



Anesthetic Management of Thoracic Endovascular Aortic Repair

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Mariya Geube and Christopher Troianos

Main Messages

1. TEVAR has evolved as a less invasive alternative treatment than the open aortic repair in a wide range of aortic diseases, including thoracic descending and abdominal aortic aneurysms, aortic dissections, penetrating aortic ulcers, acute pathologies of the ascending aorta and aortic arch, and traumatic aortic injury
2. TEVAR is associated with lower rate of blood transfusions, spinal cord ischemia, kidney insufficiency and short term mortality compared with open surgical repair of descending thoracic aortic aneurysms; however, TEVAR is associated with a higher re-intervention rate than open aortic repair, mostly due to occurrence of endoleak
3. TEVAR is safely performed under general, regional or local anesthesia, with similar rates of technical success, conversion to open repair, operative mortality and acute kidney insufficiency; the most common anesthetic technique used for TEVAR is general anesthesia, which has certain advantages—ability to control ventilation during the apnea periods, limited patient movement, improved patient tolerance, creation of iliac conduits, and the use of transesophageal echocardiography
4. TEE is a sensitive tool for assessing aortic pathology, such as aortic dissection, size of the aortic aneurysm, presence of intramural thrombus; it has a great value intraoperatively for detecting early myocardial ischemia in high risk patients or for assessment of intravascular volume status, and can also help guiding wire placement in the true lumen of the aorta and detection of small endoleaks.
5. Spinal cord protection in TEVAR is indicated when there is an extensive aortic coverage of the stent graft, left subclavian occlusion affecting the flow in the cervical spinal network, prior abdominal aortic aneurysm repair; inte-

M. Geube (✉)
Department of Cardiothoracic Anesthesiology,
Cleveland Clinic Foundation, Cleveland, OH, USA
e-mail: Geubem@ccf.org

C. Troianos
Anesthesiology Institute, Cleveland Clinic
Foundation, Cleveland, OH, USA
e-mail: troianc@ccf.org

grated approach to spinal cord protection includes placement of subarachnoid drain, blood pressure augmentation, treatment of blood loss anemia, frequent neurologic status monitoring in the postoperative period

6. Endoleaks present a complication unique to endovascular aneurysm repair; they are identified as the most common cause of aneurysm rupture after TEVAR, and the most common indication for reintervention
7. Type I and III endoleak warrant surgical intervention, while type II and IV may be treated expectantly and require long term follow up

Descending thoracic aortic aneurysms have a high prevalence in the modern society and are frequently discovered incidentally as a consequence of cardiovascular workup for another medical problem. They are classified by location, extent of the disease, size and shape, which determines the complexity of the surgical procedure, and the clinical outcome [1]. Isolated descending thoracic aneurysm is confined to the aorta between the left subclavian artery and the diaphragm, while the thoracoabdominal aneurysm is an extensive disease of the aorta between the left subclavian artery and the aortic bifurcation. Indications for repair of descending thoracic aortic aneurysms are rupture or impending rupture, malperfusion syndrome, refractory pain, rapid growth of aneurysm (> 1 cm per year) or an absolute aneurysm dimension of >6.5 cm or 6.0 cm in connective tissue disorders [2, 3].

Conventional open surgical repair has been the gold standard for treatment of symptomatic descending thoracic aortic disease for many years. It is associated with substantial morbidity and mortality in an aged population with multiple coexisting conditions. TEVAR was initially reserved for patients considered very high risk for open surgery or in difficult-to-reach aortic segments. Currently, this has evolved as a less invasive alternative treatment modality with an excellent perioperative morbidity profile in a

wide range of aortic diseases. Technological evolution in medical imaging and devices has enabled TEVAR to be used in more proximal— aortic arch and ascending aorta—or more distal—thoracoabdominal aortic disease.

Indications for TEVAR

The indications for TEVAR are listed in Table 11.1.

Despite the favorable safety profile and multiple applications of TEVAR, the endovascular approach should be considered with caution in patients with connective tissue disorders. Progression of the aortic disease is expected and associated with high re-intervention rate in these patients.

Outcome Comparison of TEVAR Versus Open Repair

Comparative studies of TEVAR versus open surgical repair [13–15] favor TEVAR for reduced 30-day mortality, shorter intensive care unit stay, and shorter hospital length of stay. The incidence of spinal cord ischemia, blood transfusions and acute kidney insufficiency is lower in TEVAR, however, the long-term need for re-intervention is higher, mainly due to the occurrence of endoleaks. The incidence of stroke and myocardial infarction is similar between the two techniques. Despite the low intraoperative morbidity and mortality, the late complications from TEVAR outnumber those in open surgical repair. These include endoleaks, aneurysm progression-related death, and stent graft migration. TEVAR is associated with significantly higher health care costs, determined by the price of the device, the number of stent grafts placed, and the extensive lifelong follow-up [3]. Treating ruptured thoracic aortic aneurysms with TEVAR present another expanding field for the endovascular approach. Several large studies examining the outcomes after endovascular versus open surgery for ruptured aneurysms have confirmed a slightly reduced mortality [16] and improved composite outcomes—death, stroke, paraplegia—with TEVAR [17, 18].

