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REVIEW

THORACIC AORTIC CHALLENGES

Endovascular TAAA repair: current status and future challenges

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ABSTRACT

Open surgical repair has been the gold standard for treatment of thoracoabdominal aortic aneurysms (TAAAs). Currently open surgical repair has been reserved mostly for young and fit patients with connective tissue disorders, using separate branch vessel reconstructions instead of 'island' patches, and distal perfusion instead of "clamp-and-go" technique. Endovascular repair has been gaining widespread acceptance because of its potential to significantly decrease morbidity and mortality. Several large aortic centers have developed dedicated clinical programs to advance techniques of fenestrated-branched endovascular repair (FBEVAR) using patient-specific and off-the-shelf devices, offering a minimally invasive alternative to open repair allowing treatment of increasingly older and sicker TAAA patients. In this article, we review the current technical aspects of endovascular TAAA repair and the literature of open *versus* endovascular outcomes of TAAA repair.

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KEY WORDS: Thoracic aortic aneurysm; Abdominal aortic aneurysm; Endovascular procedures; Cone-beam computed tomography.

Although thoracoabdominal aortic aneurysms (TAAAs) account for only 10% of all aortic aneurysms, these operations pose a formidable challenge and are associated with high morbidity and mortality.[1] Although degenerative aneurysms are most common, an increasing number of patients with genetically triggered aortic diseases are treated for chronic post-dissection TAAAs.[2] Open surgical repair has been standard of care since the 1950's.[3] Endovascular TAAA repair was introduced in the late 1990's using fenestrations and early 2000's using directional branches, offering a less invasive approach with potential reduction in complications.[4] The technique has evolved from a physician-modified endovascular grafts to off-the-shelf and patient-specific manufactured endografts. Several improvements in device design and perioperative care have further improved and simplified these procedures.[5] Concurrent to the development of endovascular techniques, open surgical repair was refined by modifications of the original Crawford's technique utilizing 'island patches' and a "clamp-and-go approach," without cerebrospinal fluid (CSF) drainage or other adjuncts for end organ protection.[6] Much of the work in the last two decades by Safi and Coselli focused on improvements of the technique by adding separate branch vessel bypass grafts and distal perfusion.[7] Although the results of open TAAA repair have improved significantly over time, these operations are is still associated with high mortality and morbidity.[8, 9] Furthermore, results outside large specialized aortic centers are dismal.[10] The current European Society for Vascular Surgery 2019 Clinical Practice Guidelines on the Management of Abdominal Aorto-iliac Artery Aneurysms recommends endovascular treatment as the preferred option for most infrarenal and juxtarenal aortic aneurysms when feasible.[11] Although the guidelines for standard infrarenal endovascular repair do not translate

into guidelines of complex endovascular TAAA repair, it is only logical to assume that the benefits of endovascular approach will be even greater when this is applied to more challenging anatomy given that more extensive dissection, higher clamp site, visceral ischemia and reconstruction of the visceral arteries in open repair are all factors associated with increased morbidity.

Evolution of the technique

The advantages of an endovascular approach are several. First, these procedures can be performed percutaneously, avoiding need for thoracolaparotomy incision, division of the diaphragmatic muscle (Figure 1), cardiopulmonary bypass, aortic cross clamping and minimizing blood loss. Second, the uninterrupted aortic flow into the renal, mesenteric and lower extremities vessels minimizes the physiological demand and end-organ ischemia. Nonetheless, there are shortcomings imposed by specific anatomical criteria. Small vessels such as the intercostal arteries cannot be reconstructed by endovascular means, raising concern that extensive aortic coverage may increase the risk of spinal cord injury.

Fenestrated and branched stent grafts were initially applied in patients with short infrarenal necks. The first devices had non-reinforced fenestrations and were typically not aligned by bridging stents. Subsequently, several changes were made including reinforcement of fenestrations, addition of diameter reducing ties, and separation of the distal bifurcated from the proximal fenestrated components. Balloon-expandable covered stents became the standard for fenestration stenting in place of bare stents. Low-profile devices and preloaded systems were added in the last decade. Currently, industry-manufactured designs can be categorized as patient-specific devices and off-the-shelf stent grafts (Figure 2).

Preloaded wires and catheters are intended to provide direct access to branches and fenestrations, thereby decreasing catheter manipulations that are needed to access the target vessels. The overall goal is to minimize manipulations, reduce operative time and decrease lower extremity ischemia. These systems have been widely used with fenestrated devices such as the p-Branch® stent-graft (Cook Medical, Bloomington, IN, USA), and more recently have been modified to allow upper extremity access for TAAAs. The low-profile device with upper extremity preloaded guidewire system (LP-PGS) uses one or two preloaded 0.018" wires that are accessible via femoral or brachial approach. The device utilizes a 20-Fr delivery system with a long 8-Fr nosecone that is connected to the tip of the 20-Fr cannula. The delivery system is advanced using a through-and-through brachial-femoral wire, and the nosecone exits *via* a 12-Fr brachial sheath. Once the nosecone is uncapped, the preloaded wires are revealed and labeled to its intended vessel (Figure 3).[12]

The largest experience with custom-made devices is with the Cook patient-specific platform (Cook Medical, Inc., Brisbane, Australia). The devices were pioneered in the late 1990s in Western Australia by Michael Lawrence Brown, David Hartley and John Anderson. In the last decade, several other manufacturers have developed their own iterations. At present, patient-specific devices include the Zenith Fenestrated platform (Cook Medical), Terumo Aortic (Vascutek, Terumo, Inchinnan, UK) and Jotec TAAA device (Jotec GmbH, subsidiary of CryoLife, Kennesaw, GA, USA), whereas off-the-shelf devices are

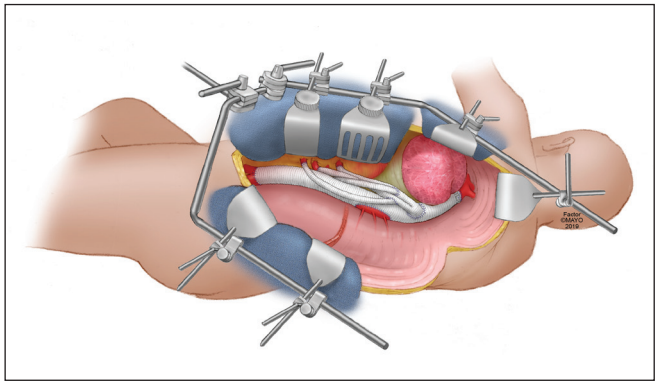

Figure 1.—Illustration depicting thorcolaparotomy and open surgical repair of Extent II thoracoabdominal aortic aneurysm. By permission of Mayo Foundation for Medical Education and Research. All rights reserved.

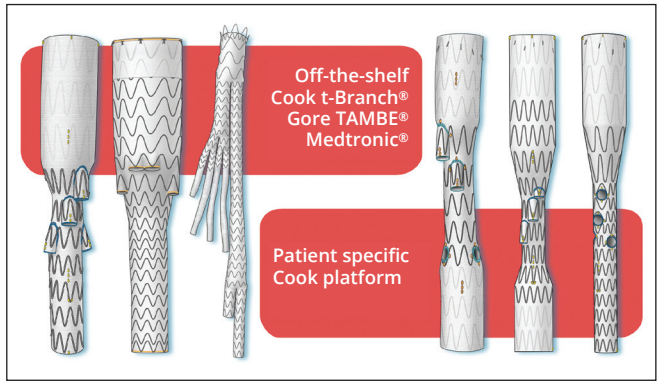

Figure 2.—Illustrations of the current off-the-shelf devices and the patient-specific platform for endovascular thoracoabdominal aortic aneurysm repair. By permission of Mayo Foundation for Medical Education and Research. All rights reserved.

