Systematic Review

# Mid-to-long-term outcomes of the frozen elephant trunk procedure in aortic pathology: a systematic review and meta-analysis

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**Background:** The frozen elephant trunk (FET) provides single-stage repair of complex, concomitant aortic arch and descending aortic disease, integrating both conventional and endovascular approaches. While multiple meta-analyses affirm short-term safety, long-term outcomes remain largely unknown, especially regarding overall survival and freedom from re-intervention. This current systematic review and meta-analysis aims to summarize the short- and long-term outcomes following the use of FET in aortic pathology.

**Methods:** Studies with at least two years of follow-up data on FETs were identified in five electronic databases, which were searched from inception of records until July 2025. The primary outcome of interest was mortality, with short-term data presented as either 30-day or in-hospital mortality, and long-term data as aggregated Kaplan-Meier curves. Subgroup analysis was also compared by etiology. Secondary outcomes included relevant morbidity outcomes.

**Results:** Following independent screening, 28 studies were included for analysis, with 11,292 patients and a mean follow-up period of 40.4 months. Actuarial overall survival at 1, 5 and 10 years was 86.2%, 78.8% and 67.9%, respectively. Long-term survival for acute dissection for these points was marginally higher, at 86.2%, 82.4%, and 75.2%, respectively. Overall freedom from distal reintervention at 1, 5, and 10 years was 93.9%, 87.4% and 81.5%, respectively. Comparatively, pooled short-term mortality was marginally higher in the aortic dissection cohort than the overall cohort at 7.7% [95% confidence interval (CI): 6–11%] and 7% (95% CI: 5–9%), respectively. The breakdown for these was 254/3,379 and 742/9,428 patients, respectively. For the overall cohort, postoperative spinal cord injury (SCI), postoperative cerebrovascular accident (CVA), and acute renal failure (ARF) requiring dialysis were 4%, 8% and 11%, respectively. Pooled mean intensive care unit (ICU) length of stay was 7 days. A high level of heterogeneity was present, likely due to the mixed etiologies included.

**Conclusions:** Our long-term data expands on previous literature while affirming similar favorable long-term survival for the FET procedure. The consistent pattern of improved late-survival in acute dissections supports the hypothesis that early false-lumen exclusion and acute remodeling result in clear long-term benefits. The need for re-intervention has remained consistent with the published literature, further highlighting the importance of patient selection.

**Keywords:** Frozen elephant trunk (FET); survival; freedom from reintervention; systematic review

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## Introduction

Diseases of the aortic arch and descending aorta often present some of the greatest challenges facing cardiothoracic surgeons. Borst and colleagues first introduced the elephant trunk procedure, allowing for treatment of arch and descending aorta pathology as a single- or multi-stage procedure (1). Kato *et al* in the mid-1990s further expanded upon this technique, and then the first custom made arch prosthesis was created by the Hannover group, coined the “frozen elephant trunk” (FET), shortly after (2). The FET provides a single-stage repair of complex, concomitant aortic arch and descending aortic disease under circulatory arrest, affording patients the benefits of a combined conventional and endovascular approach. It has a clear indication in the presence of malperfusion by restoring the patency of the true lumen and excluding tears in the proximal descending aorta, which maintain false lumen pressurization (3). The FET has also been applied in instances of chronic aortic dissection, as well as arch and descending aortic aneurysms (2). FET can also offer a definitive repair of the thoracic aorta and provide a landing zone for a thoracic endovascular aortic repair (TEVAR) in certain patient populations (4). In these instances, it may alleviate the need for further open re-interventions.

Whilst multiple meta-analyses have affirmed the relatively safe short-term profiles of the FET, less is known about the long-term outcomes, especially with regard to overall survival and freedom from re-intervention (5). Tian *et al.* explored this previously in a systematic review and meta-analysis with a minimum follow-up of one year, demonstrating an actuarial survival of 82.0% at 5 years and a freedom from re-intervention of 86.8% at the same time point (6). Since this study, numerous large institutional reports of the use of FET have been published with high-fidelity, long-term data. The aim of this systematic review is to summarize the contemporary evidence assessing the outcomes of FET with mid-long-term follow-up. The primary aim is to evaluate the short-term and long-term mortality following the use of the FET in aortic pathology. The secondary aim of this study is to assess its morbidity.

