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Experience with Zone 2 Arch Replacement Followed by Thoracic Endovascular Aortic Repair

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Abstract

Background Transverse open aortic arch replacement remains a complex operation. A simplified arch replacement into zone 2, with debranching the head vessels proximally, creates a suitable landing zone for future endovascular repair and is increasing in popularity as of late. Still, limited data exist to assess contemporary rates of morbidity and mortality. Therefore, we aim to evaluate current outcomes for patients who underwent open zone 2 aortic arch replacement.

Methods All patients who underwent zone 2 arch replacement at a single academic institution from January 2019 to June 2023 were assessed. Indication for operation was either aneurysmal disease ($n = 37$), acute aortic syndrome ($n = 38$), or residual arch/descending thoracic aorta dissection ($n = 67$). Patient demographics and operative characteristics were evaluated, and the frequency of subsequent thoracic endovascular aortic repair (TEVAR) was noted. Mortality and major morbidity were then assessed.

Results A total of 142 patients underwent open zone 2 arch replacement. Median cardiopulmonary bypass, cross-clamp, and deep hypothermic circulatory arrest times for the entire cohort were 195, 122, and 36.5 minutes, respectively. Concomitant frozen elephant trunk was performed in 45.1% of the cohort ($n = 64$). In-hospital mortality was 7.8% ($n = 11$) for the entire cohort. Spinal cord ischemia occurred in 3.5% ($n = 5$); these patients all received frozen elephant trunks and had neurologic recovery by discharge. Stroke occurred in 9.2% ($n = 13$) of the study cohort. A total of 38.7% ($n = 55$) went on to get subsequent TEVAR, with median time to TEVAR of 52 days (8, 98.5).

Conclusion Zone 2 arch replacement allows staged repair of the thoracic aorta and readily accommodates future TEVAR therapy. This option for the treatment of the aortic arch can be performed safely in a wide variety of patient pathologies. Given the safety of this operation, cardiac surgeons should utilize this approach more frequently.

Keywords
- aorta
- arch
- TEVAR
- landing zone
- cardiac surgery
- arch replacement

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Introduction

Thoracic endovascular aortic repair (TEVAR) has greatly changed the management of thoracic aortic disease. TEVAR is now the primary therapy for most patients with aortic dissection and aneurysmal disease (AN) in the descending thoracic aorta (DTA) due to superior perioperative morbidity and mortality compared with open repair; long-term outcomes are encouraging as well.[1–5] With growing experience surrounding TEVAR, centers are performing more complex endovascular repairs more proximal in the aorta, sometimes even up to zone 0 (►**Fig. 1**). However, TEVAR in the aortic arch can be technically complicated, especially after prior DeBakey I aortic dissection.[6–9] Furthermore, in patients with genetic aortopathies, landing a TEVAR device in the native aortic arch confers a high risk of retrograde Type A aortic dissection—nearly 25% in some studies.[10,11] While there are reports of technical success in this population, it is in small cohorts and with limited follow-up.[12]

Open arch replacement is currently the gold standard for management of arch pathology, although it is a demanding operation that poses notable risks of neurologic injury and mortality to the patient.[13–16] Furthermore, the arch operation itself does not address the DTA (►**Fig. 2A, B**). One way to address this is with antegrade TEVAR under direct visualization, known as a “frozen elephant trunk” (FET). FET can be performed relatively quickly and safely, albeit with a slightly increased risk of spinal cord injury (SCI) due to coverage of the DTA.[17]

Our institution favors a multidisciplinary hybrid approach to treating complex disease in the aortic arch and proximal DTA. In patients with an unsuitable proximal landing zone in the aortic arch, we utilize a variation of the “classic” open transverse arch replacement. This technique involves a distal anastomosis into zone 2 of the arch, debranches the innominate artery (IA) and left common carotid artery (LCCA) more proximally on the arch, and establishes at least 3 cm of straight, parallel Dacron distal to the LCCA (►**Figs. 2C, –3**).[18] In addition, avoiding dissection of the distal-most arch allows for a more straightforward exposure, can reduce the risk of injury to the recurrent laryngeal nerve, and decreases circulatory arrest times.[18] Zone 2 arch replacement is increasing in popularity, and

