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Distal Repair After Total Aortic Arch Replacement With Frozen Elephant Trunk in Patients With Chronic Multilevel Thoracic Aortic Disease

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Short title: Distal Aortic Repair After Frozen Elephant Trunk

WHAT THIS PAPER ADDS

Total arch replacement with the frozen elephant trunk was associated with a peri-operative mortality of 10.1% (elective 8.4%, non-elective 13.7%). One stage repair was achieved in 46.8% of patients, but late distal failure occurred in 21%. Where there was no primary distal seal, further repair was ultimately indicated in 84% of patients, but performed in only 70% of these with no associated mortality. Earlier distal endovascular repair and better assessment of patient fitness may help reduce the interval mortality from rupture and the proportion of patients who are turned down for the second stage.

Objective: To examine the management of distal aortic disease after total arch replacement with the frozen elephant trunk (TAR + FET) in patients with chronic thoracic aortic disease.

Methods: Two centre retrospective study of consecutive patients treated between January 2010 and December 2019. Primary endpoint was 30 day/in hospital mortality. Secondary end point was mid-term survival. Data are presented as median (IQR). Chi squared or Fisher's exact test was used as appropriate. Estimated survival (standard error) was assessed by the calculating Kaplan–Meier product limit estimator with right censoring of survival data. A *p* value of < .050 was considered to be statistically significant. STROBE guidelines were followed.

Results: A total of 158 patients (72 men; median age 70, IQR 64, 75; median distal aortic diameter 58 mm (46, 68; 127 aneurysmal disease, 31 chronic dissection) underwent TAR + FET. Peri-operative mortality was 10.1% (9/107 elective, 7/51 non-elective). Of 74 (46.8%) patients with a primary distal seal, seven (9.5%) died peri-operatively, distal seal was maintained during follow up in 51, nine underwent late distal repair (two planned, seven unplanned; one open, eight endovascular; one peri-operative death) with a median interval to unplanned repair of 777 days (462, 1480), and seven with loss of seal had no intervention. Distal seal failed in 2/28 (7%) patients with a distal seal length > 30 mm and device oversizing > 10%, compared with 12/39 (31%) patients who did not meet these criteria (*p* = .031). In 84 patients without primary distal seal, nine (10.7%) died peri-operatively, the distal aorta remained below the size threshold for repair during follow up in 12 patients, 44 had distal repair (median aortic diameter 64 mm, 60, 75; eight open, one hybrid, 35 endovascular repairs; no mortality) at a median of 256 days (135, 740), and 19 did not have distal repair at the end of the follow up period: six died before planned repair at a median interval of 115 days (85, 120); eight were considered unfit; one was assessed as fit but declined; and four patients were awaiting assessment). Median follow up was 46 months (26, 75): no patients were lost to follow up. Estimated ± standard error five year survival was 61.5 ± 4.1%: elective 70.6 ± 4.7%, non-elective 43.2 ± 7.2%.

Conclusion: TAR + FET achieved primary distal seal in 47% of patients, but late failure occurred in 21% of patients. Distal repair was ultimately indicated in 84% of survivors without primary distal seal

and of these 70% underwent repair, almost 10% died before planned repair, and 13% were considered unfit. Earlier distal endovascular repair and better assessment of patient fitness may improve mid-term outcomes.

Keywords: Distal repair, Frozen elephant trunk, Total arch repair

INTRODUCTION

A two stage open repair is the traditional approach for extensive proximal and distal thoracic aortic disease,[1] but a significant proportion of patients do not undergo distal repair because of death after the first stage or in the interval between stages, or a decline in their fitness.[2–5] Unlike total arch replacement (TAR) with a conventional floating trunk, the frozen elephant trunk (FET) technique has the advantage of achieving a primary distal seal in anatomically suitable patients thereby avoiding a second-stage procedure. Patients with more extensive distal disease still require a second stage repair which is increasingly performed using endovascular techniques in those with favourable anatomy.[6–14] The aim of the present study was to examine the early and mid-term outcomes of TAR + FET with emphasis on the management of distal aortic pathology.

MATERIALS AND METHODS

The Strengthening the Reporting of Observational Studies in Epidemiology (STROBE) guidelines were followed in preparing the manuscript.[15] This was a retrospective, two centre case series using routinely collected data conducted within the clinical audit framework; no intervention was performed, and patients were not contacted outside their routine clinical care. Specific ethics approval was not required, and patient consent was not sought in line with guidance from the UK Health Research Authority and UK Policy Framework for Health and Social Care Research (www.hra-decisiontools.org.uk).

Study cohort

Prospectively maintained databases were interrogated from two cardiovascular centres in the United Kingdom (University Hospitals Birmingham, and Liverpool Heart and Chest Hospital). Data were collected for 158 consecutive patients who underwent TAR + FET for chronic multilevel thoracic aortic disease between January 2010 and December 2019. During the study period, a total of 138 patients with multilevel aortic disease underwent aortic arch repair using alternative techniques, and 68 patients treated with TAR + FET were excluded from analysis (Table 1).

Pre-operative assessment and patient selection

All patients were discussed in a multidisciplinary team meeting consisting of cardiothoracic aortic surgeons, vascular and endovascular surgeons, interventional radiologists, and adult congenital cardiologists. Open and endovascular treatment options were considered before a decision was reached to proceed with TAR + FET. The diameter threshold for elective distal aortic repair in patients without heritable thoracic aortic disease (HTAD) was 60 mm regardless of operative approach or pathology.[16] In HTAD, elective distal repair was assessed using aortic diameter and body surface area with intervention considered at a diameter $\geq$ 50 mm. The principal selection criteria for treatment were patients with multilevel thoracic aortic disease (1) with the potential to achieve a one stage repair, and (2) to provide a stable platform for planned or anticipated distal aortic repair. In asymptomatic patients, fitness assessment included biochemical/haematological analysis, echocardiography, and pulmonary function testing. Coronary angiography was performed in selected elective patients. In non-elective patients, fitness assessment was tailored according to the urgency of repair.