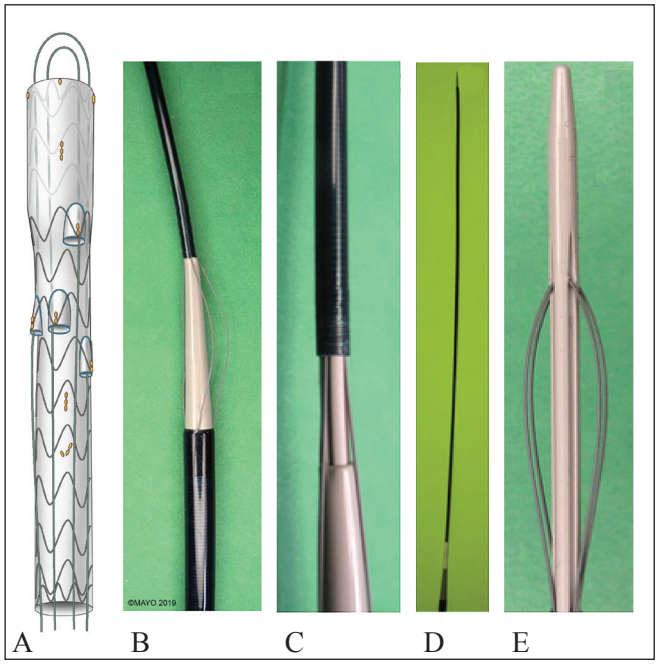

Figure 3.—Schematic of novel low profile preloaded guidewire delivery system demonstrating route of preloaded wires. A) Illustration of fenestrated-branched stent-graft with four branches and the route of the two preloaded wires. B) Picture of the distal 8-Fr nose cone of the delivery system designed to be inserted from femoral access and exit through the brachial sheath. C) Picture demonstrating the unsheathing of the distal nose cone to reveal the preloaded wires. D) Long delivery system designed to enter via femoral access and exit via the upper extremity sheath. E) Two loops of preloaded wires housed in the distal nose cone, which is completely unsheathed. By permission of Mayo Foundation for Medical Education and Research. All rights reserved.

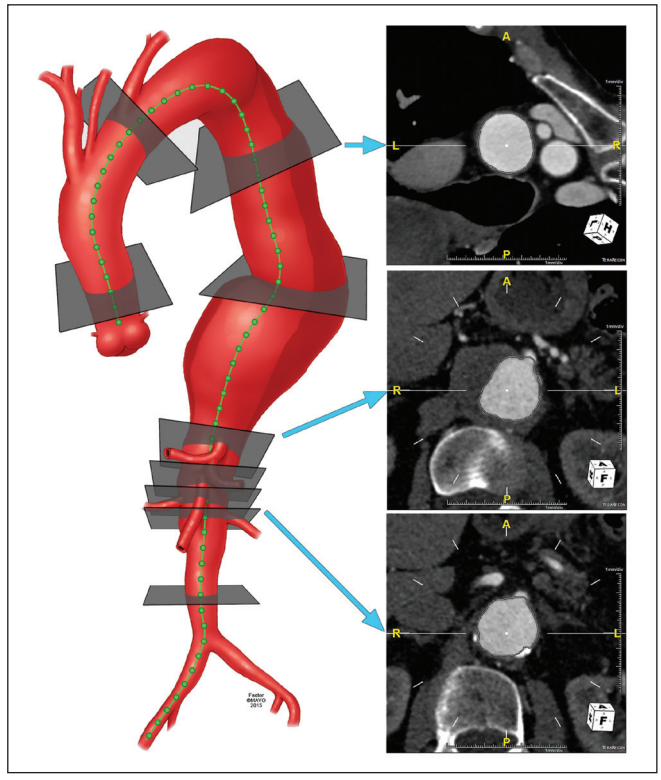

Figure 4.—Computed tomography angiography analysis in patients with complex aortic aneurysms include three-dimensional reconstructions and centerline of flow measurements. Axial imaging is used for vessel diameter measurements and vessel location in relation to clock position. By permission of Mayo Foundation for Medical Education and Research. All rights reserved.

include the Cook t-Branch, Gore Excluder thoracoabdominal branch endoprosthesis (*i.e.*, TAMBE, W.L. Gore & Associates Inc., Flagstaff, AZ, USA),[13] Medtronic Valiant modular branched graft (Medtronic, Minneapolis, MN, USA), Colt device (Jotec GmbH) and Terumo Aortic (Vascutek, Terumo).

Planning and technical assessment

Preoperative planning is the foundation for any successful endovascular aortic repair. Detailed planning requires triangulation of the renal mesenteric vessels using centerline technique in a three-dimensional workstation (Figure 4). All of the following are required to design patient-specific endografts and to assess the suitability of the off-the-shelf device:[10, 11]

- assessment of proximal and distal sealing zones (size, surface, angulation);
- the gap between the partially and fully deployed endograft and the visceral artery bearing aortic wall;
- the longitudinal distances between target vessels and angulations of and radial positions between target vessels;
- an estimate of vessel wall calcification and possible distortion while using stiff wires, sheaths, and devices.

Adjunctive useful preoperative anatomical considerations are:

- patency of left subclavian and hypogastric arteries;
- patency and number of intercostal arteries;
- evaluation of access sites: common femoral arteries, iliac arteries, brachial accesses.

Although clinicians may be tempted to delegate the planning phase to manufacturers planning centers, this is a risky strategy at best. Although technically accurate planning will be provided, it will be devoid of clinical judgment and compromise. Such grafts may be a "true fit" but prove impossible to implant. Nevertheless, consultative engagement with the planning center, rather than delegation provides invaluable insight. Later, these centers can be used as an expert resource for planning the more complex

repairs. Used irresponsibly, planning centers can become a way for inexperienced physicians outside high-volume centers to gain access to a technique that they never fully master.

There has also been continuous improvement in the development of advanced imaging support to perform complex endovascular aortic procedures. The initial cases were performed with portable C-arms, and sizing was achieved using simple axial imaging. However, it rapidly became clear that three-dimensional workstations with centerline-of-flow reconstructions are essential for accurate planning. In addition, case complexity mandates high-quality operative imaging. This has led to the use of hybrid operative rooms with flat panel detectors and fusion imaging software.

The intraoperative management of advanced imaging equipment requires specific training for the operators (surgeons, radiologists, and radiographers). Interventionists require a detailed knowledge of the fluoroscopic options, including imaging settings, angulation, radiation exposure, and protection. In 2011, Dijkstra *et al.* evaluated the use of intraoperative guidance by means of C-arm cone-beam computed tomography (CBCT) and the use of postoperative CBCT to assess for successful aneurysm exclusion after fenestrated-branched repair.[14] They concluded that CBCT is a valuable addition to complicated aortic interventions. Onlay fusion allows fluoroscopy images to be overlaid on CT images using the CBCT technology. Kobeiter and associates have confirmed the value of this advanced imaging software.[15] They reported a case of thoracic endovascular aortic repair using fusion imaging without the need for any operative contrast injection. Our research team at the Mayo Clinic demonstrated that use of onlay fusion and CBCT during fenestrated-branched procedures were associated with a decrease in radiation exposure and the operator's effective dose.[16] In addition, CBCT allowed immediate on-table assessment and identified intraoperative technical problems leading to immediate revision and avoiding early secondary interventions. A more recent publication from our group demonstrated that the traditional completion digital subtraction angiography (DSA) alone provides inadequate assessment of the technical result for fenestrated-branched endovascular aortic repair (F-BEVAR). Compared to CBCT, also CTA offers little information in the first 30 days, and can safely be delayed to 2 months or longer in patients who do not have a clinical indication. Based on the results of our analysis, we have changed our clinical protocol for F-BEVAR procedures by eliminating of traditional completion DSA and pre-dismissal CTA.[17] We recommend CBCT routinely with rotational DSA and CTA only in patients who have a clinical indication.