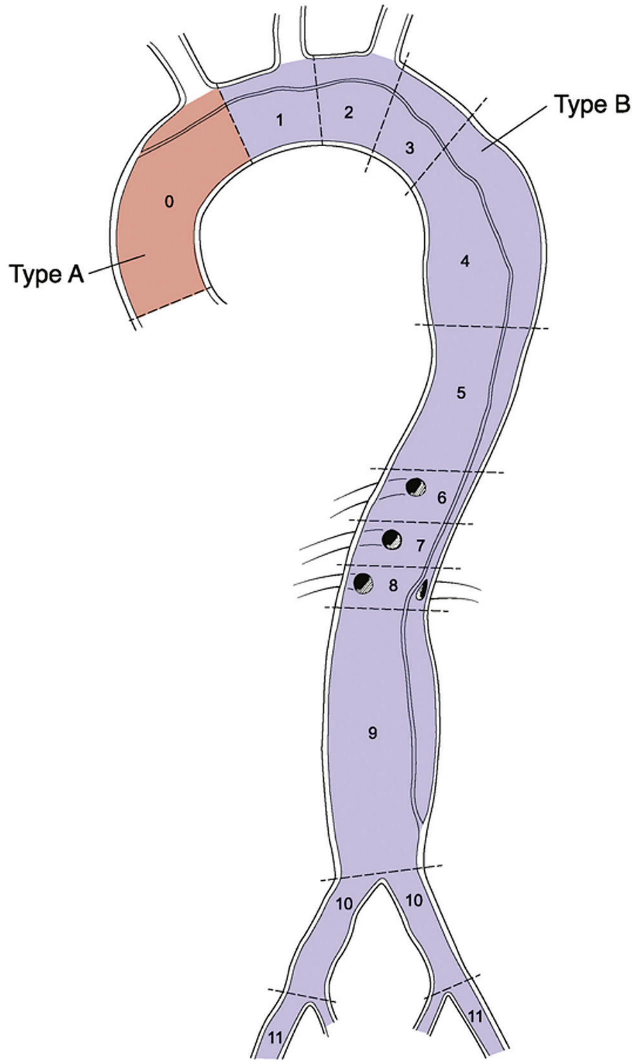

Fig. 1 Schematic of the zones of the aorta. Reproduced with permission from Lombardi et al.[9]

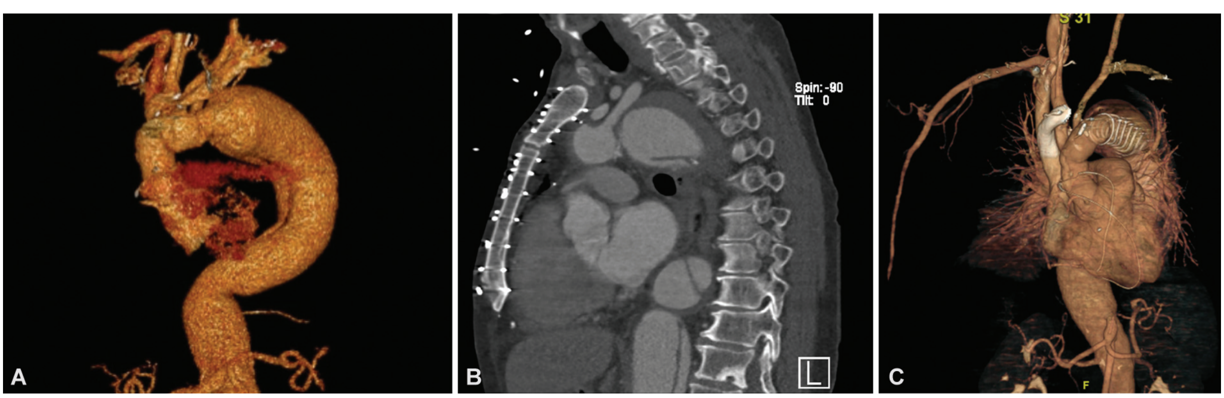

Fig. 2 Computed tomography (CT) scan of a patient who underwent a prior repair of a DeBakey I dissection with a “classic” zone 3 arch replacement (**A**). The residually dissected aorta grew in size, requiring repair. However, no landing zone was left behind, as the LSA is adjacent to the aneurysm (**B**), and all head vessels sit directly adjacent to one another. The patient thus required carotid-subclavian transposition, followed by redo zone 2 arch replacement and FET, with debranching of the IA and LCCA proximally on the arch (**C**). This is in preparation for a future open thoracoabdominal aneurysm repair. IA, innominate artery; FET, frozen elephant trunk; LCCA, left common carotid artery; LSA, left subclavian artery.

