Use of custom Dacron branch grafts for "hybrid" aortic debranching during endovascular repair of thoracic and thoracoabdominal aortic aneurysms

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Supplemental material is available online.

Objectives: A significant number of patients with thoracic and thoracoabdominal aortic aneurysms are unsuitable for endovascular repair owing to the absence of graft seal zones. "Hybrid" techniques, including open aortic debranching procedures, allow creation of proximal and/or distal landing zones and expand the potential applications of endovascular repair. We report our experience with aortic arch and thoracoabdominal debranching using custom fabricated Dacron branch grafts, which greatly simplify aortic debranching by providing inflow via a single anastomosis and incorporate a side arm for introduction of the stent graft.

Methods: Between November 14, 2005, and December 18, 2006, a total of 53 thoracic endograft procedures were performed at our institution. Of these, 13 (25%) involved either open aortic arch or abdominal debranching to create proximal or distal landing zones for endovascular repair. Patients undergoing arch debranching ($n = 7$) had aneurysms involving the transverse arch with less than 2 cm of proximal landing zone distal to the innominate artery, necessitating stent graft coverage of both the innominate and left common carotid arteries. Patients undergoing complete abdominal debranching ($n = 6$) had either thoracoabdominal aortic aneurysms (extent II, $n = 1$; extent V, $n = 3$) or visceral button false aneurysms after prior open thoracoabdominal aortic aneurysm repair ($n = 2$). In all cases, endovascular aneurysm exclusion was performed at the same operation.

Results: Mean patient age was 63 ± 11 years (range 46-83 years); all patients had significant comorbidities, including prior open aortic surgery in 8 (62%). There were no perioperative (30 day) deaths and no permanent neurologic deficits, either cerebrovascular accident or paraparesis/paraplegia. At a mean follow-up of 7.5 ± 6.0 months, there has been no late mortality and all debranching bypass grafts remain patent without need for further intervention. Computed tomographic scans demonstrate no type I or III endoleaks, and all aneurysms are thrombosed with stable ($n = 4$) or decreasing aortic dimensions ($n = 9$).

Conclusions: "Hybrid" aortic debranching using custom fabricated Dacron branch grafts with a single inflow source combined with endovascular aneurysm exclusion appears to be a safe alternative to conventional open repair for thoracoabdominal and arch aneurysms and avoids the need for cardiopulmonary bypass and aortic cross-clamping. This technique may be ideally suited to patients with significant comorbidity or prior open aortic surgery. Longer term follow-up is needed to determine the durability of this approach.

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Abbreviations and Acronyms

CCA	= common carotid artery
CPB	= cardiopulmonary bypass
CT	= computed tomography
EEG	= electroencephalogram
TAAA	= thoracoabdominal aortic aneurysm

Endovascular repair of thoracic aortic disease is emerging as the preferred treatment strategy in a majority of patients, inasmuch as increasing data suggest that endovascular repair may be performed with lower perioperative morbidity and mortality rates, with similar midterm survival, as compared with standard open aortic repair.^{1,2} However, anatomic requirements for the only thoracic endograft commercially available in the United States (Gore TAG; W. L. Gore & Associates, Inc, Flagstaff, Ariz) and approved by the Food and Drug Administration include 20 mm or more of suitable proximal and distal neck length with proximal and distal neck diameters of 23 to 37 mm. Because of these anatomic constraints, a significant number of patients, many of whom are not ideal candidates for open surgery, are excluded from standard endovascular repair.³

Consequently, in an attempt to expand the pool of patients suitable for endovascular repair, “hybrid” techniques, including open aortic arch and thoracoabdominal debranching procedures, have been described⁴⁻⁶ to allow creation of proximal and/or distal landing zones for stent graft seal. Owing to our satisfaction with the early results of thoracic endovascular aortic repair in our own patient population, we have recently expanded the use of this technique to selected patients with aortic arch and thoracoabdominal aortic aneurysms (TAAA) who were believed to be suboptimal candidates for conventional open repair. This has generally included patients with advanced age, prior aortic surgery, or multiple comorbidities. In the current report, we describe our experience with aortic arch and thoracoabdominal debranching using custom fabricated Dacron branch grafts, which greatly simplify aortic debranching by providing inflow via a single anastomosis and incorporate a side arm for introduction of the stent graft.