## Methods

### Literature search strategy

Five electronic databases were used to perform the literature search, including MEDLINE, EMBASE, Cochrane Central Register of Controlled Trials, Cochrane Database of Systematic Reviews (CDSR), and SCOPUS. These databases were searched from inception to the 23rd of July 2025. The search strategy included a combination of keywords and Medical Subject Headings (MeSH), including “Frozen elephant trunk” AND “outcomes”. Predefined criteria for selection were used to assess all articles. The article was written in accordance with Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) recommendations (7). The PRISMA flowchart is outlined in Figure S1. Two reviewers (A.E. and B.M.) independently screened the abstracts of all identified records. Included titles were then reviewed with a full-text copy by authors A.E. and D.D. Any conflicts were then resolved by a third independent reviewer (A.G.). The reference list of selected studies was manually searched to identify any additional titles, not identified by electronic search.

### Study eligibility

Studies were eligible for inclusion if they included a patient population that underwent an aortic intervention utilizing an FET. This was limited to any open aortic intervention whereby the FET was delivered in an antegrade fashion into the proximal descending aorta. Hybrid procedures that utilized a retrograde delivery of a stented prosthesis were excluded. No distinction was made with regard to the management of the head and neck vessels, method of cerebral perfusion, zone of distal anastomoses, and proximal aortic interventions. Studies that included cohorts of patients predominantly undergoing redo surgery as a FET were excluded due to their inherently higher risk profile and the potential confounders this may introduce. To minimize the risk of publication bias associated with smaller studies, only those with 100 or more patients were included.

Furthermore, in order to present robust mid- to long-term data, only studies that report a mean or median follow-up of 2 or more years were included. Studies that did not report a mean/median follow-up were excluded. In terms of outcome data, studies were included if they published a metric of mortality; either in-hospital, 30-day, or intraoperative mortality. Studies that did not publish mortality data were excluded. When trials/registries/institutions published duplicate studies with an extended length of follow-up or larger study populations, the most up-to-date study or those with the most complete dataset were included. Included studies were limited to those in English and only involving human subjects. Abstracts, case reports, conference presentations, editorials, and reviews were excluded.

### Outcomes

The primary outcome of the study was mortality. Short-term mortality (30-day or in-hospital) was presented as the primary endpoint because it is clinically meaningful and commonly reported in surgical series, enabling pooling across heterogeneous study designs and permitting a low-assumption, robust meta-analysis. Long-term mortality was presented as aggregated Kaplan Meier curves utilizing the algorithm presented by Guyot *et al.* (8). Subgroup analysis was performed based on patient cohorts in the study (acute dissection *vs.* mixed cohorts). Secondary endpoints were spinal cord injury (SCI) resulting in either permanent or temporary neurological deficit, postoperative stroke, intensive care unit (ICU) length of stay in days, and acute renal failure (ARF) requiring dialysis.

### Data extraction

Three independent reviewers (C.D., D.T., L.M.) extracted data directly from publication texts, tables, and figures. A fourth reviewer (A.E.) independently reviewed and confirmed the integrity of all extracted data. Attempts were made to clarify missing data with the authors. For baseline variables, nominal data were recorded as the number of events (n) and expressed as a percentage. Continuous variables were either expressed as a mean and standard deviation (SD) or median and interquartile ranges (IQRs). For statistical analysis, medians and IQR were first converted to mean and SD utilizing the method outlined by Wan *et al.* (9). When data were exactly uniform, the SD was listed as zero. Baseline continuous data were collated using the metaprop function and the pooled result was expressed as a weighted mean (n) and 95% confidence interval (CI). Nominal data were collated and expressed as a proportion and percentage.