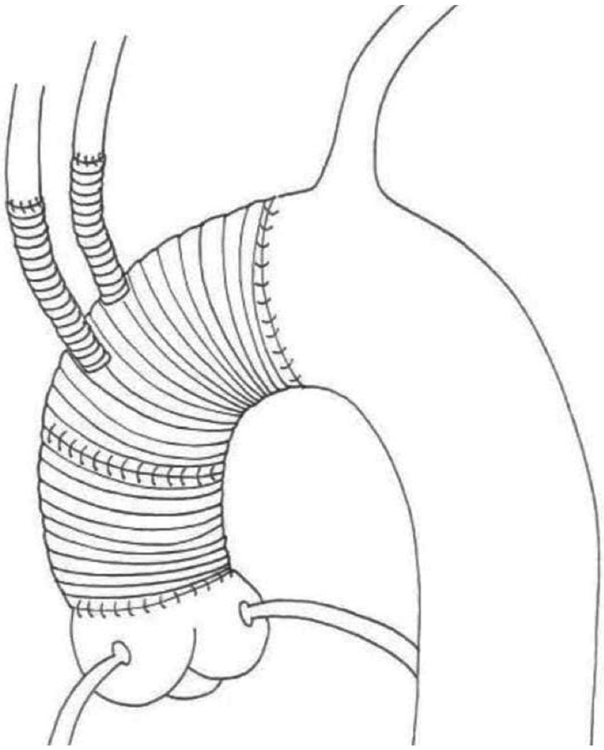

Fig. 3 Schematic of zone 2 arch replacement. Note that the IA and LCCA have been debranched more proximally onto the arch, and the presence of at least 3 cm of Dacron distal to the reimplanted head vessels. IA, innominate artery; LCCA, left common carotid artery.

small series have shown acceptable results, with low rates of mortality, stroke, and spinal cord injuries, although data are limited in larger cohorts.[18–20] This technique is amenable to either concomitant FET or subsequent TEVAR. Concomitant FET is especially useful in patients with large aneurysms in zones 3 to 4, patients with large tears in the distal arch that cannot be resected with a standard zone 2 arch and select patients with acute Type A dissection who are high risk for ongoing malperfusion despite arch replacement. The FET can then be extended with a TEVAR later, as well, depending on the anatomy of the distal aorta and presence of any further disease. However, in most patients, zone 2 arch replacement alone provides an appropriate landing zone for future TEVAR. This allows the patient to potentially avoid left subclavian transposition due to the growing utilization of single-branched arch endografts (►**Fig. 4**). Our institution is a relatively new, high-volume aortic center performing this operation as our primary arch operation, often with the goal of future staging. Hence, we sought to characterize our early outcomes for open zone 2 arch replacement, with the hypothesis that this operation can be done in a new, high-volume center with reasonable morbidity and mortality.

Materials and Methods

Cohort

Study was approved by the institutional review board (STUDY00014540, approved December 6, 2021). Patient consent for investigation and image publication was waived for this study. All patients who underwent a zone 2 arch replacement at a single academic institution from January 2019 to June 2023 were queried retrospectively for study inclusion. All patients under the age of 18 were excluded from analysis. Aortic dissections and reoperative sternotomies were included. This resulted in a final cohort size of 142 patients. This group was divided into three cohorts based on pathology: aneurysm (AN, $n = 37$), acute aortic syndrome (AAS, $n = 38$), and residual dissection (ResD, $n = 67$). Acute aortic syndrome included Type A dissection, ascending/arch intramural hematoma, and penetrating ascending/arch ulcer. Residual dissection included all Type B dissections and residual dissections after prior Type A repair. Chronic dissection was defined as greater than 14 days from date of dissection. Patients who were operated on within 24 hours after diagnosis/symptom onset were deemed as emergent. Patients who were operated after 24 hours but before

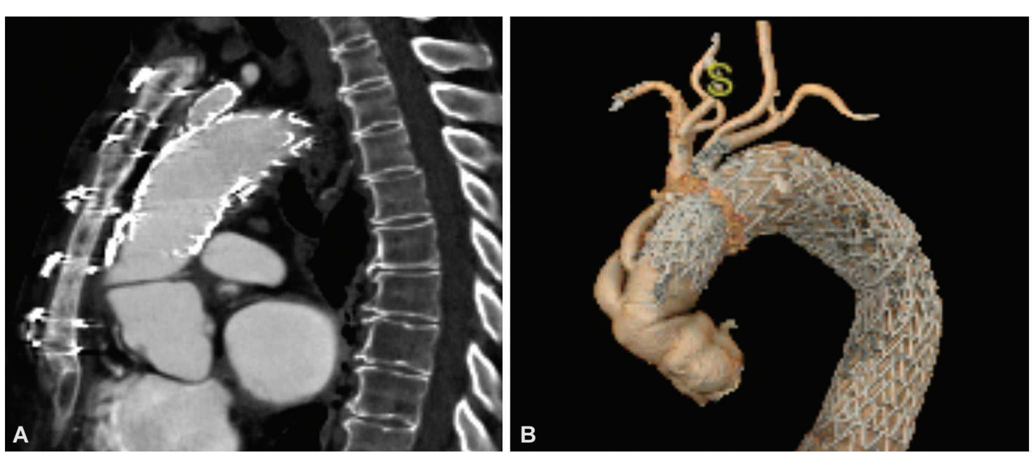

Fig. 4 Patient who underwent zone 2 arch replacement with subsequent single-branched arch endograft: sagittal CT imaging (**A**) and 3D CT reconstruction (**B**). The side branch was used to stent the LSA, obviating the need for cervical transposition or bypass. Note the proximal debranching of the IA and LCCA, thus creating an appropriate landing zone for the TEVAR. CT, computed tomography; LCCA, left common carotid artery; LSA, left subclavian artery; TEVAR, thoracic endovascular aortic repair.

