surg. 2009;49:1117–24.

Bischoff MS, Di Luozzo G, Griepp EB, et al. Spinal cord preservation in thoracoabdominal aneurysm repair. Perspect Vasc Surg Endovasc Ther. 2011;23(3):214–22.

Conrad MF, Ergul E, Patel VI, et al. Evolution of operative strategies in open thoracoabdominal aneurysm repair (TAA). J Vasc Surg. 2011;53:1195–201.

Conrad MF, Ye JY, Chung TK, et al. Spinal cord complications after thoracic aortic surgery: long-term survival and functional status varies with deficit severity. J Vasc Surg. 2008;48:47–53.

Coselli JS, Bozinowski J, LeMaire SA. Open surgical repair of 2286 thoracoabdominal aortic aneurysms. Ann Thorac Surg. 2007;83:S862–4.

Crawford RS, Pedraza JD, Chung TK, et al. Functional outcome after thoracoabdominal aneurysm repair. J Vasc Surg. 2008;48:828–35.

Lancaster RT, Conrad MF, Patel VI, et al. Further experience with distal aortic perfusion and motor-evoked potential monitoring in the management of extent I-III thoracoabdominal aortic aneurysms. J Vasc Surg. 2013;58:283–90.

Mohebali J, Latz CA, Cambria RP, Lancaster RT, Conrad MF, Clouse WD. The long-term fate of renal and visceral vessel reconstruction after open thoracoabdominal aortic aneurysm repair. J Vasc Surg. 2021;74(6):1825–32.

Patel VI, Ergul E, Conrad MF, et al. Continued favorable results with open surgical repair of Type IV thoracoabdominal aortic aneurysms. J Vasc Surg. 2011;53:1492–8.