Procedural details

All TAR + FET procedures were performed through a median sternotomy using cardiopulmonary bypass with deep hypothermic circulatory arrest. Cerebral protection was achieved with two vessel selective antegrade cerebral perfusion, and cerebral near infrared spectroscopy monitoring.

Commercially available devices were used in all patients: E-Vita Open (Plus) (Jotec GmbH, Hechingen, Germany) (*n* = 51), and Thoraflex (Terumo Aortic, Inchinnan, UK) (*n* = 107). The supra-aortic vessels were revascularised using a combination of inclusion patches and bypass grafts. The stent graft component of the prosthesis was 100 mm (*n* = 5), 130 mm (*n* = 7), 150 mm (*n* = 106), and 160 mm (*n* = 40) in length and the anastomosis between the proximal cuff of the FET and the native aorta was in zones 0 (*n* = 11), 1 (*n* = 1), 2 (*n* = 52), and 3 (*n* = 94). Additional cardiovascular procedures were performed in 61 patients: 23 coronary artery bypasses; 21 aortic root replacements, of which two were valve sparing; 15 aortic valve replacements and one resuspension; four aberrant right subclavian artery reconstructions; one tricuspid valve repair; and two synchronous thoracic endovascular aortic repair (TEVAR).

Post-operative follow up

All patients had computed tomographic angiography (CTA) of the entire aorta in the peri-operative period when clinically stable. On discharge from hospital, all patients were entered into a surveillance programme. Images were transferred electronically from referring centres and patients reviewed in the outpatient clinic if further intervention was required.

Definitions and data collection

The DeBakey classification was used to define the extent of aortic dissection. Established criteria were used to confirm the diagnosis of HTAD. Aortic rupture was defined by the finding of fresh blood in the chest at operation or demonstrated on CTA.

The following data were retrieved: demography, comorbidity, operative details and duration, adjunctive procedures, staging approach, early (30 day) mortality and major complications, unplanned re-interventions, total hospital and critical care length of stay, patient survival, and re-intervention during follow up. In hospital mortality was defined as any death prior to hospital discharge. Post-operative permanent stroke (cerebrovascular accident [CVA]) was defined as new

focal neurological (motor or sensory) deficit persistent at the time of discharge. Permanent spinal cord ischaemia (SCI) was defined as the inability to weight bear or walk unaided (paraplegia, Grade 3 SCI). All cases of suspected SCI were confirmed by a neurologist and magnetic resonance imaging of the spinal cord was performed to confirm the diagnosis prior to transfer for rehabilitation. Major non-fatal complications were defined as early re-operation, respiratory failure requiring tracheostomy, renal replacement therapy (RRT), permanent SCI and permanent CVA.

The primary endpoint was in hospital mortality. Secondary endpoints were survival and freedom from distal aortic re-intervention. Follow up ended and data were exported for analysis on 31 December 2021. No patients were lost to follow up. Survival status was verified by cross-referencing local electronic patient records with the NHS wide mortality database (Primary Care Mortality Database, Spine, NHS Digital) derived from death records from the Office for National Statistics. This NHS database holds the administrative data for all deaths within the United Kingdom. The cause of death was not available in many of the patients. Patients who lived far from the two institutions were followed up by the referring centre which informed us of any late complications and/or re-interventions and transferred CTA images electronically for assessment.

Statistical analysis

This was performed using R environment (version 4.0.3, The R Foundation for Statistical Computing, Vienna, Austria; https://www.r-project.org). Continuous variables were presented as median (IQR), and categorical data were presented as proportions/counts. Student's t-test and Wilcoxon rank sum test were used to analyse continuous data, and chi-squared or Fisher's exact test was used to analyse categorical data as appropriate. The effect size was presented as odds ratio (OR) with 95% confidence interval (CI). Overall survival was assessed by calculating Kaplan–Meier product limit estimator with right censoring of survival data. Median follow up was reported as the observed follow up in all subjects (irrespective of outcome). Survival was presented as estimated proportion surviving with

standard error (SE). Multivariable analysis of association of demographic, anatomical and clinical parameters with in hospital mortality and overall survival was conducted using logistic regression and Cox proportional models. Variable selection into the models was performed using stepwise algorithm with step () function. A *p* value of < .050 was considered to be statistically significant.

RESULTS

Patients

A total of 158 patients underwent TAR + FET for chronic multilevel thoracic aortic disease. Demographic details and prior aortic repairs are shown in Tables 2 and 3, respectively.

Early outcome after total arch replacement with the frozen elephant trunk

The overall in hospital mortality was 10.1% (*n* = 16): 8.4% (9/107) after elective and 13.7% (7/51) after non-elective repair (Table 4). The overall 30 day mortality was 7.6% (*n* = 12); 5.6% (6/107) after elective and 11.8% (6/51) after non-elective repair. Major complications occurred in 53 (37%) operative survivors and included early re-operation (*n* = 26), tracheostomy (*n* = 24), vocal cord palsy (*n* = 7), transient (*n* = 10), and permanent CVA (*n* = 4), temporary SCI (*n* = 5; all patients were ambulant unaided on discharge), temporary RRT (*n* = 15), and permanent RRT (*n* = 1). The indications for early re-operation were intrathoracic bleeding (*n* = 13), femoral artery exploration with/without thrombo-embolectomy (*n* = 3), bleeding from saphenous vein harvest site (*n* = 1), resection for small bowel ischaemia (*n* = 2), drainage of pericardial effusion (*n* = 4), removal of mediastinal packs (*n* = 1), ligation of subclavian artery for endoleak (*n* = 1), and commencement of circulatory support with extracorporeal membrane oxygenation (*n* = 1).