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discharge were deemed as urgent. Two patients (one in the AN group and another in the ResD group) had a Type IA endoleak from a prior TEVAR prompting their arch replacement. Demographics, operative characteristics, perioperative outcomes, distal interventions, and mortality data were abstracted from the medical record. Median follow-up time after arch replacement was 405 days.

Operations

All surgeries were performed with a median sternotomy. Several patients also underwent left carotid-subclavian (CS) transposition either before, during, or after arch replacement. Preoperative transposition was performed in most elective patients, especially if they were undergoing arch replacement plus FET. Intraoperative and postoperative transposition were done for patients who required more urgent arch replacements. Options for arterial cannulation include central aortic, IA, or right axillary artery. Patients were placed on cardiopulmonary bypass (CPB), with deep hypothermic circulatory arrest (DHCA) utilized for portions of the arch replacement. Patients were cooled to anywhere from 18 to 28°C (depending on patient pathology and surgeon preference). Once DHCA was initiated, the aortic arch was resected into zone 2, and the LCCA and IA were "proximalized" with the use of a commercially prefabricated arch graft. Antegrade cerebral perfusion (ACP) was used on all patients during DHCA as a form of cerebral protection, with the perfusate running at 18°C at a flow rate of 10 mL/kg/min for a goal radial pressure of 50 to 60 mm Hg. Neuro monitoring was performed with near-infrared spectroscopy, along with bispectral index monitoring to ensure electroencephalogram silence. Some patients also had a brief initial period of retrograde cerebral perfusion during the circulatory arrest period prior to initiating ACP. Several patients had an FET done at the time of zone 2 arch replacement; if dissection was also present in the DTA, intravascular ultrasound was used to confirm true lumen placement of a wire, with transesophageal echocardiography as an adjunct. The wire was placed in the femoral artery and brought up into the arch prior to initiating bypass. The graft was then deployed antegrade during circulatory arrest. Subsequent TEVARs were performed in patients with residual dissections and distal aneurysms, including in preparation for total aortic reconstruction.

Statistics

Statistical analysis was performed in R version 4.2.2 for Windows (R Core Team 2022). Demographics, operative characteristics, distal interventions, and perioperative outcomes were summarized in tables using the mean ± standard deviation or median ± interquartile range for numeric variables, and count (%) for categorical variables.

Results

Demographics

Demographics are shown in ►**Table 1**. A total of 65.5% ($n = 93$) of the cohort was male. A total of 81% ($n = 115$) of the cohort were White, 7.8% ($n = 11$) were Black, 5.6% ($n = 8$) were of Asian descent, 2.1% ($n = 3$) were Native American, 0.7% ($n = 1$) were Hispanic or Latino, and 2.8% ($n = 4$) were of unknown ethnicity. The ResD group was 77.6% male ($n = 52$), and AN group 48.7% male ($n = 18$), and the AAS group 60.5% male ($n = 23$). The proportion of illicit drug use in the three groups was 18.4% ($n = 7$) in the AAS group, 2.7% ($n = 1$) in the AN group, and 3% ($n = 2$) in the ResD group.

Operative Details

Operative details are shown in ►**Table 2**. A total of 37.3% ($n = 53$) underwent prearch CS transposition, 7.8% ($n = 11$) underwent concomitant CS transposition, and 16.9% ($n = 24$) underwent postarch CS transposition. A total of 67.2% ($n = 45$) of the ResD had a prior sternotomy, as did 35.1% ($n = 13$) of the AN group and 2.6% ($n = 1$) of the AAS group. The AN and AAS cohorts most frequently utilized central cannulation (56.8% [$n = 21$] and 60.5% [$n = 23$], respectively), whereas the ResD cohort most often used axillary cannulation (62.7% [$n = 42$]). ACP was delivered most commonly through the right axillary artery in the ResD cohort (55.2%, $n = 37$), and the AN group more often used direct innominate cannulation (51.4%, $n = 19$). The AAS group had a near-equal utilization of innominate cannulation (31.6%, $n = 12$) and direct ostial cannulation of the carotids with balloon-tipped catheters (39.5%, $n = 15$). FET was utilized 65.7% ($n = 44$) of the time in the ResD group, 13.2% ($n = 5$) of the time in the AAS group ($n = 5$), and 40.5% ($n = 15$) of the time in the AN group. Median CPB, cross-clamp, and DHCA times for the entire cohort were 195, 122, and 36.5 minutes, respectively.

