Open and Endovascular Management of Aortic Aneurysms

Nicholas J. Swerdlow, Winona W. Wu, Marc L. Schermerhorn

Abstract: **Aneurysmal disease can affect any segment of the aorta, from the aortic root to the aortic bifurcation. The treatment of aortic aneurysms has evolved dramatically in the past 3 decades, with the introduction of endovascular aneurysm repair using stent grafts causing a major paradigm shift in the field of aortic aneurysm surgery. While the technical details of the management of aortic aneurysms vary greatly depending on the location of an aneurysm, the principles remain the same. Successful aortic aneurysm treatment depends on either open replacement or endovascular exclusion of the aneurysmal segment with healthy artery proximal and distal to the repair. Major aortic branches of the arch and visceral segment add additional technical complexity to aneurysms involving these regions. Even as endovascular repair becomes the primary treatment modality for most aortic aneurysms, open repair remains an essential treatment modality in many circumstances. Additionally, long-term results of endovascular repair suggest that younger patients with long life expectancy and low-perioperative risk may benefit more from open repair. Therefore, technical expertise in both endovascular and open treatment is necessary for a comprehensive aortic aneurysm surgery practice. (*Circ Res*. 2019;124:647-661. DOI: 10.1161/CIRCRESAHA.118.313186.)**

Key Words: aortic aneurysm ■ morbidity ■ mortality ■ stents

Abdominal Aortic Aneurysms

Screening

Aortic disease is the direct cause of close to 10 000 deaths annually in the United States.[1] The goal of aortic aneurysm repair is to prevent the high morbidity and mortality associated with aneurysm rupture. Multiple randomized controlled trials have demonstrated that one-time, ultrasound-based abdominal aortic aneurysm (AAA) screening is effective at reducing aneurysm-related mortality and incidence of aneurysm rupture.[2–5] The largest of these trials, the Multicentre Aneurysm Screening Study, randomized over 67 000 men aged 65 to 74 years to ultrasound-based AAA screening versus no screening and found that screening lead to a 40% reduction in aneurysm-related mortality, a benefit that persisted for over a decade.[2,3] A subsequent Cochrane Review of randomized trials again demonstrated this 40% reduction in aneurysm-related mortality and an over 50% reduction in aneurysm rupture.[5] Therefore, the United States Preventative Services Task Force recommends one-time ultrasound-based AAA screening in men 65 to 75 who have ever smoked (https://www.uspreventiveservicestaskforce.org/Page/Document/UpdateSummaryFinal/abdominal-aortic-aneurysm-screening). Similarly, Medicare covers one-time AAA screening for men 65 to 75 who have smoked 100 cigarettes in their lifetime and anyone with a family history of AAA (https://www.medicare.gov/coverage/ab-aortic-aneurysm-screening.html).

Indications for Treatment

The goal of elective AAA repair is to prevent rupture, given the severe morbidity and mortality associated with ruptured aneurysms. Therefore, the decision to treat an AAA is based on the associated risk of treatment, the risk of aneurysm rupture, the patient's life expectancy, and patient preference. The primary determinant of rupture risk is maximum aneurysm diameter, with negligible rupture risk in aneurysms <4 cm in diameter compared with an annual risk of 30% to 50% in aneurysms >8 cm (Table 1).[6] Other factors independently associated with rupture include female sex, active smoking, and chronic obstructive pulmonary disease.[7] The Society for Vascular Surgery recommends repair for all patients of acceptable perioperative risk with an AAA ≥5.5 cm in diameter as well as all patients with saccular and symptomatic aneurysms.[8] These guidelines also suggest repair for women at a diameter of 5.0 to 5.4 cm.

Historical Perspective

Before the 1990s, open repair was the only treatment option for AAAs and, while still conferring higher survival compared with observation, was characterized by high perioperative morbidity and mortality.[9] However, the paradigm of AAA repair forever changed after the introduction of endovascular AAA repair (EVAR), first described by Parodi et al.[10] Since then, the use of endovascular techniques in the treatment of aortic aneurysms has expanded dramatically, and EVAR is now the primary treatment for AAA. Before the endovascular era, operative mortality following AAA repair was ≈5%. After the adoption of EVAR, overall AAA repair operative mortality fell to 2.4% in 2008.[11] The introduction of this minimally invasive approach also allowed for AAA repair in patients previously unsuitable for repair because of excessive perioperative

From the Beth Israel Deaconess Medical Center, Harvard Medical School, Boston, MA.
Correspondence to Marc L. Schermerhorn, MD, Beth Israel Deaconess Medical Center, 110 Francis St, Suite 5B, Boston, MA 02215. Email mscherm@bidmc.harvard.edu

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Nonstandard Abbreviations and Acronyms

AAA	abdominal aortic aneurysm
AKI	acute kidney injury
ATAA	ascending thoracic aortic aneurysm
CAAA	complex abdominal aortic aneurysm
CIA	common iliac artery
CSF	cerebrospinal fluid
DTAA	descending thoracic aortic aneurysm
EVAR	endovascular AAA repair
FEVAR	fenestrated EVAR
IFU	Instructions for Use
IIA	internal iliac artery
IMA	inferior mesenteric artery
LSA	left subclavian artery
SCI	spinal cord ischemia
SMA	superior mesenteric artery
TAA	thoracic aortic aneurysm
TAAA	thoracoabdominal aortic aneurysm
TEVAR	thoracic aortic aneurysm repair

risk and has been associated with a decrease in deaths from AAA rupture.[11,12]

Endovascular Versus Open Treatment

Four randomized trials compared EVAR to open AAA repair. The EVAR-1 trial randomized 1082 patients to EVAR or open repair in the United Kingdom, the DREAM trial (Dutch Randomized Endovascular Aneurysm Management) randomized 351 patients in the Netherlands and Belgium, the OVER trial (Open Versus Endovascular Repair) randomized 881 patients at Veterans Affairs Medical Centers, and the ACE trial (Anevrysme de l'aorte abdominale, Chirurgie versus Endoprothese) randomized 316 patients in France. A *Cochrane Systematic Review* of these trials found that EVAR had 67% lower 30-day mortality compared with open repair, 1.4% versus 4.2%, respectively.[13–17] The association between EVAR and lower perioperative morbidity and mortality compared with open repair has been corroborated by large observational studies and meta-analyses.[17–19]

The early survival benefit of EVAR is lost over time, in large part because of catch-up mortality in the EVAR group in older and sicker patients that would not have survived open repair.[20] There is also likely contribution from higher rates of late complications with EVAR leading to higher late mortality.[21] In the 15-year results from the EVAR-1 randomized trial, there was no difference in survival between the groups over the duration of follow-up. Beyond 8 years, EVAR was found to have higher all-cause and aneurysm-related mortality, primarily because of more aneurysm rupture in the EVAR group.[22] Similarly, over the duration of the DREAM and OVER trials, there was no difference in overall survival, despite the early survival advantage of EVAR.[23,24] In our propensity-matched analysis of Medicare beneficiaries, the early higher survival with EVAR persisted for 3 years, after which survival was the same. However, to account for difference in area under the survival curves, we found that the restricted mean survival benefit associated with EVAR persisted through 7 years.[25] These long-term results indicate that younger patients with longer life expectancy and lower perioperative risk may benefit more from open repair. They also caution against the overuse of endovascular repair in these patients and in patients with unsuitable anatomy.