Materials and Methods

Between November 14, 2005, and December 18, 2006, a total of 53 thoracic endograft procedures were performed at our institution. Of these, 13 (25%) involved either open aortic arch or abdominal debranching to create proximal or distal landing zones for endovascular repair (Table E1). Indications for surgery included either saccular or fusiform aneurysm (n = 11) or false aneurysm after prior aortic surgery (n = 2). Criteria for repair included symptoms, rapid enlargement (>5 mm in 12 months), or absolute size. For fusiform aneurysms, this generally included a diameter of 6 cm or more, whereas for saccular aneurysms a protrusion of 2 cm or more beyond the aortic wall for the saccular component was considered an indica-

tion for treatment in the absence of symptoms.^{6A} Patients undergoing arch debranching (n = 7) had aneurysms involving the transverse arch with less than 2 cm of proximal landing zone distal to the innominate artery, necessitating stent graft coverage of both the innominate and left common carotid arteries (CCAs) (Figure 1, A). Arch debranching was performed without cardiopulmonary bypass (CPB) via a median sternotomy with extension of the incision along the anterior border of the left sternocleidomastoid muscle. The procedure involves creating inflow from the proximal ascending aorta using trifurcated grafts (Vascutek USA, Ann Arbor, Mich) originally designed for head vessel reimplantation during open total arch replacement (Figure E1) or with a new “hybrid antegrade graft” (Vascutek USA) (Figure E2) designed to debranch the innominate artery and left CCA with concomitant antegrade stent graft insertion across the aortic arch without the need for femoral exposure (Figure 2). In either case, the proximal anastomosis to the proximal ascending aorta is performed first by a partial occlusion clamp technique (Figure E1, A) after administration of 100 U/kg intravenous heparin to a goal activated clotting time of 250 seconds or more. After completion of this anastomosis, the left CCA is dissected free above its origin from the aortic arch. Care is taken not to manipulate the proximal portion of the artery before clamp placement to minimize the potential for cerebral embolization. A 5-minute test occlusion of the carotid is then carried out with intraoperative electroencephalogram (EEG) monitoring to ensure adequate perfusion of the left side of the brain despite proximal left CCA clamping. In the event of focal EEG slowing indicative of cerebral ischemia, blood pressure augmentation is performed and the test clamp repeated. No patient in this series demonstrated EEG changes that persisted after blood pressure augmentation. Although not required in this series, potential alternatives in the setting of EEG changes unresponsive to blood pressure augmentation include the use of a shunt from the ascending aortic debranching graft to the arch vessel or the use of CPB with mild hypothermia to prolong the tolerable period of arch vessel clamping.

After successful test occlusion, the carotid is reclamped and divided. End-to-end anastomosis of the first side branch to the left CCA is then carried out with running 5-0 monofilament suture and the carotid reperfused after careful deairing. The proximal stump of the left CCA is then oversewn. The same procedure is then followed for the innominate artery. The left subclavian artery was not debranched but simply covered in all patients in this series. Prior work has demonstrated the safety of left subclavian coverage in selected patients⁷; adequacy of contralateral vertebral flow was confirmed preoperatively in all patients with ultrasonography as well as computed tomographic (CT) imaging. In addition, all patients having arch debranching undergo preoperative transthoracic echocardiography and coronary angiography to rule out significant valvular or coronary artery disease, which should be addressed surgically at the time of the procedure.

Patients undergoing complete abdominal debranching (n = 6) had either TAAAs (extent II, n = 1; extent V, n = 3) (Figure 3) or visceral button false aneurysms after prior open TAAA repair (n = 2) (Figure E3). Given the low rate of spinal cord complications with endovascular repair,^{1,2,5,6} the presence or absence of patent intercostals did not factor into the decision for conventional open versus hybrid TAAA repair. All patients underwent midline laparotomy to allow full access to the celiac axis, superior mesenteric

Figure 1. A. Preoperative 3-dimensional CT scan reconstruction of a large transverse arch aneurysm. Note adequate proximal landing zone in ascending aorta and distal landing zone in descending thoracic aorta. **B.** One-month postoperative CT scan from the same patient demonstrating arch debranching graft extending from proximal ascending aorta to left common carotid and innominate arteries. Two stent grafts have been placed, which cover the ostia of the innominate, left common carotid, and left subclavian arteries.

