Endovascular Repair of Thoracoabdominal Aneurysms
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Background—Morbidity and mortality after conventional repair of thoracoabdominal aneurysms remain high. Alternative techniques have been proposed and are the subject of this report.

Methods and Results—Endovascular grafts that have a means of incorporating the visceral vessels into the aortic repair were divided into devices with fenestrations and those with formal branches. Hybrid procedures whereby an extra-anatomic bypass procedure is used to provide inflow to the renal and mesenteric arteries followed by aortic relining with stent grafts were reviewed and tabulated. A description of the techniques and review of the current results are provided. Only 4 series with >10 cases of hybrid procedures have been published. The experience with such a procedure suggests feasibility, but most reports describe a persistently high risk of mortality (up to 25%). Larger series of fenestrated stent grafts to treat juxtarenal aneurysms have been published, and intermediate-term results confirm the safety and efficacy of the procedure. A larger multicenter trial is under way. Other pure endovascular methods have been used to treat thoracoabdominal aneurysms with both reinforced fenestrations and directional branches. Without counting small series (<10 cases), 2 series exist with ~100 cases that noted perioperative mortality rates between 3% and 6%, without evidence of late ruptures.

Conclusions—Endovascular repair of thoracoabdominal aneurysms is feasible and is associated with relatively low perioperative mortality. Several methods of visceral vessel incorporation have been described. Because of persistently high mortality, hybrid procedures will likely be relegated to nonsurgical and nonendovascular patients with sizable aneurysms. Endografts with branches continue to evolve and will be assessed in the context of clinical trials.

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Key Words: aneurysm • aorta • dissection • stents • thoracoabdominal aortic aneurysm

Surgical repair of thoracoabdominal aneurysms was first described in 1955 by Etheredge et al.1 The procedure has been improved by the use of techniques designed to limit visceral and lower extremity ischemia, adjuncts to minimize the risk of spinal cord ischemia, and advances in critical care. However, the operation involves the surgeon replacing the aorta from above the aneurysm to a healthy distal aorta or iliac arteries, which necessitates the reimplantation of some or all of the visceral and intercostal arteries as either a patch or with separate bypass grafts. Although the contemporary results of these extensive operations are considered acceptable in the context of the untreated risk of aneurysm rupture, such an undertaking remains daunting for the patient and physician. Patients selected to undergo such a repair are faced with a mortality risk ranging from 3% to 17%,2–6 with an incidence of perioperative death at centers with extensive experience <10%. The risk of spinal cord ischemia, despite the variety of adjuncts that may be employed, remains substantial, between 4% and 11%.4–8 Postoperative renal complications are also considerable and include the risk of worsening renal function, which ranges from 17% to 25%,9,10 with up to 15% of patients ultimately requiring hemodialysis.10 Cardiopulmonary complications after aortic surgery are also common.11,12 Furthermore, the published results from high-volume centers may not be representative of the cardiovascular surgical community at large. A recent medical statewide audit in California noted a 19% perioperative mortality after elective thoracoabdominal aneurysm repair, with a staggering first-year mortality of 31%.13 However, untreated, large thoracoabdominal aneurysms have a high risk of rupture,14 and emergent operations are associated with a dismal prognosis.15 In light of the aforementioned outcomes, alternative methods of aneurysm exclusion have been explored. Most paradigms use strategies that eliminate the need for aortic cross-clamping and minimize surgical incisions and dissection.