To summarize outcome data, a meta-analysis of proportions was performed using the forest function, with a Freeman-Tukey arcsine transformation. A random-effects model was utilized to account for varied study design, experience of the surgeons, center protocol, and population. Results were expressed as forest plots where appropriate, with cumulative proportion expressed as a single percentage. Heterogeneity was assessed using the $I^2$ test statistic. Low heterogeneity was denoted by $I^2<50\%$, moderate heterogeneity by $I^2$ 50–74%, and high heterogeneity by $I^2\geq75\%$. Statistical significance was denoted by $P<0.05$. Kaplan-Meier survival curves were digitized, where numbers at risk were presented, and an algorithmic computational tool was utilized to derive individual patient data as outlined by Guyot *et al.* (8). Small-study effects were assessed visually using funnel plots generated in R with the funnel function. Event and censoring data were compiled for 5 years, and overall survival curves were produced. All analysis was carried out using R Version 4.5.1 (Vienna, Austria).

## Results

### Study characteristics

The literature search identified a total of 4,248 studies (Figure S1). No additional articles were identified after manual searches of reference lists. After removing duplicates, a total of 3,031 articles were screened. After full review, 28 studies with 11,292 patients were included in the systematic review (10-37). All included studies were observational—mostly retrospective single-center cohorts, with two registry/database series. The cohort sizes ranged from 100 to 1,672 patients. The recruitment years for patients ranged from 1994 to 2023. Most papers examined a cohort of mixed arch pathology (either acute dissection, chronic dissection, or aneurysm), whereas 11 papers assessed a cohort of patients with Acute Dissection only, accounting for 5,243 out of the 11,292 patients overall. A wide range of grafts were utilized, including the Thoraflex Hybrid (Vascutek, Inchinnan, Scotland, UK), Evita Open and Open Plus (Jotec GmBH, Hechingen, Germany), Cronus (MicroPort, Shanghai, China) and Frozenix J Graft open stent graft (Japan Lifeline, Tokyo, Japan). The pooled mean follow-up was 40.4 months (95% CI: 39.6–41.3). Study data are summarized in Table S1.

### Baseline demographic data

All studies reported baseline demographic data. The weighted mean age of patients was 59.1 years (95% CI: 55.9–62.3) and 71.2% (95% CI: 66.7–75.4%) were male. Hypertension was present in 75.5% (95% CI: 71.2–79.2%). Regarding etiology, most cases were acute dissection (70.3%, 95% CI: 61.5–77.8%), with aneurysmal disease accounting for 19.2% (95% CI: 14.6–25.2%) and chronic dissection for 11.6% (95% CI: 8.7–15.6%). Connective tissue disorder was reported in 4.4% (95% CI: 3.3–5.8%), malperfusion syndrome was present in 22.8% (95% CI: 15.7–31.9%), and previous cardiac surgery in 11.6% (95% CI: 7.4–17.7%).

**Table 1** Baseline patient characteristics

| Characteristic | Study No. | Pooled weighted estimate (95% confidence interval) | Heterogeneity $I^2$, % |
|---|---|---|---|
| Age, years | 28 | 59.1 (55.9–62.3) | 99.6 |
| Males, % | 28 | 71.2 (66.7–75.4) | 94.6 |
| Hypertension, % | 20 | 75.5 (71.2–79.2) | 93.3 |
| Aetiology, % | | | |
| Acute dissection | 26 | 70.3 (61.5–77.8) | 96.6 |
| Aneurysm | 15 | 19.2 (14.6–25.2) | 95 |
| Chronic dissection | 16 | 11.6 (8.7–15.6) | 93.9 |
| Connective tissue disorder, % | 18 | 4.4 (3.3–5.8) | 85.4 |
| Malperfusion syndrome, % | 13 | 22.8 (15.7–31.9) | 96.7 |
| Previous cardiac surgery, % | 17 | 11.6 (7.4–17.7) | 97.5 |

Between-study heterogeneity was substantial across most variables ($I^2$ typically >90%). These results are summarized in *Table 1*.