Table 11.1 Common indications and outcomes for TEVAR [4]

Indication for TEVAR	Outcomes and evidence
Descending thoracic aortic aneurysm	Lower rate of blood transfusions, spinal cord ischemia, and short term mortality compared with open surgical repair. Equal rate of all-cause mortality at 5 years
Thoraco-abdominal aneurysm	Fenestrated graft stenting is feasible in patients with significant comorbidity who are considered high risk for open surgical repair [5]
Acute type B* aortic dissection with complications (20%)—Rupture, malperfusion, refractory pain	Indicated for urgent repair. High procedural success rate and low intraoperative mortality, and emergency conversion. Proximal entry coverage reduces the flow to the false lumen and improves perfusion to spinal cord, kidneys and lower extremities
Acute type B aortic dissection without complications (80%)	Similar survival at 2 years compared with patients on optimal medical therapy, but enhanced true lumen remodeling and delayed aneurysm dilatation with TEVAR [6, 7]. Elective procedure or conservative management with follow-up are both reasonable options
Chronic type B aortic dissection	Stent graft treatment does not reduce the risk of rupture nor has a survival benefit. Lower success rate of excluding completely the false lumen than in acute dissection [8]
Acute type A* aortic dissection	Evidence is limited to case series as a salvage procedure in patients at very high risk for open repair [9]
Penetrating aortic ulcer and intramural hematoma	No consensus on first line therapy. Progression of intramural hematoma to dissection is observed in 16–36%. TEVAR should be considered in symptomatic patients with refractory chest pain, increasing size, formation of pseudoaneurysm or contained rupture
Traumatic aortic transection	Associated with dismal prognosis due to multiorgan injuries. TEVAR has shown superior to open repair due to the localized aortic pathology, with significantly lower early mortality and paraplegia rate [10]
Ruptured thoracic descending aortic aneurysm	60% pre-hospital mortality and 30–50% 30-day mortality after TEVAR [11]. Coverage of left subclavian artery may be required to achieve good proximal seal. Management of spinal cord ischemia is expectant and spinal drain may be placed after hemodynamic stability has been achieved [12]

According to the Stanford classification, type A aortic dissection refers to a dissection with origin in the ascending aorta or aortic arch. Type B aortic dissection refers to a tear originating in the descending aorta distal to the left subclavian artery

Preoperative Assessment and Optimization of the Patient

Patients presenting for TEVAR undergo extensive preoperative work-up, because they have a high prevalence of cardiovascular disease, chronic pulmonary disease, and chronic renal insufficiency.

Cardiovascular Assessment

Based on the perioperative risk of major adverse cardiac events greater than 5%, TEVAR is considered a high risk surgery. The most common cardiovascular complications after TEVAR are myocardial infarction, arrhythmias, and conges-

tive heart failure. There is a high (30–70%) prevalence of coronary artery disease among patients with aortic aneurysms [19]. Testing and medical optimization are thus warranted prior to the procedure in symptomatic patients and should be tailored to their existing comorbidities and the risk of aortic rupture [20]. Preoperative electrocardiography and transthoracic echocardiography are important studies used to assess the perioperative risk for cardiovascular complications. Stress testing is reserved for patients with poor functional capacity—less than four metabolic equivalents (METs) on exercise testing [21, 22]. Routine revascularization in patients with stable coronary artery disease before elective vascular surgery does not improve mortality or reduce postoperative adverse cardiac events, and

is currently not recommended [23]. Cardiac optimization includes life style modifications and medical optimization such as smoking cessation, blood pressure and serum glucose control, and continuation of statin, beta blocker, and aspirin therapy. In case of emergent TEVAR with unknown cardiac status, intraoperative trans-esophageal echocardiography can be used to facilitate intraoperative cardiovascular assessment and management.

Renal Injury Risk Assessment

Baseline renal function should be determined preoperatively, because renal insufficiency is a known risk factor for postoperative cardiovascular complications. The strongest predictors for acute kidney insufficiency (AKI) after TEVAR are preexisting renal dysfunction, increased age, involvement of the renal arteries in the acute aortic pathology with evidence of malperfusion, preoperative exposure to radiocontrast agents, high complexity and prolonged procedures, emergency surgery, and perioperative hypotension [24]. These factors reflect the larger dose of intraoperative contrast, renal microembolism, and inflammatory response. Adequate hydration before radiocontrast imaging studies and planning the surgery several days after the contrast load, are strategies to minimize the risk of contrast induced renal injury. The use of intravascular ultrasound during TEVAR can significantly reduce the total dose of intravenous contrast administered during the procedure [25].

Surgical Considerations for TEVAR

Preoperative Imaging and Evaluation

Contrast enhanced computed tomography of the aorta extending from supra-aortic vessels to the femoral arteries with three-dimensional volumetric reconstruction of the image is routinely performed preoperatively. This provides important information on the location and shape of the aneurysm, tortuosity of the thoracic descending

aorta, and the origin of the aortic branches. Computed tomographic angiography (CTA) guides the surgeon to determine whether the patient's anatomy is suitable for endograft placement, the size of the stent graft, and the need for custom designed stent grafts. This imaging has the advantage of rapid acquisition, high spatial resolution, and provides the ability to image heavy calcifications and to detect the location of contrast extravasation in aortic rupture or endovascular leak. If coverage of the left subclavian artery is planned, head and neck CTA is obtained to determine the presence of a complete circle of Willis and patent vertebral arteries.

Devices for Thoracic Endovascular Aortic Repair

Stent grafts are composed of a metal skeleton attached to an impermeable fabric deployed proximally into a healthy aortic segment and distally beyond the degenerated segment, thus excluding the diseased aortic wall from the circulation. A landing zone map divides the aortic arch and descending aorta into five segments, which are used as landmarks for endograft seal zone [26] (Fig. 11.1).

