Hybrid approaches in the treatment of aortic arch aneurysms: Postoperative and midterm outcomes

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Background: The combined open surgical and endovascular approach for the treatment of aortic arch aneurysms has emerged as a safe treatment modality. This platform may have an especially important role in treating patients of old age and with a greater comorbid burden. We describe our institutional experience with the hybrid aortic arch approach, with midterm outcomes.

Methods: From 2005 to the present, 685 patients have undergone thoracic endovascular repair (TEVAR); 104 had a hybrid arch repair (open plus endovascular approach). Of these, 47 patients had treatment for an aortic arch aneurysm with or without a proximal ascending aortic aneurysm. All these patients had a median sternotomy approach for arch vessel debranching and antegrade with or without retrograde TEVAR stent grafting of the arch. Results from a prospectively maintained database are reported.

Results: Twenty-eight patients had type I repair, 8 patients had type II repair, and 11 patients had type III arch hybrid repair. Those with type III repair were excluded from the analysis. Stent graft deployment rate was 100% after arch vessel debranching. Mean age was 71 ± 8 years. Fourteen percent of cases involved a redo sternotomy. Average cardiopulmonary bypass time was 215 ± 64 minutes, with a crossclamp time of 70 ± 55 minutes and a circulatory arrest time of 19 ± 10 minutes. The paraplegia rate was 5.5% ($n = 2$), with a stroke rate of 8% ($n = 3$). In-hospital mortality was 8% ($n = 3$). There were no postoperative endoleaks. The mean length of stay was 17.2 ± 14 days. The median follow-up was 30 ± 21 months. Freedom from all-cause mortality was 71%, 60%, and 48% at 1, 3, and 5 years, respectively. The aortic reoperation rate was 2.7% ($n = 1$). No patient has a type 1 or 3 endoleak at latest follow-up.

Conclusions: The hybrid approach to aortic arch aneurysm involving a zone 0 stent graft landing can be safely adopted with good midterm results in a cohort of old patients with significant comorbidity. This procedure can be performed with no type 1 or 3 endoleaks and may represent a technical advancement in the field of aortic arch surgery. (J Thorac Cardiovasc Surg 2013;145:S85-90)

The management of aortic arch aneurysms remains a clinical challenge. Open total arch procedures can be accomplished using complex circulatory management and adjunct cerebral protection, but subgroups with multiple comorbidities may still experience significant morbidity and mortality from both neurologic and cardiovascular complications.¹⁻³ In these high-risk patients, alternative therapies are sought. The introduction and regulatory approval of thoracic endovascular repair (TEVAR) for descending aortic disease has seen its application to many off-label uses, including aortic dissection,^{4,5} traumatic

transection,⁶ infection/fistula, and penetrating atherosclerotic ulcers.^{7,8} This application has been extended to the use of TEVAR for stenting the aortic arch with open great vessel debranching. The “hybrid” aortic arch repair, with debranching and reimplantation, or with bypass of aortic arch vessels and TEVAR with endografting of the aortic arch, is evolving toward a front-line treatment option for complicated pathologic conditions of the aortic arch,⁹⁻¹¹ especially in patients with a severe comorbid status.

Combining open surgical and endovascular techniques, the hybrid arch repair seeks to limit operative, bypass, and circulatory arrest times by simplifying and shortening the arch repair. The arch hybrid concept entails reimplantation or bypass of all aortic arch vessels, and TEVAR implantation landing proximally in “zone 0” (ascending aorta–innominate origin), which is either suitable for use as a landing zone natively or has been replaced with a Dacron graft to construct an artificial landing zone (Figure 1). Multiple studies have demonstrated the feasibility of this approach to the aortic arch, demonstrating acceptable mortality and morbidity.⁹⁻¹¹ We report our institutional experience with the arch hybrid operation, with midterm follow-up on these patients.

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Abbreviations and Acronyms

CPB	= cardiopulmonary bypass
CTA	= computed tomography angiogram
NIRS	= near-infrared spectroscopy
TEVAR	= thoracic endovascular repair

METHODS

From 2005 to the present, 685 patients have undergone TEVAR at our institution. Of these, 104 underwent TEVAR for proximal aortic repair: 57 ascending/hemiarch replacements with antegrade stenting of the descending aorta for DeBakey type I dissection and 47 hybrid arch debranching procedures. The variations of these repairs can be classified as types I, II, and III.