### Operative data

There was a wide range of distal aortic anastomoses, ranging from zone 0 (24%) to zone 3 (35.9%). Most distal FET graft anastomoses were performed at zone 2 (69.7%). The extent of proximal aortic surgery demonstrated variable reporting, with a root replacement being performed in 16.6% of cases, an ascending aorta in 14.7% of cases, and a valve-sparing root replacement in 6.2%. A concomitant coronary artery bypass grafting (CABG) was performed in 10.3% of cases. The weighted mean cardiopulmonary bypass time (CPBT) was 214 minutes (95% CI: 200–227) and the weighted mean cross clamp time was 123 minutes (95% CI: 107–139).

The weighted mean antegrade cerebral perfusion (ACP) time was 42 minutes (95% CI: 34–50) and the weighted mean hypothermic circulatory arrest (HCA) time was 59 minutes (95% CI: 45–73). These results were associated with significant heterogeneity, with $I^2$>90% for most parameters. A complete overview of operative data is summarized in Table S2 and the aggregate data is summarized in *Table 2*.

### Primary endpoint

All 28 papers reported short-term mortality either as in-hospital mortality or 30-day mortality. The pooled short-term mortality was 7.1% (95% CI: 5.7–8.9%). This result was associated with large heterogeneity ($I^2$=88.7%; *Figure 1*). The pooled short-term mortality in patients who had a FET in the acute dissection pathology was 7.7% (95% CI: 5.5–10.6%). This result was also associated with significant heterogeneity ($I^2$=83%). The operative mortality was reported by 8 studies with a pooled result of 7.4% (95% CI: 5.7–9.5%), and this was associated with moderate heterogeneity ($I^2$=63%, *Figure 2*).

### Secondary endpoints

A total of 18 studies reported postoperative SCI, with a pooled result of 4% (95% CI: 3–5%). This result was associated with moderate heterogeneity ($I^2$=68%; Figure S2). Thirteen studies reported ICU length of stay in days, with a pooled mean result of 7.23 days (95% CI: 3.51–10.94), This result was associated with large heterogeneity ($I^2$=99%; Figure S3). Twenty-two studies reported postoperative cerebrovascular accident (CVA), with a pooled rate of 8.2% (95% CI: 6.3–10.7%). This result was associated with high heterogeneity ($I^2$=90%; Figure S4). Twenty-three studies reported the incidence of postoperative ARF requiring dialysis, with a pooled incidence of 11.3% (95% CI: 8.6–14.8%). This result was associated with high heterogeneity ($I^2$=91%; Figure S5). Outcome data is summarized in *Table 3*.

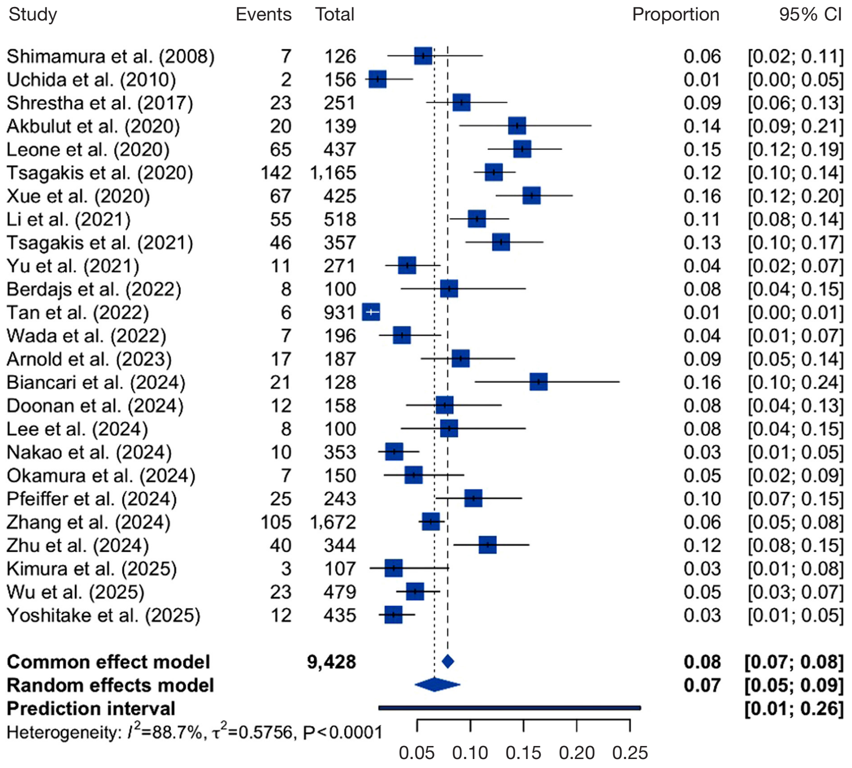
### Survival and re-intervention curve analysis