At least 2 cm of normal aortic wall are required on the proximal and distal end of the aortic pathology for successful stent graft deployment. There are several devices approved by Federal Drug Administration for use in thoracic endovascular aortic aneurysm repair [3]. TEVAR has been performed with success in thoracic aortic pathologies other than aortic aneurysms. Examples include acute and chronic aortic dissection, ascending aortic or arch pathologies, penetrating aortic ulcers, traumatic aortic injury, thoracoabdominal aneurysms and ruptured aortic aneurysms [27]. In the presence of aortic dissection, the goal of the endovascular repair is to cover the proximal intimal tear, to exclude the aneurysmal segment of the aorta, and to ensure distal perfusion of the major aortic side branches [3]. TEVAR can be performed in high risk patients with complex aortic aneurysms involving the origin of major aortic branches (landing

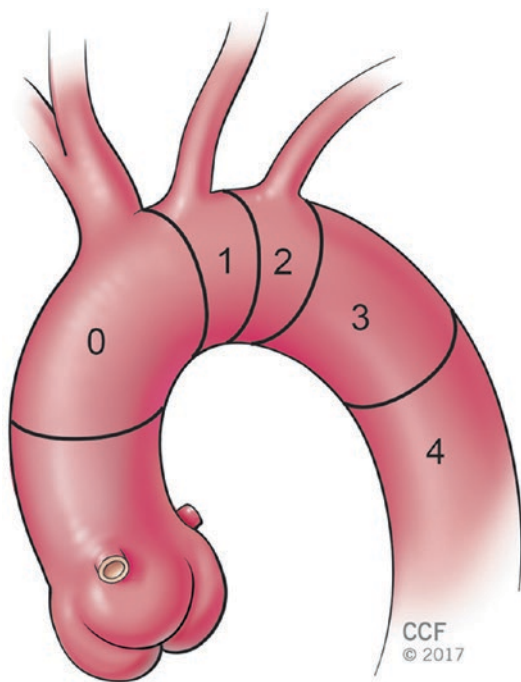


Fig. 11.1 Landing zone map of the thoracic aorta. The classic TEVAR seal zones extend from the left carotid artery to the celiac artery (landing zone 2 and 4). Reprinted with permission, Cleveland Clinic Center for Medical Art and Photography © 2017. All Rights Reserved

zones 0 and 1, or below zone 4, Fig. 11.1). These are best managed with fenestrated or branched endografts. Fenestrated endografts are custom made grafts that accommodate the specific anatomy of the patient and have openings in the endograft fabric that are positioned over the origin of the visceral arteries. Branched endografts have small side arm grafts constructed into the main endograft, which are then extended into the artery to maintain its patency [28]. Follow-up CTA after TEVAR is required before discharge, at 3 months, and annually thereafter to assess repair stability, device integrity, presence of endoleaks, and size of the aortic aneurysm.

Choice of Anesthetic Techniques

Various anesthetic techniques can be used for TEVAR. The EUROpean collaborators on Stent-graft Techniques for abdominal aortic Aneurysm

Repair registry [29] reported that 69% of cases were performed with general anesthesia (GA), 25% with regional anesthesia (RA) and 6% with local anesthesia (LA). Early reports failed to show any difference in the technical success of the endovascular repair, the rate of conversion to open surgical repair, mortality rate, or the incidence of acute kidney injury among different anesthetic techniques [30]. A more recent registry study reported decreased pulmonary complications and length of hospital stay with local/regional technique compared to GA [31]. TEVAR is most commonly performed with GA. The advantages include the ability to control ventilation during the required periods of apnea, limited patient movement, improved patient tolerance in prolonged procedures, creation of iliac conduits, and use of transesophageal echocardiography (TEE).

TEVAR can be performed with spinal or epidural anesthesia, which allows the patient to remain awake and avoid tracheal intubation, which is especially important in patients with severe chronic lung disease. The patient's breathing can be assisted with non-invasive ventilation, if the supine position increases their breathing difficulty. Regional anesthetic techniques can also provide optimal pain control in the early postoperative period. The disadvantages of regional anesthesia are patient discomfort and movement, poor compliance with breath holds during the procedure, sympathectomy with hypotension, and inability to obtain a timely neurological exam after the procedure. Regional anesthesia is performed with success in the authors' institution among patients with advanced lung disease who are considered high risk for postoperative pulmonary complications and prolonged intubation. After subarachnoid catheter placement, a local anesthetic is injected into the catheter and capped until stent deployment. After deployment, the SA catheter is opened and cerebrospinal fluid (CSF) is drained. The concentration of the local anesthetic in the CSF decreases quickly after opening the SA drain, necessitating supplementation of the regional anesthetic with light sedation at a time when the procedure is near completion.

The use of local anesthetic alone for TEVAR is possible when a percutaneous approach is planned [32]. There are certain advantages of local anesthesia, such as avoidance of inhalational agents, muscle paralysis, airway manipulation, and mechanical ventilation, while allowing for early detection of neurological impairment due to stroke or spinal cord ischemia.

Intraoperative Monitoring and Management

Invasive Hemodynamic Monitoring

The need for invasive monitoring during TEVAR is determined by the potential for catastrophic bleeding and cardiovascular collapse during the procedure. Although TEVAR is theoretically less invasive than an open surgical repair, the anesthetic planning should include intraoperative monitoring and vascular access adequate to manage the patient in case of emergent conversion to open repair (about 2%). Arterial, central venous and large bore peripheral venous catheters are routinely placed. The preferred site for placement of the arterial catheter is the right radial artery, in case of left subclavian artery involvement. Surgeons frequently access the left brachial artery for placing ancillary devices, leaving the right side available for blood pressure monitoring. In aortic dissection, accessing the true lumen may be difficult. In this circumstance, the wire can be placed through the arterial access of the right arm, which needs to be free of intravascular devices and monitors, and prepped in the surgical field. Central venous access is indicated for administration of vasoactive medications and for central venous pressure monitoring.