artery, both renal arteries, as well as the ilia. Cerebrospinal fluid drains as well as lumbar epidural catheters were placed preoperatively in all patients having abdominal debranching for spinal cord protection and postoperative analgesia, respectively. Mobilization of the left colon and takedown of the splenic flexure allows exposure of the left renal and superior mesenteric arteries at their origins from the aorta. Splenectomy (required in $n = 3$) may facilitate this exposure, although we do not advocate its routine performance. The celiac axis is isolated at its origin from the aorta in the lesser sac above the pancreas. The hepatic flexure of the colon is taken down and a limited Kocher maneuver performed. This allows isolation of the right renal artery where it emerges beneath the inferior vena cava. After completion of vessel exposure at their origins from the aorta, systemic heparin at a dose of 100 U/kg was administered to a goal activated clotting time of 250 or more. Inflow was via a single proximal anastomosis from the left iliac system ($n = 5$) or infrarenal aorta ($n = 1$); the latter patient (patient 2) was status-post prior extent II TAAA repair and had an 8.7-cm visceral button false aneurysm (Figure E3, A). Because her aortic bifurcation and bilateral common iliac arteries below her prior TAAA graft were aneurysmal as well, her distal aorta and common ilia were replaced with a bifurcated Dacron graft. The mesenteric debranching graft was then anastomosed end to side to this new aortic graft (Figure E3, B).

The mesenteric and renal debranching procedures were performed in all cases by either trifurcated (Figure 4, A) or 4-vessel branch grafts (Figure 4, B) (Vascutek USA) with distal anastomoses to the left renal artery, superior mesenteric artery, celiac axis, and right renal artery. These specialty multibranch grafts consist of a 14-mm main body with either 10-mm or 8-mm side branches. The proximal end of the 14-mm main body was anastomosed end to side with 4-0 monofilament suture to the left iliac artery or an infrarenal aortic graft to provide inflow for the mesenteric and renal arteries. The distal anastomoses were generally performed in an end-to-end manner, with the proximal vessels being divided and oversewn at their origins from the aorta to prevent retrograde type II endoleak (Figure 4); occasionally, the celiac axis was sewn end to side to the terminal limb of the debranching Dacron graft (Figures 3, 4, A, and E4). A 10-mm side limb attached to the proximal end of the mesenteric debranching graft just above the inflow anastomosis allowed for antegrade stent graft deployment without the need for additional groin or iliac exposure. The debranching graft was generally covered with omentum, if available, at the completion of the procedure.

In all cases, endovascular aneurysm exclusion was performed at the same operation with the Gore TAG device (W. L. Gore & Associates, Inc). This device consists of a self-expanding unibody graft

Figure 2. A. Intraoperative marker arteriogram demonstrating large aortic arch aneurysm and completed proximal ascending aorta to left common carotid and innominate artery bypass. The stent graft introducer sheath has been advanced antegradely into the ascending aorta over a stiff guidewire via the proximal antegrade limb of the arch debranching graft. **B.** Completion arteriogram after stent graft deployment demonstrating complete exclusion of the aneurysm sac by the stent grafts with no endoleak; arch debranching graft is widely patent.

Figure 3. One-month postoperative 3-dimensional reconstruction CT scan of a hybrid stented extent II TAAA repair in an 83-year-old woman. Note trifurcated bypass graft extending from left common iliac artery to the mesenteric and renal vessels (A) combined with endovascular aneurysm exclusion via stent grafts extending from the left subclavian artery to just above the aortic bifurcation (B).

with a nitinol frame and expanded polytetrafluoroethylene fabric. Device fixation is achieved with balloon expansion after endograft deployment. An adequate landing zone was defined as a 20-mm length or more of suitable aorta or pre-existing Dacron graft with diameters of 23 to 37 mm, in accordance with device instructions for use. As mentioned, antegrade stent graft deployment via a 10-mm Dacron side arm has become our preferred technique inasmuch as it avoids the need for additional femoral or iliac exposure. Generally, this involves introduction of an appropriately sized Gore introducer sheath (20F-24F) through the side arm, either antegradely into the ascending aorta for arch debranching (Figures 5 and E5) or retrogradely into the infrarenal aorta for visceral debranching procedures. This strategy allows rapid deployment of the endograft after great vessel or visceral revascularization and adds only a short time to the operative procedure. We strongly prefer completing the operation in a single setting rather than staged endograft deployment during a delayed subsequent procedure as described by others.⁸ On-line monitoring of spinal cord function with somatosensory and motor evoked potentials was used in all patients in this series according to previously described techniques.⁹

Comorbidities were defined according to standard definitions. All procedural outcomes and complications were prospectively recorded. Patient follow-up included clinical examination and CT imaging at 1 month, 6 months, and 12 months postoperatively and annually thereafter. All data are presented in accordance with the "Reporting Standards for Endovascular Aortic Aneurysm Repair" of the Ad Hoc Committee for Standardized Reporting Practices in Vascular Surgery of The Society for Vascular Surgery/American Association for Vascular Surgery.¹⁰ The study was approved by the Duke Institutional Review Board and informed consent was obtained from all patients.

