

“Hybrid” Repair of Aneurysms of the Transverse Aortic Arch: Midterm Results

G. Chad Hughes, MD,* Mani A. Daneshmand, MD, Keki R. Balsara, MD, Hardean A. Achneck, MD, Bantayehu Sileshi, MD, Sean M. Lee, MD, and Richard L. McCann, MD

Department of Surgery, Duke University Medical Center, Durham, North Carolina

Background. Aneurysms of the transverse aortic arch, especially those involving the mid to distal arch, are technically challenging to repair with conventional open techniques. We present our results with a combined open/endovascular approach (“hybrid repair”) in such patients.

Methods. From August 11, 2005, to September 18, 2008, 28 patients underwent hybrid arch repair. For patients (n = 9) with distal arch aneurysms but 2 cm or more of proximal landing zone (PLZ) distal to the innominate artery, right to left carotid-carotid bypass was performed to create a PLZ by covering the left carotid origin. For patients (n = 12) with mid arch aneurysms but 2 cm or more of PLZ in the ascending aorta, proximal ascending aorta-based arch debranching was performed. For patients (n = 7) with arch aneurysms with no adequate PLZ (“mega aorta”) but adequate distal landing zone, a stage 1 elephant trunk procedure was performed to create a PLZ. For the first two groups, endovascular aneurysm exclusion and debranching

were performed concomitantly, whereas the procedures were staged for the group undergoing an initial elephant trunk procedure.

Results. Mean patient age was 64 ± 13 years. Primary technical success rate was 100%. Thirty-day/in-hospital rates of death, stroke, and permanent paraplegia/paresis were 0%, 0%, and 3.6% (n = 1), respectively. At a mean follow-up of 14 ± 11 months, there have been no late aortic-related events. Two patients (7%) required secondary endovascular reintervention for a type 1 endovascular leak. No patient has a type 1 or 3 endovascular leak at latest follow-up.

Conclusions. Hybrid repair of transverse aortic arch aneurysms appears safe and effective at midterm follow-up and may represent a technical advance in the treatment of this pathology.

(Ann Thorac Surg 2009;88:1882–8)

© 2009 by The Society of Thoracic Surgeons

Aneurysms of the transverse aortic arch, especially those involving the mid to distal arch, are technically challenging to repair with conventional open techniques. This challenge is compounded by arch aneurysms frequently extending into either the ascending aorta or descending aorta, or both (so-called “mega aorta syndrome” or “extensive aortic aneurysm”), and may require a two-stage approach for repair. Thoracic endovascular aneurysm repair (TEVAR) is associated with lower perioperative morbidity and mortality rates than conventional open repair, with similar early and midterm follow-up results [1, 2]. Recent reports [3, 4] have described the use of a combined endovascular and open surgical approach to the treatment of transverse arch aneurysms with the aim that these “hybrid” techniques might lower perioperative morbidity and mortality rates, allow single-stage treatment of some pathology previ-

ously requiring two-stage repair, and shorten the time between stages (thus minimizing interval mortality) for patients still requiring two-stage repair. In the current report, we describe our experience with a combined open/endovascular approach (“hybrid repair”) in such patients.

Patients and Methods

Between March 23, 2005 (date of Food and Drug Administration approval of the first available thoracic device in the United States) and October 23, 2008, 178 thoracic endograft procedures were performed at our institution. Of these, 28 (16%) were hybrid arch repairs (performed between August 11, 2005 and September 18, 2008) and form the basis of this report. Indications for surgery included either saccular (n = 11) or fusiform (n = 17) aneurysms of the transverse arch. In 10 patients (36%), the aneurysm was secondary to aortic dissection and included unrepaired chronic type A dissection in 2, residual arch/descending dissection after prior type A dissection repair in 5, acute type B dissection with associated distal arch/proximal descending aneurysm in 2, and chronic type B dissection with associated distal arch/proximal descending aneurysm in 1. Criteria for

Accepted for publication July 10, 2009.

*Recipient of the 2008 Clifford Van Meter President’s Award.

Presented at the Fifty-fifth Annual Meeting of the Southern Thoracic Surgical Association, Austin, TX, Nov 5–8, 2008.

Address correspondence to Dr Hughes, Duke University Medical Center, Box 3051, Division of Thoracic and Cardiovascular Surgery, Department of Surgery, Durham, NC 27710; e-mail: gchad.hughes@duke.edu.

repair were as described previously [5]. The presence of a connective tissue disorder such as Marfan or Loeys-Dietz syndrome was considered a contraindication to hybrid arch repair. The study was approved by the Duke Institutional Review Board, and the Board waived the need for individual patient consent.

