Hybrid Approaches to Thoracic Aortic Aneurysms
The Role of Endovascular Elephant Trunk Completion

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Background—Thoracic aortic aneurysm affecting the arch and proximal descending thoracic aorta requires 2-stage repairs that include proximal elephant trunk graft placement and completion of thoracic or thoracoabdominal repair. The application of endovascular grafting to complete the proximal procedure avoids a thoracotomy and may improve the morbidity and mortality of the patient population at risk.

Methods and Results—A retrospective review of 399 thoracic endovascular grafts at our institution between 2000 and 2004 identified 22 patients who required elephant trunk and endovascular completion. Three patients underwent mesenteric bypass in addition to their proximal repairs. Mean follow-up was 10 months (range 1 to 42 months); there were no ruptures, and all patients returned for follow-up. Technical success was achieved in all patients. The 1-, 12-, and 24-month mortality rates (by Kaplan-Meier analysis) were 4.5%, 15.8%, and 15.8%, respectively. Caudal migration of the endograft occurred in 1 patient, and all but 2 aneurysms decreased or remained stable in size. The 2 patients with growth included a type III endoleak (which resolved after treatment) and pressurization through an expanded PTFE stentgraft. Three cases of transient paraparesis occurred (all in patients requiring mesenteric bypass or abdominal aortic aneurysm repair), and there were no paraplegias or strokes.

Conclusions—Endovascular completion of elephant trunks is feasible and can be accomplished with minimal mortality. Meticulous imaging follow-up is required to detect persistent aneurysm pressurization and to verify the integrity of the repair. Improvements in implant design and delivery systems will further simplify the second-stage portion of these complex aneurysm repairs. (Circulation. 2005;112:2619-2626.)

Key Words: aneurysm □ aorta □ dissection □ stents □ grafting

Aortic aneurysms that conjointly affect the arch and more distal aorta continue to challenge physicians. Single-stage operations involve large incisions and substantial mortality risk. The 2-stage approach first requires a median sternotomy associated, then, under hypothermic circulatory arrest, placement of an elephant trunk graft with or without arch repair. The second-stage procedure (completion operation) requires a left thoracotomy or thoracoabdominal approach to extend the elephant trunk graft to the healthy distal aorta, with possible reimplantation of intercostal or visceral vessels. The morbidity and mortality risks associated with the 2-stage approach remain substantial and have been reported previously.1–3

Endovascular procedures have been widely used to treat infrarenal aneurysms and, more recently, thoracic aortic aneurysms. We have explored the use of these technologies to complete elephant trunk graft repairs and thus avoid the requisite thoracotomy or thoracoabdominal incision. However, limitations exist with respect to anatomy that is amenable to such treatments. Proximally, stentgrafts must oppose healthy aorta to achieve a seal (to prevent leakage alongside the device) and fixate (which prevents migration). Aneurysms that involve the arch or proximal descending thoracic aorta by definition lack the required healthy proximal tissue and thus preclude such an approach without occlusion of brachiocephalic vessels, the use of extra-anatomic bypass grafts, the use of branched endovascular devices, or performance of the endovascular procedure in combination with surgical modification of the proximal aorta to include elephant trunk graft placement with or without arch repair. These techniques obviate the need for an open surgical approach to the thoracoabdominal aorta and may drastically diminish the complication rate but have uncharted long-term results. The feasibility of this strategy and intermediate-term follow-up of these patients is the subject of this report.

Methods

Between January 2000 and December 2004, 399 patients underwent thoracic aortic endovascular grafting, 22 of whom underwent a hybrid approach involving proximal arch repair with elephant trunk graft placement in addition to an elephant trunk graft with or without arch repair.
Surgical Modification of the Distal Landing Site

Inadequacy of the distal landing site was defined as dilation or dissection of the visceral aortic segment. The involvement of the visceral vessels required further surgical measures to be accomplished before placement of an endovascular device. This included either use of a mesenteric bypass procedure or wrapping of the distal thoracic aorta. The former was accomplished after the proximal elephant trunk procedure but was staged with respect to implantation of the endovascular graft. Through a retroperitoneal incision limited to the abdominal cavity, visceral flow was reestablished with the infrarenal aorta or left common iliac artery as a source for inflow in conjunction with ligation of the native vasculature. Circumferential distal aortic wraps were performed at the time of elephant trunk graft placement (via a posterior pericardial approach), when mesenteric bypass was not feasible, with a polyester graft sutured anteriorly to create a distal seal in excess of 2 cm (Figure 2).