The rapid adoption of EVAR has provided a AAA treatment option for many patients who are not candidates for open repair. Conversely, there remain patients with anatomic constraints that preclude the use of EVAR. Nonetheless, there remains a proportion of patients who are candidates for EVAR and open repair. Young patients who are otherwise healthy may benefit from open repair given its superior durability. Additionally, patients with anatomic features that make the need for reintervention more likely, such as a highly angulated neck, may benefit from an open approach. Finally, patients with connective tissue disorders should be treated with an open approach if possible as long-term endovascular complications are inevitable in this population secondary to progression of their disease. In addition to patients with substantial medical comorbidity, EVAR is preferred in patients for whom open repair would pose additional technical challenges, such as patients with a hostile abdomen. For patients eligible for both EVAR and open repair, shared decision-making based on a thorough discussion of risks and benefits of each approach is paramount (Table 2).

While open repair remains an integral part of a comprehensive aortic aneurysm treatment program, rates of open AAA repair have declined dramatically in the endovascular era.[26] Therefore, fewer surgeons and centers have a high-volume open aneurysm practice. While there is a modest volume-outcome relationship with EVAR, the relationship between open AAA repair outcomes and surgeon/center volume is dramatic.[27] Therefore, open AAA repair should be performed by experienced surgeons at high-volume centers.

Endovascular Repair

Procedure

Successful EVAR excludes an aneurysm from blood flow through placement of a bifurcated stent graft, most commonly introduced through the femoral arteries (Figure 1). Sac exclusion is dependent on adequate proximal and distal seal between the graft fabric and the vessel wall. For infrarenal AAAs, the proximal seal zone is the aneurysm neck—healthy aorta distal to the lowest renal artery and proximal to the start of an aneurysm. The distal seal zone is most commonly in the common iliac arteries (CIA).

Table 1. Estimated Annual AAA Rupture Risk by Aneurysm Size*

Aneurysm Size, cm	Annual Rupture Risk (%/y)
<4	0
4–5	0.5–5
5–6	3–15
6–7	10–20
7–8	20–40
>8	30–50

AAA indicates abdominal aortic aneurysm.
*Adopted from Brewster et al.[6]

Table 2. Patient Factors Favoring Endovascular or Open AAA Repair

Favors Open Repair	Favors EVAR
Younger patient	Older patient
Few medical comorbidities	Multiple medical comorbidities
Connective tissue disorder	Prior aortic surgery
Anatomy not favorable for EVAR	Prior abdominal surgery

AAA indicates abdominal aortic aneurysm; and EVAR, endovascular AAA repair.

There are currently multiple EVAR devices approved for commercial use in the United States. The specific anatomic criteria depend on the Instructions for Use (IFU) of each graft. However, these criteria all depend on the same anatomic measurements: neck length, neck diameter, neck angle, and iliac diameter. Despite the availability of multiple devices, ineligibility for EVAR based on IFU is common, especially in women, with as high as 66% with infrarenal AAAs ineligible.[28] Therefore, use of these devices outside the IFU is common. Results of studies evaluating the implication of use outside the IFU are mixed, however, there is evidence that nonadherence to IFU may be associated with higher rates of complications.[29,30] Graft choice depends on anatomic criteria, device availability, and surgeon experience/preference. While each graft has been evaluated through prospective trials, direct comparison between graft types is limited.

Adequate proximal seal is paramount to successful EVAR. In addition to neck length, angle, and diameter, other characteristics that influence the proximal seal are neck calcification, reverse tapering, and mural thrombus. To improve proximal seal, some devices use suprarenal fixation, in which an uncovered stent extends above the renal arteries. Observational studies have demonstrated that suprarenal fixation is associated with a slightly higher risk of perioperative renal complications.[31,32] When selecting a device using suprarenal fixation, this difference must be weighed against potential improved proximal fixation. The Ovation Abdominal Stent Graft System (Endologix, Irvine, CA) has introduced a new mechanism for proximal seal. In addition to suprarenal fixation, this device contains sealing rings in the proximal seal zone which are filled with polymer that sets in situ.[33]

Infrarenal devices are designed to seal distally in the CIAs. However, aneurysmal CIAs pose a technical challenge by preventing adequate distal seal. Surgeons have overcome this obstacle with 2 techniques: internal iliac artery (IIA) embolization and branched iliac devices. IIA embolization, performed before or concomitantly with EVAR, facilitates extension of the iliac seal zone into the external iliac artery. The most common complication following IIA embolization is buttock claudication, occurring in ≈30% of patients and more commonly following bilateral embolization. However, these symptoms resolve within 1 year in more than half of these patients.[34] Though still rare, IIA embolization has been associated with increased risk of ischemic colitis following EVAR; thus, physicians must be alert to this complication in these patients.

The Gore Iliac Branch Endoprosthesis (Gore Medical, Flagstaff, AZ) preserves the IIA in patients with aneurysmal CIAs via a branched iliac component. This device was approved for commercial use in the United States in 2016 and is currently the only iliac branch device on the market. The Ivestigational Device Exemption trial of the Iliac Branch Endoprosthesis demonstrated high rates of technical success and excellent early patency.[35] While long-term data are limited, early results demonstrate high long-term patency as well, with estimated freedom from IIA occlusion at 60 months of 86%.[36]

Arterial Access

When EVAR was first introduced, femoral artery access was obtained through surgical cutdown. However, advances in percutaneous arterial closure devices have facilitated percutaneous EVAR, and bilateral percutaneous access is now used for most cases.[37,38] The Percutaneous EVAR randomized trial demonstrated that percutaneous EVAR is noninferior to femoral cutdown and reduces operative time.[39] Large, retrospective observational studies have found that percutaneous EVAR is associated with shorter operative time, fewer wound complications, and shorter length of stay.[37,38] Given these results, we support a percutaneous-first approach to EVAR and over 90%

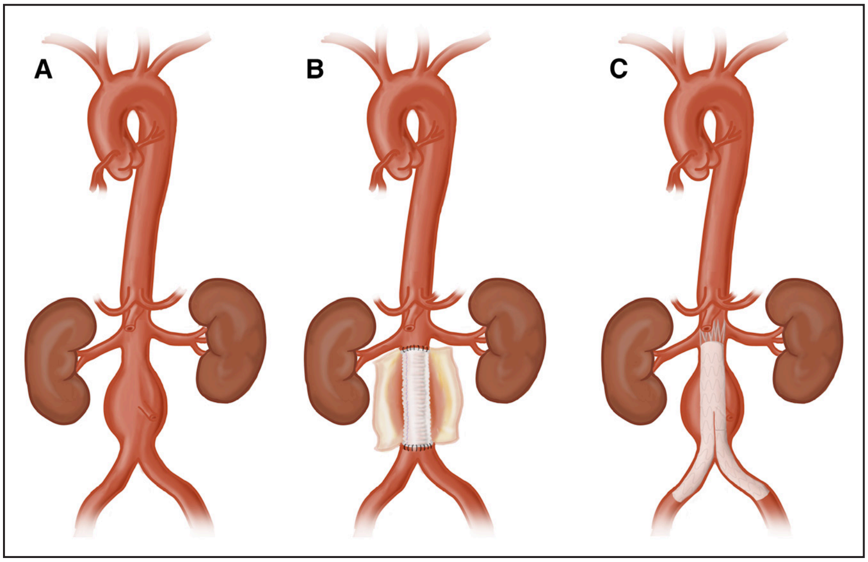

Figure 1. Open and endovascular abdominal aortic aneurysm (AAA) repair. A, Unrepaired infrarenal AAA. **B**, Open AAA repair with a tube graft from the infrarenal neck to the aortic bifurcation. **C**, Endovascular abdominal aortic aneurysm repair with proximal seal in the infrarenal neck and distal seal in the common iliac arteries.

of EVARs performed at our institution are performed with successful bilateral percutaneous access.