Results

Patient Demographics

Patient demographics are presented in Table E1. Mean patient age was 63 ± 11 years (range 46-83 years); all patients had significant comorbidities, including prior open aortic surgery in 8 (62%), and were at high risk for conventional open repair. Aneurysms were degenerative in 11 patients and anas-

tomotic false aneurysms after prior aortic surgery in 2. The latter were both visceral button false aneurysms after TAAA repair 6 months (patient 10) and 6 years (patient 2) earlier. Of the 11 degenerative aneurysms, 1 (patient 1) distal arch aneurysm was due to chronic type B dissection in a patient who originally underwent emergency thoracic endografting for relief of mesenteric malperfusion resulting from an acute type B dissection several months earlier. In follow-up, a large (7.8 cm) aneurysm of the distal arch/proximal descending thoracic aorta developed. Additional proximal endovascular cuff placement to the level of the left CCA failed to obtain a proximal seal and thus an arch debranching procedure was subsequently performed with further proximal endovascular extension into the ascending aorta. Another transverse arch aneurysm (patient 3) was due to chronic residual type A dissection after prior ascending aortic replacement 9 years earlier.

Maximum aneurysm diameter averaged 6.5 cm (range 4.0-8.7 cm). Ten (77%) of the patients were symptomatic with pain symptoms. Thirty-one percent (4/13) of the cases were urgent ($n = 2$) (aneurysm repaired during the same hospital admission as it was discovered) or emergency ($n = 2$) (aneurysm repaired within 24 hours of admission); the latter cases were performed on an emergency basis for dynamic mesenteric and renal malperfusion owing to acute type B dissection into an existing 7-cm extent V TAAA (patient 6) and for severe abdominal and back pain with impending rupture of a 7.4-cm visceral button false aneurysm after open TAAA repair at another institution 6 months previously (patient 10). All patients were in hemodynamically stable condition without frank rupture at the time of surgery.

Thirty-day Outcomes

Technical success, defined as aortic debranching combined with successful endograft deployment with secure proximal and distal fixation,¹⁰ was achieved in all cases. One patient

Figure 4. Hybrid stented TAAA repair. A, A trifurcated Dacron graft is used to bypass the left renal, superior mesenteric, and right renal arteries end to end. The celiac axis is anastomosed end to side to the distal main body portion of the graft. All aortic side branches are sequentially ligated at their origins (to prevent type II endoleak) and divided just prior to anastomosis to the debranching graft. Thoracic endografts are then deployed to exclude the TAAA, in the process covering the origins of the mesenteric and renal arteries. **B,** A 4-branch Dacron graft is used to bypass the left renal, superior mesenteric, celiac, and right renal arteries, all in an end-to-end fashion. As in A, all aortic side branches are sequentially ligated at their origins to prevent type II endoleak and divided with subsequent anastomosis to the branches of the Dacron graft. Endovascular aneurysm exclusion is performed during the same operation, immediately after completion of the debranching procedure.

(patient 3), status-post prior supracoronary ascending aortic Dacron graft replacement for repair of an acute type A dissection 9 years earlier, required institution of CPB during arch debranching to repair a main pulmonary artery injury; in addition, CPB with the heart decompressed greatly facilitated dissection of the ascending graft for creation of the proximal anastomosis of the arch debranching graft. Another patient (patient 4) underwent concomitant on-pump coronary artery bypass grafting immediately before arch debranching for

Figure 5. A, Drawing demonstrating stent graft being introduced antegradely across the aortic arch via the proximal antegrade limb of the debranching graft. **B,** After the stent graft is deployed in position, the proximal antegrade Dacron limb is oversewn and divided.

a significant left main coronary stenosis discovered on preoperative coronary angiography.