Endovascular Device Design

After surgical procedures were performed to address the proximal or distal landing sites, cross-sectional imaging studies were obtained, reconstructed, and reviewed on a 3D workstation (Leonardo, Siemens Medical, or Aquarius, Terarecon). Proximal elephant trunk graft diameters, distal aortic diameters, and length measurements were obtained with images orthogonal to a centerline of flow. Diameter discrepancies between the proximal and distal landing zones were commonly noted, given the fixed size of the elephant trunk or arch repair (generally a 24- to 26-mm graft, which dilated to 26 to 28 mm) in contrast to the distal aortic diameters (range 20 to 40 mm). In such cases, tapered devices were used, and when the desired aortic coverage exceeded 12 cm, 2 or more pieces (with ≥5 cm overlap) were used. The timing of the second-stage procedure was based on patient recovery from the first procedure and device availability.

Reverse Endovascular Elephant Trunk Procedure

In the absence of significant coronary artery disease and the presence of focal pathology limited to the inferior aspect of the aortic arch and proximal descending thoracic aorta, the stentgraft component was placed before the open portion of the repair. Electively, under hypothermic circulatory arrest, the proximal end of the endovascular...
A prosthesis was sutured to the aorta or used to construct the distal anastomosis for a more proximal arch repair.

Endovascular Device Implantation

Endovascular implants were placed under regional or general anesthesia in a dedicated interventional operative suite equipped with a floor-mounted imaging system (Siemens Medical). Cerebrospinal fluid drainage was used perioperatively and continued for 24 to 72 hours. Patients underwent anticoagulation with heparin (100 U/kg) with a target activated clotting time >300 seconds during the procedure. Devices were delivered through a femoral access site or, when necessary, via a conduit sewn to the common iliac artery. Right brachial access was obtained at the onset of the procedure, which allowed guidewires and catheters to be selectively directed through the elephant trunk and abdominal aorta and into the desired iliofemoral vessels in a retrograde manner. Through-and-through access, when established in this manner, helped to direct the delivery system through the inherent tortuosity of the arch and that induced by the elephant trunk graft (Figure 3). A minimum of 5 to 7 cm of overlap was intended when the endovascular grafts were placed into the elephant trunk grafts (Figure 3). Deployment was performed without modification of the patient’s heart rate or blood pressure when the Zenith system was used or by the induction of brief periods of bradycardia and hypotension when homemade systems or Talent or TAG devices were used. In cases in which the entire aorta was involved, the distal aspect of the tubular thoracic repair was either combined with a bifurcated component, which allowed extension into each of the iliac arteries, or a tapered device was used and brought into 1 of the iliac arteries followed by a femoral-femoral graft with occlusion of the contralateral iliac vessel with an endovascular plug.

Endovascular Definitions

Unless otherwise specified, the present results are reported in accordance with the most recent endovascular reporting standards.

Figure 3. Tortuosity of the proximal repair site was noted as a result of the inherent structure of the aneurysmal arch (A) or induced by the elephant trunk graft (B). The same patient depicted in Figure 3B (postoperative CT scan) is displayed in Figure 3B. Note the lengthening of the elephant trunk graft. This effect complicates analyses to assess the stability of the endograft position (migration) and underscores the importance of radiographic landmarks (Figure 1) on the elephant trunk at the time of surgical implantation. L indicates lateral.
The postoperative or discharge CT scan (or 30-day study if the discharge scan was not available) was used as a baseline for migration and aneurysm size change (using images perpendicular to the centerline of flow). All films were reviewed by at least 2 physicians, and discordant results were adjudicated by a third physician.

**Success**
Technical success was defined as the ability to deliver an endovascular graft into the elephant trunk, resulting in a patent aorta without any unintended occlusion of brachiocephalic or visceral branch vessels. Procedural success mandated technical success, required the absence of type I or III endoleak, and was determined at each follow-up visit.

