ORIGINAL PAPER

Nagoya J. Med. Sci. **87**. 558–572, 2025
doi:10.18999/nagjms.87.3.558

Midterm results of aortic arch replacement with frozen elephant trunk for chronic dissecting aortic aneurysm involving the aortic arch

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ABSTRACT

We performed total aortic arch replacement (TAR) with a frozen elephant trunk (FET) for chronic dissecting aortic aneurysm (DAA) involving the aortic arch as the initial surgery and carefully observed these aortic findings with periodic computed tomography (CT) follow-up. Additional surgical interventions were considered when aortic events were observed. Midterm outcomes were evaluated to clarify the feasibility of this strategy. Thirty-seven patients underwent TAR with FET between 2014 and 2020. The median follow-up period was 48.6 months. There was 1 case of operative mortality (2.7%) and 11 late deaths, including five aortic-related deaths. Aortic events occurred in 26 patients (72.2%), including 14 cases of stent-induced new entry (SINE), eight cases of aneurysmal enlargement, two cases of graft infection, and one each of additional aortic dissection and aortic root enlargement. Thirty-one procedures were performed, including 14 open surgeries, 16 thoracic endovascular aortic repairs (TEVAR), and 1 endovascular aortic repair (EVAR) with coil embolization. The freedom rate from aortic events was 36.9% at three years and 22.8% at five years. The distal aortic arch showed significant shrinking (slope, –1.96; $P<0.001$), but the lower descending aorta showed significant enlargement (slope, 0.87; $P<0.001$). The diameter of the middle descending aorta was a predictor of SINE (>40.5 mm) and aneurysm enlargement (>40.2 mm). The present study showed acceptable early outcomes but frequent aortic events during follow-up. Cautious periodic CT is mandatory to perform additional reinterventions at the proper time, and scheduled surgical intervention, including TEVAR, is essential for cases with enlarged middle descending aortas.

Keywords: chronic aortic dissection, open stent graft, stent induced new entry, aortic events

Abbreviations:
DAA: dissecting aortic aneurysm
TAR: total aortic arch replacement
FET: frozen elephant trunk
CT: computed tomography
SINE: stent graft-induced new entry
TEVAR: thoracic endovascular aortic repair

Received: December 17, 2024; Accepted: March 17, 2025
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HR: hazard ratio

INTRODUCTION

Surgical repair of chronic dissecting aortic aneurysm (DAA) involving the aortic arch remains challenging because of the extended range of diseases (eg, chronic non-A non-B type DAA or chronic DAA after ascending aortic replacement for acute type A DAA).[1] One-stage surgery from the aortic arch to the thoracoabdominal aorta can be performed via median sternotomy with left thoracotomy; however, these surgeries are associated with great surgical risk.[2] Staged surgery with total aortic arch replacement (TAR) followed by secondary descending or thoracoabdominal aortic repair can decrease the surgical risk; however, aortic events may occur while waiting for the second surgery. The European Society of Cardiology (ESC) guidelines suggest that TAR with frozen elephant trunk (FET)[3] may be a valuable alternative for selected patients.[4] FET introduces blood flow into the true lumen and may close the proximal entries of the false lumen. It may function as a radical surgery for chronic DAA, similar to how stent grafts can be used for entry closure in subacute type B DAA. Therefore, we developed a strategy for staged surgery for chronic DAA involving the aortic arch. TAR with FET is performed as the initial surgery and careful observation of these aortic findings is achieved with periodic follow-up computed tomography (CT). When any aortic event is observed, we consider performing additional surgical interventions, including thoracic endovascular aortic repair (TEVAR).

Frozenix (Japan Lifeline Co Ltd, Tokyo, Japan), an open stent graft, has been commercially available in Japan[5] since July 2014. Herein, we review our clinical experiences, including survival, aortic events, and changes in aortic findings, of patients who underwent TAR with Frozenix for chronic DAA involving the aortic arch. This retrospective observational study evaluated the feasibility of our surgical strategy.

METHODS

Patients

This retrospective observational study was conducted at Nagoya University Hospital and was approved by the Institutional Review Board (Nagoya University Graduate School of Medicine IRB 655-2). A total of 37 consecutive patients underwent TAR with FET using Frozenix for chronic DAA involving the aortic arch at Nagoya University Hospital from September 2014 to March 2020. There were 29 males and 8 females with a median age of 65.0 (lower and upper quantile [q1–q3], 57–69 years). Twenty-eight patients had received ascending aortic replacement for acute type A DAA, six had chronic type B DAA (defined as non-A non-B type DAA), and the other three had chronic type A DAA. The median period from the previous surgery or the onset of aortic dissection to the present surgery was 66.6 (q1–q3, 26.2–96.5) months.