Multivariable regression analysis identified the following independent predictors of in hospital mortality: age (OR 1.13, 95% CI 1.01 – 1.27, *p* = .033); coronary artery disease (OR 6.68 95% CI 1.36 – 32.67, *p* = .019); and post-operative RRT (OR 38.51 95% CI 7.15 – 207.36, *p* < .001).

Primary distal seal was achieved in 74 patients of whom 39 had a maximum descending thoracic aortic (DTA) diameter ≥ 55 mm. Twenty three (31.1%) of these patients underwent non-elective repair. Seven (9.5%) patients died in the peri-operative period, four of whom had a DTA ≥ 55 mm. The median length of distal seal in the 67 operative survivors was 52 mm (34, 80) with a median device oversize at the distal landing zone of 4 mm (3, 5) or 10% (5, 14). Twenty eight (42%) patients had a distal seal > 30 mm in length and device oversizing > 10%.

In 84 patients with no primary distal seal, 58 had a maximum DTA diameter ≥ 55 mm. Twenty eight (33.3%) of these patients underwent non-elective repair. Nine (10.7%) patients died in the peri-operative period, seven of whom had a DTA ≥ 55 mm.

Distal aortic repair

A total of 53 patients had distal aortic repair: 28 TEVAR, 15 fenestrated branch (FB)EVAR, one visceral hybrid open endovascular repair, and nine open repairs (Table 5). Of 44 endovascular repairs, 12 were performed with prophylactic cerebrospinal fluid drainage, with spinal cord neuromonitoring in 15. Of nine open repairs, all were performed using full cardiopulmonary bypass with prophylactic cerebrospinal fluid drainage, with spinal cord neuromonitoring used in six patients. Data on maximum DTA diameter before TAR + FET and prior to distal re-intervention in patients with primary distal seal and no seal are shown in Tables 6 and 7.

Of the 67 operative survivors with a primary distal seal, this was maintained during follow up in 51 patients. Two patients underwent elective FBEVAR distal to the sealed FET. In 14 patients there was loss of distal seal. Seven of these patients had an unplanned distal repair (one for distal stent graft induced new entry at a median of 777 days (462, 1480): there was one death on day 35 after open DTA repair complicated by CVA and permanent SCI, and no major complications in the remaining eight patients. Seven patients had loss of distal seal and no intervention. In five of these patients, the principal pathology in the proximal aorta had been treated by TAR and the distal aorta

was below size threshold for repair when the distal seal was lost and so no distal intervention was indicated. In two patients, the distal aorta was above size threshold and further intervention was indicated: one patient died of a non-aortic cause and one died of rupture. Excluding the two patients who had planned distal FBEVAR, distal seal was lost in two of 28 (7%) patients with a distal seal length > 30 mm and device oversizing > 10%, compared with 12 of 39 (31%) patients who did not meet the criteria (p = .031).

Of the 75 operative survivors with no primary distal seal, the distal aorta remained below the size threshold for repair during follow up in 12 patients. Of the remaining 63 patients, 44 (median aortic diameter 64 mm, 60, 75) underwent distal repair (34 elective, 10 non-elective) (one for one for distal stent graft induced new entry) at a median interval of 256 days (135, 740). There were no peri-operative deaths, but eight patients (three TEVAR, two FBEVAR, three OSR) had major complications. Of the remaining 19 patients, six patients with size threshold aneurysms at the time of their proximal surgery died after a median interval of 115 days (85, 120), while eight patients who had elective TAR + FET were considered unfit for further intervention and five died during follow-up (Table 8). One patient was assessed as fit for FBEVAR but declined and subsequently died. Four patients were being assessed or awaiting distal repair at the end of follow up period.

Mid-term outcomes

Median follow up after TAR + FET was 46 months (26, 75). Estimated ± standard error survival at one, three, and five years for the entire cohort was 79.7% ± 3.2%, 69.1 ± 3.7%, and 61.5% ± 4.1%. The five year survival was 70.6 ± 4.7% after elective repair, and 43.2 ± 7.2% after non-elective repair (Fig. 1).

There was no significant difference in five year survival comparing patients with a primary distal seal (64.2 ± 6.0%) and those with no initial distal seal (59.0 ± 5.6%) (HR 0.81, 95% CI 0.50 – 1.30, p = .38) (Fig. 2). Patients in both groups were similar in terms for indication for repair (primary seal: 56, 75.7%, aneurysm, 13, 17.6%, chronic dissection *vs*. no primary seal: 65, 77.4%, aneurysm, 15,

17.9%, chronic dissection) and the proportion with acute presentation (primary seal: 23, 31.1%, *vs.* no primary seal: 28, 33.3%). Patients who had a primary distal seal > 30 mm in length with device oversizing > 10% (77.0% ± 8.3%) had similar survival to those who did not meet these criteria (65.7% ± 8.7%) (HR 0.67, 95% CI 0.29 – 1.55, p = .35). There was no significant difference in five year survival comparing patients who had distal repair (77.8 ± 6.3%) and those who did not (63.0 ± 5.4%) (HR 0.59, 95% CI 0.33 – 1.05, p = .090) (Fig. 3).

Cox regression analysis identified the following independent predictors of survival: chronic obstructive pulmonary disease (OR 3.72, 95% CI 2.01 – 6.87, p < .001); peripheral arterial disease (OR 2.94, 95% CI 1.24 – 6.97, p = .014); chronic dissection (OR 0.27, 95% CI 0.09 – 0.81, p = .020); stroke after TAR + FET (OR 2.97, 95% CI 1.36 – 6.51, p = 007); RRT after TAR + FET (OR 3.33, 95% CI 1.83 – 6.06, p < .001); and distal repair (OR 0.21, 95% CI 0.11 – 0.42, p < .001.