**Migration**
Device migration was defined as cranial or caudal movement of the proximal or distal component of the device in excess of 5 mm with respect to a fixed landmark. The fixed landmarks included the left common carotid artery proximally and the celiac artery distally or the aortic bifurcation in the setting of a mesenteric bypass. All measurements were performed with centerline-of-flow analyses, which obviated the difficulties related to arch and elephant trunk graft tortuosity. Given the material properties of implanted prosthetic implants and the natural tendency for dilation or slight stretch (especially when crimped grafts are used), it is possible to note movement of the endograft with respect to the fixed anatomic landmarks that results in an erroneous conclusion (Figure 3B and 3C). Therefore, the length of the elephant trunk graft from the last patent arch vessel to the end of the graft (with the clips used as a reference when available) and the degree of stent-to-elephant-trunk-graft overlap was also measured.

**Results**
Between January 2000 and October 2004, of 399 thoracic endovascular repairs, 22 patients underwent combined endovascular and open repair of arch and descending thoracic aneurysms. Twenty patients had endovascular completion of proximal elephant trunk grafts. As a result of extensive distal aneurysmal disease, 3 of these patients required extra-anatomic visceral bypasses to allow for endovascular stent-graft coverage of the entire abdominal aorta, and possibly the iliac, vasculature. Two patients were treated with reverse endovascular elephant trunks. In 21 patients, the procedures were performed electively, and in 1 patient, who presented with an aortoesophageal fistula 8 years after elephant trunk graft placement, emergent treatment was performed outside of study protocols on a compassionate use basis. The interval between the first and second stages ranged from 3 days to 102 months (with a mean of 17.8 months); however, when this calculation was limited to patients who underwent the first stage of the repairs at our institution, the mean interval between procedures was 7 months. Follow-up ranged from 3 days to 102 months (with a mean of 10.2 months), and no patients were lost to follow-up. The average length of stay after the second-stage procedure was 9 days, and mean time spent in the intensive care unit was 3 days. Additional demographic, device, and procedural data are depicted in the Table.

**Adjunctive Procedures**
A number of strategies pertaining to the subclavian artery were used depending on the involvement of the subclavian artery in the aneurysm proper, the location of the elephant trunk graft (distal to the left subclavian artery or between the left carotid and subclavian arteries), the presence of coronary flow derived from internal mammary grafts, or the status of the vertebral arteries. Subclavian artery coverage was required in 9 patients (41%). In all of those patients, the elephant trunk had been placed between the subclavian and left common carotid artery. Extra-anatomic reconstruction (carotid subclavian bypass) was performed in 5 patients, before completion procedures. A single patient underwent a carotid subclavian bypass after endograft implantation as a result of a retrograde leakage through the subclavian artery and arm claudication. The remaining 3 patients had subclavian coverage without revascularization, although glue embolization of a single subclavian artery was required to treat a retrograde leak in 1 of these patients. Three patients required mesenteric bypass procedures before the second-stage elephant trunk graft. Iliac conduits were necessary in 4 patients (18%, all female) for device introduction, 2 of which were performed urgently after failed device introduction.

**Mortality**
No intra procedural deaths occurred. Overall Kaplan-Meier 1- and 12-month mortality rates were 4.5% and 15.8%, whereas

### Demographics, Comorbidities, and Details of the Proximal and Endovascular Procedures

| Details regarding proximal procedure, n (%) | CABG and elephant trunk | 3 (14) |
| Connective tissue disease, n (%) | 2 (9) |
| Pathology of aneurysmal dilation, n (%) | Nonspecific | 18 (82) |
| Proximal aortic dissection | 4 (18) |
| Endovascular devices used, n (%) | Zenith | 18 (82) |
| AVR and elephant trunk | 2 (9) |
| CABG, AVR, and elephant trunk | 4 (18) |
| Combination (Zenith, TAG) | 1 (4.5) |

AVR indicates aortic valve replacement. Severe chronic obstructive pulmonary disease was defined as an FEV1 (forced expiratory volume in 1 second) <1 L, and chronic renal insufficiency implies a baseline creatinine greater than 2 mg/dL.