Data collection

Procedural and postoperative outcomes were collected from hospital charts. Follow-up data were obtained from hospital charts, physicians who managed the patients during follow-up, or directly from the patients. Postoperative outcomes, including various postoperative complications, were defined according to Japan Cardiovascular Surgery Database (JCVSD) protocols.[6] Thirty-day mortality was defined as death for any reason within 30 days of the procedure. Operative

mortality was defined as 30-day mortality and death within any time interval following surgery among patients who were yet to be discharged from the hospital. Major morbidity was defined as new neurological dysfunction that continued for >72 h, reoperation for any reason, need for mechanical ventilation for >24 h after surgery, renal failure (blood creatinine >2.0, need for dialysis), or deep sternal wound infection. Transient neurological dysfunction was defined as dysfunction that completely recovered within 72 h, regardless of the radiological findings.

Surgical procedure

We defined an aortic diameter >55 mm as a surgical indication. We principally performed TAR with FET for chronic DAA involving the aortic arch; however, it is not suitable in the presence of the following anatomical features: multiple entries, multiple false lumens, or an extremely shrunken true lumen of the descending aorta. We performed TAR and descending aortic replacement via median sternotomy and left thoracotomy in 3 cases and TAR with fresh elephant trunk in 2 cases with these such anatomical features during the same clinical period.

TAR with FET was performed via median sternotomy under hypothermic circulatory arrest with selective cerebral perfusion (SCP) at a nasopharyngeal temperature of 25 °C. The aortic arch vessels were reconstructed with a four-branched main graft in 18 patients and a 3-branched synthetic graft with a main graft in 19 patients. The proximal aortic arch was opened principally at the orifice of the brachiocephalic artery and a Frozenix device was inserted into the true lumen of the descending aorta and deployed under circulatory arrest. A guidewire was used in 8 cases.

The Frozenix size was selected based on the preoperative CT findings. The diameters were set to be approximately 10% larger than the diameter of the true lumen of the descending aorta in the deployed range. Because the true lumen generally has an elliptical shape, the average of the major and minor axes of the elliptical shape was taken as the diameter of the true lumen. They were 21 mm in 2, 23 mm in 3, 25 mm in 5, 27 mm in 8, 29 mm in 14, 31 mm in 2, 35 mm in 1, 37 mm in 2). The Frozenix length was set to reach the straight portion of the descending aorta, but its distal end was principally placed above the aortic valve level. In some early cases, the non-stented portion was lengthened to reach the straight portion; however, the non-stented portion was shortened in other cases.

Follow-up protocol

Periodic CT follow-up is routinely performed within one month and six months and then every year thereafter. The aortic diameters, including the true and false lumens, were measured at the distal arch, middle (at the pulmonary hilus), and lower portion (above the diaphragm) of the descending aorta and upper abdominal aorta (at the level of the celiac artery). Changes of >5 mm were defined as statistically significant. A diameter >60 mm with continuous enlargement of the descending or thoracoabdominal aorta was defined as aneurysmal enlargement, and additional surgical intervention was performed. Re-intervention is also indicated for cases of stent graft-induced new entry (SINE), defined as any new entry related to FET. SINE occurs either symptomatically or silently; in the former cases, SINE was diagnosed using enhanced CT and TEVAR was principally performed, while in the latter cases, SINE was diagnosed based on findings of periodic CT examinations. Any changes in the aortic shape, diameter, or stent position on plain CT were confirmed on enhanced CT, and elective TEVAR was performed (Figure 1). Aortic events were defined as SINE, aneurysmal enlargement, rupture, or reintervention for any aortic pathology. All deaths were noted. Aortic event-related mortality was defined as the mortality related to aortic events.

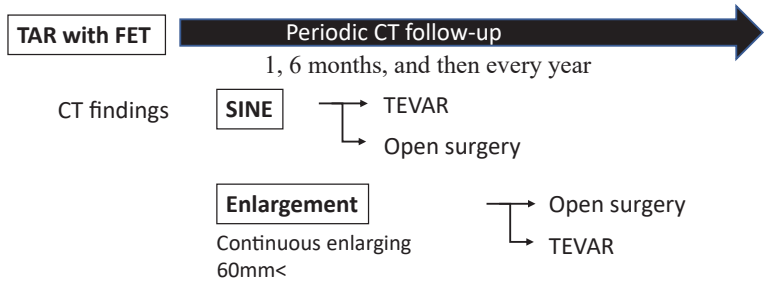

Fig. 1 Follow-up protocol

TAR: total arch replacement
FET: frozen elephant trunk
SINE: stent-induced new entry
TEVAR: thoracic endovascular aortic repair
CT: computed tomography