Image Fusion

The minimally invasive nature of EVAR comes at the cost of radiation and iodinated-contrast exposure. Efforts to reduce radiation exposure to both the patient and provider are centered around the As Low as Reasonably Achievable (ALARA) principle. Techniques for radiation reduction include proper shielding, limiting angulation, shuttering, and minimizing digital subtraction angiography.[40] Live 3-dimensional roadmapping with computed tomographic (CT) angiography-fluoroscopy image fusion has also emerged as an important tool in reducing radiation exposure, contrast volume, and operative time during EVAR.[41] This software, available with most modern imaging systems, overlays a 3-dimensional reconstruction of the preoperative CT scan on the 2-dimensional fluoroscopy, allowing for vessel navigation without contrast injection and reducing the need for repeat exposure in different projections. At our institution, image fusion is now used routinely on all complex endovascular aortic interventions.

Endoleaks

A major set of complications unique to EVAR is endoleak, persistent blood flow in the aneurysm sac. Endoleaks are categorized by the source of flow, described in Table 3.[42] Type I and III endoleaks represent direct arterial flow into the sac and are, therefore, considered most dangerous. There is growing evidence that some of these endoleaks present immediately after EVAR may resolve spontaneously.[43] However, persistent and late-type I and III endoleaks have been associated with aneurysm rupture and mortality.[44] Therefore, persistent type I and III endoleaks and those discovered during follow-up warrant prompt treatment (Table 3).

Endovascular techniques for type Ia endoleak treatment attempt to restore apposition between the stent graft and aortic wall. This can be achieved with placement of EndoAnchors (Medtronic, Minneapolis, MN), an aortic cuff, or a Palmaz stent (Cordis, Milpitas, CA). If aneurysmal degeneration has resulted in loss of healthy infrarenal neck, the proximal seal zone can be extended proximally into the visceral segment with a fenestrated graft. Type Ib endoleaks can be treated with iliac extension and IIA coiling if necessary. Type III endoleaks are treated with relining of the overlap zone or fabric tear causing the leak. If these endoleaks cannot be treated via an endovascular approach, conversion to open repair is indicated if the patient is of appropriate operative risk.

Type II endoleaks represent back-bleeding into the aneurysm sac, most commonly from lumbar arteries or the inferior mesenteric artery (IMA). These endoleaks are common after EVAR, occurring in ≈10% of patients, and up to a third will resolve spontaneously.[45] However, despite the frequency with which they occur, their natural history is poorly defined and no definitive treatment guidelines exist. Given the high rate of resolution and low rate of associated aneurysm rupture, we routinely observe type II endoleaks and only intervene when they are associated with sac expansion.

When treating type II endoleaks, the mainstay of therapy is embolization of the endoleak and its source. Numerous techniques for accessing the endoleak have been described. First-line treatment is frequently transarterial embolization. Lower lumbar arteries feeding the endoleak can be accessed through the IIA and the IMA can be accessed through the superior mesenteric artery (SMA). If transarterial embolization fails, the sac can be accessed via direct puncture using a translumbar approach or via transcaval puncture.[46,47] In patients who have exhausted minimally invasive alternatives, open type II endoleak management is an option in patients with appropriate operative risk. This consists of exposure of the aneurysm, sacotomy, removal of thrombus and previous coils, oversewing of bleeding vessels, and rewrapping the sac around the graft, eliminating the dead space.[48] Graft explant is rarely necessary.

Reports of type II endoleak treatment document high initial technical success. However, regardless of the technique used, reintervention for recurrent leak is common. Long-term results following type II endoleak treatment are limited, clear indications remain unclear, and assessing the efficacy of these interventions is difficult.[49]

Long-Term Follow-Up

EVAR is associated with higher rates of aneurysm-related reinterventions compared with open repair.[22,25] Indications for reintervention include stenosis or occlusion, kinking, or graft failure, including device migration and fabric tears.[23,25] These complications can frequently be treated with endovascular reintervention, however, if severe, may require conversion to open repair with or without graft explant.[50] Graft infection is another potentially devastating complication following EVAR and frequently requires graft explant.[50,51] Finally, while rare, retrograde type B aortic dissection has been reported following EVAR.[52] Therefore, consistent long-term follow-up with imaging evaluating graft patency, residual sac diameter, and presence of endoleak is crucial. The Society for Vascular Surgery guidelines recommend initial postoperative CT angiography one-month postoperatively followed by annual surveillance with either CT angiography or duplex ultrasound.[8] Surveillance at 6-month intervals is recommended for patients with a known type II endoleak.

Table 3. Endoleak Classification*

Endoleak Type	Description
Type I	
A	Leak from the proximal seal zone
B	Leak from the distal seal zone
C	Leak from a fenestration, branch end point, or branch occluding plug/coil
Type II	Retrograde flow from a branch artery in the excluded segment (eg, lumbar artery)
Type III	
A	Loss of apposition or disconnect between components
B	Fabric tear
Type IV	Flow through porous fabric
Type V	Sac expansion (indicating sac pressurization) without identifiable endoleak

*Adopted from Fillinger et al.[42]

Open Repair

Procedure

Open AAA repair consists of replacement of the aneurysmal segment with a synthetic graft (Figure 1). In most cases, a tube graft from the infrarenal neck to the bifurcation is sufficient. However, if the bifurcation or proximal CIA are diseased, a bifurcated graft can be used. Successful repair relies on exposure of the abdominal aorta and proximal and distal vascular control.

The abdominal aorta is approached through a transperitoneal or retroperitoneal approach—both which have their own advantages and disadvantages. A transperitoneal approach is performed with the patient supine through a midline laparotomy. It provides rapid access to the distal abdominal aorta and the bifurcation. The aneurysm neck is exposed by packing the bowel in the right abdomen and dividing the ligament of Treitz. More extensive mobilization is necessary to expose the visceral segment and supraceliac aorta. A retroperitoneal approach is performed with the patient in the right lateral decubitus position through a left flank incision extending inferiorly parallel to the rectus abdominis. The peritoneal and retroperitoneal contents are moved anteromedially, exposing the entire abdominal aorta and the left iliac artery. This provides excellent exposure of the visceral segment; however, exposure of the right CIA bifurcation can occasionally be difficult.

Randomized trials and observational studies have compared these 2 approaches. A meta-analysis of randomized trials found that a retroperitoneal approach reduced ICU stay, hospital stay, and blood loss during elective open AAA repair.[53] A meta-analysis also including observational studies demonstrated similar findings and found that a retroperitoneal approach was associated with lower rates of ileus and pneumonia.[54] Neither study found a difference in mortality. Additionally, violation of the peritoneum carries risk of hernia and bowel obstruction, a drawback of transperitoneal exposure.[55] The choice of exposure depends on patient anatomy and surgeon preference. Patients with hostile neck anatomy or a short neck may benefit from a retroperitoneal approach and subsequent better exposure of the visceral segment. Conversely, patients with right CIA aneurysms necessitating a bifurcated graft may benefit from a transperitoneal approach. In the absence of anatomic restraints, we prefer a retroperitoneal approach.

With the aorta exposed, vascular control is obtained. During AAA repair, an infrarenal aortic cross-clamp location should be used whenever possible. Suprarenal clamping is associated with higher rates of acute kidney injury (AKI) and higher overall complication rates.[56] Hostile neck anatomy may necessitate a suprarenal clamp location. In these cases, efforts should be made to minimize renal ischemia time and the clamp should be moved distally once the proximal anastomosis is completed. Distal control is obtained by clamping the bilateral CIAs or with balloon occlusion if adequate distal control cannot be obtained via a cross-clamp.

When access has been obtained, the sac is opened, thrombus is removed, and the aneurysmal segment is replaced with a synthetic graft. The choice of graft configuration depends on the distal extent of aneurysmal disease. After back-bleeding lumbar vessels are ligated and the aortic reconstruction is complete, the aneurysm sac is closed around the graft.