Role of TEE

TEE is a sensitive tool for diagnosing aortic pathology. It can be used to evaluate and confirm significant atheroma burden, aortic dissection, size of the aortic aneurysm, and presence of intraluminal thrombus. Patients who present for

elective aortic surgery have already undergone various imaging modalities to determine the type and extent of the aortic pathology, and provide information about the individual's aortic anatomy. One important shortcoming of TEE is the difficulty in visualizing the distal ascending aorta and proximal aortic arch, because of the interposition of the left mainstem bronchus between the esophagus and this portion of the thoracic aorta. Important applications of TEE in TEVAR are for patients with high risk for serious cardiovascular adverse events, for early detection of myocardial ischemia, and for volume assessment. The intraoperative use of TEE is especially helpful in emergent TEVAR, because usually the patients have insufficient preoperative cardiac work-up. TEE is an invaluable imaging tool to distinguish between true and false lumens and to guide placement of wires in the aorta and to detect distal dissection flap fenestrations. Although the standard for intraoperative endoleak diagnosis is angiography, small leaks may be missed. TEE in color flow Doppler mode is more sensitive for detecting type I endoleak after stent deployment than angiography [33].

Hemodynamic Goals During Induction and Maintenance of Anesthesia

The ultimate intraoperative anesthetic goals are to provide adequate oxygen delivery, maintain normovolemia, optimize perfusion to vital organs, and maintain normal body temperature. The main concern during induction of general anesthesia is to maintain tight blood pressure control and avoid a sympathetic surge during laryngoscopy and intubation. Placement of pre-induction arterial catheter, use of anxiolytics and pain medications are useful to help achieve these goals.

Hemodynamic Management During Aortic Endograft Deployment

Endograft deployment is difficult in the proximal descending thoracic aorta or aortic arch in nor-

mal hemodynamic conditions because of the high velocity blood flow in this part of the aorta. There are certain techniques that can be used to decrease the cardiac output to facilitate stent deployment. Frequently used pharmacologic agents are adenosine (which causes a brief asystolic pause), esmolol (which decreases the heart rate and has transient effect on the blood pressure), propofol and nitroglycerin. Other non-pharmacologic techniques include rapid transvenous pacing of the right ventricle at a rate 130–180 beats per minute. This causes loss of atrioventricular synchrony, severe decrease of ventricular filling and ejection, and dramatic decrease in the stroke volume and blood pressure. Cessation of flow can also be achieved by temporary balloon occlusion of the aorta proximally to the landing zone. Balloon expansion is accompanied by significant proximal hypertension, which is transient and should not prompt correction. Any pharmacological manipulation during this time can lead to prolonged hypotension after the stent deployment, which is detrimental for the brain and spinal cord perfusion.

Body Temperature Control

Body temperature control and prevention of hypothermia during TEVAR is of paramount importance. The chest, abdomen and legs are exposed to the ambient temperature and predisposed to rapid heat loss. Although mild hypothermia may benefit spinal cord protection, more severe hypothermia must be avoided because of the risk for adverse intraoperative and postoperative cardiac events, coagulopathy, and residual muscle paralysis, which preclude timely extubation and the ability to perform an early neurological exam. The use of devices for active rewarming, such as fluid warmer, a heated airway circuit and forced air warming devices on the upper body, along with higher room temperature are recommended. Lower body warming devices or underbody warm mattresses should be avoided due to local hyperthermia in the area of the spinal cord and lower extremities, which can exacerbate ischemia of the spinal cord and the legs.

Spinal Cord Ischemia

TEVAR, as opposed to open surgical repair, avoids many of the critical intraoperative insults that contribute to the development of spinal cord ischemia (SCI), such as aortic cross clamping, severe hemodynamic perturbations, cardiopulmonary bypass, reperfusion injury, and deep hypothermic circulatory arrest, when used. Nevertheless, placement of a stent graft leads to abrupt exclusion of the segmental blood supply to the spinal cord and is associated with 1–10% incidence of ischemic spinal cord injury [34].

Spinal cord perfusion is dependent on a single anterior and two posterior spinal arteries, and on a complex arterial network at the proximal—cervical vascular network—and distal portion of the spinal cord—pelvic vascular network [35]. The cervical vascular network originates from the subclavian arteries, which give rise to the vertebral arteries, then to the anterior spinal artery. The anterior spinal artery receives blood supply from the thoracic intercostal arteries, which arise directly from the thoracic descending aorta. Perfusion of the distal portion of the spinal cord arises from the lumbar and sacral arteries, which form a collateral network with branches of the inferior mesenteric and hypogastric arteries, which in turn are branches of the internal iliac arteries. The most vulnerable segment of the spinal cord is between T4 and L2, where sacrificing the intercostal arteries may significantly disrupt the perfusion to the spinal cord and lead to watershed infarction. The pathogenesis of SCI after TEVAR is multifactorial with the following contributing factors:

1. Extensive aortic coverage of the stent graft with complete exclusion of the intercostal arteries. Stent graft length more than 20 cm is associated with significant increase in the incidence of SCI [36]
2. Extension of the stent graft into normal aorta because of proximal and distal landing zones, thus increasing the length of the aorta excluded from direct spinal cord perfusion
3. Destabilization and embolization of atheromatous debris from the aortic wall due to guide wire manipulation and stent deployment

4. Left subclavian artery occlusion affecting blood flow in the proximal cervical network;
5. Back flow from the interrupted segmental arteries into the aneurysmal sac, which causes “steal” from the spinal cord collateral network
6. Prior abdominal aortic aneurysm repair
7. Intraoperative hypotension
8. Hypogastric artery occlusion
9. Emergent surgery [37, 38]

Integrated Strategy for Spinal Cord Protection

Paraplegia and paraparesis due to SCI remain the most feared complications of endovascular repair of descending thoracic or thoracoabdominal aortic aneurysms. A variety of strategies have been described to reduce the ischemic insult to the spinal cord with varying degrees of efficacy [39].