Techniques and Results

Development of Endovascular Aortic Repair
Endovascular aneurysm repair was initially developed to treat patients who were considered to be unfit or at high risk to undergo a conventional open surgical repair. Devices, procedural techniques, and patient selection have evolved substantially since the initial endovascular procedure described by...
Parodi et al in 1991. In 2004 and 2005, the results of a randomized trial comparing endovascular aneurysm repair with open surgery for infrarenal aneurysms concluded that endovascular aneurysm repair was superior to open surgical repair in fit patients with respect to aneurysm-related death at 30 days, an observation that persisted through 4 years of follow-up. The extrapolation of similar technologies to treat thoracic aortic pathology yielded similar yet less convincing evidence on lower risks of morbidity and mortality after thoracic endovascular aneurysm repair through 1 year of follow-up. However, the visceral segment is the most challenging portion of the thoracoabdominal aorta and is complicated by the presence of visceral and renal branches, which frequently have concomitant occlusive or aneurysmal disease. Two primary strategies have been employed in an effort to ameliorate the risks of conventional thoracoabdominal aneurysm repair. The first involves a hybrid procedure in which extra-anatomic bypasses are created to perfuse the visceral and renal vessels from the iliac arteries, followed by relining of the aorta with stent grafts. An alternative approach, which relies solely on endovascular techniques, has been described with 2 different types of devices. The first utilizes fenestrations, or controlled holes in the fabric or the prosthesis, that are aligned and then adjoined to the respective visceral artery orifice with a balloon-expandable stent graft. The second method involves aortic endografts to which branches are attached, then mated to each target vessel with a self-expanding stent graft. In some series, the 2 different techniques incorporating visceral arteries may be combined within a single device. The techniques and results of these 3 less invasive procedures are discussed in this report.

Hybrid Repairs

Techniques

Extra-anatomic bypass procedures have been utilized to treat occlusive disease of the visceral arteries for years. Modifications of these techniques have been employed to “debranch” the visceral segment. Inflow to the extra-anatomic bypass can be achieved from the aorta or iliac artery, depending on the distal extent of the thoracoabdominal aneurysm. The bypass graft then provides retrograde flow into each visceral artery that is anastomosed in a functional end-to-end manner to allow end-organ perfusion with the proximal visceral artery ligated to eliminate the risk of back bleeding into the aneurysmal sac after endovascular exclusion (Figure 1). The extra-anatomic bypass portion of the procedure is accomplished through a retroperitoneal or transperitoneal approach that may extend into the lower chest but does not require an aortic crossclamp or single-lung ventilation. Performing the visceral anastomoses sequentially minimizes the total ischemic time to the kidneys, theoretically limiting the physiological derangements associated with extended cross-clamp times.

The endovascular portion of the repair can be done at the same time as the visceral bypass or in a staged manner. Typically, thoracic devices are used to reline the aorta down to the infrarenal segment, at which point a distal bifurcated device may be implanted to fixate and seal within the iliac arteries if necessary. Multiple components may be required to traverse the length of extensive aneurysms, and such devices are “tromboned” together, allowing the substantial overlap between the segments to form a seal connecting the devices in a modular fashion. Access through the femoral vessel for such devices may pose a challenge, necessitating the use of conduits to prevent damage to the iliac system. Aneurysms that involve the more proximal descending thoracic aorta or aortic arch may also require extra-anatomic bypasses of the brachiocephalic arteries or the use of elephant trunk graft techniques.

Results

Only 4 series with >10 patients in addition to a number of case reports have been published. Although 1 report attempts to compare conventional treatment with the hybrid approach, no prospective comparison studies have been published. All of the authors have confined the experience with hybrid procedures to very ill patients who may be precluded from a conventional repair. Summary data are presented in Table 1. The mortality for this strategy remains sobering and even underestimated. In most of the reports, when a staged procedure was employed, survival data and complications are available only for patients who returned for the endovascular stage. Thus, analogous to staged arch/thoracoabdominal aneurysm repair, some patients may not have survived the first stage, may have ruptured during the interval delay, or may have simply refused to undergo further surgery. Results from our own center led us to conclude that visceral segment extra-anatomic bypass procedures are used only in the setting of a large aneurysm when conventional repair is contraindicated and a pure endovascular approach is not feasible. Examples of such situations include the need for an acute repair (in the absence of a rapidly available customized device) and in the setting of extreme aortic tortuosity.