Patient-specific devices

The challenge in device design for TAAAs is the variability of the aortic and visceral branch anatomy.[18] Patient-specific devices can be customized to fit each patient's anatomy individually.[19] The Cook Zenith Fenestrated (Cook Medical) stent graft became available for commercial use in Europe in 2005. In the USA, the Food and Drug Administration (FDA) has approved the Zenith Fenestrated device for treatment of patients with short-neck AAAs in 2012. However, the FDA-approved version can be customized with up to three fenestrations, of which two can be of the same type, limiting its application to patients with short neck infrarenal or juxtarenal aneurysms. These limitations of the Zenith Fenestrated platform do not apply in the rest of the world or in a few USA centers with wider access to investigational devices. Patient-specific thoracoabdominal devices can be manufactured with any number and combination of fenestrations or branches (Figure 5). Directional branches can be down- or up-going, straight or helical, and can also be designed as internal branches. Several adjuncts can be incorporated with the device such as tapering of the main body, diameter reducing sutures and preloaded wire or catheters to facilitate easier target vessel cannulation. The contralateral limb of the bifurcated device can be inverted for patients with a short distance between the renal arteries and aortic bifurcation because of a previously implanted endograft or aortoiliac surgical graft. Currently, in the USA, the Zenith Fenestrated platform can be fully utilized only through FDA-approved Investigational Device Exemption protocols, which means that all patients treated with the investigational device have to be enrolled in an FDA-monitored prospective trial. Currently, there are 10 centers in the USA that have this exemption, including ours (Mayo Clinic, Rochester, MN, USA). The main limitation of patient-specific devices is the time delay needed for manufacturing the device, which is typically up to 3-4 weeks, and may be associated to an increased risk of rupture in the setting of large aneurysms and/or rapid aneurysm growth.

Off-the-shelf devices

The Cook t-Branch stent graft has four down-going straight branches in the mid-portion of the device for incorporation of the celiac artery, superior mesenteric artery and both renal arteries (Figure 6).[19] The 202-mm long main body

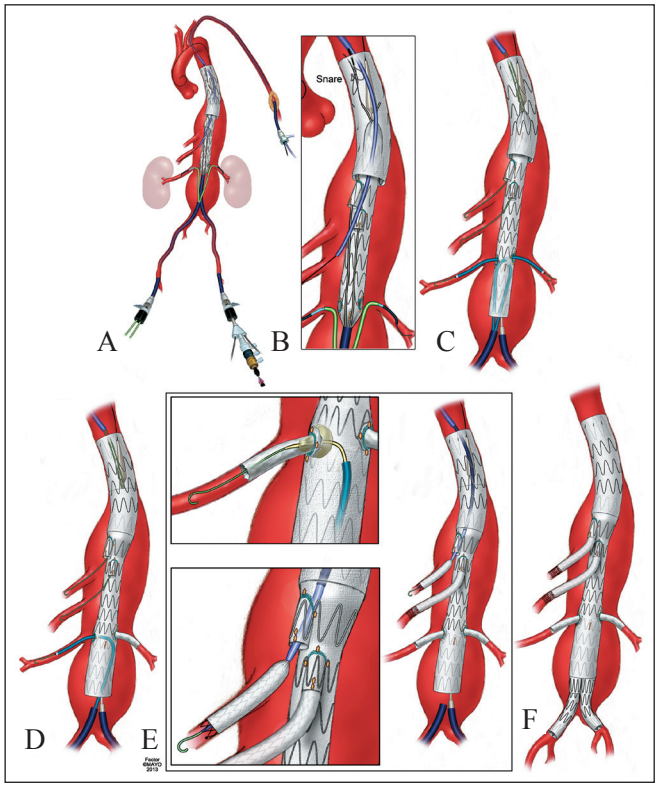

Figure 5.—Steps for implantation of a patient-specific two-branch two-fenestration stent-graft. The procedure is performed *via* bilateral femoral and left brachial access (A). After deployment of the proximal thoracic component and pre-catheterization of the renal arteries (B), the fenestrated component is deployed. Access into the celiac and superior mesenteric artery branches are established using pre-loaded wires/catheters (C). The renal arteries are accessed via femoral approach (D). Once all vessels are catheterized, the diameter-reducing tie is removed, and side vessel stenting is performed using balloon-expandable covered stents for the renal arteries (E), followed by self-expandable stent-grafts for the SMA and celiac axis (F). The repair is completed by placement of a distal bifurcated extension (G). By permission of Mayo Foundation for Medical Education and Research. All rights reserved.

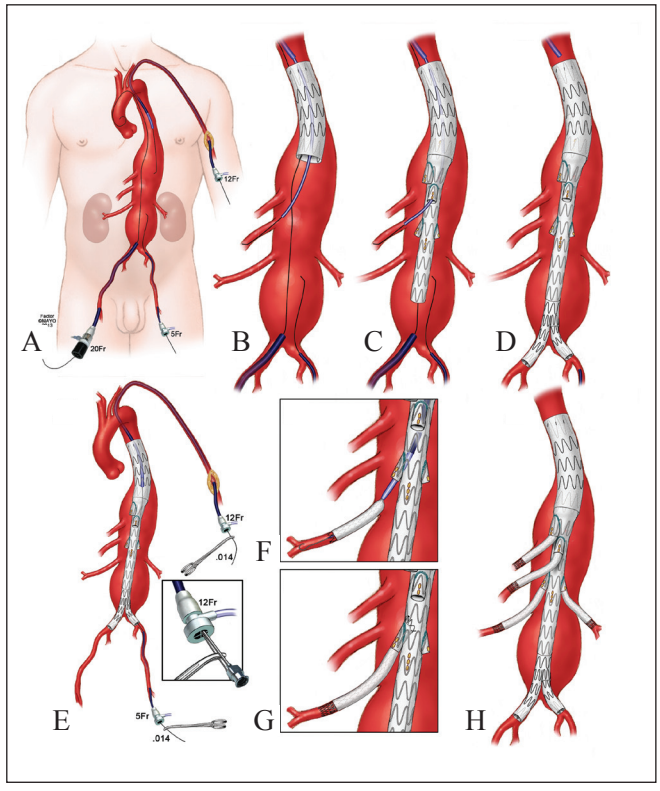

Figure 6.—Steps for implantation of an off-the-shelf t-Branch stent-graft with four directional branches. The procedure is performed *via* bilateral femoral and left brachial access (A). A tubular component is deployed proximally (A), followed by the multi-branch component (B) and the distal extensions (C). Once all aortic components are deployed flow is restored to the lower extremities and only a small sheath is maintained in one of the femoral arteries (E). Each branch is accessed via the brachial approach and bridged to the target vessel by placement of self-expandable stent-grafts (F). Self-expandable bare-metal stents may be used distally to secure the attachment to the target vessel (G). The repair is completed by placement of all four side-branch stents (H). By permission of Mayo Foundation for Medical Education and Research. All rights reserved.

is tapered; the diameter is 34 mm at the top and 18 mm at the bottom. Celiac and superior mesenteric artery cuffs are 8 mm in diameter located in the 01:00 and 12:00 clock-positions, and the right and left renal artery cuffs are 6 mm in diameter located at 10:00 and 03:00 positions, respectively. The device has a 22-Fr delivery system and no preloaded wires or catheters are included.[20] If one or more of the four side-branches is not used for visceral vessel incorporation during the implantation, the unnecessary side-branch can be eliminated by extending the side-branch with a stent graft within the aorta, which is then occluded with an endovascular plug. It is estimated that >50% of the TAAA population are suitable for the device in a single procedure, with even greater suitability with staged procedures.[21]

The Gore TAMBE is an off-the-shelf, modular, multi-component system composed of a multibranch stent graft, a distal bifurcated component, and iliac limb extensions. It has four portals with either antegrade or retrograde orientation for the renal arteries, which are accessed through the brachial-axillary or femoral approach, respectively. The TAMBE with retrograde renal portals has a proximal diameter of 26, 31, or 37 mm; length of 215 mm; and distal diameter of 20 mm. The antegrade renal portal device has a proximal diameter of 31 or 37 mm, length of 160 mm, and distal diameter of 20 mm. Both options require a

22-Fr introducer sheath, with the exception of the 31-mm antegrade configuration, which requires a 20-Fr sheath. A 12-Fr brachial or axillary artery sheath is needed for access into the antegrade portals. Its use is indicated for pararenal and type IV TAAAs and, differently from the Cook t-branch, it is integrated with preloaded removable guidewire tubes. Another characteristic of the TAMBE is that its four branches have been specifically designed for the placement of the Gore Viabahn Baloon Expandable Endoprosthesis (VBX) as bridging stent.[13]

Staging of the endovascular repair

The more extensive aneurysms involving the entire thoracoabdominal aorta (Crawford's Extent I and II TAAAs) are preferentially treated with a staged approach to prevent spinal cord ischemia, which is caused by the extensive coverage of the intercostal and lumbar arteries. Staging allows the blood supply of the spinal cord to adjust to the decreased flow and shortens the procedure time. Staging can be performed using several strategies, including selection coil embolization of intercostal arteries, temporary aneurysm sac perfusion, or proximal thoracic endovascular aortic repair.