Perioperative Outcomes

Perioperative outcomes are shown in ►**Table 3**. The incidence of permanent cerebrovascular accident (CVA) in the entire cohort was 9.2% ($n = 13$), although the rate of CVA in the AN group was 5.4% ($n = 2$). No patient suffered permanent SCI after arch replacement; however, 3.5% ($n = 5$) of the entire cohort suffered a transient SCI that resolved by discharge. Those five patients all received a 15-cm FET at the time of arch replacement. Incidence of confirmed vocal cord dysfunction (with either fluoroscopy or laryngoscopy) after arch replacement was 7.75% ($n = 11$). No patient required dialysis by the time of discharge. Incidence of in-hospital mortality was 7.75% ($n = 11$). Median intensive care unit length of stay was 5 days in the ResD group, 3 days in the AAS group, and 3 days in the AN group. Twenty patients (14.1%) died over the study period.

Distal Interventions

Distal interventions are shown in ►**Table 4**. In the entire cohort, 55 patients (38.7%) underwent subsequent TEVAR. Median time to TEVAR was 52 days (8, 98.5). No patients in the AN or AAS group received an open thoracoabdominal repair, as opposed to 16.4% ($n = 11$) in the ResD group. Fenestrated or branched thoracoabdominal endografts were used almost exclusively in the aneurysm group: 18.9% ($n = 7$) in the AN group, 3.0% ($n = 2$) in the ResD group, and none in the AAS group.

Table 1 Preoperative demographics

Characteristic	Aneurysm ($n=37$)	Acute aortic syndrome ($n=38$)	Residual dissection ($n=67$)	Total ($n=142$)
Age at operation	66.08 (40.94, 72.21)	59.87 (47.69, 68.92)	61.26 (53.45, 68.64)	61.46 (48.47, 70.46)
Timing of zone 2 arch				
Elective	30 (81.08%)	0 (0%)	59 (88.06%)	89 (62.68%)
Urgent	5 (13.51%)	8 (21.05%)	6 (8.96%)	19 (13.38%)
Emergent	2 (5.41%)	30 (78.95%)	2 (2.99%)	34 (23.94%)
Male	18 (48.65%)	23 (60.53%)	52 (77.61%)	93 (65.49%)
Smoking				
Current	6 (16.22%)	10 (26.32%)	12 (17.91%)	28 (19.72%)
Former	17 (45.95%)	6 (15.79%)	28 (41.79%)	51 (35.92%)
Never	14 (37.84%)	20 (52.63%)	27 (40.3%)	61 (42.96%)
Alcohol				
None	20 (54.05%)	17 (44.74%)	26 (38.81%)	63 (44.37%)
Rare/social (1–7/wk)	15 (40.54%)	14 (36.84%)	34 (50.75%)	63 (44.37%)
Excessive (>8/wk)	2 (5.41%)	4 (10.53%)	7 (10.45%)	13 (9.15%)
Illicit drugs	1 (2.7%)	7 (18.42%)	2 (2.99%)	10 (7.04%)
HTN	30 (81.08%)	32 (84.21%)	63 (94.03%)	125 (88.03%)
Prior MI	3 (8.11%)	4 (10.53%)	4 (5.97%)	11 (7.75%)
Preop creatinine	0.84 (0.69, 1.05)	1.05 (0.84, 1.25)	1.02 (0.83, 1.24)	0.99 (0.78, 1.21)
Chronic lung disease	14 (37.84%)	4 (10.53%)	15 (22.39%)	33 (23.24%)
Preop EF				
≤35	1 (2.7%)	1 (2.63%)	1 (1.49%)	3 (2.11%)
36–54	6 (16.22%)	8 (21.05%)	13 (19.4%)	27 (19.01%)
≥55	25 (67.57%)	17 (44.74%)	50 (74.63%)	92 (64.79%)
Heart failure	6 (16.22%)	2 (5.26%)	12 (17.91%)	20 (14.08%)
Diabetes	5 (13.51%)	3 (7.89%)	5 (7.46%)	13 (9.15%)
Ethnicity				
American Indian or Alaska Native	1 (2.7%)	1 (2.63%)	1 (1.49%)	3 (2.11%)
Asian	1 (2.7%)	3 (7.89%)	4 (5.97%)	8 (5.63%)
Black	3 (8.11%)	2 (5.26%)	6 (8.96%)	11 (7.75%)
Hispanic	0 (0%)	0 (0%)	1 (1.49%)	1 (0.7%)
White	31 (83.78%)	31 (81.58%)	53 (79.1%)	115 (80.99%)
Unavailable or unknown	1 (2.7%)	1 (2.63%)	2 (2.99%)	4 (2.82%)
Height (cm)	170.29 ± 10.57	172.53 ± 10.8	176.41 ± 9.85	173.81 ± 10.55
Weight (kg)	76.29 ± 15.38	87.67 ± 20.59	94.79 ± 19.47	88.1 ± 20.18
BAV	3 (8.11%)	2 (5.26%)	6 (8.96%)	11 (7.75%)

Abbreviations: BAV, bicuspid aortic valve; EF, ejection fraction; HTN, hypertension; MI, myocardial infarction.