For patients (n = 9) with aortic pathology involving the distal arch but with 2 cm or more of proximal landing zone (PLZ) distal to the innominate artery, right to left carotid-carotid bypass was utilized to create a PLZ for stent graft seal. In all cases, the procedure was performed immediately before the endograft portion of the case, as previously described [6]. The proximal left common carotid artery (CCA) was ligated below the bypass graft anastomosis (functional end-to-end distal anastomosis) to prevent type 2 endovascular leak. Three patients (33%) in this cohort required an iliac conduit to allow safe

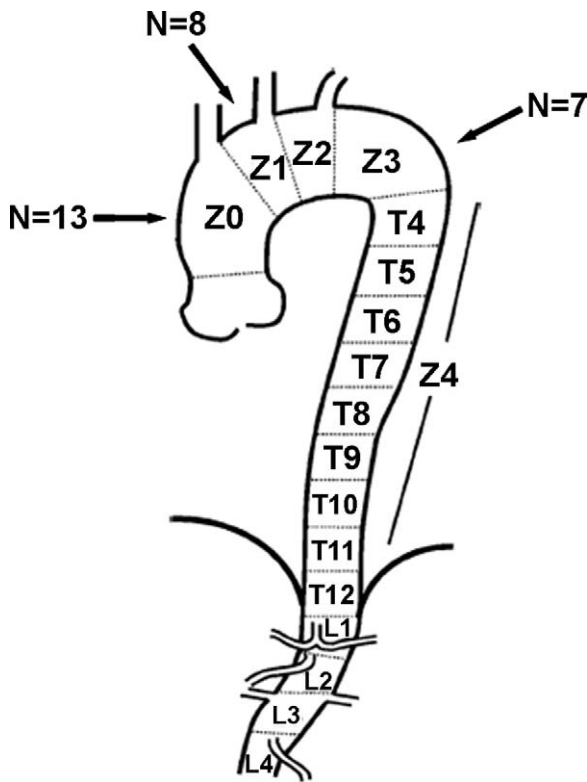


Fig 1. Aortic landing zone map devised by Ishimaru [7] and location of proximal landing zone (PLZ) for hybrid arch patients in the present series. Eight of 9 patients undergoing adjunctive carotid-carotid bypass had zone 1 PLZ, with the exception being 1 patient status post ascending aorta to right subclavian artery (SCA) bypass at the time of type A dissection repair at another institution; she subsequently underwent right subclavian to right carotid to left carotid artery bypass to create a zone 0 PLZ. All patients undergoing ascending aortic-based arch debranching procedures (n = 12) had zone 0 PLZ, in addition to the single carotid-carotid bypass patient (n = 13 total zone 0 PLZ). Patients (n = 7) undergoing first-stage total arch replacement/elephant trunk had zone 3/4 PLZ in the elephant trunk graft. (Modified from Ishimaru S, *J Endovasc Ther* 2004;11:II62-71 [7], with permission from Allen Press Publishing Services.)

Fig 2. Intraoperative photograph demonstrating completed concomitant ascending aortic replacement and arch debranching procedure. The arch debranching graft (black arrow) has been anastomosed to the proximal end of the ascending graft, thus creating several centimeters of proximal landing zone (PLZ) in the ascending graft above the takeoff of the debranching graft. The endograft has been deployed within the ascending graft and the proximal antegrade limb of the debranching graft (used for introduction of the endograft and not visible) has been oversewn.

introduction of the introducer sheath necessary for the procedure. The left subclavian artery (SCA) was fully covered in all of these patients, and 3 (33%) underwent adjunctive left carotid-subclavian bypass during the same operation as endovascular repair. Indications for left carotid-subclavian bypass were as previously described [5]. One patient in this group had undergone prior ascending aortic replacement for repair of a type A aortic dissection at another institution and had concomitant ascending aorta to right SCA bypass performed as part of that procedure. This bypass served as inflow for subsequent right subclavian to right carotid to left carotid bypass, thus allowing a zone 0 PLZ, using the aortic landing zone map devised by Ishimaru [7]. The other patients in this group had zone 1 PLZ (Fig 1).

For patients (n = 12) with aneurysms involving the mid transverse arch but with 2 cm or more of PLZ in the ascending aorta, ascending aortic-based arch debranching was performed as previously described [4-6] using a custom designed "hybrid antegrade arch graft" (Vascutek USA, Ann Arbor, MI) to debranch the innominate and left CCA; the graft incorporates an antegrade limb that allows endograft introduction across the arch without need for femoral exposure. The left SCA was fully

covered in all of these patients, and 2 (17%) underwent adjunctive left carotid-subclavian bypass during the same operation. In 3 of these patients (25%), the ascending aortic-based arch debranching procedure involved redo sternotomy status post prior type A dissection repair. The existing Dacron graft served as PLZ as well as the proximal anastomotic site for the arch debranching graft in these cases. One additional patient underwent supracoronary ascending aortic replacement at the time of arch debranching to create PLZ, given his ascending aortic diameter of 4.6 cm, which was too large for stent graft proximal seal; the arch debranching graft was subsequently anastomosed to the new ascending Dacron

graft (Fig 2). Thus, a total of 4 patients (33%) in this group had PLZ in Dacron grafts. The TEVAR portion of the procedure (zone 0 PLZ; Fig 1) was performed immediately after arch debranching and before closure of the sternotomy in all of these cases.