Minimally invasive segmental artery coil embolization (MISACE) consists in the selective preventive embolization and occlusion of segmental arteries in order to promote the spinal collateral network. This technique has demonstrated promising results in a limited single-center experience,[22] and a prospective randomized trial is currently ongoing to evaluate the efficacy of this method to prevent SCI in type I-II TAAAs. The main potential pitfall of this technique is that multiple staging endovascular procedures may be required before the endograft implantation, with subsequent time delay in the main procedure. An alternative easier way to occlude segmental arteries at their origin has been recently described; this consist in the pre-emptive deployment of a tapered modified Zenith Alpha stent-graft, that accommodates to the aneurysmatic descending thoracic aorta, thus occluding the origin of intercostal arteries and promoting thrombosis along the entire length of the graft[23] between the aneurysm wall and stent-graft–covered portion. Temporary aneurysm sac perfusion (TASP) implies the incorporation of sac perfusion branches that are integrated in the main custom-made aortic stent-graft. The perfusion branch is left patent in the initial procedure and is secondarily occluded a few days later using an Amplatzer plug, which can be deployed under local anesthesia. An alternative option of TASP consists in leaving the endovascular repair incomplete by not placing the contra-lateral iliac limb extension or one of the bridging stents (*e.g.*, celiac stent). Limitations of perfusion branches are the potential risks of increased sac pressure due to poor outflow via small segmental arteries and disseminated intra-vascular coagulopathy from large endoleak into a blind sac.

Patients with distal aortic arch aneurysms or dissections may require total arch reconstruction using elephant trunk technique to allow a suitable landing zone for distal endovascular repair. Our preference has been to use thoracic endovascular aortic repair as first stage strategy, allowing coverage of proximal intercostal arteries and minimizing the extent of the second stage procedure. The first step involves coverage of the descending thoracic aorta with a thoracic endovascular graft down to the level of the celiac axis. For patients with suitable aortic segments in zones 3 and 4, the procedure is usually a straightforward stenting of the thoracic aorta with one or two endografts, tapering the diameter to 30-34 mm in preparation for the definitive repair. Distally, the thoracic aorta is covered just above the celiac artery, leaving a type IB endoleak prior to the second stage procedure. If the aorta is diseased up to the left subclavian artery, the landing zone may need to be extended more proximally into zone 2. In these cases, left subclavian artery revascularization is routinely performed using either a left carotid-left subclavian bypass or a thoracic branch endograft with a single inner side branch for the subclavian artery. Extension into zone 0 can also be performed using an endovascular approach with two or three inner branches, if the patient is not an ideal candidate for total arch reconstruction.

The second stage procedure is the actual fenestrated-branched endovascular device implantation. This is usually done with a minimum of one-week interval from the first stage procedure, but more often requires 6-8 weeks due to the time delay for device manufacturing. A single stage procedure is indicated if the patient has a symptomatic TAAA or rapid expansion of a very large aneurysm. If there is suspicion of spinal cord ischemia, which can be identified using neuromonitoring, during or at the end of the fenestrated-branched repair, the patient may be left with temporary aneurysm sac perfusion.[24] The technique uses a side-branch or the contra-lateral gate of the iliac limb, which is left unstented during the initial procedure to allow blood flow into the aneurysm sac, and hence, to the lumbar and intercostal arteries. The sac can then be closed in another session a few days to weeks after the main procedure once the patient recovers and has a stable neurologic examination.

Procedural steps of fenestrated-branched endovascular aortic repair

The patient is positioned supine and the procedure is performed under general anesthesia to allow for neuromonitoring. Use of both brachial and femoral access is preferred in our institution for most TAAAs with four visceral target vessels unless there is a contra-indication to brachial access, such as a diseased aortic arch with thrombus. Our preference is open surgical exposure of the upper brachial artery in the axilla. Bilateral percutaneous femoral access is obtained using the pre-closure technique. Open surgical exposure of the femoral arteries is performed in a minority of patients with small, calcified arteries, or in those with a high bifurcation of the femoral artery. Temporary conduits may be used to facilitate early pelvic and lower limb perfusion in complex cases when prolonged operative time is expected. Permanent surgical conduits are considered in patients with small, diseased iliac arteries and anticipated access difficulties.

Most TAAA devices are designed with a preloaded guidewire system that exits via the brachial access. First, brachial-femoral access is established using a long 0.035" Metro guidewire (Cook Medical), which is introduced from the femoral sheath and snared via the brachial approach. This helps stabilize the introduction of the main delivery system and allows immediate access to the directional branches or fenestrations using the preload guidewires. The fenestrated-branched endovascular graft is deployed in a staggered fashion starting from the top to the level of the superior mesenteric artery fenestration or branch. The celiac artery and the superior mesenteric artery are accessed from the brachial approach, and 0.035" Amplatzer guidewires are positioned into both vessels. The distal portion of the device is then deployed, and the renal arteries are cannulated through the fenestrations (*via* femoral access) or branches (*via* brachial access) using the preloaded guidewire system. The target vessels are incorporated with bridging stent grafts. Most often balloon expandable covered stents are used for fenestrations and self-expandable stent-grafts for branches. The repair is extended distally using a universal bifurcated device and iliac limbs. Iliac branch devices may be needed in patients with concomitant iliac aneurysms. Finally, a rotational CBCT with rotational digital subtraction angiogram is obtained to evaluate presence of endoleak or technical problems such as stent compression, vessel dissection or thrombosis. At completion, the sheaths are removed, and the brachial access is closed surgically whereas the femoral arteries are closed using percutaneous technique. A detailed description highlighting the steps of fenestrated branched endovascular repair with patient-specific and off-the-shelf devices can be found in our previous publication.[19, 25, 26]

Prevention of spinal cord injury

Paraplegia is one of the most devastating complications of open and endovascular TAAA repair. In open surgery, reimplantation of patent segmental arteries, usually between T7 and L2 can be done if the adjacent aortic tissue is suitable for anastomosis. However, in endovascular TAAA repair, revascularization of the intercostal arteries is not feasible. To minimize risk spinal cord ischemia, preconditioning has been advocated to develop collateral networks using staged repair. Neuromonitoring and CSF drainage are used routinely in patients with Extent I to III TAAAs. It should be recognized, however, that CSF drainage is also associated with potential risk of severe complications, such as intracranial hemorrhage or spinal hematoma, in up to 2.5% of patients undergoing open or endovascular TAAA repair.[27] While CSF drainage is used to prevent, one-third of SCIs at Mayo Clinic were caused by the placement of the spinal drains; the rate of paraplegia due to CSFD was 1%.[28] Our group previously recommended routine drainage for all patients who had supraceliac coverage ≥5 cm stent-graft coverage (or two sealing stents), which is often the minimum extent of coverage used for Extent IV TAAAs. However, our philosophy has changed given the exceedingly low rate of SCI among patients with Extent IV TAAAs and the occurrence of spinal hematomas in a few patients. Most recently, we no longer recommend CSF drainage during first-stage TEVARs and for patient with pararenal, extent IV and most Extent III TAAAs. Exceptions are patients with occluded internal iliac arteries, who may still benefit from a spinal drain.