Discussion

Treating disease in the aortic arch and subsequently establishing an adequate proximal landing zone for future TEVAR can be challenging (►**Fig. 2**). Our institutional approach to open arch replacement creates at least 3 cm of straight, parallel Dacron in zone 2 of the aorta. This procedure can be performed with acceptable morbidity and mortality in a variety of pathologies, including elective aneurysms, acute aortic syndrome, and chronic residual Type B dissections,

Table 2 Operative characteristics

Characteristic	Aneurysm ($n=37$)	Acute aortic syndrome ($n=38$)	Residual dissection ($n=67$)	Total ($n=142$)
Prior sternotomy (%)	13 (35.14%)	1 (2.63%)	45 (67.16%)	59 (41.55%)
Arterial cannulation				
Central	21 (56.76%)	23 (60.53%)	22 (32.84%)	66 (46.48%)
Femoral	0 (0%)	3 (7.89%)	0 (0%)	3 (2.11%)
Axillary	15 (40.54%)	9 (23.68%)	42 (62.69%)	66 (46.48%)
Innominate	1 (2.7%)	3 (7.89%)	3 (4.48%)	7 (4.93%)
Venous cannulation				
Central	33 (89.19%)	37 (97.37%)	62 (92.54%)	132 (92.96%)
Femoral	4 (10.81%)	1 (2.63%)	5 (7.46%)	10 (7.04%)
ACP strategy				
Axillary	14 (37.84%)	8 (21.05%)	37 (55.22%)	59 (41.55%)
Balloon catheters	4 (10.81%)	15 (39.47%)	7 (10.45%)	26 (18.31%)
Innominate cannulation	19 (51.35%)	12 (31.58%)	15 (22.39%)	46 (32.39%)
Other	0 (0%)	2 (5.26%)	1 (1.49%)	3 (2.11%)
Combination	0 (0%)	1 (2.63%)	7 (10.45%)	8 (5.63%)
Proximal extent of repair				
Supracoronary graft/STJ anastomosis	25 (67.57%)	25 (65.79%)	51 (76.12%)	101 (71.13%)
Wheat	3 (8.11%)	3 (7.89%)	5 (7.46%)	11 (7.75%)
Bentall	7 (18.92%)	4 (10.53%)	9 (13.43%)	20 (14.08%)
David	2 (5.41%)	6 (15.79%)	2 (2.99%)	10 (7.04%)
AVR type				
Wheat				
Bio	3 (100%)	3 (100%)	4 (80%)	9 (81.82%)
Mechanical	0 (0%)	0 (0%)	1 (20%)	1 (9.09%)
Bentall				
Bio	5 (71.43%)	3 (75%)	7 (77.78%)	15 (75%)
Mechanical	2 (28.57%)	1 (25%)	2 (22.22%)	5 (25%)
Valve repair	2 (5.41%)	0 (0%)	3 (4.48%)	5 (3.52%)
CABG	5 (13.51%)	2 (5.26%)	3 (4.48%)	10 (7.04%)
Other valve operation				
None	36 (97.3%)	37 (97.37%)	67 (100%)	140 (98.59%)
Mitral	1 (2.7%)	1 (2.63%)	0 (0%)	2 (1.41%)
Tricuspid	0 (0%)	0 (0%)	0 (0%)	0 (0%)
FET	15 (40.54%)	5 (13.16%)	44 (65.67%)	64 (45.07%)
Cross-clamp time	119 (92, 138)	140.5 (102.25, 196)	119 (98.5, 147)	122 (97.25, 154.75)
CPB time	182 (161, 204)	207 (174.25, 268.75)	199 (171.5, 226)	195 (170.25, 229.25)
DHCA time	31 (28, 35)	41 (33, 49.75)	39 (32.5, 49.5)	36.5 (31, 47.75)
Lowest temperature	24 (20, 24)	18 (18, 22)	22 (18, 24)	22 (18, 24)
Prearch CS transposition/bypass	13 (35.14%)	1 (2.63%)	39 (58.21%)	53 (37.32%)
Concomitant CS transposition/bypass	5 (13.51%)	0 (0%)	6 (8.96%)	11 (7.75%)
Postarch CS transposition/bypass	3 (8.11%)	11 (28.95%)	10 (14.93%)	24 (16.9%)

Abbreviations: ACP, antegrade cerebral perfusion; AVR, aortic valve replacement; CABG, coronary artery bypass grafting; CPB, cardiopulmonary bypass; CS, carotid-subclavian; DHCA, deep hypothermic circulatory arrest; FET, frozen elephant trunk; STJ, sinotubular junction.