All arch debranching patients underwent preoperative transthoracic echocardiography and coronary angiography to rule out significant valvular or coronary artery disease, which was addressed surgically at the time of the hybrid arch procedure. Adjunctive cardiac surgical procedures were performed in 4 patients (33%): coronary artery bypass grafting (CABG) in 2, aortic valve replacement in 1, and as described above, supracoronary ascending aortic replacement for ascending aneurysm in 1. The arch debranching procedure was performed on cardiopulmonary bypass in these 4 patients, as well as in an additional patient (total $n = 5$ [42%] on pump) after prior ascending aortic Dacron graft replacement for type A dissection repair 9 years earlier. Cardiopulmonary bypass was necessary in this patient to repair an intraoperative main pulmonary artery injury.

For patients ($n = 7$) with aneurysms involving the transverse arch with no adequate PLZ (mega-aorta) but adequate distal landing zone (DLZ), a first-stage total arch replacement (stage 1 elephant trunk procedure) was performed to treat the proximal aortic pathology and create PLZ. This was performed using a modified Mt. Sinai technique (Fig 3) [8, 9]. In 3 patients (43%), the procedure involved redo sternotomy after prior type A dissection repair ($n = 2$) or mechanical root replacement ($n = 1$); the existing ascending/root graft was deemed unsuitable for PLZ in these patients, thus necessitating total arch replacement. Concomitant cardiac surgical procedures were performed in 4 patients (57%), including CABG ($n = 3$) and CABG plus aortic valve replacement ($n = 1$). Unlike the previously described hybrid approaches, the arch replacement procedure and TEVAR were staged.

Surgical considerations specific to the first stage include choosing the diameter of the elephant trunk graft so that it matches that of the proposed DLZ in native aorta. Specifically, a graft diameter 2 to 4 mm smaller than that of the distal aorta was utilized to allow for the natural dilation that occurs in Dacron grafts after implantation. Matching the diameter of the elephant trunk graft and DLZ allows a single endograft to complete the repair in many cases. Further, using a smaller diameter elephant trunk allows the endografts to be deployed from proximal to distal if multiple devices are required, which simplifies the second-stage endovascular repair. Four large hemoclips are placed on the distal end of the graft to assist with identification under fluoroscopy. Two pacing wires (# 0) are likewise attached to the distal end of the elephant trunk to allow the graft to be snared at the second-stage operation to provide countertraction as the endovascular graft is advanced into the elephant trunk. This helps avoid the tendency of the Dacron graft to invert on itself. Several additional endovascular techniques [6] facilitate completion of the second-stage procedure and include gaining initial access to the elephant