DISCUSSION

The present study examined the need for distal aortic repair after TAR + FET in patients with chronic multilevel thoracic aortic disease. The traditional approach in these patients has been TAR with a floating elephant trunk followed by open distal aortic replacement. While the peri-operative morbidity and mortality associated with TAR is similar whether a floating or frozen trunk is used,[2–4,6–10] the latter avoids a second stage repair, with its associated mortality and risk of interval rupture, in a proportion of patients. A two stage repair is indicated for patients with more extensive distal disease, and the clinician has the choice of using a floating or frozen trunk. Potential advantages of the FET include a reduction in the risk of SCI after the second stage by encouraging thrombosis of the proximal DTA thereby staging the occlusion of segmental spinal collaterals; and providing a more stable platform for distal endovascular repair which is increasingly the approach of choice for the second stage.[6–14]

In the present study, TAR + FET achieved a primary distal seal in 40% of patients with size threshold distal aneurysms, and 47% of all patients. Late failure occurred in a quarter of patients with half of these undergoing distal repair at a median of approximately 25 months. Previous work from this group has recommended a distal seal of more than 30 mm in length and device oversizing of over 10% in order to improve durability of the distal seal.[17] While these criteria were not used for FET planning in the present patient cohort, late loss of distal seal occurred in only 7% of those with a primary distal seal who met the criteria compared to 31% of those who did not. There was no significant impact on mid-term survival dependent of the quality of the distal seal which may be due to the relatively small sample size, but also the fact that the majority of those who originally had a 'poor' primary distal seal and had size threshold distal aneurysms underwent distal repair for loss of seal, whereas the majority of those who had a "poor" primary seal and did not have distal repair when there was a loss of seal had below size threshold distal disease. These data emphasise the importance of (1) endovascular planning to achieve a "good" durable distal seal in those who are anatomically suitable for a one stage repair, and (2) CTA surveillance to identify failure of the distal seal and allow timely re-intervention.

The predominant approach for distal repair in the present study was standard TEVAR for DTA aneurysms, and either FBEVAR for older patients or open repair for young patients with thoracoabdominal aortic aneurysms (TAAAs). The overall mortality for the two stage repair was 12% (first stage 10.1%, second stage 1.9%). While the early mortality from TAR + FET is similar to previous large series,[8,9] and in the mid-range compared with high volume North American centres using predominantly the floating trunk,[2–4] the early outcome from the distal repair is significantly better than in a number of other large studies reporting mortality rates of 6 – 19%.[3–7,10,13] The low mortality from the second stage may partly explain why the five year survival was not significantly worse in patients with more extensive distal disease and those who underwent distal repair.

Overall, 79% of survivors of TAR + FET had successful distal aortic repair either primarily by the FET or after further intervention, and this compares favourably with 64% of patients reported by Coselli and colleagues.[4] Distal repair was ultimately indicated in 84% of patients with no primary distal seal: of these 70% underwent repair, almost 10% died before planned repair, and 13% were unfit. The interval mortality in the present series is similar to that reported by Etz and colleagues,[3] and almost half that reported by two other large US centres.[4,6] The interval to the planned second stage was just over eight months, but a small group of patients succumbed before this at a median interval of almost four months. As this was a retrospective study, it is not possible to ascertain the exact reasons for the time interval between stages in each patient but they are likely to be multifactorial and include human factors as well as access to healthcare. It has been suggested that a four week interval between stages in patients undergoing endovascular TAAA repair is sufficient to allow the spinal cord collateral circulation to adapt while minimising the risk of interval rupture. Patients need longer to recover after open proximal aortic surgery, but one can anticipate that distal endovascular repair performed at an earlier stage of their recovery would have avoided interval rupture. A sub-group of patients were considered unfit for distal repair after elective TAR + FET. Two-thirds of these patients had major post-operative complications and it is possible that their fitness decreased as a consequence. It is equally possible that those who had no major complications but became unfit were not assessed adequately prior to TAR + FET and did not have the required resilience. Patient selection combined with frailty and physiological assessment, may help identify those patients who are at higher peri-operative risk and are less likely to recover sufficiently for further intervention.

Multivariable regression identified age, coronary artery disease and post-operative RRT as independent predictors of in hospital mortality. Cox regression analysis identified chronic obstructive pulmonary disease, peripheral arterial disease, and post-operative CVA and RRT as being associated

with a survival disadvantage, while chronic dissection and distal repair were associated with a survival advantage. Further work in larger patient cohorts may determine if data such as these can assist in the risk stratification of patients before TAR + FET.

The present study has a number of limitations. This was a retrospective analysis of prospectively-collected data from two centres and there would have been inherent differences in patient selection, assessment, and management, despite the fact that the two principal indications for treatment were the same in both centres. The procedure was introduced to clinical practice just before the study period and so the outcomes include the learning curve. It was not possible to determine aneurysm related mortality as data on cause of death were incomplete, and this further hampered meaningful interpretation of the findings in this subgroup. The relatively short median follow-up of 46 months implies that survival beyond three to four years must be interpreted with caution. This is evident when one examines the relationship between distal repair and survival. Univariable analysis demonstrated no statistically significant difference in survival comparing those who had and did not have distal repair. However, if the survival curve had been manipulated and censored at four years, for example, there may have been a significant difference as the confidence intervals do not overlap. Distal repair was selected for the multivariable model as the p-value on univariable analysis was less than 0.1, and ultimately was shown to be independently associated with survival. Finally, further work comparing pre- and post-operative CTA data in patients who had an initial distal seal and those who did not might prove useful for procedural planning.

In conclusion, the present study demonstrates that TAR + FET can reduce the immediate need for a second stage repair in 40% of patients with size threshold distal aortic disease. Further research is required to determine the criteria for an adequate distal seal for a durable one-stage repair. In patients with more extensive disease, distal open or endovascular repair (in appropriately selected patients) can be performed with low mortality. Earlier distal endovascular repair should be

considered to reduce the risk of interval mortality from rupture, and better assessment of patient fitness would help reduce the proportion of patients who are turned down for distal repair.