Management of the IIA and IMA

Colon ischemia is a rare but dreaded complication of open AAA repair, occurring in 1% to 2% of cases.[8] Colonic perfusion relies on the IMA and bilateral IIAs as well as collateral circulation from the SMA and circumflex femoral vessels. Loss of the bilateral IIAs during open AAA repair has been associated with increased risk of colon ischemia.[57] However, the impact of IMA ligation remains unclear. A randomized trial of IMA reimplantation did not find a reduction in colonic ischemia, and IMA ligation has not been associated with higher rates of colon ischemia in observational studies.[57,58]

About prevention of colon ischemia, the Society for Vascular Surgery guidelines recommend preservation of at least one IIA during open AAA repair.[8] If an anastomosis distal to the CIA bifurcation is required, hypogastric blood flow can be maintained through use of an end-to-side anastomosis to the external iliac artery allowing retrograde flow to the IIA or via IIA bypass. IMA reimplantation is recommended when there is increased risk for colon ischemia, such as patients with SMA occlusive disease or interrupted collateral blood flow, and when poor back-bleeding from the IMA orifice is noted.[8]

Long-Term Follow-Up

Reinterventions after open AAA repair are less common than after EVAR and the nature of these reinterventions differs. The most common reintervention following open repair is incisional hernia repair.[23,25] Late aneurysm-related complications do occur and are frequently related to para-anastomic pseudoaneurysms or aneurysm extension. Additionally, graft infection or graft enteric erosion/fistula can rarely occur, but these complications require graft explant and are associated with high morbidity and mortality. Therefore, surveillance abdominal/pelvic CT is recommended at 5-year intervals.[8]

Complex AAAs

Endovascular Versus Open Treatment

Complex AAAs (CAAA), comprised of juxtarenal AAAs—aneurysms that extend to level of the renal arteries, and suprarenal AAAs—aneurysms that extend above the renal arteries, comprise at least 15% of AAAs requiring treatment.[59] (Figure 2) These aneurysms pose a particular technical challenge for repair as they involve the visceral segment. Type IV thoracoabdominal aneurysms (TAAA), those extending above the celiac artery to the level of the diaphragm, are frequently grouped with CAAA. For open repair of CAAA, at a minimum a suprarenal clamp location is required, and depending on the proximal extent of the aneurysm, supraceliac clamping, and renal and mesenteric reconstruction may be necessary. However, this can often be addressed with a beveled proximal anastomosis including the celiac, SMA, and right renal artery, leaving only the left renal artery to be bypassed. When considering an endovascular approach, these aneurysms cannot be repaired with standard EVAR because of lack of an infrarenal neck.

Until the past 2 decades, open repair was the only treatment option for CAAA. The increased technical complexity of these aneurysm leads to increased perioperative morbidity and mortality compared with open infrarenal AAA repair. While there is significant variability in reported perioperative mortality in single-center series, ranging from 0% to 7%, 2

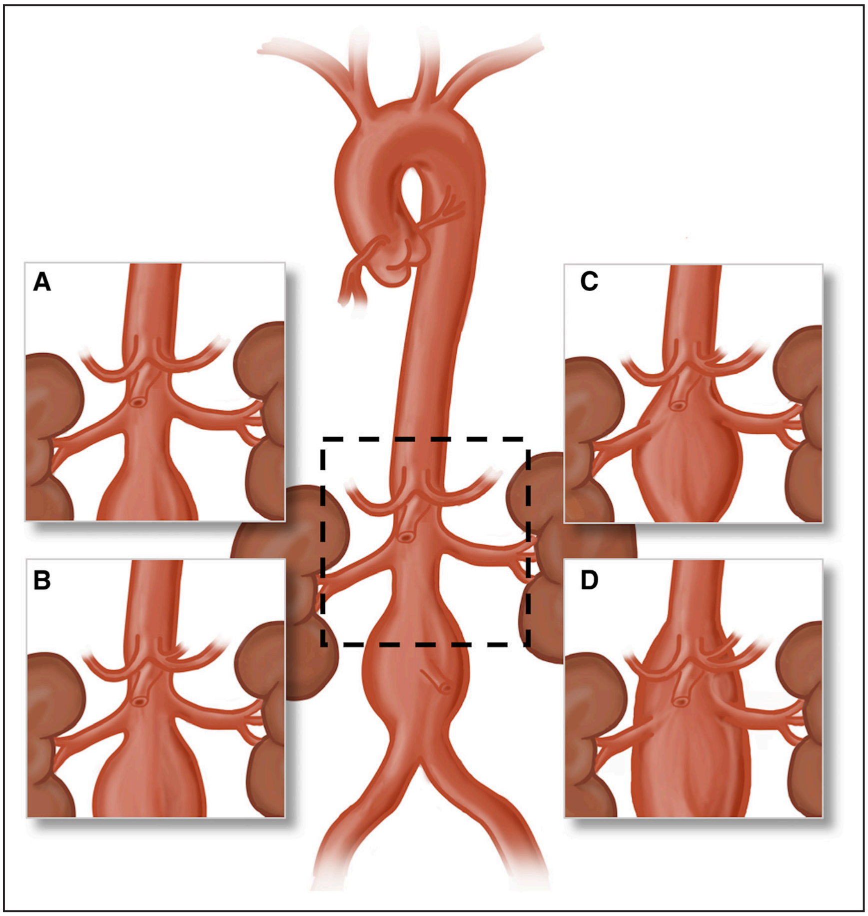

Figure 2. Classification of proximal neck anatomy of abdominal aortic aneurysms (AAA). A, Infrarenal AAA. **B**, Juxtarenal AAA. **C**, Suprarenal AAA. **D**, Type IV thoracoabdominal aortic aneurysm.

meta-analyses reported 30-day mortality of 2.9% to 4.0%.[59,60] Renal complications are especially common after open CAAA repair as these procedures require suprarenal clamping and occasionally renal artery reconstruction, with postoperative rates of AKI as high as 39%, and new onset dialysis occurring in 3% to 4% of patients.[59,60]

The lack of infrarenal neck in CAAA precludes the use of standard EVAR. Two techniques have been developed to extend the proximal seal zone cranially allowing for endovascular repair in these patients: fenestrated EVAR (FEVAR) and chimney/snorkel EVAR. FEVAR uses a graft with fenestrations for visceral vessels, typically designed for a patient's anatomy (Figure 3A). Stent grafts can be placed through these fenestrations, preserving flow to the target vessel and preventing flow into the aneurysm sac. Single-center reports have demonstrated that these procedures can be performed with high rates of technical success and 1% to 4% perioperative mortality.[61–63] While reports of long-term outcomes remain limited, reports from early trials demonstrate high long-term target vessel patency, and survival comparable to standard EVAR.[64,65] However, as with standard EVAR, reintervention and endoleaks are common after FEVAR. Estimated 5-year reintervention-free survival ranges from 50% to 60%.[65,66] In their single-center series with the median follow-up of close to 3 years, Roy et al[65] reported a type I/III endoleak rate of 10%.