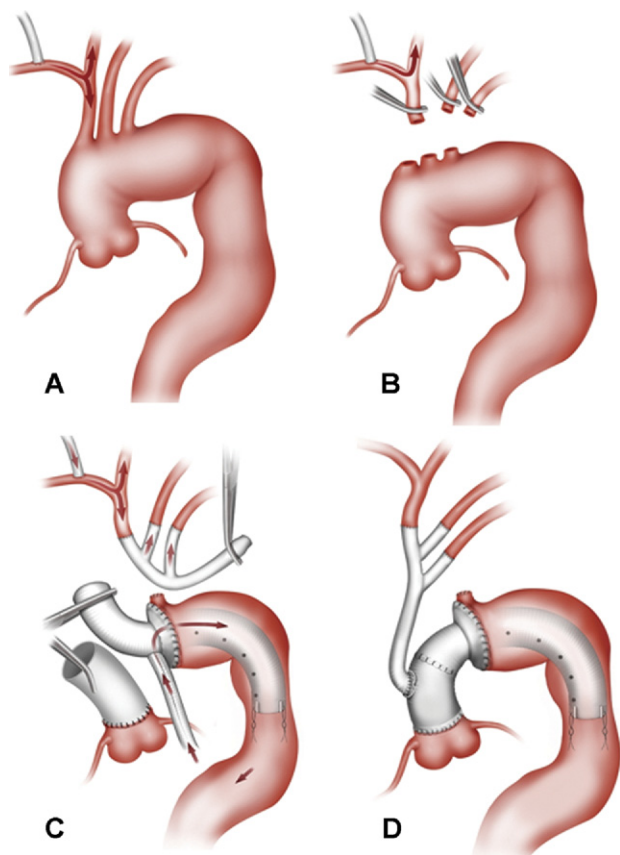


Fig 3. Drawing demonstrating modified Mt. Sinai technique [8] used for first-stage total arch replacement in patients with extensive thoracic aortic disease but adequate distal landing zone (DLZ) in descending aorta. (A) The right axillary artery is cannulated with an 8 mm Dacron graft using a side graft technique. (B) After cooling to electrocerebral inactivity by electroencephalogram, the three arch vessels are divided from their origins at the arch, clamped, and antegrade cerebral perfusion from the right axillary graft begun. (C) A trifurcated graft is then anastomosed to the arch vessels, and full flow to the upper body resumed at 12°C. The collared elephant trunk graft is then anastomosed to the divided arch, after which lower body perfusion is resumed and rewarming begun through a Y in the arterial line and the integral side arm in the elephant trunk graft. The collar allows the elephant trunk anastomosis to be better matched to the diameter of the dilated transverse arch, which decreases tension at this anastomosis [9]. (D) Completed first-stage repair.

trunk from a right brachial approach rather than trying to access the graft from below, which can be difficult in the presence of a large descending aneurysm. The wire placed from the right brachial access may then be snared (body floss technique) to guide a wire from below into the Dacron graft. The use of a 65-cm introducer sheath (Keller-Timmerman, Cook Medical, Bloomington, IN), which can be advanced well into the Dacron sleeve, also facilitates endograft passage into the elephant trunk when utilizing the Gore TAG device (W.L Gore & Assoc, Flagstaff, AZ), as this particular endograft has a tendency to hang up on the Dacron fabric.

Devices utilized for hybrid arch repairs were the Gore TAG device in 27 patients and the Zenith TX2 device (Cook Medical, Bloomington, IN) in 1 patient. Details regarding devices and technique of delivery and deployment have been previously described [10, 11]. Preoperative planning and intraoperative conduct of TEVAR were as described previously [4-6].

On-line monitoring of spinal cord function with somatosensory and motor evoked potentials was used intraoperatively in elective cases and when available for urgent cases (n = 24 cases monitored; 86%), using previously described techniques [12]. Cerebrospinal fluid drainage was used selectively (n = 2; 7%) for previously described indications [5].

Comorbidities were defined using standard definitions. All procedural outcomes and complications were prospectively recorded. Patient follow-up protocol was as previously described [5]. All follow-up was done at the Duke University Center for Aortic Surgery. This report includes all data collected through the patients' most recent follow-up visit. In addition, the Social Security Death Index was queried (available at: <http://ssdi.rootsweb.com/>) to confirm all patient deaths. For those patients dying during follow-up, cause of death was confirmed by review of medical records or family interview in all cases. Survival analyses were performed using the Kaplan-Meier method. 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 [13].

Table 1. Patient Demographics

Mean age, years	64 ± 13 (range, 31 to 84)
Female	n = 13 (46%)
Hypertension	n = 25 (89%)
Diabetes mellitus	n = 6 (21%)
Coronary artery disease	n = 11 (39%)
Chronic obstructive pulmonary disease	n = 5 (18%)
Chronic renal insufficiency (baseline creatinine ≥1.5 mg/dL)	n = 8 (29%)
Peripheral vascular disease	n = 7 (25%)
Prior open aortic surgery	n = 11 (39%)

Results

Patient Demographics

Mean aneurysm diameter was 6.1 ± 1.6 cm (range, 3.1 to 11.0 cm). Patient demographics are presented in Table 1. Eleven (39%) had undergone prior open aortic surgery, including prior ascending aortic replacement for type A dissection in 6 (21%). The distal extent of aortic coverage by the endografts was above T6 in 18 (64%) and below T6 in 10 (36%). Thirteen (46%) of the patients were symptomatic with pain symptoms; 21% (6 of 28) of the cases were urgent (aneurysm repaired during the same hospital admission as discovered). None of the cases was emergent, and all patients were hemodynamically stable without frank rupture at the time of surgery.

Procedural (30-Day) Outcomes

All patients (n = 7) undergoing first-stage elephant trunk underwent second-stage repair, with the interval between stages ranging from 8 days to 7 months (median, 10 weeks); 2 patients (29%) underwent second-stage repair during the index hospitalization. Primary technical success, defined as successful endovascular graft deployment with no type 1 or 3 endovascular leak and absence of open surgical conversion or mortality within the first 24 hours postoperatively [13], was achieved in all cases. The mean number of stent grafts per case was 1.7 ± 0.7 (range, 1 to 3); median device diameter was 34 mm.

Thirty-day/in-hospital rates of death, stroke, and permanent paraplegia/paresis were 0%, 0%, and 3.6% (n = 1), respectively. These data include first-stage elephant trunk procedures, combined debranching and endovascular repairs, as well as second-stage TEVAR in patients undergoing first-stage elephant trunk. Details of the single patient with paraplegia have been previously described [5].