Type I Hybrid Arch

Twenty-eight patients had a type I hybrid arch repair, in which there is an isolated arch aneurysm with good native landing zones (zone 0 and zone 3/4). Type 1 repair consists of reimplantation of the aortic arch vessels using a 4-branched Dacron graft, which is sewn to the native ascending aorta just above the sinotubular junction (Figure 1). This can be done without cardiopulmonary bypass (CPB) using a side-biting clamp in hemodynamically stable patients if the aorta is not calcified, but it can also be done on CPB with or without a short aortic crossclamp time.

If there is concern that the exposure of the left subclavian artery will be difficult via a median sternotomy, a preemptive left subclavian–left common carotid bypass is an option, and only innominate and left common carotid arteries are then reimplanted into the ascending aorta. After the arch debranching is complete, stent grafts can then be deployed via the fourth limb of the graft into the aortic arch.¹² In some patients, endograft implantation is delayed and the stent graft is deployed later during the same hospital stay via a retrograde iliofemoral approach. If a carotid–subclavian bypass is performed, it is critical that the proximal left subclavian artery be ligated or coiled to prevent a type II (branch vessel) endoleak on aortic arch stenting. Recently, when a subclavian branch is necessary, we have been placing it into the extrathoracic subclavian artery via the second intercostal space in the left side of the chest.

Type II Hybrid Arch

Eight patients underwent a type II hybrid arch repair. This is undertaken in patients with proximal extension of aneurysmal disease into the ascending aorta, making the native aorta unsuitable for a zone 0 stent graft landing. This can be addressed by replacing the ascending aorta, creating a Dacron ascending zone 0. At our institution, ascending aorta replacement, or a type II hybrid arch solution, is undertaken for a zone 0 diameter greater than 3.7 cm, inasmuch as we and others have noted an increased risk of retrograde type A dissection in the deployment of proximal stent grafts when the ascending aortic diameter is greater than 4 cm.

Type II arch hybrid operations require CPB and sometimes a brief interval of circulatory arrest for proximal aortic reconstruction, which can be done using either retrograde or selective antegrade perfusion strategies. After arch debranching and reconstruction of zone 0 with an ascending aortic graft, the endograft can be deployed through the arch with a Dacron zone 0 landing zone.

Type III Hybrid Arch

Eleven patients underwent type 3 hybrid arch repairs: a total arch replacement with a descending elephant trunk, combined with a delayed

second-stage retrograde TEVAR repair, for extensive aortic diseases such as “mega-aorta” syndrome. Type 3 hybrid arch repairs are not classic hybrid arch repair procedures. All patients had either selective antegrade perfusion or a combination of antegrade and retrograde cerebral perfusion during the circulatory arrest period. These patients are not included in further analysis owing to significant differences in patient population, disease process, and most important, operative technique, inasmuch as the TEVAR solution is not into zone 0.

In all cases, the patient was deemed unsuitable for traditional open repair owing to age or other comorbidities. Patients were preoperatively evaluated with a multislice computed tomography angiogram (CTA). CTA images were processed into 3-dimensional images by an outside service (M2S, West Lebanon, NH) for preoperative planning and proper sizing of endografts deployed in the arch. Surgery was performed in the hybrid operating room equipped with a universal floor-mounted angiographic C-arm system for fluoroscopic guidance during and after endograft deployment.

Intraoperative transesophageal echocardiography was used in all cases. All patients also underwent at least one form of intraoperative neuro-monitoring: intraoperative electroencephalogram, somatosensory-evoked potentials, and when available, cerebral oximetry using near-infrared spectroscopy.

Statistical Analysis and Follow-up Methods

All statistical comparisons were done using SPSS 19 (SPSS Inc, Chicago, Ill). Categorical variables were compared using Fisher's exact test. Continuous variables were compared using the Student *t* test. Long-term survival was monitored through the national Social Security Death Index and cumulative survival was calculated using Kaplan-Meier analysis. All patients were followed up postoperatively with regular contrast CTA imaging (at discharge, 30 days, 6 months, and yearly). Follow-up was 100% in all groups. Institutional review board approval was obtained.

RESULTS

From 2005 to the present, 36 type I and II hybrid arch operations were performed at the hospital of the University of Pennsylvania. Mean age was 70.7 ± 8 years; 23 (64%) were male (see Table 1 for demographics). Forty-two percent of the patients had prior stroke, 33% had previous myocardial infarction, and 81% had some history of smoking. Twenty-nine (81%) had aneurysmal disease of the aortic arch (mean aortic diameter, 7.1 ± 1.5 cm). Four had chronic aortic dissection; 2 had pseudoaneurysm of the aortic arch secondary to remote traumatic transection, and 1 had proximal degeneration in the setting of prior TEVAR (for descending aortic aneurysm). Surgical history (Table 2) included coronary artery bypass grafting ($n = 3$), patent foramen ovale repair ($n = 1$), type A dissection repair via sternotomy approach ($n = 1$), and thoracoabdominal aortic aneurysm repair ($n = 1$). Two patients had prior thoracic aortic endograft repairs: 1 had proximal degeneration of the prior repair, and 1 had a new unrelated saccular aneurysm in the mid arch.