Chimney/snorkel EVAR uses a standard EVAR device and extends the seal zone cranially with additional stent grafts placed parallel to the main device, maintaining flow to the target vessels. Like FEVAR, this technique can be performed with high technical success and low-perioperative morbidity and mortality, with pooled 30-day mortality of 3% to 4%.[67] However, this technique is prone to type I endoleaks in the gaps between the main device and the chimneys. The rate of early type I endoleak is as high as 16% in pooled analysis.[67] Additionally, while long-term results following chimney/snorkel EVAR remain limited, there is concern about the durability of these repairs, as rate of chimney thrombosis at 3 years has been reported as high as 15%.[68]

There have been no randomized trials comparing open and endovascular CAAA repair and comparison of these techniques relies on meta-analyses and national registries. A review of 30-day outcomes from the National Surgical Quality Improvement Program database found that open repair was associated with higher odds of death and renal complications compared with FEVAR.[69] In a retrospective review of single-center studies, Nordon et al[70] reported a slightly lower 30-day pooled mortality following FEVAR compared with open repair, 1.4% compared with 3.6%. AKI, but not new onset dialysis, was also more common after open repair. In a recent systematic review, Rao et al[71] reported no difference in 30-day mortality and postoperative AKI, though the FEVAR group had higher rates of baseline comorbidities. Major complications were more common after open repair. However, in both studies, reinterventions were more common after FEVAR.

The factors influencing the decision between open and endovascular CAAA repair are similar to those for infrarenal

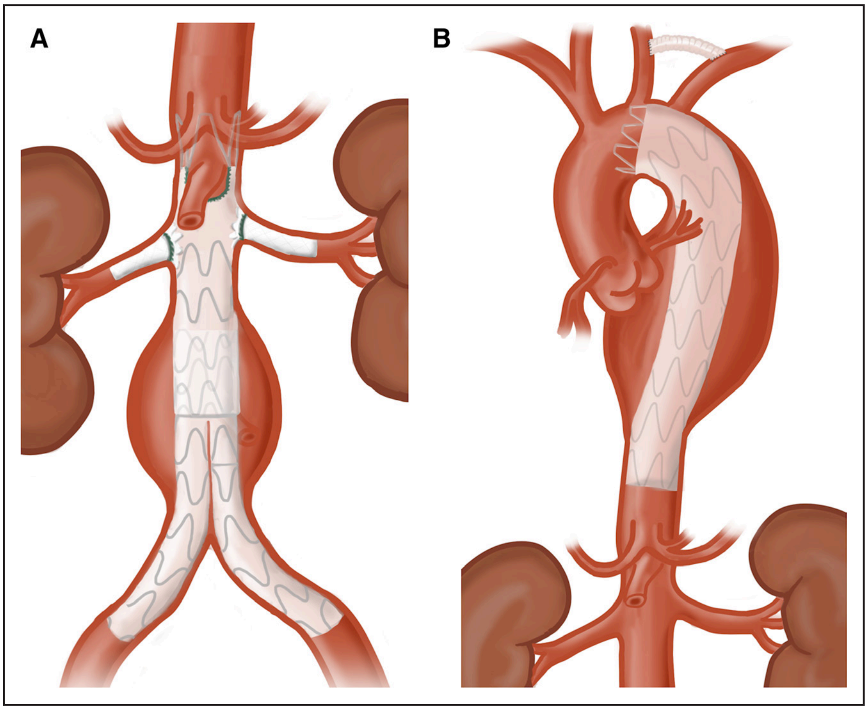

Figure 3. Endovascular repair of complex abdominal aortic aneuryms and descending thoracic aortic aneurysms. A, Fenestrated endovascular aortic aneurysm repair with fenestrations for the renal arteries and a scallop for the superior mesenteric artery. **B**, Thoracic endovascular aneurysm repair with coverage of the left subclavian artery (LSA) and left common carotid to LSA bypass.

AAA (Table 2). Notably, as the number of open AAA repairs performed nationally continues to dwindle, so will the number of open CAAA repairs. The dramatic volume-outcome relationship of open infrarenal AAA repair persists with CAAA.[72] Furthermore, total open aortic volume is not sufficient, as this relationship is specific to complex volume. While the volume-outcome relationship EVAR is modest, FEVAR introduces more complexity. The volume-outcome relationship of FEVAR is not defined and warrants further study.

Endovascular Repair

In the United States, there is currently only one fenestrated graft Food and Drug Administration-approved for commercial use, the Cook Zenith Fenestrated AAA Endovascular Graft (Cook Medical, Bloomington, IN). This device is indicated for juxtarenal AAA and incorporates up to 3 visceral vessels. The device is custom made for a patient's anatomy and requires 6 weeks for manufacturing and delivery. It is, therefore, not an option for patients needing urgent or emergent repair. Use of this device for elective juxtarenal AAA repair is associated with high technical success, low-perioperative morbidity and mortality, and excellent long-term target vessel patency.[73] However, a substantial portion of patients with complex AAA do not meet the anatomic criteria of this device and no commercially available endovascular treatment option is available. For this subset of patients who are also unfit for open repair, there are ongoing clinical trials of custom-manufactured or physician-modified devices that are not constrained by these anatomic criteria. Chimney/snorkel EVAR also remains an option for this patient population, especially those in need of urgent or emergent intervention. Finally, there are also ongoing clinical trials of off-the-shelf fenestrated devices that can accommodate variable visceral anatomy.

Open Repair

Open CAAA repair requires exposure of the visceral aortic segment. This facilitates placement of a suprarenal clamp for juxtarenal AAAs or supraceliac clamp with associated visceral artery reconstruction if necessary for suprarenal AAAs and type IV TAAAs. Therefore, a retroperitoneal approach should be used whenever possible as this allows for proximal extension of the dissection into the supraceliac segment or descending thoracic aorta. This exposure is more challenging from a transperitoneal approach and frequently necessitates a formal medial visceral rotation.

Renal complications are common after CAAA repair as these procedures require suprarenal aortic clamping and a subsequent period of renal ischemia.[59,71] Both pharmacological and perfusion techniques for renal protection are used commonly. The most common pharmacological intervention is infusion of mannitol before cross-clamping. Additionally, cold renal perfusion with crystalloid during aortic cross-clamping is also common. While analyses of the benefits of these techniques have largely shown mixed results, a recent analysis from the Vascular Quality Initiative found that cold renal perfusion was associated with a lower odds of postoperative AKI in patients with prolonged renal ischemia time.[59,74]

Thoracic Aortic Aneurysms

Screening

Thoracic aortic aneurysms (TAA) include aneurysms of the root and ascending aorta, the aortic arch, and the descending aorta, with some aneurysms involving multiple segments. Thoracoabdominal (TAAA) aneurysms involve a portion of both the descending thoracic and the abdominal aorta (Figure 4). It is estimated that the ascending aorta is involved in 60% of TAA, the descending aorta is involved in 40%, and the arch is involved in 10%; 10% of TAA are thoracoabdominal.[75] While the cause of most descending TAA (DTAA) resembles that of AAA, ascending TAA (ATAA) differ, as many of these aneurysms are associated with either connective tissue disease or bicuspid aortic valve.[75]