Table 3 Perioperative outcomes and mortality

Characteristic	Aneurysm ($n = 37$)	Acute aortic syndrome ($n = 38$)	Residual dissection ($n = 67$)	Total ($n = 142$)
Transient neuro deficit	1 (2.7%)	1 (2.63%)	0 (0%)	2 (1.41%)
Permanent CVA	2 (5.41%)	4 (10.53%)	7 (10.45%)	13 (9.15%)
Transient SCI	1 (2.7%)	0 (0%)	4 (5.97%)	5 (3.52%)
Permanent SCI	0 (0%)	0 (0%)	0 (0%)	0 (0%)
Prolonged vent	6 (16.22%)	9 (23.68%)	16 (23.88%)	31 (21.83%)
Trach	0 (0%)	1 (2.63%)	4 (5.97%)	5 (3.52%)
New dialysis				
Temporary	1 (2.7%)	2 (5.26%)	4 (5.97%)	7 (4.93%)
Persisted after discharge	0 (0%)	0 (0%)	0 (0%)	0 (0%)
None	36 (97.3%)	36 (94.74%)	63 (94.03%)	135 (95.07%)
Wound infection	2 (5.41%)	1 (2.63%)	3 (4.48%)	6 (4.23%)
Postop atrial fibrillation	14 (37.84%)	14 (36.84%)	22 (32.84%)	50 (35.21%)
Pneumonia	4 (10.81%)	6 (15.79%)	15 (22.39%)	25 (17.61%)
Postop pacemaker	1 (2.7%)	1 (2.63%)	0 (0%)	2 (1.41%)
Postop vocal cord dysfunction				
After zone 2 arch	4 (10.81%)	2 (5.26%)	5 (7.46%)	11 (7.75%)
After CS	0 (0%)	0 (0%)	4 (5.97%)	4 (2.82%)
None	33 (89.19%)	36 (94.74%)	58 (86.57%)	127 (89.44%)
ICU days	3 (1, 6)	3 (2, 6)	5 (2.5, 11)	4 (2, 8)
Hospital LOS	11 (9, 16)	11 (8.25, 19)	12 (9, 22)	11 (9, 18.75)
Dispo				
Home	33 (89.19%)	25 (65.79%)	50 (74.63%)	108 (76.06%)
SNF	2 (5.41%)	6 (15.79%)	4 (5.97%)	12 (8.45%)
Rehab	0 (0%)	4 (10.53%)	7 (10.45%)	11 (7.75%)
Death	2 (5.41%)	3 (7.89%)	6 (8.96%)	11 (7.75%)
30-d mortality	3 (8.11%)	3 (7.89%)	3 (4.48%)	9 (6.34%)
30-d readmit	4 (10.81%)	3 (7.89%)	10 (14.93%)	17 (11.97%)
Follow-up since operation (mo)	9.86 (4.14, 24.08)	10.78 (3.68, 26.84)	14.92 (4.34, 32.84)	13.31 (3.91, 29.01)
Died	7 (18.92%)	6 (15.79%)	7 (10.45%)	20 (14.08%)
Time to death (d)	67 (36.5, 122)	168.5 (13, 398.25)	15 (11.5, 58.5)	49 (15, 158)

Abbreviations: CS, carotid-subclavian; CVA, cerebrovascular accident; ICU, intensive care unit; LOS, length of stay; SCI, spinal cord injury; SNF, skilled nursing facility.

Table 4 Distal interventions

Characteristic	Aneurysm ($n = 37$)	Acute aortic syndrome ($n = 38$)	Residual dissection ($n = 67$)	Total ($n = 142$)
TEVAR	11 (29.73%)	13 (34.21%)	31 (46.27%)	55 (38.73%)
Time arch to TEVAR (d)	60 (3.5, 97.5)	37 (8, 90.25)	52 (14, 103)	52 (8, 98.5)
F/BEVAR	7 (18.92%)	0 (0%)	2 (2.99%)	9 (6.34%)
Arch endograft	6 (16.22%)	1 (2.63%)	5 (7.46%)	12 (8.45%)
Open thoracorepair	0 (0%)	0 (0%)	11 (16.42%)	11 (7.75%)

Abbreviations: F/BEVAR, fenestrated or branched thoracoabdominal endografts; TEVAR, thoracic endovascular aortic repair and is becoming increasingly standard across centers performing open aortic surgery. Overall, the cohort experienced a stroke rate of 9.2%. This is at least partially driven by surgeon experience; 66.7% ($n = 10$) occurred within the first year of each surgeon's practice. ACP strategy and lowest temperature during circulatory arrest were similar between patients who experienced a stroke and patients who did not experience a stroke. Furthermore, our stroke rate compares favorably with other reported stroke rates for open arch replacement, ranging from 5 to 14% in the literature.[13,21,22] Patients who underwent subsequent TEVAR were treated within a median of 52 days from their arch replacement.