In-hospital/30-day mortality rate was 0%. In addition, there were no permanent neurologic deficits, either cerebrovascular accident or paraparesis/paraplegia. One patient with an extent II TAAA (patient 8) undergoing complete mesenteric and renal debranching with endovascular stent grafting from the left subclavian artery to the aortic bifurcation had bilateral lower extremity weakness on postoperative day 1 after “capping” of the cerebrospinal fluid drain; this resolved completely with blood pressure augmentation and additional cerebrospinal fluid drainage to a pressure less than 10 mm Hg. No patient had new acute renal failure necessitating hemodialysis. The obligatory period of renal ischemia inherent in the hybrid TAAA procedure during renal debranching is short, typically 8 to 12 minutes, owing to serial revascularization of individual vessels with end-to-end anastomosis. One patient with preoperative acute renal failure resulting from dynamic renal malperfusion from an acute type B dissection extending into an existing extent V TAAA (patient 6) did not recover renal function postoperatively despite technically successful renal revascularization. Major complications¹⁰ were seen in 2 (15%) patients: symptomatic left hand ischemia resulting from left subclavian artery coverage by the stent graft and requiring left carotid-subclavian bypass on postoperative day 2 (patient 11) and hospital-acquired pneumonia requiring intravenous antibiotics as well as upper gastrointestinal bleeding requiring therapeutic endoscopy

and blood transfusion (patient 7). Median hospital length of stay was 9 ± 7 days. Overall, 11 (85%) of 13 patients were discharged home. Both patients (patients 6 and 10) discharged to an acute rehabilitation facility required emergency surgery and were in renal failure preoperatively.

Follow-up Outcomes

No patient was lost to follow-up. Clinical success, defined as absence of death as a result of aneurysm-related treatment, type I or III endoleak, graft infection or thrombosis, aneurysm expansion or rupture, or conversion to open repair,¹⁰ was 100% at a mean follow-up of 7.5 ± 6.0 months (range 1-18 months). One patient (patient 1) had a late (18 months) type II endoleak with retrograde filling of the aneurysm sac from the left subclavian artery, which was successfully treated with coil embolization. This is the only patient to require secondary surgical or endovascular intervention to date. Aneurysm diameter has remained stable in 4 and decreased by 5 mm or more in 9, although aneurysm shrinkage has been seen in all patients with a follow-up of 6 months or more.

Discussion

Thoracic endovascular aneurysm repair is a relatively new approach to the treatment of thoracic aortic disease. It is gaining in popularity owing to low perioperative morbidity and mortality rates as well as promising early and midterm follow-up results.^{1,2} Application of this technology has generally been limited to disease of the intrathoracic aorta, inasmuch as anatomic requirements for proximal and distal seal zones preclude the repair of arch aneurysms or TAAAs.³ Although branched and fenestrated endografts are currently being used in investigational protocols to treat aortic arch and thoracoabdominal disease,^{11,12} even proponents of these complex endovascular techniques admit that these procedures are unlikely to be adopted by the average center in the near future.¹² Consequently, recent reports⁴⁻⁶ have described the use of a combined endovascular and open surgical approach to the treatment of both transverse arch aneurysms and TAAAs with the hope that these “hybrid” techniques might lower perioperative morbidity and mortality rates for patients who are suboptimal candidates for conventional open repair.

The current report describes our experience with aortic arch and thoracoabdominal debranching procedures in a group of patients deemed suboptimal candidates for conventional open repair owing to significant comorbidities such as chronic obstructive pulmonary disease, renal disease, or prior open aortic surgery. Short-term results in these high-risk patients were very acceptable with no perioperative deaths, strokes, or permanent spinal cord ischemic events and a 15% rate of major morbidity. This report differs from prior reports,⁴⁻⁶ which have tended to use multiple bypass grafts with multiple inflow sources, a technique that necessar-

ily complicates the debranching procedure. Although our technique with a single inflow source theoretically places “all of one’s eggs in one basket,” since multiple vascular beds are fed via a single graft, no graft occlusions were noted in follow-up. In addition, because the single graft feeds multiple vascular beds, total graft flow should be greater, which may further improve long-term patency. Of note, Zhou and associates⁶ described a 6.4% rate of perioperative renal bypass thrombosis in their series in which multiple grafts were used for abdominal debranching.