Subarachnoid (SA) Drain

Strategies to reduce the incidence of SCI are directed towards optimizing spinal cord perfusion pressure, which is the difference between the mean arterial pressure and either the CSF pressure or central venous pressure—whichever is higher. Spinal cord perfusion is improved by draining CSF, augmentation of arterial pressure, reducing central venous pressure, or a combination. Common indications for placement and the clinical management of SA drain are explained in Table 11.2.

There are two different approaches to intraoperative management of the subarachnoid drain. One is to measure the SCF pressure continuously and to drain intermittently to maintain a CSF pressure of 10 mmHg [41, 42]. The other approach is to drain continuously with a system that allows drainage with CSF pressure over 10 mmHg and to measure pressure intermittently. Risks from SA drain placement are spinal headache, subarachnoid hemorrhage, subdural and epidural hematoma, infection, and catheter fracture [43].

Table 11.2 Placement and clinical management of subarachnoid drain during TEVAR

Indication for SA drain
<ul style="list-style-type: none"> • Type I or type II aneurysm (Crawford classification) • Stent graft length > 20–25 cm • Hybrid procedures including the aortic arch or visceral branches • Previous surgery of the abdominal aorta
Placement technique
<ul style="list-style-type: none"> • Seated or latero-decubital position • Preferably awake patient • Insertion at L3–4 or L4–5 level • Intrathecal length > 5 cm
Management of SA drain [40]
<ul style="list-style-type: none"> • Connection to a non-pressurized transducer • Zero-point at ear lobe • Continuous drainage to maintain CSF pressure at 10 mmHg • Limit drainage to 25 ml per hour • Intermittent monitoring of CSF pressure with transducer • Avoid elevated central venous pressure • Clamp the SA drain during patient transport
Additional measures
<ul style="list-style-type: none"> • Maintain mean arterial pressure 85–100 mmHg • Maintain spinal cord perfusion pressure > 70 mmHg • Maintain hemoglobin >10 g/dL • Maintain normal cardiac output/index • Avoid underbody or lower body forced air warming devices

Blood Pressure Augmentation

Augmentation of the mean arterial pressure can be achieved with fluid administration and/or use of vasopressor agents. A targeted mean arterial pressure of 85–100 mmHg is typically well tolerated. The ultimate goal is to ensure a spinal cord perfusion pressure above 70 mmHg [44], which is achieved when the CSF pressure is 15 or less with a mean arterial pressure of 85 mmHg. Vasopressor support is sometimes required to achieve a higher mean arterial pressure. Another important intervention is to maintain low central venous pressure, which reduces venous congestion. If the central venous pressure is higher than the CSF pressure, the spinal cord perfusion gradient becomes dependent on the difference between the mean arterial and central venous pressures.

Surgical Interventions

New endovascular techniques have evolved to decrease the insult on spinal cord perfusion. These include coil embolization of large lumbar arteries to prevent reverse flow from the collateral network into the aneurysmal sac, and use of branched stent grafts to preserve perfusion into larger intercostal arteries. Another approach includes a staged procedure consisting of coil embolization of feeding arteries, followed by stenting of the aorta. This aims to improve the ischemic tolerance and allow remodeling of the collateral network of the spinal cord before the stent placement [45]. Temporary aortic sac perfusion is another approach, in which a fenestrated stent graft is placed, allowing flow into the aneurysmal sac to supply the segmental arteries during the most vulnerable period. Coil embolization is performed at a later date. Lastly, staged operations of long segments of the descending aorta with or without hybrid techniques have become popular. Stenting smaller segments at each stage allows for excluding vital feeding vessels over a longer period of time, which promotes the development of the spinal cord collateral network [46].

Neurophysiologic Monitoring

Intraoperative monitoring of spinal cord integrity with motor- and somatosensory evoked potentials is used in some institutions. Although these methods are very sensitive to detect early spinal cord ischemia, they are complex, require trained specialists to interpret the findings and can be influenced by anesthetic agents. In addition, they cannot be used in the postoperative period. The anesthetic management must be tailored to minimize interference of this monitoring technique by limiting the alveolar concentration of inhaled agent to 0.5 MAC, supplemented by intravenous anesthetics, and withholding paralytic agents, if motor evoked potentials are monitored. Recent experience with the use of near infrared spectroscopy has been described as a noninvasive trend monitor of paraspinal vasculature perfusion, which is part of the spinal cord collateral network [47].

Postoperative Considerations

Although TEVAR is less invasive than open surgical repair, the advanced age and multiple comorbidities that typically comprise these patients' clinical profile, make them susceptible to a variety of postoperative complications. The intensive care management of patients with TEVAR aims to optimize end organ function and to identify and manage complications early in their course.