Currently, perioperative outcomes for contemporary open arch replacement are similar to small series for arch endografts.[13–16,18–24] However, these endograft series involve specially selected patients, which were performed as part of clinical trials and may not be reproducible. As endovascular outcomes continue to improve, a higher proportion of arch disease will be treated with TEVAR. Careful evaluation of these patients in a multidisciplinary setting with cardiology, cardiac surgery, and vascular surgery is thus required to safely address complexities present in many of these cases. The data from our study revealed that in appropriate patients—even those with complex arch pathology—staging with upfront open aortic surgery in a high-volume aortic center can be done safely in preparation for subsequent TEVAR. Furthermore, landing an endovascular device in Dacron is certainly preferrable to short or ectatic native landing zones—and perhaps even preferrable to healthy native aortic tissue, although this requires further investigation. Staging also limits the amount of aortic coverage with each procedure, potentially reducing spinal cord risk compared with a more extensive single operation. Finally, in patients with genetic aortopathies, TEVAR placement in native arch confers significant risk for iatrogenic entry tears and late degeneration.[10–12]

Multiple strategies exist to either treat the DTA at the time of arch replacement or provide a landing zone for future TEVAR; the zone 2 arch replacement is just one option that is becoming increasingly popular, partially due to its technical feasibility. Isolated arch debranching with proximalization of the head vessels remains a viable option for those patients in whom arch surgery is not feasible or desirable, and while this technique is less commonly performed in the modern era, it allows for zone 0 TEVAR.[25] Traditional arch with FET provides both therapy to the DTA and a stable landing zone for future endovascular operations.[17] Modern variations of the FET have taken this a step further and now include techniques for stenting various head vessels to proximalize the FET as far as zone 0, all with promising results.[25–29] These include techniques and products such as B-SAFER (branched stented anastomosis frozen elephant trunk repair), SAVSTEB (stent-bridging of the supra-aortic vessel anastomoses), the FET-LSSB (FET with left subclavian side branch), and the E-vita open ZERO (zone 0 multibranched FET).[26–29]

Management of aortic arch pathology requires constant evolution as emerging technologies become available. Our technique evolved over the study period in several ways. Early in our experience, all patients undergoing zone 2 arch replacement received a CS transposition, in preparation for either FET at the time of arch replacement or subsequent TEVAR. While the frequency of complications for transposition is low at our institution (incidence of vocal cord dysfunction was 2.8% [$n = 4$]), this can be a difficult operation at lower-volume centers, with recurrent nerve injury rates as high as 7.5% in some series.[30,31] Furthermore, our 3.5% rate of SCI events, while temporary, were all associated with the use of a 15-cm FET. With the commercial availability of branched arch endografts, a shift in practice toward using zone 2 deployment of these devices with endografting of the left subclavian artery has occurred whenever feasible. The creation of 3 cm landing zone with no concern of encroaching on the head vessels (►**Fig. 4**) also allows for the inclusion of many patients who would be otherwise excluded from this approach due to a short landing zone in zone 2 and likely provides more durability by landing into surgical graft as opposed to native tissue. Furthermore, avoiding the need for a cervical transposition and FET reduces the number of interventions the patient undergoes, the risk of central neurologic injury, and the risk of recurrent laryngeal nerve injury. Currently, our use of cervical transposition and FET are limited to specific anatomic concerns, including those with dissected subclavian arteries beyond the vertebral takeoff, or with iliac vessels which are insufficient caliber. When employed, a shorter endograft (typically 10 cm) is used for the FET to minimize risk of SCI, unless specific anatomic factors favor a 15-cm device, such as a large distal arch aneurysm, or a large zone 3 to 4 fenestration with concern for endograft malposition into false lumen.

There are notable limitations to this study. Our study only reports outcomes after zone 2 arch replacement; the study does not include outcomes after subsequent TEVAR, and only 39% underwent future TEVAR therapy. Furthermore, the study period is only 4.5 years, with a median follow-up of 405 days. Long-term outcomes for modern open arch surgery are necessary, especially as arch TEVAR is being utilized in younger populations and more complex aortic disease. Studies with larger sample sizes are currently underway, comparing staged zone 2 arch replacement/TEVAR outcomes with isolated arch TEVAR. However, as branched arch devices increase in popularity, it is as critical to compare outcomes between open arch/TEVAR/transposition and open arch/branched endograft therapies, as well.

Conclusion

In summary, as TEVAR continues to expand into the aortic arch, difficulties in establishing a stable proximal landing zone will arise more frequently. Zone 2 arch replacement is another strategy that allows for staged repair of the thoracic aorta and readily accommodates future TEVAR therapy. This safe and effective option for the treatment of the aortic arch provides a solution for patients without sufficient healthy parallel aorta for standard TEVAR. Given the safety of this operation, cardiac surgeons should continue to utilize this approach more frequently, especially when aortic pathology extends into the distal arch, or when an ectatic arch precludes a durable repair with TEVAR alone, thus avoiding Type 1A endoleaks and use of TEVAR outside of the intended instructions for use.

Conflict of Interest

S.Z. serves as a scientific advisor for W.L. Gore (Newark, DE). The other authors have no conflict of interest to report.

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