Open repair of aneurysms of the aortic arch with CPB and deep hypothermic circulatory arrest, although now performed routinely and safely in centers with expertise, still carries a perioperative death or stroke rate approaching 15% for total arch replacement, even in expert hands.¹³ Likewise, TAAAs remain a formidable surgical challenge with data from a national United States database suggesting a mortality rate of 20% and a complication rate of over 60% for conventional open TAAA repair in low-volume centers.¹⁴ In addition, of those patients surviving surgery, more than 20% were discharged to another institution because they were not ready for discharge home. Although results in expert centers are clearly superior to these data with regard to open TAAA repair,¹⁵ room for improvement certainly exists. Consequently, the availability of a “hybrid” option for high-risk patients may allow surgeons to be more selective with regard to patient selection for standard open surgery, which should lead to improved results. In addition, the “hybrid” option may have advantages in these high-risk patients, including the potential to offer therapy to patients who are not candidates for conventional open repair.

Our current indications for a hybrid debranching procedure combined with endovascular aneurysm exclusion include patients with significant comorbidities who have degenerative aneurysms of either the aortic arch or thoracoabdominal aorta. Although 1 patient in this series had the Marfan syndrome, we do not advocate endovascular repair for this patient population except for instances, such as in our patient, in which the endovascular stent graft seal zones are completely within an existing Dacron graft. In addition, the avoidance of redo thoracoabdominal exposure, CPB, and aortic crossclamping would appear to make complete abdominal debranching combined with endovascular false aneurysm exclusion an attractive solution to the not infrequent problem of visceral button false aneurysm after prior open TAAA repair. This is especially true given the significant morbidity and mortality associated with open repair of this complication.¹⁶ Chronic obstructive pulmonary disease has been identified as a risk factor for adverse outcome with both open aortic arch¹³ and TAAA repair.¹⁷ In the present series, 11 (85%) of 13 patients had significant chronic obstructive pulmonary disease, yet the incidence of pulmonary morbidity was quite low, with only 1 patient having a perioperative pneumonia requiring intravenous antibiotic therapy

and no instances of prolonged mechanical ventilation or tracheostomy. Thus, these patients would also seem to be good candidates for a hybrid approach when feasible.

In summary, “hybrid” aortic debranching with custom fabricated Dacron branch grafts with a single inflow source combined with endovascular aneurysm exclusion, a technique that avoids the need for CPB and aortic crossclamping, appears to be a safe alternative to conventional open repair for thoracoabdominal and aortic arch aneurysms. This technique may be ideally suited to patients with significant comorbidity or prior open aortic surgery. Longer term follow-up is needed to determine the durability of this approach.¹⁸ However, given that the long-term survival of patients undergoing repair of degenerative thoracic and thoracoabdominal aneurysms is limited (eg, approximately 30% survival at 10 years after open TAAA repair,^{19,20} this latter concern is unlikely to be an issue in the majority of these patients.

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Discussion

Dr D. Craig Miller (Stanford, Calif). I would like to welcome Chad Hughes to the Western Thoracic. If you keep doing this for 15 years in a row, like Walter Wolfe, we will make you an honorary member. It is nice to see the work from Duke come out west.

I want to compliment you for doing it right. You have a combined cardiothoracic and vascular surgical team in which the cardiothoracic surgeon is involved at the first step, the decision-making step, should anything be done regardless of whether it is endovascular or open. That is crucial, and I think that is the paramount difference between the indications we have seen today, which none of us would disagree with, and those we saw yesterday, in which a peripheral vascular surgeon is making that decision in a vacuum and perhaps patients are not being well served. You have done it right, and your results, albeit short term and small in number, are absolutely spectacular given the protoplasm you were dealing with.

My only question involves the grafts. They were Vascutek grafts, and I am still unclear whether they were custom fabricated for you or whether you made them at the back table, which is what we do. I would hope, since many of them are long tortuous small-caliber small-flow grafts, that these were Gelsoft or knitted grafts and not Gelweave or a woven graft or the Microvel Double Velour Hemashield (Boston Scientific Corporation, Natick, Mass)-knitted compared with the woven grafts we have all learned that with low flow, a knitted graft probably is going to have better patency.

Dr Hughes. Dr Miller, thank you very much for your comments. I hope we can get papers on the program 15 years in a row and get out here like Dr Wolfe.

I agree 100% with your first comment regarding the team approach. I think that is key. I learned that from Joe Bavaria at the University of Pennsylvania, where they have a very integrated program with their vascular surgeons. We have modeled that at Duke, and all these patients are reviewed jointly by me and the vascular surgeons. We each bring something separate to the table, the vascular surgeons especially with their endovascular techniques, which we are now learning. I think we are where the vascular surgeons were maybe 5 to 7 years ago, when they were learning from the radiologists.