Statistical analyses

Continuous variables were assessed for the fit of a normal distribution using the Shapiro-Wilk test and expressed as the median and interquartile range. Categorical variables were presented as numbers and percentages. Survival and freedom from aortic events were analyzed for midterm outcomes using the Kaplan-Meier method with a log-rank test and Wilcoxon's test. Aortic events during the midterm follow-up period were a major concern in this surgical strategy. Risk factors for aortic events were assessed mainly based on preoperative CT examination findings using a Cox proportional hazards model. Cutoff values were determined using receiver operating characteristic (ROC) analysis. The risk stratification model according to the diameter of the middle descending aorta was assessed using a Cox proportional hazards model. A mixed linear model was employed to evaluate the changes over time in the aortic diameter of the distal arch, middle and lower portion of the descending aorta, and the upper abdominal aorta to account for the variation in individual aortic diameters. The model was fitted using the restricted maximum likelihood method, and *P*-values were obtained using Satterthwaite's degrees-of-freedom method. Statistical significance was set at $P < 0.05$. Statistical power was calculated using the null hypothesis setting as a standard normal distribution.

Statistical analyses for the Kaplan-Meier method and Cox proportional hazards model were performed using SPSS Statistics software (version 28.0; IBM, Armonk, NY, USA). Analyses and visualization of the mixed linear model were conducted[7-10] using the R packages lme4, lmerTest, and ggplot2 in R version 4.1.1.

RESULTS

Patient characteristics

The baseline patient characteristics are shown in Table 1. Most patients had hypertension (51.4%) and there was a high incidence of hyperlipidemia (24.3%) and diabetes mellitus (13.5%). Five patients (13.5%) had a history of stroke and had a relatively high surgical risk (Logistic European System for Cardiac Operative Risk Evaluation [EuroSCORE], 21.5%; Euroscore II, 4.7%).

Table 1 Patient characteristics

Preoperative characteristics (n=37)	
Age, years, median (q1–q3)	65.0 (57–69)
Male, n (%)	29 (78.4%)
Pathology	
Post ascending aorta replacement, n (%)	28 (75.7%)
Chronic type A, n (%)	3 (8.1%)
Chronic type B, n (%)	6 (16.2%)
Duration from the previous surgery or the onset, month, median (q1–q3)	66.6 (26.2–96.5)
Hypertension, n (%)	19 (51.4%)
Hyperlipemia, n (%)	9 (24.3%)
History of stroke, n (%)	5 (13.5%)
Diabetes mellitus, n (%)	5 (13.5%)
Renal failure, n (%)	10 (27.0%)
Hemodialysis, n (%)	4 (10.8%)
Connective tissue disease, n (%)	4 (10.8%)
Logistic Euroscore/Euroscore II	21.5%/4.7%
Operative variables	
Operation time, min, median (q1–q3)	570 (450–675)
CPB time, min, median (q1–q3)	262 (216–313)
Cardiac arrest time, min, median (q1–q3)	128 (100–173)
SCP time, min, median (q1–q3)	153 (122–184)
Lower body ischemic time, min, median (q1–q3)	66 (51–77)
Lowest temperature, °C, median (q1–q3)	24.8 (23.5–25.8)
Perfusion site: Asc. Ao., femoral a., left subclavian a.	13, 20, 13 (individual, 4; with femoral a., 9)
Graft: 4 branched main graft, a 3-branched graft	18 (48.6%), 19 (51.4%)
FET length: 60 mm, 90 mm, 120 mm, n (%)	3 (8.1%), 15 (40.5%), 19 (51.4%)
FET diameter, mm, median (q1–q3)	29 (25–29)
FET landing position, median (q1–q3)	Th7.0 (Th6.5–Th8)
FET/true lumen diameter, median (q1–q3)	1.15 (1.06–1.23)
SG/descending aorta angle, °, median (q1–q3)	12.0 (7.3–19.3)

q1: lower quantile
q3: upper quantile
CPB: cardiopulmonary bypass
SCP: selective cerebral perfusion
FET: frozen elephant trunk
SG: stent graft
Asc. Ao.: ascending aorta
femoral a: femoral artery
Euroscore: European System for Cardiac Operative Risk Evaluation

There were 4 cases of connective tissue disease (eg, Marfan syndrome). Concomitant procedures included the David procedure (n=1), the Bentall procedure (n=2), aortic valve surgery (n=4), and coronary artery bypass grafting (n=1).