Other major perioperative morbidity was seen in 6 patients (21%) and included respiratory failure requiring reintubation (n = 2), left neck hematoma requiring reexploration after carotid-subclavian bypass (n = 1), mediastinal bleeding requiring reexploration (n = 1), left upper extremity ischemia secondary to left SCA coverage by the endograft requiring left carotid-subclavian bypass on postoperative day 2 (n = 1), and intraoperative left common iliac rupture requiring covered stent repair and subsequent femoral-femoral bypass after stent thrombosis on postoperative day 1 (n = 1). The median hospital length of stay was 6 days for endovascular repairs.

Follow-Up Outcomes

Follow-up is 100% complete. The incidence of type 1 or 3 endovascular leak at any follow-up visit was 7% (n = 2); both were proximal type 1 endovascular leaks in arch debranching patients where the endograft PLZ was in an ascending aortic Dacron graft. Both were treated successfully with proximal endograft cuff extension. Three patients (11%) had type 2 endovascular leaks noted on follow-up imaging. Of these, 2 were due to retrograde flow from the left SCA and were successfully treated with late coil embolization. The other is a small type 2 endo-

vascular leak secondary to an intercostal artery and is being followed. No patient has a type 1 or 3 endovascular leak at latest follow-up.

Clinical success, defined as absence of death as a result of aneurysm-related treatment, persistent type 1 or 3 endovascular leak, graft infection or thrombosis, aneurysm expansion or rupture, or conversion to open repair [13] was 100% at a mean duration of follow-up of 14 ± 11 months (range, 1 to 36). Overall actuarial midterm survival is 70% at 36 months, with an aorta-specific actuarial survival of 100% during this same interval.

Comment

Aneurysms of the transverse aortic arch, especially those involving the mid to distal arch, are technically challenging to repair with conventional open techniques. These challenges relate to difficulties with exposure, need for deep hypothermic circulatory arrest, and frequent requirement for a two-stage approach to complete repair. Total arch replacement, although now performed routinely and safely in centers with expertise, still carries a perioperative death or stroke rate approaching 15%, even in expert hands [8, 14]. Further, a significant number of patients may become unfit or refuse the second stage, and perioperative second stage mortality rates approach 10% for patients fit enough to undergo an additional open procedure for downstream repair [15]. This is in contrast to the results of the present report, in which no deaths or strokes were seen in 28 consecutive patients undergoing hybrid arch repair. Similar low rates of perioperative morbidity and mortality with hybrid arch repair have been reported by others [3, 16].

Potential advantages of the hybrid approach over conventional repair for arch pathology are several. First, these procedures, which avoid the need for cardiopulmonary bypass and aortic cross-clamping in most patients, may have advantages for high-risk patients, including the potential to offer therapy to patients who are not candidates for conventional open repair [4]. Second, endovascular grafts can be deployed from the ascending aorta down to the level of the celiac axis, thus allowing pathology of the arch and descending aorta previously requiring either extensive single stage repair through bilateral thoracosternotomy [17] or two-stage repair [15, 18-20] to be treated in a single-stage procedure. Finally, for patients still requiring a two-stage approach, the second-stage endovascular repair may be performed much sooner than a second open procedure (even during the same hospitalization as arch replacement, as was done in nearly a third of patients in the current series), given the minimal physiologic insult of TEVAR and the fact that it is well tolerated even by patients who have recently undergone major open surgery. This represents a significant advance over conventional open second-stage repair and may eliminate the known risk of death from distal aortic complications between stages [15, 18-20]. Further, large series of patients undergoing first-stage elephant trunk demonstrate that only approximately 50% return for open second-stage repair [15, 18-20], a number

that should be greatly improved when the second procedure is performed using endovascular means. This is evidenced by all patients in the current series who underwent first-stage elephant trunk also underwent subsequent second-stage repair.

The so-called frozen elephant trunk technique [21-23] has also been suggested as a means to treat extensive thoracic aortic aneurysm in a single-stage procedure. This technique involves placement of an endovascular stent graft antegrade through the open arch at the same operation as the elephant trunk procedure. Although this approach has the advantage of eliminating the potential for interval aortic-related death between stages, it adds additional physiologic insult to an already significant operation. That is especially true with regard to renal function if contrast angiography is utilized for the endovascular graft portion of the case. As such, we believe these procedures are best staged, even if only for a few days, to allow the patient some recovery period after total arch replacement. The results of the present series would appear to support this contention, given the lack of interval mortality between staged repairs. Further, rates of spinal cord ischemia appear increased with the frozen elephant trunk approach, averaging 10% in most series [21, 23]. One potential explanation for this observation is that the ability to maintain supranormal mean arterial pressures to augment spinal cord blood flow may be limited by bleeding complications in this scenario, and that the use of cerebrospinal fluid drainage may be contraindicated owing to concerns over coagulopathy and central nervous system bleeding complications. There were no episodes of spinal cord ischemia after second-stage endovascular grafting in patients undergoing initial elephant trunk in the present series, which may support this hypothesis.