*Two patients were diagnosed with connective tissue disorders, 1 with Marfan syndrome and 1 with Ehlers-Danlos syndrome.*
aneurysm-related mortality was 4.5%, 11.3%, and 11.3% at 1, 12, and 24 months, respectively (Figure 4). The only in-hospital death (or 30-day mortality) was the woman treated emergently for an aortoesophageal fistula. After endovascular completion of her elephant trunk graft, she had continued hemorrhage, refused open repair, and died 24 hours later. At autopsy, the endograft and elephant trunk were well apposed, and it appeared that the hemorrhage resulted from persistent intercostal flow into the esophageal defect. A second aneurysm-related death occurred 7 months after the endovascular completion. This patient presented with a proximal dissection and had Marfan syndrome and morbid obesity (weight 210 kg). A primary ascending repair had been performed at another institution. Continued arch growth, chronic renal insufficiency (creatinine 3.4 mg/dL), and postprandial pain resulted in his transfer to our institution. In the setting of a rapidly enlarging aortic arch, a repeat arch reconstruction was performed with placement of an elephant trunk graft. This was well tolerated and followed by a 3-vessel mesenteric bypass (excluding the right kidney, which was minimally functional). The aorta was then lined with a tapered stentgraft that terminated proximal to the mesenteric inflow within the left common iliac system. A femoral-femoral bypass graft in conjunction with surgical ligation of the right common iliac artery was performed. Over the ensuing 3 months, his aortic growth persisted, and a retrograde endoleak through a patent inferior mesenteric artery was treated with glue embolization. Two weeks later, his renal function deteriorated, and hemodialysis was initiated. A number of days later, during dialysis, he developed hypotension, followed by the rapid development of multisystem organ failure. Urgent angiographic evaluation of his aorta noted near arch occlusion at the site of the proximal elephant trunk anastomosis (Figure 5A). He died shortly thereafter, and these findings were confirmed at autopsy. The final death in the present series of patients was unrelated to the aneurysm and was attributed to an intracranial malignancy.

Technical success was ultimately achieved in all patients. In 2 patients, modification of the endovascular plan was required. Inability to advance the delivery sheath of a home-made device into the aortic arch resulted in delivery failure; however, 3 days later, a commercially manufactured prosthesis (TAG, WL Gore) was successfully placed into the elephant trunk graft. Extreme arch tortuosity resulted in the inability to deliver a second device (Zenith), but during the same procedure, a TAG device was deployed successfully. In the latter case, the disparate proximal and distal diameters required the use of a Zenith graft distally, which
resulted in a composite prosthesis. Procedural success was 90% at 1 and 12 months.

**Endoleaks**

Endoleaks (perigraft flow) were noted in 7 of the 22 patients. Type II endoleaks (in the setting of an adequate seal at the proximal and distal aspect of the repair) were the most common (5 of the 7 cases), but there was 1 type III leak (from a modular joint, previously discussed) and a single leak of unknown origin. Retrograde flow from a patent subclavian artery (1 patient) and a patent inferior mesenteric artery in 1 patient treated with a mesenteric bypass and elephant trunk completion accounted for 2 of the 5 type II leaks. Persistent intercostal flow was noted in the remaining 3 cases, none of which have required treatment or resulted in aneurysmal growth. Secondary interventions were performed (extension grafts) to treat all type I or III leaks.

**Migration**

Four patients had >5 mm of stent movement based on centerline-of-flow analyses. As mentioned previously, this method of analysis used static points in the native aorta as fixed landmarks, whereby migration was defined as movement of the device relative to one of the landmarks. However, most elephant trunks had a component of tortuosity and crimping from the polyester, which, after placement of the endovascular graft, lengthened to a certain extent (Figure 3). In this circumstance, it is unlikely that migration of the device occurred with respect to the proximal fixation system; it more likely represented stretching of the implanted fabric. When specifically evaluated with respect to movement or the proximal fixation system (elephant trunk graft to stentgraft overlap) or the distal fixation system (celiac artery or aortic bifurcation after mesenteric bypass), 2 patients had evidence of migration. One patient implanted with a TAG device had 23 mm of caudal movement of the proximal fixation system. One patient, implanted with a Zenith device, was noted to have cranial migration (7 mm) of the distal fixation system that occurred immediately after a reverse elephant trunk procedure and was attributed to traction during the procedure.