Mortality

The early clinical outcomes are summarized in Table 2. There was no 30-day mortality, but 1 patient (2.7%) died in the hospital due to stroke. The midterm clinical outcomes of the 36 total cases, excluding one early mortality, are summarized in Table 2 and Figure 2. Late death occurred in 11 cases, including aortic-related death in five cases (aneurysmal rupture, n=3; aorto-esophageal fistula, n=2). Aneurysmal rupture included refusal to undergo staged surgery, SINE, and abdominal aortic aneurysmal rupture after descending aorta replacement due to infection (n=1 for each). Six non-aortic-related deaths occurred (necrotic pancreatitis, myocardial infarction, cerebral hemorrhage, peritonitis, septicemia, and unknown in one each). The 3- and 5-year survival rates were 83.3% and 65.7%, respectively (Figure 3).

Table 2 Early and mid-term results

Early outcomes (n=37)	
30-day mortality, n (%)	0 (0%)
Operative mortality, n (%)	1 (2.7%)
ICU stay, days, median (q1–q3)	7.3 (1–35)
Hospital stay, days, median (q1–q3)	33 (13–82)
Prolonged ventilation (>24 hr), n (%)	16 (43.2%)
Stroke, n (%)	6 (16.2%)
Re-sternotomy for bleeding, n (%)	3 (8.1%)
Deep sternum infection, n (%)	3 (8.1%)
Gastro-intestinal complication, n (%)	2 (5.4%)
Reoperation for graft infection, n (%)	1 (2.7%)
Paraplegia, n (%)	1 (2.7%)
Perioperative myocardial infarction, n (%)	1 (2.7%)
Hemodialysis required, n (%)	0 (0%)
Mid-term mortality (n=36)	
Follow-up period, months, median (q1–q3)	48.6 (32–65)
All causes of death, n (%)	11 (30.6%)
Aortic mortality, n (%)	5 (13.9%)
Aortic rupture, n (%)	3 (8.3%)
Aorto-esophageal fistula after reintervention, n (%)	2 (5.6%)
Other causes of death, n (%)	6 (16.7%)
Stroke, n (%)	1 (2.8%)
Myocardial infarction, n (%)	1 (2.8%)
Sepsis, n (%)	1 (2.8%)
Peritonitis, n (%)	1 (2.8%)
Pancreatitis after reintervention, n (%)	1 (2.8%)
Unknown, n (%)	1 (2.8%)

ICU: intensive care unit
q1: lower quantile
q3: upper quantile

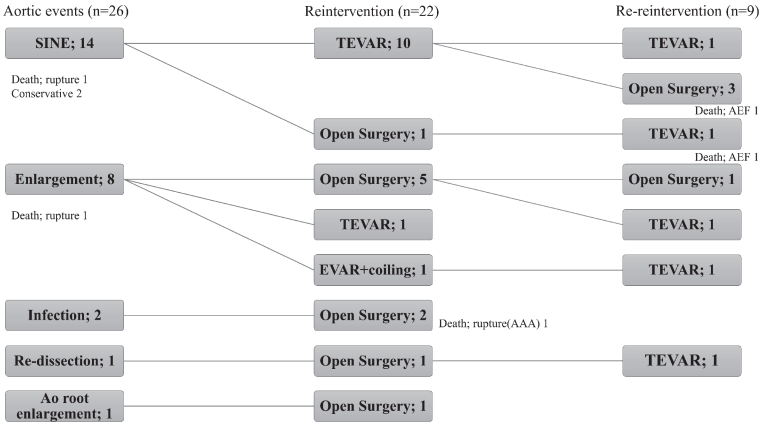

Fig. 2 Causes of re-intervention for aortic events

SINE: stent-induced new entry
TEVAR: thoracic endovascular aortic repair
EVAR: endovascular aortic repair
AEF: aorto-esophageal fistula
AAA: abdominal aortic aneurysm
Ao: aortic

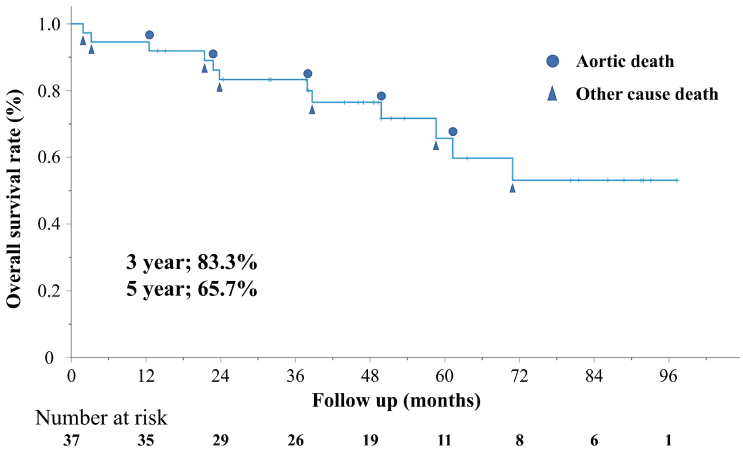

Fig. 3 The overall survival rates

Closed triangles and closed circles indicate aortic-related deaths and other causes of death, respectively.