Now, we are learning these endovascular techniques from the vascular surgeons. I believe over time more and more cardiac surgeons will be involved in these kinds of procedures.

With regard to the grafts, they are Gelweave and maybe we should switch to Gelsoft grafts per your recommendation. In the early patients in the series, we used the 3-vessel grafts that were originally made for open arch surgery. We implanted both head vessels, and for the belly Vascutek had a graft that had 4 side branches that we were using. We now have had Vascutek design a special graft for the arch that has the integrated limb and has only 2 distal side branches for the innominate and the carotid. They have also now made us a custom graft for the belly that has one branch that goes this way for the superior mesenteric artery, one this way for the renal, one for the celiac, and then a longer one for the right renal with an antegrade limb. I think if they can make the graft for you, it is a little bit better.

Dr Miller. It takes away the fun for the junior resident, though, who no longer gets to put the grafts together.

We still go for the left subclavian if we are doing this, and I think for the audience we should be doing this more. Number one, the antegrade approach for stent graft deployment is much safer. We have not done a lot, but every time we do it we kick ourselves for flogging from the groin and having all those access problems that can lead to real trouble. I think we should be doing this more, but if you are there and you are going to bypass 2 vessels, why not bypass all 3? We have been burned, as has everybody, with a cavalier approach to covering the left subclavian artery. Even if you know the right vertebral is the dominant vessel, it is not just the arm claudication ischemic symptoms, but it is the posterior fossa basilar strokes. They are unpredictable. I think almost everybody will now be turning the corner into a more aggressive left subclavian revascularization, whether it be a supraclavicular, carotid-subclavian transposition, or something else. You are there, and it is sitting right there. Granted, it is deep, but you can get to it, and why not make a quadruple prosthesis? Do all 3 arch vessels and your fourth limb for the antegrade stent graft deployment, which takes 5 or 10 minutes. Isn't it amazing when you are close to it how easy it is compared with when you are doing it from a long distance down below?

The pump standby that you mentioned is key. As recently as 2 weeks ago, one of these end-to-side proximal anastomoses dehiscd

off the ascending aorta right before our eyes, and the patient needed the pump. It is absolutely essential, and it is going to be more important as we move to the hybrid operating rooms, which are a little more crowded. There is better imaging, but the pump driver and pump must be available, because you can get into trouble. It is also perhaps easier, warm beating partial bypass, especially if the ascending aorta to which you are sewing is thin and friable.

Dr Matthew Slater (*Portland, Ore*). Dr Miller stole my thunder because we have a limited experience, but we have been anastomosing to the left subclavian to obviate all the issues that come up.

My actual question is technical. In the angiography suite, the imaging equipment at our institution is better and so sizing is a little more straightforward. I have found some difficulty in sizing with fluoroscopy in the operating room. Do you have any technical hints for using single-plane fluoroscopy in the operating room that have been useful in the arch, which is a hard place to size?

Dr Hughes. Are you talking about sizing the stent grafts?

Dr Slater. Yes, sizing the stent grafts and positioning them in the arch with somewhat suboptimal fluoroscopy as opposed to a fluoroscopy suite.

Dr Hughes. I think the majority of our stent graft sizing information comes from our preoperative imaging with a true 90° flow lumen measurement. We use the Tera Recon system, which I can't say enough about. Either the IVUS (Volcano Corp, Rancho Cordova, Calif) system or the M25S can provide very accurate arch measurements, at least in my experience. If we have any question we will just use IVUS, with the caveat that with the IVUS system catheter may not be exactly in the center of the aorta. It may not be providing a true 90° flow lumen measurement with the IVUS catheter, but if I have any questions about sizing based on my CT scan, I will use IVUS as kind of a tie breaker to help decide stent graft size. On those arch grafts, we put radiographic markers around where the proximal anastomosis comes off, which are very easily seen during fluoroscopy. Thus, we know not to go past this point with the stent graft. We do not have fixed imaging yet either. We have the 9-900 OEC C-arm (Bighorn Biomedical Services, Inc, Moorcroft, Wyo), which is acceptable but not ideal. We have been able to use that in all these cases with pretty much no problem, even in the big patients.