**Sac Morphology**

Aneurysm size was assessed annually. Growth was noted in 2 patients (9%) at 12 months. An endoleak (treated with an extension graft when growth was noted) and seroma development through an expanded PTFE graft (TAG prosthesis) were the ascribed causes of growth. The latter patient developed increasing respiratory distress and was noted to have severely compressed left pulmonary vasculature due to the enlarging aneurysm sac (Figure 5B). He has refused further intervention. Sac shrinkage of more than 5 mm was noted in 7 of 22 patients by the 12-month follow-up visit.

**Neurological Events**

No paraplegia or strokes occurred. Three patients experienced transient postoperative neurological events (13.6%) attributed to spinal cord perfusion. All but 1 of the patients recovered and were ambulatory before hospital discharge. The single patient with a more significant deficit ultimately recovered but required prolonged rehabilitation before returning home. All of the patients exhibiting transient defects had mesenteric bypass procedures in addition to their elephant trunks (2 patients) or prior abdominal aortic aneurysm repair (1 patient). No strokes occurred in the present series of patients.

**Discussion**

Despite consistent improvement in perioperative strategies used for open 2-stage procedures to address arch and proximal descending thoracic aortic aneurysms, there is still substantial morbidity and mortality associated with this approach.1,3,9,10 Mortality rates of 5.1% for the first-stage operation, 3.6% during the interval period (of which 75% were due to rupture), and 6.2% for the second-stage operation were reported by Safi and colleagues3 and recently updated1 and confirmed by others.12 In our own series of 142 elephant trunks, the first-stage operative mortality rate was 2%, and of those patients who underwent the distal repair, a 4% mortality rate was noted.9 Endovascular therapy avoids a left lateral thoracotomy. Stenting of the aorta as a completion of arch repair has been reported with a variety of techniques9,13–18; however, in some series, up to 25% of the patients have become paralyzed. The present series represents the largest number of endovascular completions to date and also provides intermediate-term follow-up. We noted that the mortality surrounding the endovascular procedure was exceptionally low and, coupled with a low rate of neurological complications or other serious adverse events, that endovascular completion of arch and elephant trunk repairs can be performed safely.

Significant procedural evolution occurred during the present series. Initiating the procedure from the right brachial artery eliminated the potentially challenging retrograde elephant trunk cannulation and provided a means to achieve wire access into the desired femoral or iliac vessel if necessary. Modifications to the proximal implant included the use of hemoclips, and a pacer wire loop also proved useful during the endovascular procedure and for visualization of the terminal end of the elephant trunk graft on follow-up imaging studies (Figure 1).9 The importance of flexibility, fixation, and sealing is magnified when dealing with such complex anatomy. Delivery failure with homemade devices resulted in preferential use of commercially manufactured endografts. The TAG device was the most deliverable and resulted in successful deployments where other grafts failed. However, the absence of an active fixation system with TAG may be associated with a higher incidence of migration (the only caudal migration of the proximal stent in the present series). Given the complex aortic morphology, it was beneficial to have access to tapered prostheses, which allowed us to accommodate patients with disparate proximal and distal diameters.

Complications relating to the composite result (elephant trunk graft and endovascular prosthesis) were noted. The first occurred in the complex patient with a proximal dissection described earlier. Progressive thrombosis of the proximal elephant trunk anastomosis after marked hypotension associated with hemodialysis resulted in his death (Figure 5A). The potential cause of this problem may relate to the undersized
anastomosed to normal arch tissue. Although no permanent complication and possibly less durable. We recommend a total elephant trunk graft length of 10 to 15 cm and that it be made the endovascular portion of the repair much more desirable than risking growth within the thorax, without treatment. A stable or shrinking aneurysm sac appears more desirable than risking growth within the thorax, where the relatively high-pressure aortic system is in close proximity with the lower-pressure pulmonary vasculature. In 1 case, a growing sac has resulted in clinical complications as a result of pulmonary vascular compression (Figure 5B). The length of the elephant trunk graft is intended to provide a region of adequate overlap (a minimum of 5 cm; Figure 6) for stentgraft insertion. However, excessive length of the elephant trunk graft or marked arch tortuosity (Figure 3) can make the endovascular portion of the repair much more complicated and possibly less durable. We recommend a total elephant trunk graft length of 10 to 15 cm² and that it be anastomosed to normal arch tissue. Although no permanent paraplegia occurred in the present study, the use of this technique must be contrasted with an open surgical approach in which the potential to reimplant intercostals exists. However, the absence of intraprocedural hypotension and lower risk of bleeding may offset the risk of paraplegia. As we gained experience with the endovascular portion of the repair, feedback between the physicians resulted in evolution and modifications of both portions of the aortic repair.