Neuromonitoring with continuous motor-evoked potential (MEP) and somatosensory-evoked potential (SSEP) can be used to monitor spinal cord and leg ischemia during endovascular TAAA repair.[29] Changes in the neuromonitoring triggers intraoperative maneuvers such as initiation (at 10 mmHg) or increase (down to 0-5 mmHg) of CSF drainage and permissive hypertension with increments in target mean arterial pressure up to or above 90-100 mmHg. If these maneuvers do not reverse the changes in neuromonitoring, pelvic circulation is restored by retracting the femoral sheaths and allowing circulation to be restored to the hypogastric arteries and lower extremities. If neuromonitoring changes persist at the end of the procedure,

temporary aneurysm sac perfusion can be allowed by leaving one of the visceral branches or the contralateral gate of the bifurcated device unstented. A limitation of MEP/SSEP monitoring is that it requires general anesthesia and cannot be applied postoperatively. In our experience, 80% of the patients with spinal cord ischemia develop delayed symptoms one to three days after the procedure. Only one in five patients has symptoms immediately after the procedure. Nonetheless, Spanos *et al.* reported that, in their series, two-thirds of patients with spinal cord ischemia presented with immediate postoperative symptoms.[30] Near-infrared spectroscopy (NIRS) can be used as an alternative or complementary method to neuromonitoring and it can be used during the postoperative course. However, the data on the sensitivity and specificity of these neuromonitoring methods remains scarce and further investigation is needed.[31, 32]

Open *versus* endovascular repair: what is the evidence?

There are few comparative studies directly assessing the efficacy of endovascular TAAA treatment *versus* open repair.[33-35] The published comparative studies that do exist lack granularity, making cross-cohort comparison difficult, and report heterogeneous outcomes. Moreover, most centers with large endovascular experience include their initial learning curve, and substantial improvements in mortality and morbidity have occurred in the last five years. Since the advent of endovascular TAAA repair, several centers have reported their institutional experiences with open TAAA repair.

Two very recent systematic reviews and meta-analyses have concisely summarized the literature and evidence for open surgical repair, and open *versus* endovascular repair.[36, 37] A meta-analysis by Rocha and co-authors comparing open and endovascular TAAA repair showed lower rates of spinal cord ischemia (risk ratio 0.65, 95% CI: 0.42-1.01, P=0.05) and renal impairment requiring dialysis (risk ratio 0.44, 95% CI: 0.23-0.85, P=0.01) with endovascular approach as compared to open repair.[37] This meta-analysis only included comparative studies with double-arm cohorts, with a total of eight studies meeting the authors' inclusion criteria. However, inconsistent reporting of outcomes across the studies coupled with an observational design of these studies limits the ability to draw meaningful conclusions from this analysis. Although mortality, stroke, paraplegia and dialysis are widely used outcomes, none of the studies in the meta-analysis reported all of these specific end-points.[37] Nevertheless, the analysis highlights the differences in patient populations selected for endovascular *versus* open repair, with patients in the former group being older and harboring numerous medical comorbidities such as cardiovascular and renal disease.

A further meta-analysis of single arm studies assessing outcomes for open TAAA repair-only reported postoperative incidences of paraparesis and paraplegia ranging from 2-11% and 0-10%, respectively.[36] The study included 9963 patients reported in 30 publications. The largest results stemmed from the near three decades' experience at the Texas Heart Institute, commencing with Crawford in his original paper of 1509 patients, and followed by subsequent studies by Coselli *et al*.[38, 39] While in-hospital mortality was reported in all studies, other outcomes such as renal impairment requiring permanent dialysis and stroke were reported by less than half. In this analysis, permanent dialysis was required in almost 8% of open surgical patients. Mortality rates were highest for Crawford Extent II TAAAs (10.3%) and lowest for Extent I TAAAs (7.0%). The overall patient survival at 5 years was 69.3%. Using meta-regression analysis, the authors demonstrated that lower procedural mortality was significantly associated with higher case volume.[36]

Another recent comparative study of 879 TAAA repairs by Locham *et al.* found in-hospital mortality rates to be significantly higher after open repair (15% *vs.* 5%, P<0.001) and hospital length of stay to be increased.[35] Propensity score matching of cohorts has been utilized by two studies as a statistical proxy for a randomized study.[33, 34] Indeed, this has been an effective strategy given the inherent difficulties and biases with designing a randomized head-to-head study. Both of these studies used nearest neighbor matching with preceding logistic regression to control for predictors. In the study by Ferrer *et al.*, there was no significant difference in 30-day mortality and paraplegia between endovascular and open matched pairs. Rates of survival at two years were similar (82.8% *vs.* 84.9%, P=0.9), as were rates of freedom from intervention at 24 months (91.0% *vs.* 89.7%, P=0.3).[34]

The majority of experience with open TAAA repair has been described by several large series originating from a handful of pioneering institutions, the original being the experience in Houston. Crawford *et al.* presented their vast experience of 1509 patients who underwent open TAAA repair between 1960 and 1991.[40] The 30-day mortality was 8% and the incidence of spinal cord ischemia including paraplegia or paraparesis was 16%. Dialysis was required in 9% of the patients. In 2016, Coselli *et al.* published the

largest worldwide series on open TAAA repair in 3309 patients.[38] The 30-day mortality was 7.5% and the rate of any permanent spinal cord injury was 5.4% with as low as 2.9% permanent paraplegia rate. Based on the extent of the aneurysmal disease, the rates of paraplegia were 15%, 31%, 7% and 4% in patients with Extent I, II, III and IV TAAAs in the 1993 series by Crawford *et al.*, and 1%, 5%, 4% and 1% in the 2016 series by Coselli *et al*., respectively.[38, 40] However, these excellent outcomes are the result of years of experience and can only be achieved in centers of excellence. A series of 1273 TAAA patients from Estrera *et al.* in 2015 with 25 years of follow-up data, showed 5-year survival rates were less than 60% after open repair.[41] At 15 and 20 years, overall survival was just over 30%, but this must be interpreted in the context of a mean patient age of 64.2 years. Indeed, 5-year and even 15- and 20-year survival rates are often reported by studies but the utility of these metrics in older patients is questionable, particularly more so in the endovascularly-treated cohort.

An analysis from the Nationwide Inpatient Sample from the year 2003 evaluating open repair for intact TAAA shows that the mortality was markedly higher nationwide (22%) than reported in the meta-analyses and single-institutional studies.[9] However, as this study methodology compromised interrogation of the NIS database using ICD-9CM disease codes, it is possible that this cohort also captured patients with descending thoracic aneurysms and dissecting aneurysms, which may have an unpredictable effect on the mortality rate. The authors' found a noticeable improvement in mortality over time decreasing from 27.4% in the year 1988 to 15.0% in 1998 (P<0.001).[9] Additionally, mortality in patients treated at high volume centers (median 12 [range 5-31] annual TAAA cases) was 42% lower than compared to low volume centers (median 1 [range 1-3] cases per year). The rate of perioperative death within 24 hours of surgery was significantly lower in high volume centers compared to low volume centers (27.6% *vs*. 42.3%).

Similar to the Nationwide Inpatient Sample analysis, the mortality was higher than in a Californian statewide survey of Medicare patients including 797 elective repairs between 1991 and 2002; the overall 30-day mortality after open TAAA repair was 19%, and almost one-third of the patients were deceased one year after repair.[5] For octogenarians, the 30-day mortality was as high as 40% (Figure 7). These registry data reflect surgical mortality for TAAA repair in hospitals that do not usually publish their results and has been touted as much more representative of "real-world" outcomes. Though the larger series from specialized high-volume centers such as the Cleveland Clinic and Texas Heart Institute have provided informative, their collective experience is nonetheless biased towards experienced surgeons and ancillary facilities capable of dealing with perioperative and immediate postoperative complications. Thus, these larger series must be interpreted cautiously as the 30-day mortality statistics reported in most open TAAA series may underestimate the risk of surgical repair in lower-volume institutions. These results emphasize the importance of clinical volume at tertiary referral centers in minimizing operative mortality.