CONFLICTS OF INTEREST

The vascular unit at University Hospitals Birmingham receives funding from Cook Inc. and Atrium-Maquet; the cardiac unit at University Hospitals Birmingham receives funding from Jotec GmbH and Terumo Aortic; the vascular unit at Liverpool University Hospitals receives funding from Cook Inc.; and the cardiac unit at Liverpool Heart and Chest Hospital receives funding from Terumo Aortic and Artivion.

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Figure 1. Cumulative Kaplan–Meier estimate of survival after elective and non-elective total arch replacement with frozen elephant trunk in patients with chronic multilevel aortic disease.

Figure 2. Cumulative Kaplan–Meier estimate of survival after total arch replacement with frozen elephant trunk in patients with chronic multilevel aortic disease comparing those who had and did not have a primary distal seal.

Figure 3. Cumulative Kaplan–Meier estimate of survival after total arch replacement with frozen elephant trunk in patients with chronic multilevel aortic disease comparing those who had and did not have distal aortic repair.

Table 1. Open and endovascular approaches to arch repair in patients with multilevel aortic disease.

Type of repair	**Frequency**
Open repair	

Total arch replacement + floating elephant trunk	106
Total arch replacement + frozen elephant trunk	226
Chronic multilevel thoracic aortic disease	158
Acute aortic dissection*	57
Prior DTA or TAA repair*	13
Endovascular repair	
FBEVAR with proximal seal in zone 0/1	20
Hybrid arch debranching and TEVAR with proximal seal in zone 0/1	10
Parallel endografting and TEVAR with proximal seal in zone 1	2

373 DTA = descending thoracic aortic; TAA = thoraco-abdominal aortic; FBEVAR = fenestrated-branch

374 endovascular aortic repair; TEVAR = thoracic endovascular aortic repair.

375 *Excluded from analysis.

Table 2. Comorbidity data for 158 patients undergoing total arch replacement and frozen elephant trunk for chronic degenerative and post-dissection multilevel aortic disease.

Characteristics	**Frequency**
Male:Female	72:86
Age at surgery – y	70 (64, 75)
Aortic pathology	
Aneurysmal disease	127 (80.4)
Chronic dissection	31 (19.6)
DeBakey I	21
DeBakey II	1
DeBakey IIIa	8

DeBakey IIIb	1*
Heritable thoracic aortic disease	8 (5.1)*
Vasculitis	4 (2.5)*
Infective native	5 (3.2)†
Prior aortic surgery	36 (22.8)
Maximum diameter of distal aorta – mm	58 (46, 68)
Distal aortic diameter ≥ 55 mm	97 (61.4)
Presentation	
Elective	107 (67.7)
Urgent	31 (19.6)
Emergency	20 (12.7)
Renal replacement therapy	0
Diabetes mellitus	11 (7.0)
Hypertension	122 (77.2)
Hypercholesterolaemia	41 (25.9)
Chronic obstructive pulmonary disease	39 (24.7)
Peripheral arterial disease	14 (8.9)
Transient cerebral ischaemic attack/stroke	11 (7.0)
Coronary artery disease	41 (25.9)
Left ventricular ejection fraction	
>50%	136 (86.1)
31–50%	12 (7.6)
≤30%	2 (1.3)

Not available	8 (5.1)
Estimated glomerular filtration rate	74 (60, 87)

Data are presented as *n* (%) or median (interquartile range). HTAD = heritable thoracic aortic disease.

*Three of four patients with vasculitis, all six with non-HTAD DeBakey III chronic dissection, and five of eight patients with HTAD (three had DeBakey III dissections) had a dilated distal aorta (≥40 mm).

†Patients with infective native aneurysms of the aortic arch underwent total arch replacement with zone 0 distal anastomosis for Dacron prosthesis and the frozen elephant trunk sealed distally in zone 4 or 5.

Table 3. **Prior aortic procedures in 36 patients undergoing total arch replacement and frozen elephant trunk for chronic degenerative and post-dissection multilevel aortic disease.**

Type of repair	**Frequency**
Open repair	
Aortic valve replacement	2
ARR + ascending aortic repair	4
VSARR + ascending aortic repair	7
Ascending aortic repair alone	7
Aortic valve replacement + ascending aortic repair	3
ARR + ascending + Hemi-arch repair	1
ARR + ascending + total arch replacement + floating elephant trunk	1
Ascending + total arch replacement	1
Patch repair of aortic coarctation	4

Repair of aortic transection	1
Abdominal aortic aneurysm repair	4
Thoracoabdominal aortic aneurysm repair, extent IV	1
Endovascular repair	
Infrarenal endovascular abdominal aortic aneurysm repair	1
Fenestrated endovascular juxtarenal aortic aneurysm repair	1

383 ARR = aortic root replacement; VSARR = valve-sparing aortic root replacement

Table 4. Peri-operative mortality in patients after total arch replacement with frozen elephant trunk

Urgency of repair	Demography	Cause of death	Post-operative day of death
Elective	62M, chronic dissection	Intra-operative cardiac dysfunction	0
Elective	78F, degenerative aneurysm	Re-operation-bleeding, RF, AKI-RRT	32
Elective	77F, degenerative aneurysm	Re-operation-bleeding, RF, AKI-RRT, paraplegia	223
Elective	84F, degenerative aneurysm	Re-operation-bleeding, RF, CF, AKI-RRT	19
Elective	79F, degenerative aneurysm	AKI-RRT, Re-operation-bleeding-cardiac arrest	2
Elective	83F, degenerative aneurysm	AKI-RRT, pancreatitis	2
Elective	71F, degenerative aneurysm	RF, AKI-RRT	47
Elective	73M, degenerative aneurysm	Re-operation-bleeding, AKI-RRT	17
Elective	70M, degenerative aneurysm	Re-operation-AMI-SMA bypass	2
Urgent	69M, degenerative aneurysm	ARDS	5
Urgent	80M, degenerative aneurysm	Re-operation-bleeding, RF, AKI-RRT	93
Urgent	72F, pseudoaneurysm	AKI-RRT, ARDS	17
Urgent	76F, chronic dissection	CVA, AKI-RRT	8
Urgent	67M, chronic dissection	Intra-operative cardiac dysfunction	0
Emergency	72F, chronic dissection	Re-operation-bleeding, AKI-RRT	5