Spinal Cord Ischemia Detection and Rescue Treatment

The choice of anesthetic agents should provide a fast emergence that allows for immediate neurological assessment after TEVAR. A rapid wean of respiratory support and extubation of the patient's trachea in the operating room is the goal. SCI is suspected in the presence of a motor or sensory deficit not attributable to intracranial pathology. The clinical presentation of SCI is a spectrum of motor and sensory impairment, which vary in severity and onset. It is important to examine the quadriceps flexion controlled by the lumbar plexus, as opposed to toe flexion and extension, controlled by the sacral plexus. There is sometimes a presentation of SCI with sacral sparing. This presents with proximal muscle weakness, but preserved toe movement. It is important to differentiate SCI from acute leg ischemia due to vascular occlusion, which can also present with sensory and motor deficit, but the management is much different. Vascular occlusion is usually unilateral, associated with severe pain and profound loss of sensory and motor function of the ipsilateral limb, and lack of peripheral pulses. This mandates emergent intervention for revascularization. There are several helpful interventions in the event of spinal cord ischemia with new motor deficit (see Fig. 11.2).

Blood pressure augmentation (to a target of mean arterial pressure 85–100 mmHg) is accomplished with fluid volume expansion and vasopressor agents—phenylephrine, norepinephrine, and/or vasopressin. Spinal cord infarction that

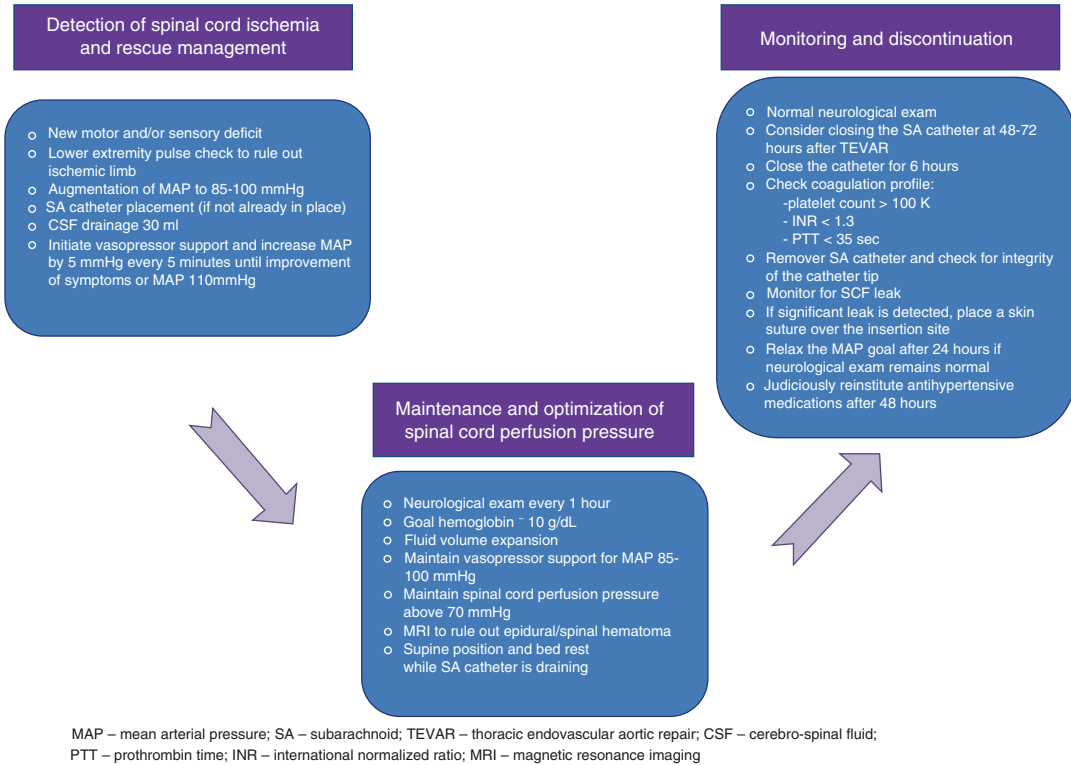


Fig. 11.2 Algorithm for rescue management of spinal cord ischemia in the postoperative period

occurs as a consequence of intraoperative embolization is often irreversible, and may not improve with blood pressure augmentation. If not already present, a subarachnoid catheter should be placed and 25–40 ml of CSF fluid should be drained immediately. Hemoglobin should be maintained to a level of 10 g/dL in the event of SCI to ensure adequate oxygen delivery. Magnetic resonance imaging is used to detect spinal cord infarction and spinal/epidural hematoma. The duration of CSF drainage is empirical and based on the patient's clinical signs, however, experimental studies have shown that the zenith of the spinal cord blood supply is in the first 48 h after the aortic stenting. After that period, the blood supply slowly recovers, suggesting augmentation of the existing collateral network [48].

Postoperative Stroke

The incidence of stroke after TEVAR is about 4% [49]. The stroke risk is increased with severe atheromatous aortic disease, guide wire instru-

mentation of the aortic arch, history of stroke, landing zone for the stent graft in the aortic arch, and left subclavian artery occlusion [50]. More often the embolic shower involves the posterior cerebral circulation (60%) rather than the anterior circulation (40%) [51]. The immediate management of the postoperative stroke is focused on the prevention of secondary ischemic insult, thus avoidance of hypercarbia, hypoxemia, hyperglycemia, hyperthermia, hyponatremia, anemia and hypotension are of paramount importance.