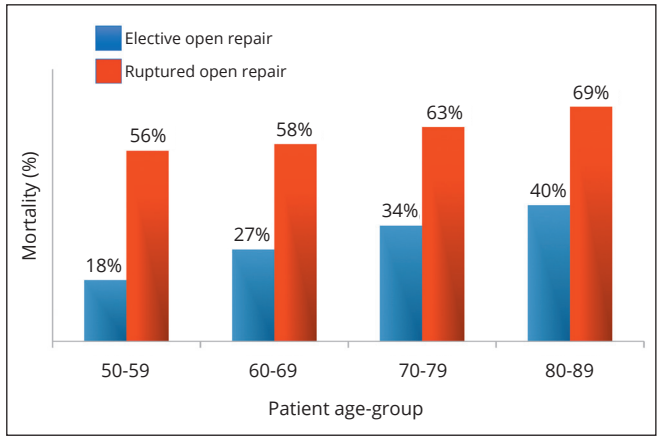

Figure 7.—Thirty-day mortality rates of open thoracoabdominal aortic aneurysm repair in four age-groups. Data derived from the National Inpatient Sample analysis by Rigberg *et al.*[8]

The effect of clinical volume on operative morbidity, particularly spinal cord ischemia is less clearly defined. Given the sobering high rates of spinal cord ischemia and paraplegia, over the subsequent years, substantial efforts have been made to create and optimize techniques for spinal cord protection and renal perfusion. This is evident in down trending rates of spinal cord ischemia, from above 15% in Crawford's original series to nearly 5% in Coselli's contemporary experience.[38-41] A fundamental difference between these studies and endovascular series relies on patient selection. Almost all open surgical series include patients with an average age of 50 to 60 years old, and lower rates of severe cardiac, pulmonary and renal disease. Conversely, the average age on endovascular reports is 70 to 80 years, and over two-thirds of the patients are considered high risk or prohibitively high risk for open surgical repair.

Despite these fundamental differences in patient selection and the effect of learning curve, outcomes are similar or better for endovascular repair (Table I, II).[24, 38, 41-60] A systematic review of contemporary outcomes of endovas-

TABLE I.—*Outcomes of open thoracoabdominal aortic aneurysm (TAAA) repair.*[38, 41-50]

Study	N.	TAAA extent	Age	Urgent (N.)	30-day mortality	SCI	Paraplegia	Dialysis
Shiiya (2019)[42]	178	I-III 143 IV 35	70 (26-88)	24	3.9%	5.1%	2.2%	0%
Latz (2019)[43]	516	I-III 516	70±10	88	8%	11.6%	7%	7.2%
Uchino (2017)[44]	130	I-III 84 IV 46	66±13	NA	2.5%	8.5%	3.8%	5.4%
Sugiura (2017)[45]	118	I-III 105 IV 13	63±13	10	4.2%	14.4%	11.9%	NA
Hicks (2017)[46]	137	I-III 66 IV 71	62±1	3	6.6%	NA	1.5%	12.4%
Coselli (2016)[38]	3309	I-III 2640 IV 669	67 (59-73)	723	4.9%	9.6%	2.9%	2.5%
Murana (2016)[47]	542	I-III 475 IV 48 V 19	65±11	64	8.5%	5.5%	4.7%	2.3%
Estrera (2015)[41]	1896	I-III 813 IV 348 V 112	64±14	171	15.9%	9.7%	7.1	16.6%
Conrad (2007)[48]	455	I-III 354 IV 101	71±10	103	8.3%	13.2%	9.5%	4.6%
Jacobs (2006)[49]	112	I 42 II 70	62 (28-80)	5	13.4%	2.7%	1.8%	1.8%
Grabitz (1996)[50]	260	I-III 208 IV 24 V 28	63±15	NA	14.5% (90-day)	13%	3.5%	13%

Age is presented as mean±SD or as median (interquartile range), in years.
SCI: spinal cord injury; NA: not available.

TABLE II.—*Outcomes of endovascular thoracoabdominal aortic aneurysm (TAAA) repair.*[24, 51-60]

Study	N.	TAAA extent	Age	Urgent (N.)	30-day mortality	SCI	Paraplegia	Dialysis
Spanos (2018)[52]	42	I-III 29 IV 13	73±7	42	14%	21%	12%	10%
Youssef (2018)[24]	108	I-III 79 IV 29	74±7	NA	9.3%	5.5%	1.8%	8%
Gallitto (2018)[53]	30	I-III 25 IV 5	73±7	8	5%	5%	1.6%	1.6%
Oderich (2017)[51]	185	I-III 73 IV 112	75±7	NA	4.3%	5%	3%	1%
Fernandez (2016)[54]	133	I-III, V 60 IV/pararenal 73	71±7	0	4%	NA	3%	6%
Eagleton (2016)[55]	354	II-III 354	74±8	NA	4.8%	8.8%	4%	2.8%
Maurel (2015)[56]	204	I-III 119 IV 85	71 (65-77)	0	6.9%	3.9%	2.5%	5.4%
Verhoeven (2015)[57]	166	I-III 115 IV 41 V 10	69±8	NA	7.8%	9.0%	1.2%	1.8%
Katsargyris (2015)[58]	218	I-III 135 IV 63	69±8	NA	7.8%	10.4%	1.5%	NA
Dias (2015)[59]	72	I-III 55 IV 17	68 (64-73)	21	6.9%	31%	9%	NA
Bisdas (2015)[60]	142	II-III 130 IV 12	70±7	NA	2.8%	16%	8%	NA

Age is presented as mean±SD or as median (interquartile range), in years.
SCI: spinal cord injury; NA: not available.

cular and open thoracoabdominal aortic aneurysm repair by Rocha *et al.*, included 71 studies, of which 24 and 47 reported outcomes after endovascular and open TAAA repair, respectively. Endovascular cohort patients were older and had higher rates of coronary artery disease, chronic obstructive pulmonary disease, and diabetes. Endovascular repair was associated with higher rates of SCI (13.5%; 95% CI: 10.5-16.7%) compared with open repair (7.4%; 95% CI: 6.2-8.7%; P<0.01) but similar rates of permanent paralysis (5.2% [95% CI: 3.8-6.7%] *vs*. 4.4% [95% CI: 3.3-5.6%]; P=0.39), lower rates of postoperative dialysis (6.4% [95% CI: 3.2-9.5%] *vs*. 12.0% [95% CI: 8.2-16.3%]; P=0.03) but similar rates of being discharged on permanent dialysis (3.7% [95% CI: 2.0-5.9%] *vs*. 3.8% [95% CI: 2.9-5.3%]; P=0.93), a trend to lower stroke (2.7% [95% CI: 1.9-3.6%] *vs*. 3.9% [95% CI: 3.0-4.9%]; P=0.06), and similar perioperative mortality (7.4% [95% CI: 5.9-9.1%] vs. 8.9% [95% CI: 7.2-10.9%]; P=0.21).[61]

While the safety of endovascular TAAA repair may be supported by recent series, the long-term efficacy is yet to be established. Given its relatively recent introduction, larger series with longer follow-up enabling estimation of 1-, 3- and 5-year recurrence risks are lacking. The availability of endografts and operator comfort means endovascular repair may similarly be limited to so-called high-volume "centers of excellence" with hybrid operating rooms and dual open and endovascular capability. Currently, endovascular repair is only undertaken at highly specialized centers that focus primarily on endovascular techniques with minimal open volume, comparatively. The technical demands of both modalities require a substantial volume for maintenance of acceptable rates of morbidity and mortality. Preliminary work from our group has shown that endovascular repair of especially Extent IV TAAA, limited to the sub-diaphragmatic aorta, can be undertaken safely with mortality, major adverse event and paraplegia rates of 2%, 32%, and 2%, respectively; the respective rates for Extent I-III TAAAs were 8%, 36% and 5%.[51] Only two patients out of 185 (1%) required new-onset dialysis postoperatively. At 5 years, primary patency was estimated at 93% and overall survival at around 60%. More than one-third of the patients required re-intervention during two-year follow-up after endovascular TAAA repair.[51] In a study by Greenberg *et al.*, the 30-day mortality and 2-year survival were comparable for juxtarenal/suprarenal aneurysms (1.8% and 78%) and Extent IV thoracoabdominal aortic aneurysms (2.3% and 82%).