Early morbidity

Major postoperative complications included stroke (n=6, 16.2%), re-sternotomy for bleeding (n=3, 8.1%), deep sternal infection (n=3, 8.1%), perioperative myocardial infarction (n=1, 2.7%), and graft infection requiring whole graft replacement (n=1, 2.7%). Late paraplegia was observed in 1 patient (2.7%) on postoperative day 4; however, the symptoms completely recovered after spinal cord fluid drainage. The Rankin scale score at hospital discharge was severely compromised in four patients with stroke.

Midterm aortic events

Thirty-six cases, with the exception of 1 case of operative mortality, were followed up completely. The last follow-up point was August 2022, and all patients were followed for more than two years, with the exception of the above-mentioned case. The median follow-up period was 48.6 (q1–q3, 32–65) months. Aortic events occurred in 26 patients (72.2%), including SINE (n=14, 38.9%), aneurysmal enlargement (n=8, 22.2%), graft infection (n=2, 5.6%), additional aortic dissection (n=1, 2.8%) and aortic root enlargement (n=1, 2.8%). Aortic re-intervention was required in 22 (61.1%) patients, including three scheduled early stage operations, and another nine (25.0%) patients received a third intervention (Figure 2). These 31 procedures included open surgery in 14 patients, TEVAR in 16 patients, and endovascular aortic repair (EVAR) with coil embolization in 1 patient. A second open surgery was performed in 10 cases due to enlargement in five cases, infection in two cases, SINE, aortic re-dissection, and aortic root enlargement in one case each. Third, open surgeries were performed in four cases (enlargement in three and graft infection in one). These 14 open surgeries included descending aorta replacement in five cases, thoracoabdominal aorta replacement in six cases, re-TAR in two cases, and aortic root replacement in one case. TEVAR was performed in 16 cases (second intervention in 11 and third intervention in 5), including SINE in 12 cases, enlargement in 3, and re-dissection in 1 case.

SINE occurred in 14 patients, and two showed aortic rupture. One patient was rescued with emergent TEVAR, but the other patient died before the intervention. The other 12 cases were non-symptomatic and diagnosed with periodic CT, and re-intervention was performed electively in 10 cases (TEVAR in 9 and open surgery in 1 Marfan case), and 2 cases were followed-up conservatively. Aortic events due to aneurysmal enlargement were observed in eight cases, including aortic rupture in two. One patient was rescued by emergent open surgery, while the other died because of refusal to undergo surgery. The other six patients underwent re-intervention. The 3- and 5-year rates of freedom from aortic events were 36.9% and 22.8%, respectively (Figure 4).

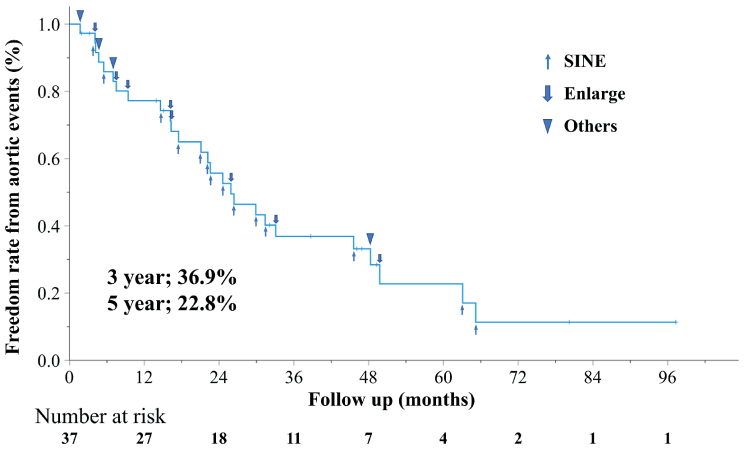

Fig. 4 Freedom rates from aortic events

The up arrow, down arrow, and down triangle indicate stent-induced new entry (SINE), additional intervention for aneurysmal enlargement, and other aortic events, respectively.