Endovascular Repair

Fenestrated Endografts

The placement of holes within an endograft that can be aligned with the renal arteries followed by deployment of uncovered balloon-expandable stents through the aortic graft into the branch is termed a fenestrated graft. This device is used to treat juxta renal aneurysms and was initially described by Browne et al in 1999. Several clinical reports have followed early experiences. A recent review of reports on fenestrated endografts noted a perioperative mortality of 1.1%, with 97% of the target vessels being successfully perfused. However, such procedures still require an acceptable, albeit markedly short (3 mm versus 15 mm), sealing zone caudal to the renal arteries. A low incidence of late endoleaks coupled with a high rate of aneurysmal sac shrinkage has been observed in a large single-center series and supports the durability of the technology through the intermediate follow-up period. Devices are commercially available in Europe and Australia, and a US trial is currently being conducted to assess the safety and efficacy of such a repair in the United States.

Reinforced Fenestrated Branches

Extrapolating fenestrated technology above the infrarenal segment to treat aneurysms involving the visceral arteries was initially described by Anderson in 2005. Mating the fenes-
tration with a balloon-expandable stent graft rather than simply an uncovered stent affords one the ability to establish a seal above the targeted visceral artery. To accomplish this, the device and technique have been modified from that employed to treat juxtarenal aneurysms. A nitinol ring is sutured around the orifice of each fenestration. This will create a thin but relatively rigid location to which the balloon-expandable stent graft can be attached. The deployment technique requires wire access into the partially deployed aortic endoprosthesis (via a sheath inserted into the contralateral femoral artery), out the target fenestration, and into the desired visceral vessel (Figure 2). Once accom-
plished, a long sheath is placed over the wire into the mid portion of the visceral vessel, and a mating stent graft of adequate length is deployed to the target vessel diameter, forming a bridge between the aortic stent graft and visceral vessel. The aortic component of the mating balloon-expandable stent graft is then inflated with a 10- to 12-mm balloon to create an hourglass-type seal against the nitinol ring sewn to the fenestration. Further flaring with a compliant balloon can be used to rivet the 2 stent grafts together. Two types of mating balloon-expandable stent grafts are available for use with this device. The Jomed stent graft (Abbott Labs) consists of a thin layer of expanded polytetrafluoroethylene sandwiched between 2 stainless steel stents. The stent graft is supplied unmounted with diameter ranges from 4 to 9 mm or 6 to 12 mm, largely relating to the thickness of the expanded polytetrafluoroethylene membrane. The Atrium stent graft (Atrium Medical) consists of a stainless steel stent surrounded on both sides by an expanded polytetrafluoroethylene graft. The stent graft is premounted on a balloon of various lengths and diameters.

A second modification allows for the treatment of aneurysms extending up into the aortic arch. Conventional fenestrated devices have an uncovered top stent with barbs to achieve fixation. Active fixation is considered critical to prevent migration, which, when it occurs in the setting of branches, could be catastrophic. However, proximal uncovered stents may not be desirable when repairs require more proximal components or the landing zone is within the tortuous portion of the thoracic aorta. Consequently, the use of a proximal uncovered stent has become optional. Active fixation is achieved by combining a fenestrated device with a proximal thoracic component that has barbs or by allowing the barbs to traverse the fabric of the proximal sealing stent to engage the aortic wall. In this manner, the aortic devices may

Table 1. Summary of 4 Reports of Hybrid Procedures to Repair Thoracoabdominal Aneurysms With >10 Patients Each

<table>
<thead>
<tr>
<th>Reference</th>
<th>No. of Patients</th>
<th>Mortality, %</th>
<th>Aneurysm Pathogenesis</th>
<th>Aneurysm Extent, I/II/III/IV</th>
<th>Length of Stay, d</th>
</tr>
</thead>
<tbody>
<tr>
<td>Black et al32</td>
<td>29 (22 elective)</td>
<td>13 elective, 100 rupture</td>
<td>Nonspecific, 21; Marfan syndrome, 6; dissection, 2</td>
<td>3/18/7/1</td>
<td>27</td>
</tr>
<tr>
<td>Resch et al22</td>
<td>13 (8 elective)</td>
<td>23</td>
<td>Nonspecific, 7; Ehlers-Danlos syndrome, 1; dissection, 5</td>
<td>0/10/2/1</td>
<td>Bypass, 13; TEVAR, 12</td>
</tr>
<tr>
<td>Zhou et al25</td>
<td>18</td>
<td>3</td>
<td>…</td>
<td>3/0/8/7</td>
<td>…</td>
</tr>
<tr>
<td>Chiesa et al26</td>
<td>13</td>
<td>23</td>
<td>…</td>
<td>7/2/0/2</td>
<td>…</td>
</tr>
</tbody>
</table>