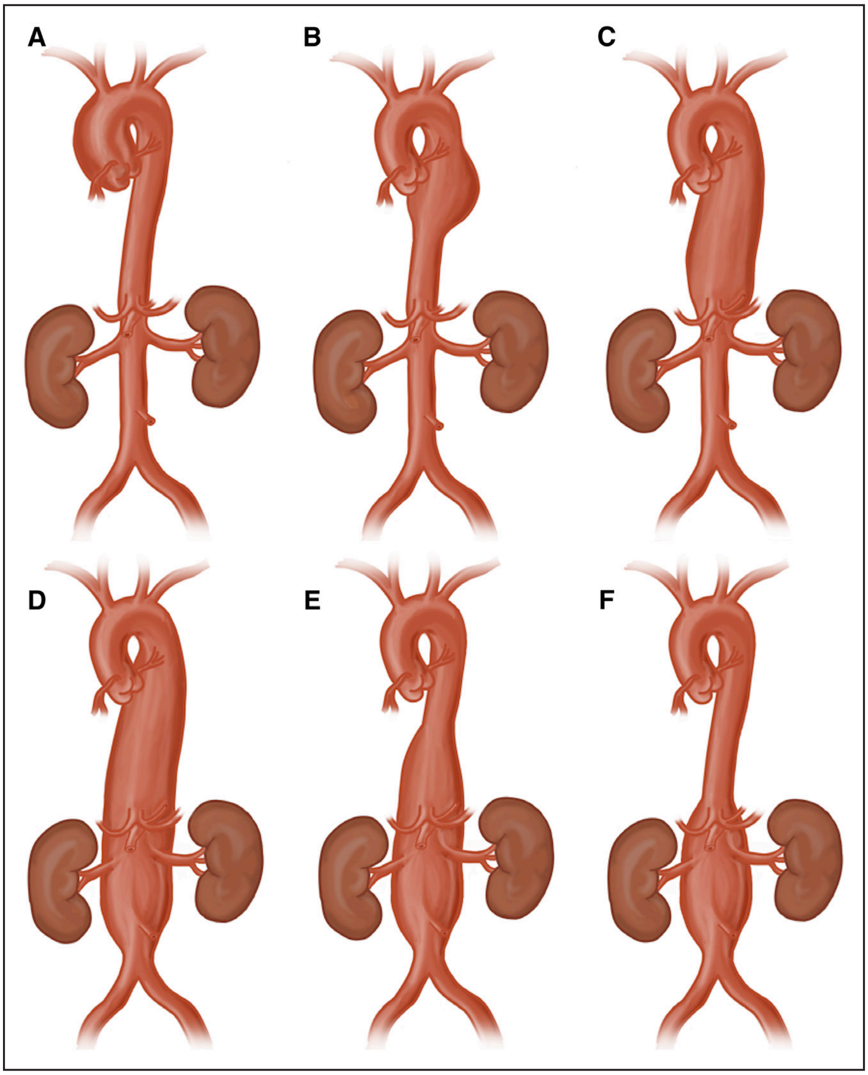

Figure 4. Anatomic classification of thoracic aortic aneurysms (TAA) and Crawford classification of thoracoabdominal (TAAA) aortic aneurysms. A, Proximal TAA involving the aortic root, ascending aorta, and proximal arch. **B**, Descending TAA. **C**, Type I TAAA extending from the left subclavian artery (LSA) origin to the suprarenal aorta. **D**, Type II TAAA extending from the LSA to the bifurcation. **E**, Type III TAAA extending from the distal descending thoracic aorta to the bifurcation. **F**, Type IV TAAA extending from the supraceliac aorta to the bifurcation.

Diagnostic evaluation of the thoracic aorta requires CT angiography or magnetic resonance imaging angiography, as the arch and descending thoracic aorta cannot be adequately visualized with echocardiography. Currently, there is no recommended screening for TAA in the general population. However, the American College of Cardiology and the American Heart Association guidelines recommend screening for populations at high risk for TAA.[76] For example, measurement of the aortic root and ascending aorta with an echocardiogram is recommended for patients with Marfan syndrome, with repeat imaging to establish a rate of growth 6-months later. Imaging of the entire aorta is indicated for patients with Loeys-Dietz syndrome or other similar genetic diseases.

Indications for Repair

The American College of Cardiology and American Heart Association guidelines recommend surgical repair of asymptomatic aneurysms of the ascending aorta and the aortic arch with maximum diameter ≥5.5 cm.[76] For DTAAs, these guidelines recommend repair if the maximum diameter is ≥5.5 cm for endovascular repair or if the maximum diameter is ≥6.0 cm when open repair is required. Similarly, the European Society for Vascular Surgery recommends repair at 5.5 cm for patients who are good endovascular candidates or fit for open repair.[77] All patients with aneurysms >6.0 cm should be considered for open or endovascular repair if of appropriate operative risk. However, there are patients for whom repair is not possible because of excessive perioperative risk or anatomic factors that make repair unfeasible. Repair is also indicated for patients with saccular TAA, thoracic aortic pseudoaneurysms, and symptomatic aneurysms.

These guidelines vary for specific high-risk populations. For instance, the threshold for repair is 4 to 5 cm for genetic disease-associated aneurysms, depending on the condition. Repair of ATAAs ≥4.5 cm should be considered in patients undergoing aortic valve replacement.[76,77] Furthermore, it is important to note that when performing thoracic aortic repair for aortic dissection, aortic diameter is not frequently the indication for the operation. In a study from the International Registry of Acute Aortic Dissection, >80% of patients undergoing repair of acute type B aortic dissection had a maximum aortic diameter of <5.5 cm.[78]

Descending Thoracic Aortic Aneurysms

Endovascular Versus Open Treatment

Before the endovascular era, open surgery was the only treatment option for DTAAs. Open DTAA repair is a major operation with substantial perioperative mortality and morbidity.

Perioperative mortality for open repair of intact DTAAs in the National Inpatient Sample was 10%.[79] Over 40% of patients experienced a perioperative complication, with respiratory and cardiac complications most common. Mortality reported from single-center series varies greatly, with mortality from high-volume centers as low as 3%.[80] Rates of paraplegia, a feared complication of both open and endovascular DTAA repair secondary to spinal cord ischemia (SCI), range from 0% to 4%.[81]

Since approval of the first thoracic stent graft in the United States in 2005, the use of thoracic endovascular aortic aneurysm repair (TEVAR) in the treatment of DTAAs has expanded rapidly and surpassed open repair as the predominant approach.[82] Investigational Device Exemption trials of TEVAR devices demonstrate that TEVAR can be performed with high technical success and perioperative mortality following TEVAR has been reported from 1.5% to 7%, with rates of paraplegia from 1% to 3%.[83]

There is great variation in reported mortality following open and endovascular repair of DTAA, which may be partially explained by varied inclusion of thoracic aortic pathologies other than aneurysmal disease, including type B aortic dissection. There have been no randomized trials comparing endovascular and open repair of DTAAs and, therefore, comparison of these techniques has relied primarily on analyses of single-center series, administrative databases, and national registries. A prospective, multi-institutional trial of the Zenith TX2 device (Cook Medical) did include an open surgery arm, though assignment was not randomly allocated. In this trial, TEVAR met the prespecified noninferiority margin in perioperative mortality compared with open repair; 1.9% versus 5.7%, respectively.[84] TEVAR was also associated with lower rate of perioperative complications. In an analysis from the National Inpatient Sample, no difference in perioperative mortality was identified, however, TEVAR was associated with lower perioperative morbidity.[85]

Long-term comparison of open thoracic aneurysm repair and TEVAR is limited. Beyond the perioperative period, most deaths are not aneurysm-related. In a propensity-matched Medicare cohort, Goodney et al[86] found that open repair was associated with higher long-term survival beyond 1-year post-procedure. These long-term results again raise concerns about the durability of endovascular repair and suggest that young patients with low-perioperative risk may benefit more from open repair.

Endovascular Repair

The principles of TEVAR are similar to those of EVAR—successful repair depends on proximal and distal seal. The proximal seal zone is normal caliber descending thoracic aorta distal to the left subclavian artery (LSA). The distal seal zone of an isolated DTAA is normal caliber distal thoracic aorta or supraceliac abdominal aorta (Figure 3B). TEVAR is generally performed with one or more tube stent grafts and choice of device depends on anatomic characteristics and surgeon/institution experience and preference.