Contrast Induced Nephropathy and Postoperative AKI

Acute kidney injury (AKI) after TEVAR is associated with increased morbidity and mortality [52]. The treatment is largely supportive and consists of hemodynamic optimization, restoration of euolemia, correction of anemia, and avoidance of nephrotoxic agents. Long term, there is a risk of worsening kidney

function several months after TEVAR, which is often due to the repetitive administration of radiocontrast during surveillance studies and to the progression of the atherosclerotic disease. Contrast induced nephropathy has a known insulting factor and highly predictable timing and thus, it is a modifiable cause of post-procedural AKI. The strongest predictor for contrast induced nephropathy is preexisting renal insufficiency. The principal intervention that reduces the incidence of contrast induced nephropathy is fluid volume expansion. Cumulative data from randomized studies have established the attenuating effect of isotonic fluid administration, several hours before and after the injection of radiocontrast agent [53]. The concomitant use of loop diuretics, mannitol or dopamine receptor agonists is not supported by the current evidence. Recently, the theory of contrast associated kidney injury in other fluoroscopic procedures, such as transfemoral aortic valve replacements, has been challenged in the absence of an association between the dose of radiocontrast agent and development of AKI [54].

Hybrid Procedures

A hybrid surgery involves TEVAR and an open surgical approach in a concurrent or staged procedure of extra-anatomic vascular transposition to expand the safe length of the stent graft without causing occlusion of important aortic branches.

Aortic Arch Debranching and Bypass Procedures

Hybrid procedures are performed when aortic pathology involves the aortic arch, and allow stent graft coverage of the supra-aortic branch vessels. These techniques are attractive alternative to the open arch replacement under deep hypothermic circulatory arrest. The most common example of a hybrid aortic arch procedure is the left carotid-subclavian artery bypass followed by TEVAR (Fig. 11.3a). It is considered when the proximal landing zone is expected to cover the origin of left subclavian artery (in 40% of the patients presenting for TEVAR). The technique

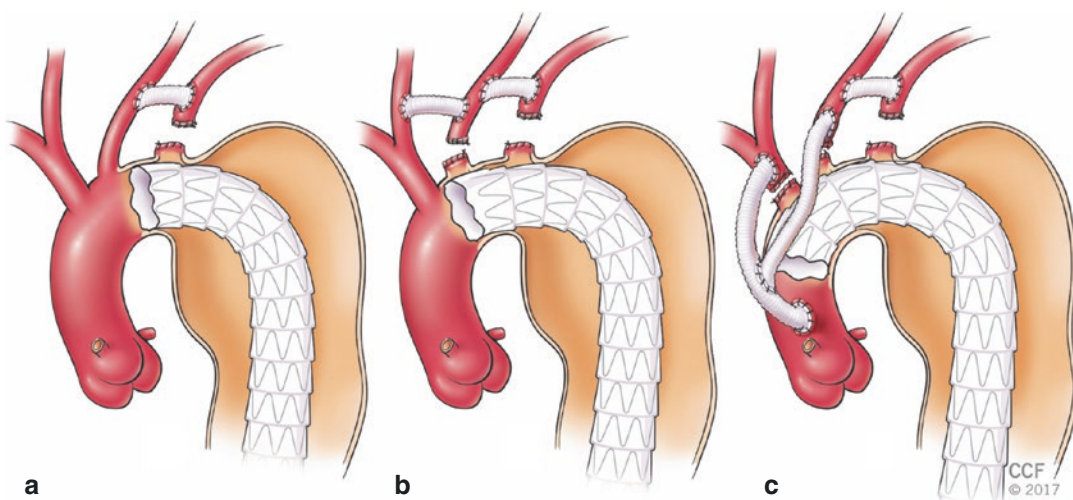


Fig. 11.3 Common aortic arch debranching procedures are used to ensure an adequate landing zone for endovascular stent grafting in proximal arch pathology. (a) Endograft with proximal seal in landing zone 2, requiring left carotid-subclavian artery bypass. (b) Endograft with proximal seal in landing zone 1, which requires carotid-

to-carotid and left carotid-subclavian artery bypass graft. (c) Endograft with proximal seal in landing zone 0, and full arch debranching with extra-anatomical bypass graft attached to the ascending aorta. Reprinted with permission, Cleveland Clinic Center for Medical Art and Photography © 2017. All Rights Reserved

includes a carotid-subclavian artery bypass graft placement with ligation of the left subclavian artery proximally, to prevent back flow into the aneurysm sac. Left carotid-subclavian artery bypass is indicated prior to TEVAR when the proximal end of the stent graft causes left subclavian occlusion and in the presence of any of the following high risk conditions: a left dominant vertebral artery, an occluded right vertebral artery, a patent left internal mammary coronary artery bypass graft, use of long segment (>20 cm) stent graft, previous abdominal aortic repair, and/or hypogastric artery occlusion [55]. If the stent landing zone is even more proximal into the aortic arch, a right-to-left carotid-carotid and left carotid-subclavian artery bypass grafting is plausible to allow aortic stent placement between the innominate and the left carotid artery (Fig. 11.3b). A full arch debranching with grafting of all three supra-aortic vessels into the ascending aorta allows the aortic stent coverage of the entire aortic arch (Fig. 11.3c) [56]

Hybrid Elephant Trunk Procedure

The classic approach for pathology involving the transverse arch with inadequate proximal landing zone is to perform a stage I elephant trunk procedure—total arch replacement—to create a proximal landing zone. A second stage procedure addresses the descending thoracic aortic aneurysm with endovascular stent grafting.

Frozen Elephant Trunk Procedure

Frozen elephant trunk (FET) is a newer technique, which extends the repair of the aorta beyond the arch into the proximal descending aorta within a single stage operation [57]. It includes ascending aortic replacement with a surgical graft, along with total arch and proximal descending repair with direct attachment of a thoracic stent graft sutured to the proximal surgical graft. The stent device is delivered in antegrade fashion through the open aorta. The length of the stent graft is 10–15 cm and the distal end is positioned in the proximal descending aorta [58].