Of the 28 type I hybrid arch repairs, 16 (57%) were done off CPB using a side-biting clamp on the ascending aorta for great vessel debranching. Twelve were done on CPB, with a mean time of 193 ± 58 minutes and a mean aortic cross-clamp time of 44 ± 27 minutes. In 18 (64%) patients the

FIGURE 1. Hybrid aortic arch repair, types I, II, and III.

TEVAR graft was deployed antegradely through the fourth limb of the aortic graft; 7 (25%) patients had concurrent retrograde TEVAR via the iliofemoral approach. Three (11%) patients did not have endografting during the same operation, but later in the same hospital stay using iliofemoral access. See Table 3 for a full enumeration of the intraoperative variables.

Eight patients did not have a suitable zone 0 for implantation of a thoracic endograft. In these patients, the ascending aorta was replaced to create a Dacron zone

0 landing zone. Therefore, these patients required full CPB and a short period of circulatory arrest for a simple open distal anastomosis, using both antegrade and retrograde cerebral perfusion strategies. Mean CPB time was 259 ± 54 minutes; mean crossclamp time was 121 ± 63 minutes. Mean circulatory arrest time for distal anastomosis was 19 ± 10 minutes, with an additional 45 ± 13 minutes of selective antegrade cerebral perfusion for arch debranching.

Thirty-day/in-hospital mortality was 3 (8%) of 36 for the entire group (Table 4). Mortality was 11% (n = 3) in the type I group and 0% in the type II group. Causes of death were all secondary to neurologic complications: 2 from spinal ischemia resulting in permanent paraplegia and 1 from complications of stroke. Although there have been no in-hospital deaths to date in patients with type II hybrid arch repairs, mortality and all other immediate postoperative

TABLE 1. Patient demographics

	All hybrids	Type 1	Type 2
Preoperative characteristics			
N	36	28	8
Age (y)	70.7 ± 8.0	69.3 ± 7.5	71.1 ± 8.3
Gender (N male)	23 (64%)	18 (64%)	5 (63%)
Prior CVA	15 (42%)	12 (43%)	3 (38%)
Chronic lung disease	14 (39%)	11 (39%)	3 (38%)
Prior MI	12 (33%)	9 (32%)	3 (38%)
Chronic renal insufficiency	6 (17%)	6 (21%)	0 (0%)
Smoker (current or history)	29 (81%)	23 (82%)	6 (75%)
Aortic disease			
Aneurysm	29 (81%)	25 (89%)	5 (63%)
Maximum diameter (mean, cm)	7.1 ± 1.5	7.1 ± 1.5	7.4 ± 1.4
Chronic dissection	4 (11%)	1 (4%)	3 (38%)
Failure of prior TEVAR	1	1	
Pseudoaneurysm (posttraumatic transection)	2 (6%)	2 (7%)	

CVA, Cerebrovascular accident; MI, myocardial infarction; TEVAR, thoracic endovascular repair.

TABLE 2. Surgical history

Surgical history	All hybrids	Type 1	Type 2
N	36	28	8
Redo sternotomy	5 (14%)	4 (14%)	1 (13%)
CABG	3 (8%)	2 (7%)	1 (13%)
Type A dissection repair	1 (3%)	1 (4%)	
PFO closure	1 (3%)	1 (4%)	
TEVAR	2 (6%)	1 (4%)	1 (13%)
TAAA	1 (3%)	1 (4%)	
AAA (open or EVAR)	5 (14%)	4 (14%)	3 (38%)

CABG, Coronary artery bypass grafting; PFO, patent foramen ovale; TEVAR, thoracic endovascular repair; TAAA, thoracoabdominal aortic aneurysm; AAA, abdominal aortic aneurysm; EVAR, endovascular repair.