A hybrid procedure is a less invasive alternative to conventional open TAAA repair. This technique comprises

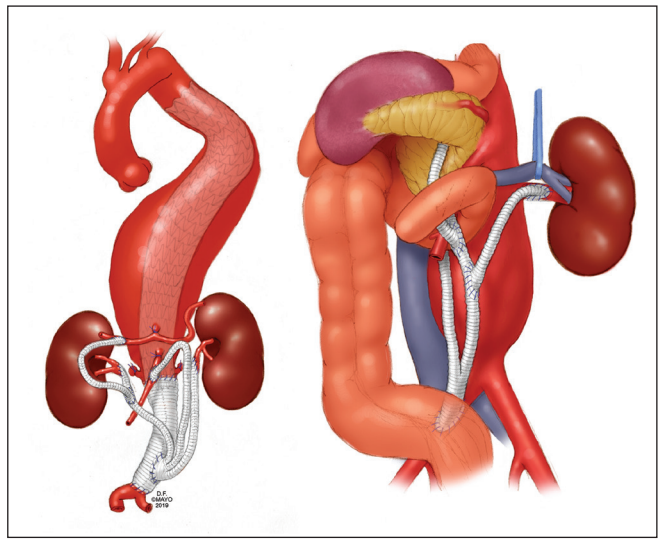

Figure 8.—Illustration depicting hybrid repair solutions for Extent III-IV thoracoabdominal aortic aneurysms. On the left, the infrarenal aorta has been repaired surgically with debranching of the celiac, superior mesenteric and renal arteries; the thoracic aorta has been repaired with an endovascular graft. On the right, the visceral vessel debranching has been done using right common iliac artery as the inflow; this facilitates a simple stenting and coverage of the abdominal aorta. By permission of Mayo Foundation for Medical Education and Research. All rights reserved.

open surgical debranching of the renal mesenteric vessels, followed by endovascular repair in a single or two stage procedure (Figure 8). The rationale for a hybrid approach is to avoid thoracotomy, single-lung ventilation, and aortic cross-clamping.[62] However, hybrid procedures are associated with significant mortality and the results vary widely between centers indicating differences in patient selection, the extent of repair and use of single and two stage procedures. A systematic review of 528 hybrid TAAA repairs showed a pooled perioperative mortality rate of 14%, and the rates of irreversible paraplegia, permanent renal failure, and mesenteric ischemia were 4.4%, 7.0%, and 4.5%, respectively.[63] Long-term follow-up is needed to evaluate the durability of hybrid procedures.

Patient selection for endovascular TAAA repair

According to an analysis of a nationwide administrative dataset between 2005 and 2014 in Germany, endovascular repair has become the most common treatment modality in thoracoabdominal aortic pathology.[64] Up to 90% of descending thoracic aneurysms and 75% of TAAAs were treated by endovascular approach during the last year of the survey. The studies showed also that the incidence of TAAA repair doubled over the ten-year period. Owing to

its minimal invasiveness, early survival benefit, decreased risk of complications, and quick recovery, the fenestrated-branched procedure has allowed treatment of elderly and fragile patients who are poor candidates for open surgery.[65] With treatment, the patient is expected to avoid deadly aortic rupture, and thus, live longer. However, these complex endovascular procedures are not without risks, and the need for secondary interventions is significantly higher than after open surgery.[34] Complications and the need for close follow-up may compromise the patient's quality of life. The risks and institutional complication rates as well as the impact on the quality of life should be carefully discussed with the patient and weighed against the risk of rupture. The most important question for many elderly patients is not "can you do it" but rather "should you do it". Hence, when is an individual patient too old, sick, or fragile to undergo this procedure? Does the benefit of longer life justify treatment given the risk of decreased quality of life in the elderly?

Although anatomical factors remain the most important eligibility criteria in endovascular TAAA repair, patients with complex aortic pathology often have widespread atherosclerosis and other comorbidities which could prevent the patient from undergoing complex endovascular repair. A thorough preoperative evaluation is needed prior to any endovascular TAAA repair including cardiac, renal and pulmonary risk assessments. American Society of Anesthesiologists (ASA) class IV is associated with a significantly higher mortality rate and reduction of life expectancy than classes I to III.[66, 67] Although we continue to evolve in the understanding of how aging and comorbidities affect treatment selection, we contraindicate F-BEVAR in patients with limited life expectancy (less than 2 years). However, advanced age should not be the only basis of exclusion for endovascular repair of TAAAs.[68] Fenestrated-branched endovascular repair in octogenarians was demonstrated to have higher early mortality compared with non-octogenarians in a study of 38 octogenarians and 169 non-octogenarians.[67] In contrast, our recent survey of 442 consecutive patients including 138 octogenarians (31%) who underwent fenestrated-branched repair of TAAAs and pararenal aneurysms at the Mayo Clinic showed no differences in 30-day mortality (2.2% *versus* 2.0%, P=0.99) and the rate of major adverse events (31% *versus* 30%, P=0.91) in octogenarians compared to non-octogenarian. Moreover, the long-term mortality was similar in both groups up to three years after the procedure. Hence, endovascular repair of TAAA is safe in carefully selected elderly patients.

There is a clinical need for a novel tool for use in combination with traditional preoperative assessment in order to predict an individual patient's outcome and survival prognosis after endovascular TAAA repair. Several multi-domain and single-domain assessment tools have been studied in patients undergoing vascular surgery.[69] Frailty, assessed by functional status, may predict short-term mortality in elderly patients after vascular surgical procedures.[70] In addition, central muscle mass, as a surrogate for sarcopenia, may help determine long-term survival prognosis in patients undergoing vascular surgical and endovascular procedures. This is usually expressed as psoas muscle area measured at L3-4 level from axial computed tomography images.[71, 72] However, these tools have not been validated specifically for endovascular repair of complex aneurysms such as TAAAs, and while others have been successful in showing the association of psoas muscle area with mid- to long-term mortality, others have failed to replicate these results.[73] Oksala *et al.* discovered that combining psoas muscle area (size) with density (quality) could yield stronger predictor of survival in patients treated for abdominal aortic aneurysms.[74] More research is needed in this area to develop clinically applicable risk stratification tools.

Conservative treatment is a reasonable option for some TAAA patients. However, patients with large TAAAs that are denied treatment have a relatively short life expectancy. The natural history of TAAA is not very well described in the literature. In 1986, Crawford and DeNatale published an observational study of patients who were denied or refused open TAAA repair. Only 24% of patients were alive after two years and half of the deaths were attributed to aneurysm rupture.[75] In a Mayo Clinic study of 57 patients with TAAA who were initially managed nonoperatively, 15 underwent subsequent repair and eight aneurysms ruptured accounting for 24% of all deaths during the follow-up.[76] The 5-year repair-free survival was 17%. In 2010, Hansen and co-authors reported 64% survival at 1 year and 52% at 2 years among 89 TAAA patients who were denied treatment.[77] Nearly all these patients died within 5 years and aneurysm rupture accounted for half of these deaths.