Figure E1. Off-pump arch debranching procedure using a trifurcated Dacron graft. **A,** Intraoperative photograph of partial occlusion clamp placed on proximal ascending aorta for creation of proximal inflow anastomosis of trifurcated graft. **B,** Completed arch debranching procedure with first side branch of trifurcated graft oversewn and not used, second side branch anastomosed end to end to proximal left common carotid artery, and distal main body anastomosed end to end to proximal innominate artery. Note radio-graphic markers placed around proximal anastomosis to facilitate identification of the graft origin under fluoroscopy.

Figure E2. A, Custom fabricated ante-grade hybrid graft (Vascutek USA, Ann Arbor, Mich) designed for arch debranching and antegrade stent graft deployment across the aortic arch without the need for femoral exposure. The proximal 10-mm side arm allows introduction of the stent graft introducer sheath antegradely into the ascending aorta. The first distal side branch is used to bypass the left common carotid artery (*L CCA*), whereas the second distal side branch is used for the innominate artery. B, Intraoperative photograph demonstrating completed arch debranching. The stent graft will subsequently be introduced antegradely across the aortic arch via the proximal side arm. C, Artist's drawing of completed arch debranching with the ante-grade graft.

Figure E3. A, Preoperative CT scan of a patient with the Marfan syndrome status-post prior extent II TAAA repair 6 years earlier, who was discovered on follow-up imaging to have an asymptomatic 8.7-cm mesenteric button false aneurysm (*arrow*). B, Nine-month post-operative CT scan. Because the aortic bifurcation and bilateral common iliac arteries below the prior TAAA graft were aneurysmal as well, the distal aorta and common iliacs were replaced with a bifurcated Dacron graft. The mesenteric debranching graft was then anastomosed end to side to this new distal aortic graft followed by endovascular false aneurysm exclusion. Note anastomoses to the superior mesenteric artery, right renal, and celiac axis (patient did not have a left kidney). The false aneurysm has been completely excluded by the stent graft with proximal and distal seal zones completely within Dacron grafts and not in the Marfan aorta.

Figure E4. Intraoperative arteriogram demonstrating debranching graft with inflow from left iliac and distal anastomoses to left renal, superior mesenteric, celiac, and right renal arteries. The celiac has been anastomosed end to side to the graft in this instance.

Figure E5. Intraoperative photograph demonstrating completed debranching procedure with antegrade limb clipped and oversewn.

TABLE E1. Patient demographic and clinical features

Patient No.	Comorbidities	Aneurysm site	Etiology	Clinical classification	Case urgency	Prior aortic surgery
1	HTN, CAD, COPD, CRI	Arch	Degenerative/ chronic dissection	Symptomatic	Elective	Thoracic endografting
2	CRI, HTN, Marfan syndrome	Visceral button	Anastomotic	Asymptomatic	Urgent	Bentall, open TAAA
3	HTN, COPD, PVD	Arch	Degenerative/ chronic dissection	Symptomatic	Elective	Type A dissection repair
4	CAD, HTN, COPD, CVD, PVD	Arch	Degenerative	Symptomatic	Elective	None
5	HTN, obesity	Arch	Degenerative	Symptomatic	Elective	None
6	Pre-operative ARF, CAD, COPD, PVD	TAAA	Degenerative	Symptomatic; acute type B dissection	Emergency	Open AAA
7	COPD, CRI, HTN, PVD	TAAA	Degenerative	Asymptomatic	Elective	Open AAA
8	COPD, HTN	TAAA	Degenerative	Symptomatic	Elective	None
9	CHF, COPD, CRI, DM, HTN	Arch	Degenerative	Asymptomatic	Elective	None
10	COPD, ESRD, HTN	Visceral button	Anastomotic	Symptomatic	Emergency	Open TAAA
11	CAD, COPD, DM, HTN	Arch	Degenerative	Symptomatic	Elective	None
12	COPD, HTN	Arch	Degenerative	Symptomatic	Urgent	AVR
13	CAD, COPD, HTN, PVD	TAAA	Degenerative	Symptomatic	Elective	Open DTA

AAA, Abdominal aortic aneurysm; ARF, acute renal failure; AVR, aortic valve replacement; CAD, coronary artery disease; CHF, congestive heart failure; COPD, chronic obstructive pulmonary disease; CRI, chronic renal insufficiency; CVD, cerebrovascular disease; DM, diabetes mellitus; DTA, descending thoracic aneurysm; ESRD, end-stage renal disease; HTN, hypertension; PVD, peripheral vascular disease; TAAA, thoracoabdominal aortic aneurysm.