Changes in aortic findings

The aortic diameter was measured periodically in all cases except one case of early mortality and one case in which the descending aorta was replaced previously. The mixed linear model revealed estimated lines in Figure 5, and the equations were as follows: aortic diameter (mm) = –1.96 × year + 54.8, distal aortic arch; aortic diameter = 0.02 × year + 45.7, middle descending aorta; and aortic diameter = 0.87 × year + 41.1, lower descending aorta. The distal aortic arch revealed significant shrinking (slope, –1.96; 95% confidence interval [CI], –2.64 to –1.25; $P<0.001$) and the lower descending aorta showed significant enlargement (slope, 0.87; 95% CI, 0.51 to 1.22; $P<0.001$); however, the middle descending aorta showed no significant changes (slope, 0.02; 95% CI, –0.50 to 0.54; $P=0.936$). The statistical power was 0.9998 for the distal aortic arch, and 0.9980 for the lower descending aorta.

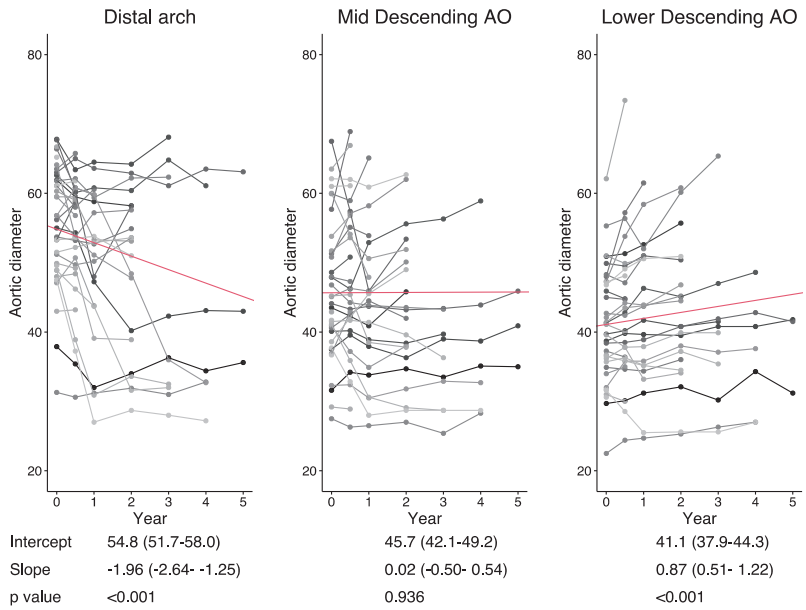

Fig. 5 Changes in the aortic diameter

Left, the distal aortic arch; center, the middle descending aortas; right, the lower descending aortas. The red line is an estimated line calculated with a mixed linear model. The intercept, slope, and *P* value are shown below the figure.

AO: aortic

Obvious changes in the diameter (<5 mm) were classified as follows: reduced distal aortic arch (n=10, 29%), unchanged (n=24, 68%), enlarged (n=1, 3%), reduced middle descending aorta (n=6, 17%), unchanged (n=23, 66%), enlarged (n=6, 17%), reduced lower descending aorta (n=1, 3%), unchanged (n=28, 80%), and enlarged (n=6, 17%). TAR with FET frequently shrank the distal aortic arch, but hardly influenced the middle descending aorta and enlarged the lower descending aorta. False lumen thrombosis was observed on the distal arch in 86% of the cases, but only in 16% of the cases in the lower descending aorta (Table 3).

Table 3 Changes of aortic findings

	Distal aortic arch	Middle descending aorta	Lower descending aorta
Change of diameter (5mm=<)			
Reduced, n (%)	10 (29%)	6 (17%)	1 (3%)
No change, n (%)	24 (68%)	23 (66%)	28 (80%)
Enlarged, n (%)	1 (3%)	6 (17%)	6 (17%)
False lumen thrombosis			
Preoperative, n (%)	2 (5%)	3 (8%)	2 (5%)
Latest, n (%)	32(86%)	14 (38%)	6 (16%)

Predictor of aortic events on the preoperative and the first postoperative CT findings

The following factors were used as predictors: aortic diameter; false-to-true lumen ratio; false lumen thrombosis at the distal arch, middle and lower descending aorta, and upper abdominal aorta; angle between the stent and aorta; position (lower descending, upper, and lower abdominal aorta); size (the maximum value); and number of re-entries.

SINE was observed in 14 patients. The preoperative middle descending aorta diameter was identified as a risk factor for SINE (hazard ratio [HR], 1.123; P=0.004). The cut-off value of the middle descending aorta diameter was determined to be 40.5 mm. There were eight cases of aneurysmal enlargement. The preoperative middle descending aortic diameter was also identified as a risk factor (HR, 1.157; P=0.009). The cut-off value was determined to be 40.2 mm.