Emergency	73F, ARSA + Ao-Oes fistula	CVA, AKI-RRT	11

384 M = male; F = female; RF = respiratory failure; AKI-RRT = renal replacement therapy for acute
385 kidney injury; CF = cardiac failure; AMI = acute mesenteric ischaemia; SMA = superior mesenteric
386 artery; ARDS = acute respiratory distress syndrome; CVA = stroke; ARSA = aberrant right subclavian
387 artery; Ao-Oes = aorto-oesophageal.

Table 5. Late secondary interventions after total arch replacement and frozen elephant trunk for chronic degenerative and post-dissection multilevel aortic disease.

	Frequency
Primary distal seal	**67**
Planned	
FBEVAR	2
Unplanned	
TEVAR	6
Open DTA repair	1
No primary distal seal	**75**
Planned	
TEVAR	18
FBEVAR	12
Open TAA repair	4
Unplanned	
TEVAR	4
FBEVAR	1
Open TAA repair	4

Visceral hybrid repair	1

388 FBEVAR = fenestrated-branch endovascular repair; TEVAR = thoracic endovascular repair; DTA =
389 descending thoracic aortic; TAA = thoraco-abdominal aortic.

Table 6. Descending thoracic aortic diameter before total arch replacement and frozen elephant trunk and prior to distal re-intervention in patients with primary distal seal.

Primary distal seal	DTA diameter prior to TAR + FET (mm)	DTA diameter at re-intervention (mm)	Interval to re-intervention (days)	Pathology
Y	23	53	1 569	Symptomatic expansion
Y	35	52	38	Rapid growth
Y	61	57	870	Type 1b EL
Y	62	60	1 519	Gradual growth
Y	65	56	1 480	Type 1b due to retracted FET
Y	67	68	470	Symptomatic SINE
Y	80	77	777	Type 1b EL

390 DTA = descending thoracic aorta; TAR+FET = total arch replacement and frozen elephant trunk; EL =
391 endoleak; SINE = stent-graft induced new entry tear.

Table 7. Descending thoracic aortic diameter before total arch replacement and frozen elephant trunk and prior to distal re-intervention in patients with no primary distal seal.

Primary distal seal	DTA diameter prior to TAR+FET (mm)	DTA diameter at re-intervention (mm)	Interval to re-intervention (days)
N	37	48	116
N	38	56	2 945
N	43	62	1 421
N	48	60	997
N	50	73	688

N	51	55	419
N	52	54	235
N	53	63	686
N	54	54	35
N	54	56	2 635
N	55	60	1 123
N	55	55	104
N	56	60	1 367
N	56	58	245
N	58	65	13
N	58	59	532
N	60	60	136
N	60	60	266
N	60	60	557
N	60	100	101
N	61	61	171
N	61	64	206
N	61	63	448
N	63	70	924
N	63	66	718
N	64	60	189
N	65	66	190
N	65	70	134
N	65	60	1 723
N	70	70	128
N	70	70	927
N	72	71	424
N	75	88	763

N	75	75	137
N	75	75	13
N	65	75	765
N	75	75	188
N	77	70	246
N	80	120	174
N	82	96	389
N	83	85	536
N	83	83	33
N	85	85	7
N	110	110	8

392 DTA = descending thoracic aorta; TAR + FET = total arch replacement and frozen elephant trunk.

Table 8. Comorbidity and peri-operative outcome data for patients with size threshold aneurysms and no distal seal after total arch replacement and frozen elephant trunk who died not proceed to second stage repair.

Urgency of repair	Demography	Complications	Outcome regarding second stage repair
Elective	68F; HT, dyslipidaemia	RF-trache, CVA	Interval death
Elective	78F; HT, CKD3	Nil	Interval death
Elective	64F; HT, COPD, DM	Nil	Interval death
Elective	68M; CAD, HT, dyslipidaemia, CKD2	Nil	Interval death
Urgent	72F; CKD2	Re-operation-bleeding, RF-trache	Interval death
Urgent	76F; CAD, HT, dyslipidaemia, PAD, CVA	AKI-no RRT	Interval death
Elective	75F; HT, CKD3	Re-operation-ALI, RF-trache, AKI-RRT	Unfit; died 8M
Elective	71M; CAD, CCF, HT, dyslipidaemia, CKD2	CVA	Unfit; died 3M
Elective	72F; dyslipidaemia, CKD2	Nil	Unfit; alive
Elective	75F; CAD, HT, COPD	Nil	Unfit; died 10M

Elective	67F; HT, CKD2	RF-trache, CVA	Unfit; alive
Elective	72F; HT, dyslipidaemia	RF-trache	Unfit; alive
Elective	72F; CAD, HT, COPD, DM, CKD3	Nil	Unfit; died 10M
Elective	67F; CKD3	RF-trache, temp paraparesis, CF, AKI-RRT	Unfit; died 31M
Emergency	76F; HT, CKD3	RF-trache, temp paraparesis	Unfit; alive

M = male; F = female; HT = hypertension; CKD = chronic kidney disease; COPD = chronic obstructive pulmonary disease; CAD = coronary artery disease; PAD = peripheral arterial disease; CVA = stroke; DM = diabetes mellitus; RF = respiratory failure; trache = tracheostomy; AKI-RRT = renal replacement therapy for acute kidney injury; CF = cardiac failure; temp = temporary.