Currently approved thoracic stent grafts require ≥20 mm proximal seal zone, however, the proximal aneurysm extent encroaches within 20 mm of the LSA in up to 40% of cases.[87] In these cases, coverage of the LSA is necessary to provide adequate proximal seal. Three treatment options exist for these patients: LSA coverage without revascularization, LSA coverage with open revascularization, and LSA coverage with endovascular revascularization. While LSA coverage has not been evaluated in a randomized fashion, there is evidence from observational studies that LSA coverage with or without revascularization is associated with higher rate of perioperative stroke after TEVAR, as well as a risk of arm ischemia.[87,88] The Society for Vascular Surgery guidelines recommend prophylactic preoperative LSA revascularization in patients undergoing elective TEVAR with anticipated LSA coverage.[87]

Open LSA revascularization is achieved with carotid-subclavian bypass or LSA transposition (Figure 3B). Currently, there are no Food and Drug Administration-approved fenestrated or branched devices for endovascular LSA revascularization, though there are currently ongoing Ivestigational Device Exemption trials of branched thoracic stent grafts with promising early results.[89,90] Nonetheless, multiple techniques for endovascular LSA revascularization have been described: LSA chimney graft, in situ laser fenestration of the TEVAR device, and use of a physician-modified fenestrated device.[91–93] However, these procedures have yet to be thoroughly evaluated and long-term results are lacking.

Complications of TEVAR include access site complication, endoleak, and systemic complications, however, paraplegia from SCI secondary to coverage of intercostal arteries is a particularly devastating complication. Reported risk of postoperative paraplegia ranges from 2.5% to 8% and is directly correlated with the extent of aorta covered. A recent meta-analysis found that multiple methods of SCI prevention were associated with a mild decrease in rate of paraplegia after TEVAR: prophylactic cerebrospinal fluid (CSF) drainage, avoidance of hypotension, mild perioperative hypothermia, and neuromonitoring.[94] At our institution, we use CSF drainage in patients at high risk for SCI, defined as >20 cm of aortic coverage, coverage of the lower 1/3 of the thoracic aorta, occlusion of the LSA or IIAs, or patients with prior aortic surgery affecting lumbar arteries or other collaterals. Intraoperatively, CSF is drained to a goal CSF pressure <10 mm Hg, and cerebral perfusion pressure is maintained >80 mm Hg.

Another rare, but frequently fatal complication of TEVAR is retrograde type A aortic dissection. A recent meta-analysis reported a pooled rate of retrograde dissection of 2.5%, though this was largely driven by patients treated for dissection. Retrograde dissection occurred in 5.1% of patients following TEVAR for dissection compared with 0.7% following TEVAR for aneurysmal disease.[95] Pooled mortality following this complication was 37%.

Open Repair

In the modern era, most isolated DTAAs can be treated endovascularly. However, open repair remains an important treatment option for patients with unsuitable anatomy, younger patients with few comorbidities, and patients with connective tissue disorders. Open DTAA repair involves replacement of the aneurysmal segment of the aorta with a tube graft, performed via a left thoracotomy. In cases of

difficult arch anatomy or severe atherosclerotic arch disease, proximal cross-clamping may not be possible, and the proximal anastomosis can be completed under hypothermic circulatory arrest.[80]

Despite advances in perioperative care, open DTAA repair remains a highly morbid operation, with mortality of 10% and over 40% of patients experiencing a perioperative complication in a large national study.[79] Proximal aortic cross-clamping can lead to profound spinal, renal, and mesenteric ischemia and subsequent complications. Distal aortic perfusion during open DTAA repair maintains perfusion to the visceral segment during cross-clamping. It is used in most open DTAA and TAAA repairs and has been associated with lower perioperative mortality and morbidity.[96] Distal perfusion can be achieved with either right or left heart bypass. With left heart bypass, oxygenated blood is taken from the left pulmonary vein or left atrial appendage and infused into a femoral arterial cannula. Complete right heart bypass can also be used and provides precise hemodynamic control, though requires a higher level of heparinization and, therefore, higher risk of bleeding. The distal aortic cross-clamp is placed just beyond the proximal anastomosis, maintaining perfusion throughout nearly the entire thoracic aorta as the proximal anastomosis is completed. When not using distal aortic perfusion, repair is achieved with a clamp and sew technique, in which the aorta is clamped and repaired sequentially, with an emphasis on speed to minimize distal ischemia time.

During open DTAA repair, the number and location of segmental arteries involved in the repair are predictive of the risk of SCI. In a large series of open TAAA repair, SCI was rare if <8 segmental arteries were involved but was 12.5% if >13 were involved.[97] CSF drainage is an important adjuvant to preventing SCI. While results of small studies have been mixed, pooled analysis supports the use of CSF drainage for patients undergoing open TAA repair.[98] For open DTAA repair at our institution, we routinely use CSF drainage, maintenance of cerebral perfusion pressure >80 mm Hg, mild hypothermia, and intraoperative neuromonitoring. Reimplantation of segmental arteries is performed if there is loss of motor-evoked potentials intraoperatively, as there is evidence that it may aid the recovery of motor-evoked potentials lost during the repair.[99] Additionally, before opening the aneurysm sac, segmental arteries are either clipped or clamped, to avoid back-bleeding and subsequent steal from spinal circulation.[97]

Thoracoabdominal Aortic Aneurysms

TAAAs involve varying extents of the aorta from the LSA to the aortic bifurcation, all with some degree of visceral segment involvement (Figure 4). Currently, open repair remains the standard of care for TAAA treatment in the United States. Successful TAAA repair involves replacement of the diseased aorta through a large left thoracoabdominal incision. When the entire visceral segment is involved, the renal and mesenteric arteries are reconstructed via a Carrel patch (typically a single patch for the right renal artery, SMA, and celiac artery with a separate left renal bypass), or a Coselli graft with a branch to each visceral vessel (Figure 5). A branched graft is preferred for patients with congenital aortic disease, as these patients are at high risk for patch aneurysms.

The need for exposure, dissection, and reconstruction of the visceral segment make TAAA repair technically complex and highly morbid. Perioperative mortality at high-volume centers has been reported as low as 8%, however, mortality from National Surgical Quality Improvement Program and the National Inpatient Sample was 10% and 22%, respectively.[100–102] As many as half of patients experience a perioperative complication, with pulmonary, cardiac, and renal complications most prevalent.[100,101] Open TAAA has a dramatic volume-outcome effect.[101] Perioperative care of this patient population requires a multidisciplinary team including cardiac and vascular surgery, cardiovascular anesthesia, and dedicated intensive care. As the number of open repairs performed nationally continues to decline, fewer centers will have sufficient volume to maintain proficiency, and it is crucial that these repairs be centralized at high-volume centers.

As with open isolated TAA repair, techniques have been developed to maintain distal perfusion and minimize renal and visceral ischemia during TAAA reconstruction. In most cases, cardiopulmonary bypass with femoral arterial cannulation is used to maintain distal perfusion. During the reconstruction of the visceral segment, renal ischemia is mitigated with direct perfusion of the renal arteries with cold crystalloid solution or blood from the bypass circuit. Visceral perfusion is also maintained with blood from the bypass circuit. Additionally, mild systemic hypothermia is frequently used to minimize the impact of ischemia.[103] Prevention of SCI during open TAAA mirrors that of open DTAA repair.