This procedure is followed by TEVAR, and the frozen stent graft serves as a proximal landing zone. The site for intraoperative arterial line monitoring during a FET procedure presents a challenge for the anesthesiologist. The most common surgical arterial cannulation site is the right axillary artery, making right upper extremity arterial pressure monitoring inaccurate during cardiopulmonary bypass. The arterial catheter can be placed in the left arm, assuming that the surgical plan includes left subclavian artery revascularization. It is common practice to have a lower extremity arterial catheter in addition to the upper extremity arterial catheter, to detect elephant trunk graft kinking. In this case, the femoral catheter will have lower blood pressure than the upper extremity arterial catheter. Spinal cord ischemia is reported in 6% of the patients undergoing a FET technique [58]. The risk of spinal cord ischemia precludes the placement of longer stent grafts in these hybrid procedures. In high risk patients, a preoperative subarachnoid drain is placed to decrease the risk of ischemic spinal cord injury.

Aortic Visceral Debranching Procedures

Similar to the aortic arch debranching techniques, hybrid procedures can also be used to treat distally extending aortic disease involving the visceral aortic segment. Aortic visceral debranching with extra-anatomic bypasses allows for retrograde perfusion of the visceral and renal arteries from the lower aorta or iliac arteries, during endovascular stent grafting of thoracoabdominal aorta. This technique has the advantage of avoiding a thoracoabdominal incision, visceral and renal ischemic time, and the use of left heart bypass. It can be performed as a single or two-stage procedure. The advantage of the single stage surgery is to avoid a possible aneurysm rupture between the interventions. The two stage procedure allows for a shorter interventional procedure, a lower incidence of acute kidney injury by avoiding administration of a contrast load immediately after an ischemic episode, and avoiding ischemia reperfusion injury with hypo-

tension [59]. Reno-visceral debranching combined with TEVAR is preserved for patients at very high risk for open surgical repair.

Complications Unique to Endovascular Aneurysm Repair

Complications unique to TEVAR include the development of endoleaks, stent graft migration, occlusion of aortic branches with acute ischemic complications, access site complications, post-implantation syndrome, and cumulative radiation exposure.

Classifications of Endoleaks and the Need for Repeat Interventions

Endoleaks occur with incomplete exclusion of the aortic aneurysm by the stent graft, due to the continued flow into the aneurysmal sac. They are the most common cause of aneurysm rupture after endovascular aortic repair, and the most common indication for reintervention (7%) [60]. Endoleaks may occur immediately or late after surgery, therefore, long term follow-up with aortic imaging is required for patients after TEVAR. There are five types of endoleaks, which differ in their mechanism, prognosis and clinical management (Table 11.3) [61, 62].

Stent Graft Migration

Stent graft migration occurs when the stent changes its position over time due to inappropriate seal at the proximal landing zone. The most common causes for migration are suboptimal graft sizing—graft is under-sized—and landing on diseased aorta.

Access Site Complications

Arterial access for endovascular aortic repair can be performed via percutaneous or cut-down techniques. Percutaneous access has a lower rate of

Table 11.3 Types of endoleaks associated with TEVAR, mechanism and clinical management

Type of endoleak	Mechanism	Clinical management
<i>Type I, Ia, Ib</i>	At the landing zone of the endograft Proximal seal zone Distal seal zone	Repair is warranted in order to prevent pressurization of the aneurysmal sac with angioplasty or stent graft extension
<i>Type II</i>	Retrograde filling into the aneurysmal sac from aortic branch vessels	Observation with serial imaging, majority resolve spontaneously. If persistent, treatment is recommended due to aneurysm sac expansion. Most common technique is arterial coil embolization
<i>Type III</i>	Component separation in the endograft, more common in the thoracic region, because of greater hemodynamic stress	Repair is indicated due to “endograft fatigue” and high risk of aneurysm rupture. Most common intervention is additional stent placement across the fabric disruption
<i>Type IV</i>	Graft porosity	Rare type, does not increase the risk of rupture and intervention is not recommended
<i>Type V</i>	Expansion of the sac with no detectable endoleak	Poorly understood mechanism, may represent unidentified type I or type III. If sac expansion is detected, treatment options include additional stent placement or open surgical repair

complications, and is associated with faster recovery and patient ambulation, and lower pain scores. The presence of arterial calcifications, prior groin exploration, and small vessel caliber may preclude the use of a percutaneous approach. Arterial thrombosis with acute leg ischemia, pseudoaneurysm formation, bleeding, infection, and arterial dissection are among the most common vascular site complications. These may require additional interventions such as thrombectomy, endarterectomy, and angioplasty to ensure arterial patency and hemostasis [28]. Iliac

surgical conduit is commonly used for entry point and passage of the endovascular device into heavily diseased iliac arteries. Arterial rupture most commonly occurs during insertion or removal of the delivery system [63].

Post-implantation Syndrome

Post-implantation syndrome is a self-limited inflammatory phenomenon, which occurs several days to several weeks after endovascular stent grafting of the aorta. It presents with fever, malaise, increased white blood cell count and C-reactive protein, and may be difficult to distinguish from infection. Factors contributing to the development of post-implantation syndrome are the stent graft material, and ongoing thrombosis of the excluded aneurysmal sac. Careful inspection of the wound sites, negative blood cultures and low procalcitonin level can help to distinguish from blood stream infection.

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