Figure I

Estimated survival after elective and non-elective total arch replacement with frozen elephant trunk in patients with chronic multi-level aortic disease.

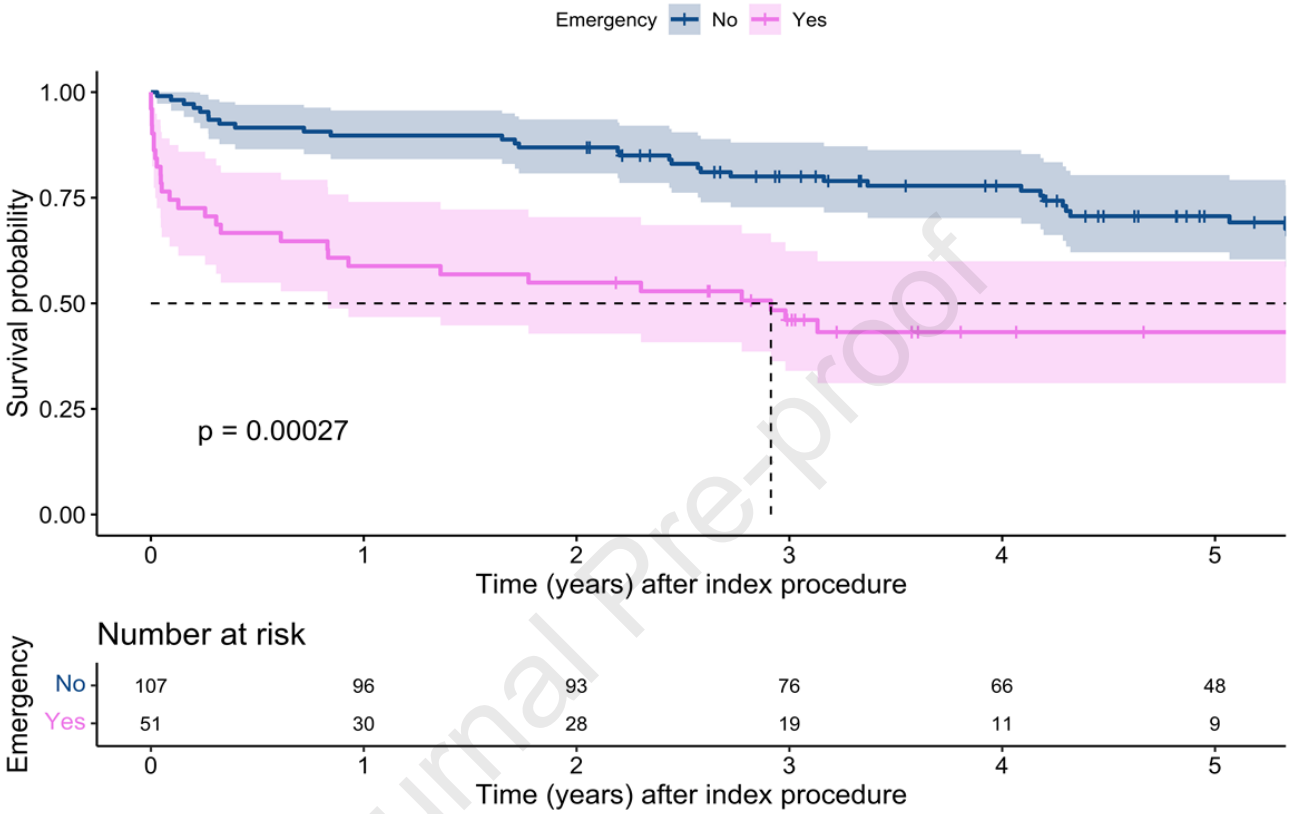


Figure II

Estimated survival after total arch replacement with frozen elephant trunk in patients with chronic multi-level aortic disease comparing those who had and did not have a primary distal seal.