Re-entries remained after surgery in all but 2 cases (average number 5.9); however, the position, size, and number of re-entries were not significant predictors of SINE or aneurysmal enlargement. Additionally, the false-to-true lumen ratio and false lumen thrombosis showed no significant influence on the risk of SINE or enlargement. However, distal arch thrombosis had a low HR for aneurysmal enlargement (HR, 0.109; P=0.051). This finding suggests a tendency toward a negative predictor of aneurysmal enlargement (Table 4).

In the risk stratification model, the incidence of aortic events increased as the diameter of the middle descending aorta increased (<39 mm, HR, 1; 40–49 mm, HR, 6.35, P=0.0174; 50 mm<, HR, 10.03, P=0.0082; Table 5).

Table 4 Predictor of aortic events on the preoperative and the first postoperative CT findings

Variable	SINE		Enlargement	
	HR (95% CI)	*P* value	HR (95% CI)	*P* value
Diameter				
Distal arch	1.017 (0.955–1.083)	0.606	1.079 (0.981–1.186)	0.116
Middle descending aorta	1.123 (1.037–1.216)	**0.004**	1.157 (1.037–1.292)	**0.009**
Lower descending aorta	1.057 (0.971–1.152)	0.202	1.097 (0.985–1.223)	0.093
True/Aorta area				
Distal arch	0.569 (0.004–81.49)	0.824	0.032 (0.000–161.7)	0.429
Middle descending aorta	0.175 (0.006–5.040)	0.309	0.161 (0.001–28.12)	0.488
Lower descending aorta	0.159 (0.004–5.980)	0.321	0.047 (0.000–54.06)	0.395
SG/Aorta angle	1.015 (0.993–1.037)	0.194	0.947 (0.863–1.038)	0.243
False lumen thrombosis				
Distal arch	1.874 (0.157–103.0)	1	0.109 (0.007–1.249)	0.051
Middle descending aorta	2.553 (0.492–15.30)	0.281	0.142 (0.003–1.405)	0.091
Lower descending aorta	1.606 (0.116–16.68)	0.631	1.040 (0.018–13.50)	1
Re-entries				
Position	0.809 (0.362–1.807)	0.605	1.183 (0.430–3.258)	0.745
Size	1.164 (0.945–1.434)	0.154	1.072 (0.877–1.311)	0.498
Number	0.979 (0.796–1.204)	0.841	0.868 (0.665–1.132)	0.296

Values are presented as hazard ratio (95% confidential interval).
CT: computed tomography
HR: hazard ratio
SINE: stent graft induced new entry
True/Aorta area: true rumen and aorta area ratio
SG/Aorta angle: the angle between the stent and aorta

Table 5 Risk stratification model according to middle descending aorta diameter

Variable	Middle descending aorta diameter				
	<39 mm	40–49 mm		50 mm<	
	HR (95% CI)	HR (95% CI)	*P* value	HR (95% CI)	*P* value
SINE (n=14)	1	N/A	N/A	5.785 (0.812–41.23)	0.0798
Enlargement (n=8)	1	3.385 (0.659–17.36)	0.1438	N/A	N/A
Aortic events (n=26)	1	6.35 (1.84–29.13)	0.0174	10.03 (1.816–55.36)	0.0082

Values are presented as hazard ratio (95% confidential interval).
HR: hazard ratio
SINE: stent graft induced new entry
N/A: not available

DISCUSSION

The present study showed relatively good early mortality, but frequent aortic events during the follow-up period. Our surgical strategy has contributed to good early clinical results; however, the midterm outcomes need to be improved. We identified risk factors for aortic events during follow-up and considered preventive measures.

SINE and aneurysmal enlargement are two major factors associated with aortic events. SINE occurred in 14 cases (38.9%) in our series, which is in line with previous reports[11-14] and was mainly treated with TEVAR. A preoperative mid-descending aorta diameter of >40.5 mm was a predictor of SINE. The intimal flap may be vulnerable in cases of large-diameter DAA. Downstream TEVAR following FET was reported to be effective in preventing SINE.[15] Considering the results of the present study, we recently performed downstream TEVAR in patients with an enlarged descending aorta. However, indications for downstream TEVAR remain controversial. The present study suggested that a preoperative middle descending aorta diameter >40.5 mm was the cut-off value for SINE, which may be a reasonable value for downstream TEVAR. The anatomy of the true lumen, where the FET was deployed, may be associated with SINE. We believe that SINE occurs more easily in the curved portion than in the straight portion, owing to the spring-back force of the FET.[16] Although the angle between the stent and aorta was not a significant predictor of SINE, FET length should be sufficient to reach the straight portion of the descending aorta. The strong radial force of the FET is another cause of SINE; therefore, we tried to keep the FET size below 110% of the true lumen diameter.[17]