There are no commercially available devices approved for total endovascular TAAA repair in the United States. However, hybrid repair for type II TAAAs with TEVAR followed by open replacement of the visceral segment and remaining abdominal aorta involved has been described. This can be performed as either a single-stage or 2-stage repair. While perioperative mortality is similar, there is evidence that a staged approach, both when performing hybrid or open repair, is associated with a lower risk of SCI.[104,105]

Currently, there are ongoing Investigational Device Exemption trials investigating custom-manufactured or physician-modified fenestrated/branched devices for TAAAs, including type II TAAAs, with stent grafts placed from the LSA to the CIAs. While results are limited to single-center clinical trials, early results demonstrate high technical success with low-perioperative morbidity and mortality compared with open repair, though evaluation of long-term durability is needed.[106,107]

Aortic Arch Aneurysms

While isolated aortic arch aneurysms are rare, ≈10% of all TAA involve the arch. Therefore, aortic arch aneurysms are usually treated in conjunction with treatment of an ATAA or DTAA. The arch is best exposed via a median sternotomy and is most often replaced with a branched graft with an individual branch for each arch vessel. Arch replacement is associated with significant early morbidity and mortality, and carries a substantial risk of neurological complications, both from cerebral ischemia and embolization. In most cases, arch replacement is performed under hypothermic circulatory arrest. Cerebral blood flow can be maintained with selective antegrade cerebral perfusion.[75]

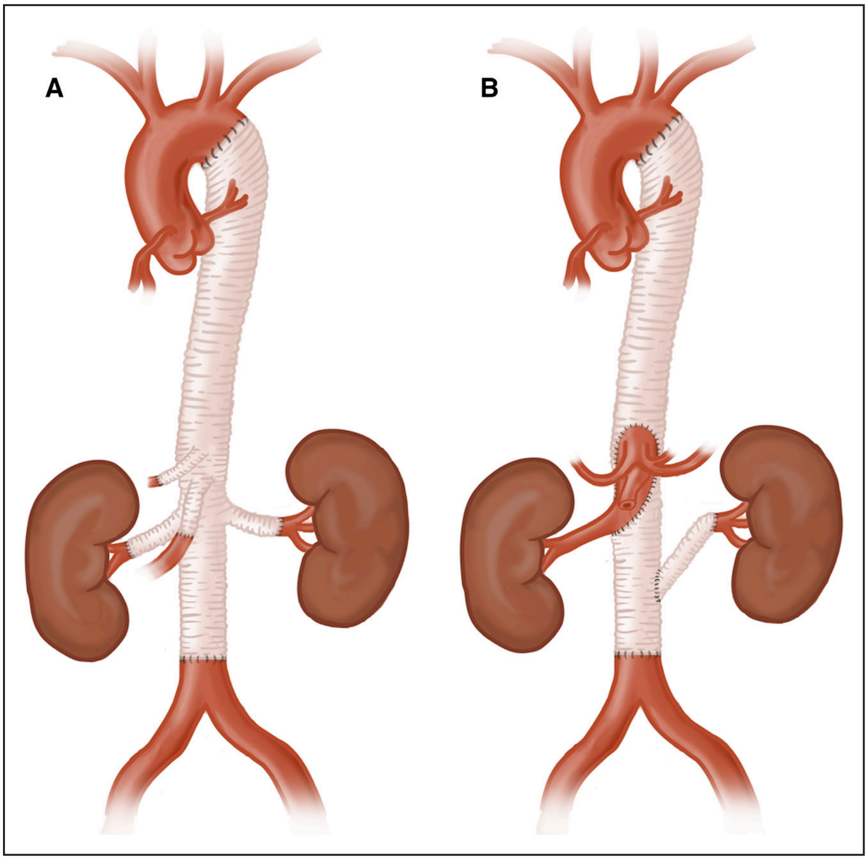

Figure 5. Open thoracoabdominal aortic aneurysm repair. A, Repair with a tube graft with branches to the celiac axis, superior mesenteric artery, and bilateral renal arteries (Coselli graft). **B**, Repair with an aortic patch containing the celiac artery, superior mesenteric artery, and right renal artery (Carrel patch) and left renal artery bypass.

In the endovascular era, 2 techniques have been developed for hybrid aortic arch repair which use a combination of open surgery and TEVAR. Supra-aortic arch debranching involves bypass to all 3 arch branches from the ascending aorta followed by TEVAR including the arch. The proximal seal zone is in nonaneurysmal ascending aorta or proximal arch. The alternative approach is endovascular-modification of the elephant truck technique, used for patients with arch and descending aneurysms. With this technique, the aortic arch is replaced with a branched graft that includes a distal tube graft extension. This extension is extended distally into the descending thoracic aorta beyond the distal anastomosis. A standard TEVAR device can then be deployed into the elephant trunk, with the distal seal zone in healthy descending thoracic aorta. The TEVAR can be performed during the index operation or as a second-stage procedure.

Results from single-institution series of these procedures vary greatly, in part because of the variety of pathology and extent of disease included. In a large meta-analysis, Cao et al[108] reported perioperative mortality following hybrid arch procedures ranging from 1.6% to 25%. The pooled mortality was 11.9% for supra-aortic debranching and 13.2% for endovascular elephant trunk procedure. Neurological complications were common, with pooled rates of stroke and SCI of 6.9% and 6.8%, respectively.[108]

Total endovascular repair of the aortic arch with fenestrated or branched devices was described as early as 1999.[109] However, there are currently no Food and Drug Administration-approved devices and these procedures remain experimental in the United Status. Currently, there are multiple devices in development and early reports suggest these procedures can be performed with high technical success and low-perioperative morbidity and mortality, however, over 20% of patients required reintervention in one study and long-term branch patency has not been evaluated.[110]

Ascending Aortic Aneurysms

The pathogenesis of ATAA differs from that of DTAA and AAA in many cases, occurring frequently in patients with Marfan syndrome, other familiar connective tissue disorders, or bicuspid aortic valves.[75] Furthermore, isolated ATAAs are rare, as most occur in conjunction with aortic root aneurysms and arch aneurysms. Therefore, ATAA repair is frequently performed in conjunction with additional procedures.[111] For aneurysms involving the root, repair can be achieved with root/ascending aorta replacement and aortic valve replacement or reimplantation or with composite replacement of the aortic valve, root, and ascending aorta with reimplantation of the coronary arteries (Bentall procedure). In single-center series of ATAA repair, use of an interposition graft alone is possible in approximately one- to two-thirds of patients.[111,112] When the arch is involved, the repair is extended with hemi- or complete arch replacement. In a large single-center series of ATAA repair, the repair involved the arch in 11% of cases.[111] Ascending aortic repair requires full cardiopulmonary bypass with a period of hypothermic circulatory arrest if needed to complete the distal anastomosis.

Open surgery remains the standard of care for ascending aortic repair. Perioperative mortality ranges from 3% to 7%, and cardiac, respiratory, and neurological complications are common.[75,111,112]

Recently, endovascular techniques have been introduced in the ascending aorta. The Zenith Ascend TAA Endovascular Graft (Cook Medical, Bloomington, IN) is a dedicated ascending aortic device that has been used for type A dissection and ATAA, however, its use remains experimental and it is not Food and Drug Administration-approved for commercial use in the United States.[113] The off-label use of descending thoracic aortic devices and abdominal aortic cuffs in the ascending aorta for high-risk patients has also been described. In a recent systematic review of these reports, pooled perioperative mortality was 15% and type I endoleak rate was 18%.[114] Long-term results are limited. At this time, endovascular repair of the ascending aorta remains experimental and should be reserved for high-risk patients with no other treatment options.

Conclusions

The endovascular treatment of aortic aneurysms with stent grafts has revolutionized the field of aortic aneurysm surgery. Endovascular aortic aneurysm repair began in the infrarenal aortic segment but its use has been rapidly expanding and endovascular techniques are now being used in the entire aorta. This innovation has allowed for definite repair in patients unsuitable for open repair. It has also introduced its own set of complications and challenges that are still not fully understood. Furthermore, the endovascular era has led to a dramatic decrease in the number of open aortic aneurysm repairs being performed. Nonetheless, open repair will always remain an essential treatment modality in the management of aortic aneurysms. Additionally, long-term results of endovascular repair suggest that younger patients with long life expectancy and low-perioperative risk may benefit more from open repair and caution against the overuse of endovascular techniques. Therefore, maintaining open aortic technical proficiency is of upmost importance.

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