TABLE 3. Intraoperative variables

Intraoperative	All hybrids	Type 1	Type 2
N	36	28	8
Off pump	16 (44%)	16 (57%)	
CPB time (m)	215 ± 64	193 ± 58	259 ± 54
Aortic crossclamp time (m)	70 ± 55	44 ± 27	121 ± 63
Circulatory arrest	7 (19%)		7 (87%)
Circulatory arrest time (total, m)			19 ± 10
SACP time for arch debranching (m)			45.0 ± 13
Number of stents implanted (median)	2	2	1.5
Adjunct CABG	7 (19%)	6 (21%)	1 (13%)
Adjunct valve repair/replace	2 (6%)	1 (4%)	1 (13%)
Two-branch reimplantation with carotid–left subclavian bypass	8 (22%)	7 (25%)	1 (13%)

CPB, Cardiopulmonary bypass; SACP, selective antegrade cerebral perfusion; CABG, coronary artery bypass grafting.

outcomes showed no significant difference between the 2 hybrid arch types (Table 4). Two (6%) of 36 patients had permanent paraplegia/paraparesis postoperatively, with an additional 5 (14%) of 36 having mild fully reversed transient neurologic events. Importantly, both cases of permanent paraplegia occurred during the first year of adopting this surgical modality.

Late type 2 endoleak (branch vessel) occurred in 1 patient, noted 3 years postoperatively. This patient had a type 1 hybrid arch repair for proximal degeneration of a prior TEVAR repair (with additional distal TEVAR for a distal type 1 endoleak in the same operation) and did not have full relining of the prior endograft repair. This patient did not undergo reintervention and died 6 years after the operation.

Follow-up was 30 ± 21 months. Late freedom from all-cause mortality was 71%, 60%, and 48% at 1, 3, and 5 years (N at risk = 22, 10, and 4), with 16 late patient deaths: all but 1 occurred in the type 1 hybrid group (Figure 2). Cumulative survival at 1 year for type II hybrids was 87% (N at risk = 3), better than type I hybrids (68%; N

TABLE 4. Postoperative outcomes

Outcomes	All hybrids	Type 1	Type 2	P (type 1 vs type 2)
N	36	28	8	
In-hospital mortality	3 (8%)	3 (11%)	0	.45
Stroke	3 (8%)	3 (11%)	0	.45
Permanent paraplegia	2 (6%)	2 (7%)	0	.6
Transient neurologic deficit	5 (14%)	3 (11%)	2 (25%)	.3
Renal failure	3 (8%)	3 (11%)	0	.45
Renal failure requiring new hemodialysis	1 (3%)	1 (4%)	0	.78
Reoperation for bleeding	1 (3%)	1 (4%)	0	.78
Atrial fibrillation	15 (42%)	11 (39%)	4 (50%)	.44
Mean hospital stay (d)	17.2 ± 14.0	16.3 ± 14.0	22.0 ± 9.6	.28

FIGURE 2. Midterm follow-up outcomes in type I and type II hybrids. Mean follow-up, 30 ± 21 months. Late stroke and endoleak rate, 0%. Aortic reoperation rate, 2.7%.

at risk = 19). Again, this difference did not rise to the level of statistical significance ($P = .244$). The aortic reoperation rate was 1 (2.8%) of 35: 1 patient required a reintervention for a retrograde type A dissection 155 days after a type I hybrid repair; the second repair was tolerated with no complications. Importantly, this single retrograde type A dissection was with a 42-mm barbed endograft for an ascending aortic diameter larger than 38 mm, which in our present algorithm is contraindicated unless a type II repair is performed.

DISCUSSION

Hybrid approaches for the treatment of aortic arch aneurysmal disease are being performed with increasing frequency. This is a reflection of the increasing comfort level of cardiovascular surgeons with endovascular technology and the improving technology of endovascular platforms, which permit successful landing of stent grafts in the proximal thoracic aorta. As the technology improves, it will be critical for the cardiovascular surgeon to be trained in advancing the field of hybrid aortic arch and ascending aorta operations. In addition, as the patient population with thoracic aortic disease seeking intervention gets older and older, embracing and honing these skills will be crucial. Although there is mounting evidence to suggest an important role for the hybrid approach for treating aortic arch disease, to this day there are no randomized trials or large non-randomized studies comparing hybrid arch procedures with conventional open surgical approaches. Interpretation of what data exist must be viewed in this context.