Health-related quality of life outcomes have been extensively investigated for infrarenal endovascular aortic repair in several randomized controlled trials and in two meta-analyses.[78, 79] These studies showed better quality of life metrics for endovascular repair as compared to open surgical repair at 1-year, but similar results beyond two years. Regarding endovascular repair of TAAAs, there is very little data. However, recently, our group at the Mayo

Clinic published a prospective series of 159 consecutive patients undergoing fenestrated-branched endovascular repair of 57 patients with pararenal aneurysms and 102 patients with TAAAs.[80] Patients were assessed using SF-36 quality of life questionnaire at baseline, 6-8 weeks, 6-months and 12-months. There was no early mortality and the rate of major adverse events was 18%. Interestingly, patients with TAAAs had worse baseline scores in their physical component of health-related quality of life. The physical component was especially low at baseline in patients who had undergone previous first stage endovascular repair of the thoracic aorta, and even more in those who underwent prior open surgical ascending aorta or arch repair. However, physical component scores were significantly lower at baseline in patients with TAAAs irrespective of prior aortic repair, which suggests that extensive aneurysmal disease is associated with a negative impact in the patient's quality of life, which starts before treatment. Both, patients with pararenal aneurysms and TAAAs experienced a decline in physical quality of life measures 6-8 weeks after surgery, and this returned to baseline after 6-12 months in patients with pararenal aneurysms but not in patients with TAAAs. Therefore, elective endovascular repair of TAAAs does have a significant impact on patients' physical quality of life that lasts at least up to 12 months after repair, and this should be considered when discussing treatment options.

Endovascular repair of ruptured TAAAs and chronic post-dissection TAAAs

Ruptured TAAAs comprise nearly one-fifth of all surgically treated TAAA and are associated with high mortality. An analysis of ruptured TAAA repair outcomes from the National Surgical Quality Improvement Database has shown pulmonary injury and renal failure rates to be substantially lower with endovascular treatment as compared to open repair (32% *vs.* 13%, P=0.004; and 58% *vs.* 37% P=0.007, respectively).[81] The feasibility of open TAAA repair in the acutely ruptured aneurysm may be limited in patients with significant co-morbidities unable to tolerate such an extensive operation. Endovascular repair with custom-manufactured endografts is impractical for use in the ruptured setting, given their lack of immediate availability for patient use.[81] Several recent series have demonstrated preliminary efficacy with off-shelf use of multibranched endografts for ruptured TAAAs, with acceptable morbidity rates.[82-84] However, catheterization failure and endoleak are substantial as reflected by rates of technical failure above 30% in certain series, suggesting larger, future studies are required.[84]

Other options for the endovascular treatment of ruptured TAAAs include physician-modified endografts.[85] However, even with the experience of nearly 150 elective patients treated with physician-modified fenestrated-branched endografts at the Mayo Clinic, it takes usually up to two hours to make the modifications which limits this technique only for contained ruptures.[5] The sandwich technique using a combination of chimney grafts and periscope configuration may enable a rapid TAAA exclusion in a setting of a rupture.[86] However, although this technique may be associated with acceptable mid-term results in symptomatic aneurysms, the risk of gutter endoleaks may limit its use in ruptured TAAAs. In situ laser fenestration may be a feasible option in some cases of contained TAAA rupture.[87] Successful in situ fenestration of the target arteries requires pre-stenting of all the incorporated visceral vessels for visualization and correct positioning of the fenestrations, and thus, it is a time-consuming and technically demanding procedure which limits its use in an emergency setting.

Small, preliminary series have also suggested feasibility of endovascular treatment for post-dissection TAAAs.[88] In a recent series of 71 patients with post-dissection TAAAs treated with endovascular approach, 30-day mortality and spinal cord ischemia incidences were 5.6% and 4.2%, respectively following intervention with fenestrated-branched endografts.[89] The freedom from reintervention rate at 1 year was 80.4±5.3%, but this dropped to just over 50% at 3 years. Other small studies have similarly provided promising results, though limited by the requisite long-term follow-up required to assess false lumen exclusion.[90, 91] In the most recent evaluation by Spear *et al.*, re-intervention was required in 6 out of 24 endovascularly treated TAAA (25%) patients; overall, aneurysm diameter remained stable in nearly three-quarters of the patients.[91] A recent multi-center study involved 221 patients from seven institutions with Extent I-III TAAAs, of which 175 were degenerative and 47 were post-dissection TAAAs.[92] The study demonstrated nearly identical outcomes irrespective of the aneurysm etiology. Post-dissection aneurysms comprise approximately 10% of the 200 and growing number of TAAAs treated with fenestrated-branched endovascular repair at the Mayo Clinic using company manufactured devices.

Limitations of endovascular TAAA repair

The use of stent-grafts to treat patients with connective tissue disease has been limited due to concerns for device

failure. These patients form a subset of a larger group of patients with genetically triggered aortic disease. Medical genetic evaluation should be strongly considered in younger patients presenting with aortic aneurysms and in those with features suggestive of a genetic disorder or familial history of aortic disease. Clinically relevant disorders include Marfan Syndrome, Turner Syndrome, vascular Ehlers-Danlos Syndrome, and Loeys-Dietz Syndrome. The current Society of Thoracic Surgeons and European Society for Vascular Surgery guidelines on diagnosis and treatment of aortic diseases recommends against endovascular repair in patients with connective tissue disease unless operative risk has been deemed prohibitive and in emergency situations.[11, 93] However, elective open surgical repair has also been associated with significant risk of morbidity and mortality; in a recent single center study of 65 patients with connective tissue disorders (56 with Marfan Syndrome), perioperative mortality was 14% and 15% required early re-interventions.[94] Potential applications of endovascular repair include patients with ruptured aneurysms as a bridge to open surgical repair, or patients with recurrent aneurysms where the stent-graft may be placed in a prior surgical graft.

Anatomical considerations that may limit the use of endovascular approach in the treatment of TAAAs include excessive aortic debris in the aortic arch, descending aorta and visceral segment (*e.g.* shaggy aorta). Endovascular TAAA repair involves a fair amount of manipulation of the aorta which can easily dislodge loose debris into the supra-aortic branches, visceral vessels, arteries supplying the spinal cord, and peripheral pelvic and lower limb arteries with potentially catastrophic consequences.[95] In addition, severe tortuosity and angulation of the aorta can make the passage and orientation of the main endovascular device difficult. This can sometimes be overcome with the use of a brachial-to-femoral application system with enough tension on the through-and-through wire. Narrow and calcified or occluded iliac arteries may also be a limiting factor. However, many access difficulties can often be overcome with the use of surgical or endovascular conduits.[96] Open surgical conduits are performed either prior to the procedure (permanent iliofemoral conduit) or in conjunction with the endovascular repair. Our preference is to use a 12 mm polyester graft anastomosed in an end-to-side fashion. This graft diameter allows the introduction of a 24-Fr delivery system without difficulty. The endoconduit or "paving and crack" technique is an alternative that applies the use of covered stents from the common iliac artery to the distal external iliac artery, with subsequent forceful dilatation to enlarge the vessel to 10 or 12 mm.[97] Because this technique requires coverage of the internal iliac artery and may reduce the collateral flow of the spinal cord, we do not recommend its use in patients with previously patent internal iliac arteries who are planned for extensive TAAA repair. Finally, the presence of suitable target vessels without excessive tortuosity, occlusive disease or early bifurcation is critical for successful endovascular branch incorporation.

Conclusions

Endovascular repair offers a minimally invasive approach to open TAAA repair, which is the largest and most morbid procedure of our specialty. The decision between open or endovascular technique should take into consideration the outcomes at each individual institution, and the suitability of each approach in a respective patient. Outcomes of open surgical repair remain stagnant in most centers, and the lowest mortality (7.5%) has been achieved after three decades of experience with over 3000 patients. Conversely, equal results have already been reported in several centers with endovascular technique in older patients with smaller patient cohorts. It is likely that continued evolution of patient selection, device design and improved perioperative care will lower the mortality and morbidity of endovascular repair even further. As the review of large nationwide data shows, the early mortality rate for elective open TAAA repair is almost unacceptably high in a "real-world" setting, reaching 20% in 30 days.[5] Therefore, in most centers with access to fenestrated-branched technology, endovascular repair has become the new gold standard in patients who have suitable anatomy and do not have contraindications. Open surgical repair should be performed in selected centers of excellence and is primarily indicated in younger patients with connective tissue disorders, in those with aortic infections and in patients with unsuitable anatomy for endovascular approach. Universally-adopted reporting standards for patient characteristics, outcomes, and the conduct of contemporary comparative studies will allow better assessment and comparisons of the risks associated with the two surgical treatment options for TAAA.

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