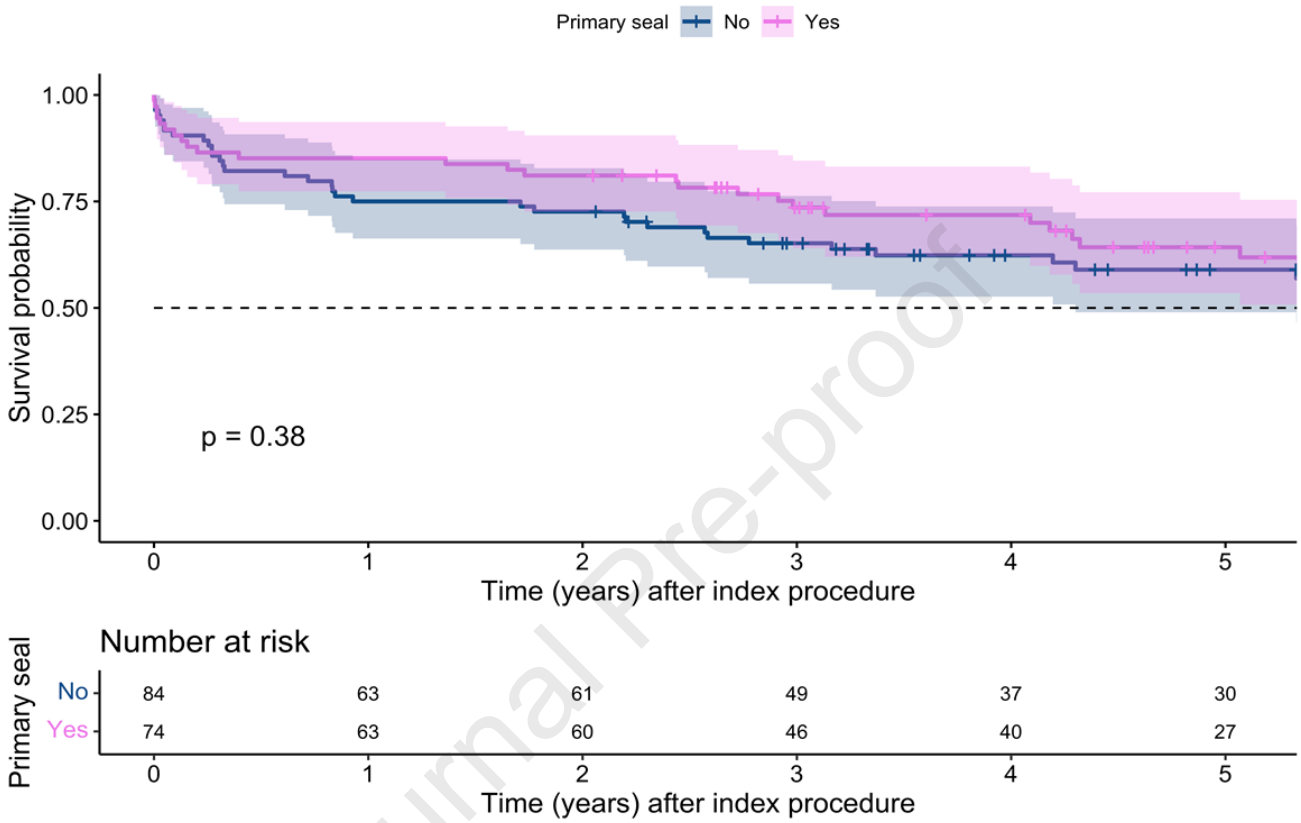
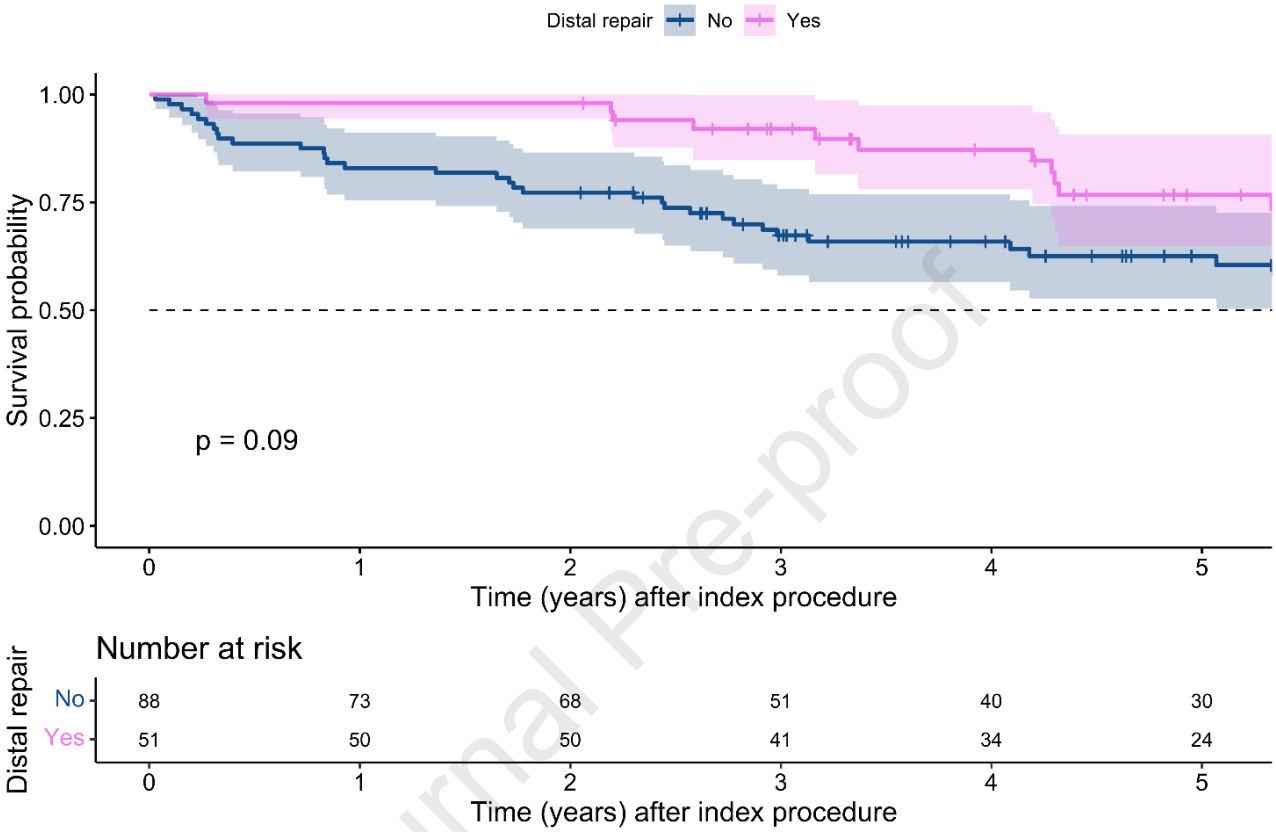


Figure III

Estimated survival after total arch replacement with frozen elephant trunk in patients with chronic multi-level aortic disease comparing those who had and did not have distal aortic repair.



Short title: Distal Aortic Repair After Frozen Elephant Trunk
Figure 1: follow H1 and H2; add – % to vertical axis labels; horizontal axes labels: Time after index procedure – y; delete axes and labels from the Number at risk section; ; in number at risk section change Emergency to a heading above No and Yes
Figure 2: follow H1 and H2; add – % to vertical axis labels; horizontal axes labels: Time after index procedure – y; delete axes and labels from the Number at risk section; in number at risk section change Primary seal to a heading above No and Yes
Figure 3: follow H1 and H2; add – % to vertical axis labels; horizontal axes labels: Time after index procedure – y; delete axes and labels from the Number at risk section; in number at risk section change Distal repair to a heading above No and Yes