Patients in all studies had severe comorbid illnesses and were not considered good candidates for conventional treatment. The pathogenesis of the aneurysms was summarized if possible to include nonspecific, associated with a connective tissue disorder, or in the setting of a chronic dissection. The extent of the aneurysm is listed according to the Crawford classification system (I, II, III, and IV). TEVAR indicates thoracic endovascular aneurysm repair.

Figure 2. An angiographic image during implantation of a fenestrated endograft is depicted. The left renal fenestration (yellow oval) is aligned, and a mating uncovered stent has been placed. A sheath had been placed into the right renal fenestration (green oval). Note the longitudinal appearance of the left renal fenestration markers in contrast to the splayed appearance of the equivalent 4 markers around the right renal area. This implies that the C-arm is perpendicular to the left renal orientation, whereas the right renal orientation is actually more anterior. A scallop was created for the inferior aspect of the superior mesenteric artery origin (red oval), and the black arrows illustrate the markers that assist with rotational alignment and longitudinal positioning.
include proximal thoracic components, a device that has fenestrations for the visceral arteries, and a bifurcated component if necessary (Figure 3). Given variability with regard to the extent of aneurysmal disease for a given patient, the length of covered aorta can be customized. The aortic devices are loaded within 18F to 22F sheaths, and the mating stent grafts are introduced through sheaths within the contralateral femoral artery that are 6F to 8F in diameter.

**Directional Branches**

Attaching a formal branch to the aortic component offers advantages and disadvantages. A branch provides a segment of overlap that can be used to provide better sealing and fixation than the thin joint between a reinforced fenestration and mating visceral stent graft. A longer overlap affords one the ability to utilize self-expanding stent grafts rather than balloon-expandable stent grafts. This may provide a means to better accommodate tortuosity and diameter discrepancies. Two critical factors will predict the success of such a design: the joint strength and amount of tortuosity. These issues have resulted in the creation of axial (caudally oriented) and helical (oriented directly toward the visceral ostium) branches.

**Branch Orientation**

In addition to axial and helical branches, other variations exist, including flow direction (antegrade and retrograde) branches and branches attached to the inside or outside of the aortic component (Figure 4). Axial branches are relatively simple. The aortic device is deployed well above the target vessel, the branches are cannulated from a brachial approach, and mating self-expanding stent grafts (Fluency, Bard, NJ) are deployed to join the target vessel and aortic graft. However, the length of the axial branch overlap segment is, by necessity, short (10 mm). Frequently, this joint must be reinforced with a balloon-expandable stent to prevent late component separation. A further issue exists with respect to flow direction. Stents exiting an axial branch are aligned with the aortic flow; however, the target vessel is not. Thus, the mating self-expanding stent graft is forced to angulate to direct blood into the target organ and seal the aneurysm. This combination is of tenuous durability. Consequently, additional long self-expanding stents (Wallstents, Boston Scientific, Nadic, Mass) may be deployed to create some columnar support for the branch, discouraging component separation and kinking. The durability of multiple layers of stents and stent grafts stacked to create a channel is dubious, yet adverse results of this combination have not been reported. An alternative approach to branched grafting involves the use of helical branches. These branches exit the aortic component posteriorly and traverse at a given pitch, terminating ~8 to
10 mm above the target vessel. The advantage of this design is the long overlap segment created (≈30 mm) and the orientation of the branch orifice in line with the direction of visceral flow rather than aortic flow. This construct, when mated with a self-expanding stent graft, may not require additional support from a balloon-expandable device or have a need for columnar support. However, such branches are bulkier to load into a delivery system.