Preemptive TEVAR is recommended for subacute DAA to reduce late mortality; however, its efficacy in chronic DAA remains controversial. TEVAR is associated with significant early benefits for chronic DAA; however, these benefits are not sustained in the midterm after TEVAR.[18] A meta-analysis demonstrated that the relative risk of SINE incidence in chronic aortic dissection is three times higher than that in acute aortic dissection.[19] The present study showed that an enlarged middle descending aorta was a predictor of SINE and aneurysmal enlargement, and that the incidence of aortic events increased as the middle descending aorta diameter increased. Considering these results, TAR with FET for chronic DAA should be recommended in the earlier phase to prevent subsequent aortic events. These results are also in line with those of preemptive

TEVAR for subacute type B aortic dissection.[20]

FET can guide blood flow only into the true lumen and may induce false lumen thrombosis. This can cause slight shrinkage of the residual false lumen in the descending aorta, and may allow additional intervention to be postponed under cautious follow-up with periodic CT examinations. However, obvious enlargement was observed in the distal aortic arch (3%), middle descending aorta (17%), and lower descending aorta (17%). Conversely, clear aortic shrinkage was observed in the distal arch (29%), middle descending aorta (17%), and lower descending aorta (3%). The mixed linear model revealed significant aortic shrinkage in the distal aortic arch and enlargement of the lower descending aorta. However, no significant changes were observed in the middle descending aorta. FET, which can close proximal entries but cannot affect distal re-entries, may thus affect the distal aortic arch, but hardly influence the middle and lower descending aorta.

Aneurysmal enlargement was observed in eight cases, and a preoperative mid-descending aorta diameter of >40.2 mm was a predictive factor. We performed an early scheduled staged surgery for three patients with severely enlarged middle and lower descending aortas. However, given the above-mentioned results, a scheduled staged intervention should be recommended for all cases with enlarged middle and lower descending aortas. In addition, a second-stage operation should not be postponed when the diameter of the descending or abdominal aorta increases.

We believe that the operative mortality rate of 2.7% in our cohort was acceptable, considering that three-quarters of the cases involved redo sternotomy after ascending aorta replacement. Spinal cord injury is another concern with FET; however, there was no complete spinal cord injury in this study. The FET was placed above the aortic valve. This may protect against spinal cord injury. We consider TAR with FET to be a useful strategy for reducing the early surgical risk of chronic DAA involving the aortic arch. However, six cases (16.2%) in our cohort were complicated by stroke, which may have been caused by embolic events. Therefore, further measures are necessary to protect the brain.

According to a national survey conducted by the Japanese Association for Thoracic Surgery in 2018, 2,344 operations were performed for chronic Type B DAA. FET with branch reconstruction was performed in 212 cases, while thoracoabdominal aortic repair was performed in 212 cases, with hospital mortality rates of 2.8% and 7.5%, respectively.[21] Although these cases were not identical to those in our cohort, the early outcomes of surgery using FET may be reasonable.

However, the use of FET in patients with Marfan syndrome remains controversial.[22] The present cohort included four cases with Marfan syndrome, with two patients experiencing aortic events after surgery. While the rate of aortic events showed no significant differences between Marfan and non-Marfan cases, we usually use a fresh elephant trunk for patients with Marfan syndrome who are expected to require a second-stage operation within a couple of months.

Limitations

Several limitations of the present study warrant mention. First, this was a retrospective observational clinical study with a relatively small number of patients. Second, the pathophysiology of chronic DAA during surgery was not identical among all cases. Finally, the indication for TAR with FET was determined independently at the institutional conference, and the timing of the additional intervention was determined experimentally.

CONCLUSION

The early outcomes of TAR with FET for chronic DAA involving the aortic arch were

acceptable; however, aortic events occurred in >70% of cases during the follow-up period. The FET shrank the distal aortic arch significantly; however, the lower descending aorta was enlarged. SINE and aneurysmal enlargement are the two major causes of aortic events. Enlargement of the middle descending aorta was a predictor of SINE (>40.5 mm) and aneurysmal enlargement (>40.2 mm). Cautious periodic follow-up CT is mandatory to perform additional reinterventions at the proper time, and scheduled surgical intervention, including downstream TEVAR, is essential for cases with severely enlarged middle and lower descending aortas.

DECLARATIONS

Conflict of interest

The authors declare no conflicts of interest.

Funding

The authors did not receive support from any organization for the submitted work.

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