The mean interval between the 2 stages was 18 months. However, when limited to patients who underwent both stages at our institution, the mean interval was 7 months. This is commensurate with the open second-stage data from our institution and from others. The fact that a significant number of referrals came from outside our institution precludes accurate knowledge of the number of elephant trunks performed before endovascular repair and the possible ruptures that may have occurred during the interval between procedures. However, attention was directed at minimizing the delay between operative stages and improved over the course of the study. Our initial experiences were limited to patients who did not recover sufficient pulmonary reserve over a period of recuperation after the first-stage procedure. Further delays arose from the absence of clinical trials allowing treatment of such cases and device customization in the setting of proximal and distal diameter discrepancies. Obviously, delaying the second-stage procedure will increase the risk of rupture, and thus, all efforts should be made to streamline the recovery from the first stage and complete the second stage expeditiously.

Thoracic endovascular aneurysm repair has been associated with a risk of stroke, particularly for aortic arch aneurysms, and paraplegia (dependent on the length of thoracic aorta covered and prior aortic repairs). Overall, the elephant trunk graft dimensions were consistent with other published series, whereas the length of the distal repair was based on the distal extent of aortic disease. Both Usui et al and Mizuno et al reported paraplegia (2 cases) and stroke (1 case) after similar types of repairs. The lack of paraplegia or stroke in the present series provides us with some optimism, yet the 3 cases of paraparesis caused us concern, particularly in the setting of extensive aortic coverage (none occurred in patients without mesenteric bypass or prior aortic repair).

Device migration is likely to be a major issue with thoracic endografts during the long-term follow-up period. Migration was uniformly assessed with a 3D workstation (Terarecon) with centerline algorithms applied. Measurement of endovascular prosthesis position from a fixed anatomic landmark (the left common carotid artery or the celiac artery), in addition to the amount of overlap with the elephant trunk proper, was performed at each follow-up interval. The magnitude of aortic forces in the proximal aorta, inherent tortuosity, and cross-sectional area alterations all predispose to displacement forces in excess of infrarenal device counterparts. Although migration was not observed frequently in the present series, the follow-up was relatively short term, and the majority of devices used had active fixation systems (barbs). Interestingly, only 1 patient was noted to have distal migration in excess of 5 mm (23 mm of distal movement); this occurred in a patient with a device without any active fixation (TAG). Several observations of elephant trunk elongation were noted.
Polyester has a known tendency to elongate with time, and in the majority of cases, the stentgrafts were not placed with the elephant trunk grafts under tension. A total of 6 patients (27.2%) had >5% increase in the length of their elephant trunk without a change in the amount of stentgraft to elephant trunk overlap segment. This implies that migration of endovascular implants when mated with a surgical graft must be assessed with respect to the overlap length between the elephant trunk graft and the endovascular prosthesis rather than with conventional methods of migration analyses.11,23

Completion elephant trunk procedure, whether open or endovascular, remains a challenge both for the patient and for the surgeon. Staged procedures using endovascular grafting to treat the descending thoracic aorta have the potential to ameliorate some of the major morbidity and mortality associated with conventional techniques. Planning of the open surgical procedure, endovascular device design, and the timing of the repairs must be coordinated by the physician team. Adequate fixation, prosthesis and delivery system flexibility, and durable aneurysm exclusion are the hallmarks of acceptable endovascular devices. Although long-term results are still pending, this early experience demonstrated the safety and intermediate-term effectiveness of a hybrid endovascular–open surgical approach.

Disclosure
Dr Greenberg receives or has received research funding from Sulzer-Vascutek and WL Gore and receives royalties for patents licensed to Cook Incorporated. Dr Lyden has received modest honoraria from Cook Inc and Medtronic. Dr Lytle owns stock in Johnson and Johnson, which makes coronary but not vascular stents.

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