In addition to the operative mortality associated with complex operations such as aortic arch hybrid procedures, the Achilles heel of this intervention remains neurologic complications. Several groups have shown that arch hybrid procedures can be performed with acceptable mortality, with a very minimal postoperative and long-term endoleak

rate.^{9-11,13-16} However, neurologic complications, including stroke and spinal cord ischemia, remain a significant cause of morbidity and associated mortality in this cohort of patients. In a systematic review of hybrid arch operations in 1886 patients, pooled mortality was 10.8%, with 15.1% mortality in diseases that extended to the ascending aorta.¹³ Pooled stroke risk was 7%, with a pooled spinal cord ischemia rate of 7%, with no difference seen with respect to the extent of proximal ascending aortic involvement. In our series of 36 patients, mortality was 8% (n = 3), with all deaths seen in the type I hybrid arch group. Eight patients undergoing type II hybrid repair had no mortality.

The stroke rate was 8%, with a paraplegia rate of 5.5%. All 3 deaths in the cohort had associated neurologic complications (2 with paraplegia; 1 with stroke), underlying the significant morbidity and mortality associated with these devastating complications in aortic arch surgery. Of note, 42% of the patients in our study had a preoperative history of stroke. Twenty-nine of the 36 patients had atherosclerotic aneurysms, with 52% of the patients having high-grade atheroma or mobile atheroma. Atherosclerotic disease is a predictor of perioperative stroke, and the large cohort of patients with prior stroke and high-grade atheroma attests to the level of comorbid status in the arch hybrid group.^{17,18} When we compared our arch hybrid and open surgical arch cohorts, the rate of high-grade (grade ≥ 3) or mobile atheroma was significantly higher in the hybrid group (48% vs 6%). Several groups report stroke rates up to 12% in patients undergoing total arch repair of atherosclerotic aneurysms.^{3,11,17-19} Our study, in addition to others, suggests that the hybrid arch approach to atherosclerotic aneurysmal arch disease can be safely adopted with neurologic outcomes at least equivalent to those of conventional open repair.

A complication unique to the hybrid aortic arch cohort of patients, unlike the conventional open group, is the occurrence of endoleak. The reporting of endoleak rates with hybrid arch repair is not very thorough, with long-term follow-up data virtually absent. Endoleak rates have ranged from 0% to 15%.^{9-12,16-18} Similar to TEVAR, hybrid arch operations with type I and III endoleaks are associated with greater morbidity than those seen with type II endoleaks. In an article by Kotelis and associates,¹⁴ patients undergoing hybrid arch repair with zone 0 proximal landing had lower endoleak rates than with zone I landing. At our institution, we do not perform zone I proximal landing. All arch aneurysms are treated with zone 0 landing. In this study, the intraoperative endoleak rate was 5 (13.8%) of 36. All these patients underwent further endovascular re-intervention with a resulting postoperative endoleak rate of 0%. On late follow-up, 1 patient had a retrograde type A dissection develop from the proximal landing zone site. This case was undertaken during our fourth year of arch

hybrid operations, with the use of a TX2 device (Cook Medical, Bloomington, Ind). After this experience, we have stopped using the TX2 stent graft device for arch hybrid operations. We have adopted primarily the use of the Gore TAG device (W. L. Gore & Associates, Inc, Flagstaff, Ariz) and at times the Valiant device (Medtronic, Inc, Minneapolis, Minn). Since this switch, we have not had a retrograde type A dissection, and we have had no distal type B dissections in the arch aneurysm cases. In other series, in patients with endoleak, the aortic reoperation rate is increased. Our aortic reoperation rate is 1 (2.7%) of 36 (a retrograde type A dissection with the use of the TX2 device proximally) during the median midterm follow-up of 30 months.

Eight patients in this study underwent type II arch hybrid repair. Owing to the required ascending aortic reconstruction, all these patients had a period of circulatory arrest. Even though these patients had a more complex operation, postoperative and midterm outcomes in these patients have been excellent. Postoperative mortality, stroke, paraplegia, and endoleak rates were all 0%. One patient died during follow-up. Inasmuch as these cases were performed more recently, this may be a reflection of the increasing experience we gained with the hybrid arch platform. In line with this idea, since our first year of hybrid arch operations, the paraplegia and aortic reoperation rates have remained at 0% in the type I arch hybrid group as well, with a single postoperative death since then.

CONCLUSIONS

The hybrid approach to the treatment of aortic arch aneurysm continues to evolve, with an increasingly important role especially in patients with a high comorbid index and old age. On the basis of the arch and ascending aortic anatomy, this procedure can be performed without CPB. Midterm follow-up on these patients has shown that the technique can be safely adopted with a low aortic reoperation rate and with no delayed stroke and endoleak. The type II arch hybrid, which involves greater complexity, can also be safely adopted with good midterm outcomes. Further follow-up will attest to the validity of this technique in aortic arch surgery.

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