One potential word of caution with regard to the use of ascending aorta-based arch debranching procedures relates to the use of existing Dacron grafts for PLZ. Both type 1 endovascular leaks observed in this series were proximal type 1 leaks around endovascular grafts with proximal seal zone in an ascending Dacron graft. That equates to a 50% type 1 endovascular leak incidence in this group, as only 4 patients had PLZ in an ascending Dacron graft. We speculate that the presence of an endograft in a Dacron graft may promote additional dilation of the Dacron above that normally occurring, thus leading to late endovascular leak formation. Alternatively, the less compliant nature of Dacron as compared with native aorta may result in suboptimal endograft apposition. Although both proximal endovascular leaks in the current series were successfully treated with proximal cuff extensions, this is technically challenging because of the 100-cm length of the devices and difficulty reaching the ascending aorta from the groin at a second procedure. In 1 of the 2 patients, the endograft had to be deployed "bareback" without a sheath to allow it to reach far enough proximally into the ascending graft to achieve proximal seal. Based on these results, we suggest oversizing the endograft 20%, as well as a PLZ of at least 4 cm, when landing in Dacron to prevent this complication.

Finally, although we continue to perform total arch replacement regularly for the treatment of extensive thoracic aortic disease, going forward, one must consider whether this operation will remain widely utilized by the thoracic aortic surgeon, especially in older patients with significant comorbidity. Although not utilized in the present series, one could hypothesize an operation whereby proximal aortic arch replacement (namely, hemiarch) is performed with concomitant performance of partial or complete arch debranching without creating an elephant trunk. The advantage of such an operation would be the shorter period of circulatory arrest needed for performance of hemiarch versus full arch, as the debranching procedure could be performed during re-warming without the need for deep hypothermic circulatory arrest. The diseased arch could then be excluded through endovascular means, either at the same operation or in a staged manner, with endografts extending from the hemiarch graft down into DLZ in the descending thoracic aorta. We would speculate that a combined hemiarch/arch debranching procedure would pose a lesser physiologic insult than total arch replacement and would likely be better tolerated by patients with limited physiologic reserve. This should serve as an area of additional investigation in the future.

In summary, the use of a hybrid endovascular and open surgical approach to the treatment of transverse arch aneurysms appears safe and effective at early mid-term follow-up and offers several advantages over conventional repair, including the potential to offer therapy to patients who are not candidates for open repair, single-stage treatment of some pathology previously requiring two-stage repair, and a shorter time between stages (thus minimizing interval mortality) for patients still requiring two-stage repair. As such, this approach may represent a technical advance in the treatment of this pathology.