**Device Delivery**

Delivery systems for these complex devices require equal attention to the implant design. It is critical for aortic grafts to be readily introduced via a femoral approach, have a method for precise deployment, and allow for postdeployment positional adjustments to allow for accurate branch alignment and cannulation. Furthermore, the time required to establish access into the aortic branches must be minimized. The braided hydrophilic sheath used with fenestrated grafts provides an atraumatic entry into the aorta and confers the ability to torque the device within tortuous or diseased iliac vessels. However, the size of the delivery system (18F to 22F) mandates the need for iliac conduits in some patients. After sheath retraction, the implant remains attached to the delivery system by wires that transcend the device handle, termed *trigger wires*. In addition to stabilizing the device positioning within the aorta during visceral vessel cannulation, the proximal and distal trigger wires allow for continued rotational and longitudinal adjustments, and a constraining wire (a trigger wire located along the posterior aspect of the device) prevents complete graft expansion of the fabric, providing space between the partially deployed prosthesis and aortic wall to facilitate branch cannulation. Directional branch delivery systems differ from fenestrated systems in the use of catheters and wires that are preloaded through the branches, traversing the delivery system. The catheters reside alongside the external aspect of the distal aortic graft, enter the branch in a retrograde fashion, and exit into the aortic device lumen (Figure 4). A wire introduced through such a catheter can be snared from the brachial artery to establish through-and-through access. Sheaths introduced over such a through-and-through wire from the brachial artery can be readily placed within the directional branch. Once branch access is established, cannulation of the target vessel is generally simple and is followed by mating stent graft deployment.

The advantages of branches over reinforced fenestrations include improved mating stent graft joint integrity and the

![Figure 4](http://circ.ahajournals.org/)

**Figure 4.** A variety of directional branches have been used. Two helical branches (red arrows, one intended for the celiac and the other for the superior mesenteric artery) and an axial branch (yellow arrow, intended for a right renal artery) are depicted.
potentially to minimize the angle between the aorta and target vessel. However, a number of distinct disadvantages of this approach exist. The first relates to the need to achieve an aortic seal well above the branch origin. This means that the amount of covered aorta, particularly in the setting of a type IV thoracoabdominal aneurysm, may exceed the amount of diseased aorta. This may result in a higher than required risk of paraplegia.39 The second disadvantage relates to the need for space within the aneurysmal sac to accommodate all of the branches. If an aneurysm is not filled with thrombus, adequate room is generally available to deploy the device, cannulate the target arteries, and place mating stent grafts. However, in the setting of a small lumen (<3.4 mm), the aorta can easily become overcrowded. It has been suggested that the aortic component may be tapered through the visceral segment to create additional space and then reexpanded distal to the visceral segment. However, the hemodynamic and displacement force effect of such a construct is not known. The introduction system of devices with directional branches, in contrast to reinforced fenestrations, is typically 1F to 2F larger. This relates to the bulk of the branches coupled with preloaded 4F catheters. More commonly, the use of directional branches for some of the visceral branches (celiac and superior mesenteric arteries) is combined with reinforced fenestrated branches for others (renals). All of the devices, regardless of the branch design, may be coupled with distal aortic bifurcated components and may also be combined with branched grafts used to treat common and internal iliac aneurysms.40 It must be understood that a great deal of the decision making pertaining to device design relates to patient-specific anatomy. For example, severe aortic tortuosity may limit the ability to predict how reinforced fenestrations will align with branches or may actually cause compression of long branches. Furthermore, aortic dissections create a constrained lumen within which the initial deployment must occur and therefore may inhibit branch cannulation, complicating the procedure. However, when the tortuosity is remote from branches or the dissection lumen is large in the region of fenestrations, the technical issues may be simple to overcome.