References

1. Bavaria JE, Appoo JJ, Makaroun MS, Verter J, Yu Z-F, Mitchell RS, for the Gore TAG Investigators. Endovascular stent grafting versus open surgical repair of descending thoracic aortic aneurysms in low-risk patients: a multicenter comparative trial. *J Thorac Cardiovasc Surg* 2007;133:369–77.
2. Stone DH, Brewster DC, Kwolek CJ, et al. Stent-graft versus open-surgical repair of the thoracic aorta: mid-term results. *J Vasc Surg* 2006;44:1188–97.
3. Gottardi R, Funovics M, Eggers N, et al. Supra-aortic transposition for combined vascular and endovascular repair of aortic arch pathology. *Ann Thorac Surg* 2008;86:1524–9.
4. Hughes GC, Nienaber JJ, Bush EL, et al. Use of custom dacron branch grafts for “hybrid” aortic debranching during endovascular repair of thoracic and thoracoabdominal aortic aneurysms. *J Thorac Cardiovasc Surg* 2008;136:21–8.
5. Hughes GC, Daneshmand MA, Swaminathan M, et al. “Real world” thoracic endografting: results with the Gore TAG device 2 Years following U.S. FDA approval. *Ann Thorac Surg* 2008;86:1530–8.
6. Hughes GC, McCann RL, Sulzer CF, Swaminathan M. Endovascular approaches to complex thoracic aortic disease. *Semin Cardiothorac Vasc Anesth* 2008;12:298–319.
7. Ishimaru S. Endografting of the aortic arch. *J Endovasc Ther* 2004;11:II62–71.
8. Strauch JT, Spielvogel D, Lauten A, et al. Technical advances in total aortic arch replacement. *Ann Thorac Surg* 2004;77:581–90.
9. Neri E, Massetti M, Sani G. The “elephant trunk” technique made easier. *Ann Thorac Surg* 2004;78:e17–8.
10. Wheatley GH, Gurbuz AT, Rodriguez-Lopez JA, et al. Mid-term outcome in 158 consecutive Gore TAG thoracic endoprosthesis: single center experience. *Ann Thorac Surg* 2006;81:1570–7.
11. Greenberg RK, O’Neill S, Walker E, et al. Endovascular repair of thoracic aortic lesions with the Zenith TX1 and TX2 thoracic grafts: intermediate-term results. *J Vasc Surg* 2005;41:589–96.
12. Husain AH, Swaminathan M, McCann RL, Hughes GC. Neurophysiologic intraoperative monitoring during endovascular stent graft repair of the descending thoracic aorta. *J Clin Neurophysiol* 2007;4:328–35.
13. Chaikof EL, Blankensteijn JD, Harris PL, et al. Reporting standards for endovascular aortic aneurysm repair. *J Vasc Surg* 2002;35:1048–60.
14. Sundt TM, Orszulak TA, Cook DJ, Schaff HV. Improving results of open arch replacement. *Ann Thorac Surg* 2008;86:787–96.
15. Safi HJ, Miller CC, Estrera AL, et al. Optimization of aortic arch replacement: two-stage approach. *Ann Thorac Surg* 2007;83(Suppl):815–8.
16. Wang S, Chang G, Li X, et al. Endovascular treatment of arch and proximal thoracic aortic lesions. *J Vasc Surg* 2008;48:64–8.
17. Kouchoukos NT, Mauney MC, Masetti P, Castner CF. Single-stage repair of extensive thoracic aortic aneurysms: experience with the arch-first technique and bilateral anterior thoracotomy. *J Thorac Cardiovasc Surg* 2004;128:669–76.
18. Safi HJ, Miller CC, Estrera AL, et al. Staged repair of extensive aortic aneurysms: morbidity and mortality in the elephant trunk technique. *Circulation* 2001;104:2938–42.
19. Svensson LG, Kim K-H, Blackstone EH, et al. Elephant trunk procedure: newer indications and uses. *Ann Thorac Surg* 2004;78:109–16.
20. Schepens MA, Dossche KM, Morshuis WJ, et al. The elephant trunk technique: operative results in 100 consecutive patients. *Eur J Cardiothorac Surg* 2002;21:276–81.
21. Karck M, Chavan A, Khaladj N, et al. The frozen elephant trunk technique for the treatment of extensive thoracic aortic aneurysms: operative results and follow-up. *Eur J Cardiothorac Surg* 2005;28:286–90.
22. Baraki H, Hagl C, Khaladj N, et al. The frozen elephant trunk technique for treatment of thoracic aortic aneurysms. *Ann Thorac Surg* 2007;83(Suppl):819–23.
23. Karck M, Kamiya H. Progress of the treatment for extended aortic aneurysms: is the frozen elephant trunk technique the next standard in the treatment of complex aortic disease including the arch? *Eur J Cardiothorac Surg* 2008;33:1007–13.

DISCUSSION

DR JOSEPH S. COSELLI (Houston, TX): Congratulations on an excellent presentation and on your terrific results on really clinically challenging cases using innovative approaches. You describe 28 patients with aortic aneurysms of the arch treated operatively with a combination of traditional open techniques as

well as TEVAR technologies in the so-called hybrid procedures. Your primary technical success was 100%, operative death and stroke, 0%, and permanent spinal cord deficits, 3.6%. Your manuscript includes some very important technical details, such as information regarding choosing the elephant trunk diameter

to optimize the landing zone. You recommend, for instance, choosing an arch graft that has a diameter 2 to 4 mm smaller than that of the distal aortic landing zone. You also emphasize the importance of oversizing the endograft by 20%, as opposed to the usual 10%, and allowing for at least 4 cm instead of 2 cm for overlap when landing in the Dacron; this is particularly important because of the Dacron's tendency to dilate over time, which caused two late type 1 endovascular leaks in your series.

Additionally, you mention placing clips and wires on the end of the elephant trunk along with some techniques for accessing the elephant trunk from the femoral artery, which can be a challenging problem. A technique that we have used in addition to these is placing a totally occluding balloon in the distal end of the elephant trunk and allowing several heart beats to expand the elephant trunk and bring it down to its full length, thereby opening it up widely for easier access. Clearly, industry has got some technological issues with the way the stent grafts, particularly the one that you used in your series, drag on the elephant trunk graft and create an accordion effect; this has created a challenging situation for all of us, and you have described some techniques in your report which I think are valuable.