**Results**
The first reported case of thoracoabdominal aneurysm repair involved a homemade device with longitudinally oriented branches.28 Subsequently, a number of series have been published describing the results of endovascular repair of thoracoabdominal aneurysms.27,29,38,41 These reports attest to the feasibility of such a repair strategy along with reassuring data on the intermediate-term results and are summarized in Table 2. However, the risk of death, paraplegia, renal failure, and other problems, despite the minimally invasive nature of the procedure, persists. Clear benefits of this approach exist and include limited pulmonary complications, less pain, decreased transfusion requirements, shorter lengths of stay, and more rapid recoveries. Data from the Cleveland Clinic noted that only 2 of 73 patients developed paraplegia, both of which ultimately required tracheostomies, after endovascular repair. Given a preoperative need for supplemental home oxygen in 20% of the patients and the fact that nearly half of all patients had been diagnosed with severe chronic obstructive pulmonary disease, the lack of major pulmonary issues is impressive. The overall length of stay was <5 days for patients who did not suffer any complications, with an overall mean length of stay of 9 days. Chuter et al42 presented a similar series of 22 patients treated for thoracoabdominal aneurysms with branched devices, but the detailed results were not available at the time this report was prepared.

**Other Designs**
A number of reports have been generated by Inoue43,44 and his group in Japan. They use a unibody design supported with nitinol rings. The advantage of such a device would be the elimination of modular joints, further limiting the risks of component separation, but such a benefit occurs at the cost of marked delivery challenges. Such a device must be deployed within the aorta, and then the branches must be retracted, with guidance into the target arteries. Although the technique has been employed to treat arch aneurysms,31 as well as more distal pathology,44 the details are not well understood, and the technology has not been used outside of the primary center.

**Future Directions**
Procedures to treat thoracoabdominal aneurysms with endovascular devices remain in their infancy. Large experiences are limited to a few centers worldwide. However, the fundamental techniques of endovascular grafting for infrarenal aneurysms and stenting for renal or mesenteric occlusive disease are now standard of care and performed by most
interventionalists who treat aneurysms. It is likely that fenestrated grafts, intended to treat juxtarenal aneurysms, will be approved for sale in the United States in the near future. Experience with these devices will allow clinicians to become familiar with the devices and techniques before undertaking more complex endeavors. New iterations of the devices and delivery systems are being tested with the intention of simplification of the technical aspects of the procedure. The need for customized devices results in a delay in treatment (as devices are manufactured and sterilized) and a potentially complicated paradigm for procedural planning and device sizing. Computerized sizing algorithms have been developed that, with minimal physician interaction, can generate device designs with an accuracy that appears to parallel that of experienced clinicians. We are hopeful that continued investigations by several groups will generate systems that can be readily disseminated and available for implantation without extensive delays. However, it remains clear that endovascular techniques parallel open thoracoabdominal aneurysm experiences in terms of the potential for encountering devastating complications (paraplegia) and the need for technical expertise.

Conclusions

New strategies to treat thoracoabdominal aneurysms are needed in an effort to minimize the morbidity and mortality of conventional open surgical procedures. Hybrid procedures, although readily available, may offer a benefit in a restricted patient population, yet the mortality rate remains high. Such procedures will ultimately be relegated to acute situations or used in the setting of very unusual circumstances, such as when both conventional open and branched endovascular repair are contraindicated. Branched grafts incorporating reinforced fenestrations, axial branches, or helical branches have all been employed with a high rate of technical success and encouraging short- and intermediate-term results. The durability of such devices remains suspect. Concerns about the strength of modular joints, mating devices that must traverse long segments of an aneurysm, and the potential to develop dilation or progressive disease at the proximal or distal sealing segment exist and may destabilize an endovascular repair. New concepts to address spinal cord perfusion, limiting the risk of renal deterioration and minimizing physiological stress during the endovascular procedure, need to be developed and employed. Despite these issues, the overall results of thoracoabdominal aneurysm repair with a totally endovascular approach, in patients unfit for open surgical treatment, provide an optimistic view of alternative management schemes for a disease whose treatment options have thwarted clinicians since the description of this disorder.

Disclosures

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References