The questions I have for you are really quite simple. One is, were all of your carotid-carotid bypasses anterior? I am also curious about your use of somatosensory and motor evoked potential monitoring in this setting. You used it in 86% of cases. I particularly raise this issue because you do not routinely use cerebrospinal fluid (CSF) drainage. You used it in only 7% of your cases. My question is how do you use the motor evoked potential or somatosensory evoked potential monitoring information? Was it truly useful in this setting? For instance, if you lose signals after your graft deployment and you don't have a CSF catheter in, what do you do? Certainly, you can increase the blood pressure to super-normal levels and perhaps even insert a CSF catheter later, but that is delayed and it may not be in enough time. So do you have any other strategies to respond to signal loss? Once again, congratulations on terrific results in challenging cases. Thank you.

DR HUGHES: Thanks, Dr Coselli, for your comments. We also have used the technique that you discuss with the balloon. We have generally used it if we have a problem when advancing the endograft into the elephant trunk, such that the Dacron graft "accordions" on itself. In this scenario, if you put, for instance, a Coda balloon up inside the Dacron graft, inflate it, and pull down, you can recover from this situation, which can be problematic. Most of these patients were done before TX2 or Talent were FDA approved, and I think the TX2 device is probably going to be a better fit for landing in an elephant trunk than TAG, because it doesn't have the flares that tend to catch on the Dacron. So we will see about that.

With regard to your question about carotid-carotid bypass, we have done all of them anteriorly, as is our preference. Some people, as you know, tunnel the graft retropharyngeally. The one potential issue with anterior placement is if someone were to subsequently need a tracheostomy; we have had 1 case where we purposely tunneled the graft somewhat high in anticipation that the patient might need a tracheostomy, although fortunately he did not. That is the one concern with this approach, but regardless, our preference has been to go anterior in all of them as we feel it is easier.

And then the other question about the evoked potentials: our indications for CSF drainage are pretty standard from the literature. If somebody has had a prior AAA or prior open thoracic aneurysm repair, especially if we plan extensive coverage, we will place a drain preoperatively. But as I presented, in about two thirds of these patients the endografts didn't extend below T6, and that has been, at least in our experience, a

low-risk population, and so we generally do not place CSF catheters preoperatively. However, we do use evoked potential monitoring with both sensory and motor evoked potentials. We feel the latter to be especially important as, in our experience, motor evoked potentials are far superior to sensory potentials in terms of detecting spinal cord ischemia, and we try to use them in all cases if we can. We use the evoked potential data as you described. In this particular series there was only one paraplegia and it was delayed; consequently, no one had abnormal evoked potentials intraoperatively. But in other cases, when you lose bilateral lower extremity motor evoked potentials, the first thing to do is raise the blood pressure, and we will run mean arterial pressures as high as 110 or 120 mm Hg even, to recover the cord, and that generally works. In our experience, the cases where you are likely to see a loss of evoked potentials are usually going to be ones where you already have a CSF catheter in place, as they are almost always in higher spinal cord risk cases. In this scenario, we will be more aggressive with our CSF drainage; specifically, we will drain to a pressure less than 10 mm Hg and we may drain more than 20 cc an hour. So we are certainly more aggressive in that setting.

Further, there are also some patients, and this is something that Dr Bavaria taught me when I was training with him, where you may find a blood pressure threshold intraoperatively below which the evoked potentials will start to go bad, and when you raise the pressure back up, they come back. We will then use this information for our postoperative management, such that we will keep the blood pressure above this level. That being said, I do not think this threshold is absolute, and it is likely that once the heparin is reversed that this threshold probably goes up a little bit. Further, based on Dr Griep's data, when one ligates all of the intercostals, the peak decrease in spinal cord blood flow does not occur until about 6 hours later, and I think that is really the danger time and you need to be aggressive about keeping the pressure high, at least through that time. Consistent with this, in our experience, many of the delayed paraplegias occur in the evening after surgery, and fortunately by raising the blood pressure, this is usually recoverable. You obviously have a lot of experience with this as well.

DR ANTHONY L. ESTRERA (Houston, TX): I appreciated your talk. It really illustrates another tool in our armamentarium for treating these complex problems. Now, my question really relates to indications for surgery. I notice your mean age was 63 and you had some really younger patients in this cohort, and the reality in our experience in Houston, we will do these kinds of procedures on patients we really don't want to operate on because we have pretty decent results with the open procedure. Hence, what are your indications and how do you decide when you are going to do this versus an open procedure? Thanks.

DR HUGHES: The one younger patient in this series had a stage 1 elephant trunk, so obviously that patient had open surgery first, but also had a concomitant symptomatic descending aneurysm that we didn't feel could wait long enough for the patient to recover for a second open surgery and therefore had a stented second stage. In general, we don't do this for connective tissue disorder patients such as Marfan or Loays-Deitz patients. Those patients all get all stages done open. But aside from that, even 50- to 65-year-olds, in general, if their anatomy is favorable for endovascular repair, we will do the repair with an endovascular approach. Obviously, the data are not mature, and time will tell whether that is the right approach, but for now we haven't seen anything to make us concerned. Maybe when we get longer follow-up we will, but that is our approach.