Aggregation of overall survival was performed on twenty-three of the studies included. Actuarial survival at 1, 5,

**Table 2** Operative data

| Parameter | Weighted pooled estimate [95% confidence interval] | Heterogeneity $I^2$, % |
|---|---|---|
| Extent of proximal aortic surgery, % | | |
| Aortic root replacement | 16.6 [12.6–21.7] | 96.9 |
| Ascending aorta only | 14.7 [5.1–35.4] | 98.5 |
| Valve sparing root replacement | 6.2 [4–9.6] | 95.7 |
| CABG | 10.3 [8.5–12.4] | 89.4 |
| Anastomosis zone, % | | |
| Zone 0 | 24 [10–47] | 96 |
| Zone 1 | 13 [4.8–30] | 93 |
| Zone 2 | 70 [57–80] | 95 |
| Zone 3 | 36 [23–51] | 97 |
| Cardiopulmonary bypass time, min | 214 [200–227] | 99.2 |
| Cross clamp time, min | 123 [107–139] | 99.7 |
| Antegrade cerebral perfusion time, min | 42 [34–49] | 99.9 |
| Hypothermic circulatory arrest time, min | 59 [45–73] | 99.9 |
| Temperature, ℃ | 25 [24–26] | 99.7 |

CABG, coronary artery bypass grafting.



| Study | Events | Total | Proportion | 95% CI |
|---|---|---|---|---|
| Shimamura et al. (2008) | 7 | 126 | 0.06 | [0.02; 0.11] |
| Uchida et al. (2010) | 2 | 156 | 0.01 | [0.00; 0.05] |
| Shrestha et al. (2017) | 23 | 251 | 0.09 | [0.06; 0.13] |
| Akbulut et al. (2020) | 20 | 139 | 0.14 | [0.09; 0.21] |
| Leone et al. (2020) | 65 | 437 | 0.15 | [0.12; 0.19] |
| Tsagakis et al. (2020) | 142 | 1,165 | 0.12 | [0.10; 0.14] |
| Xue et al. (2020) | 67 | 425 | 0.16 | [0.12; 0.20] |
| Li et al. (2021) | 55 | 518 | 0.11 | [0.08; 0.14] |
| Tsagakis et al. (2021) | 46 | 357 | 0.13 | [0.10; 0.17] |
| Yu et al. (2021) | 11 | 271 | 0.04 | [0.02; 0.07] |
| Berdajs et al. (2022) | 8 | 100 | 0.08 | [0.04; 0.15] |
| Tan et al. (2022) | 6 | 931 | 0.01 | [0.00; 0.01] |
| Wada et al. (2022) | 7 | 196 | 0.04 | [0.01; 0.07] |
| Arnold et al. (2023) | 17 | 187 | 0.09 | [0.05; 0.14] |
| Biancari et al. (2024) | 21 | 128 | 0.16 | [0.10; 0.24] |
| Doonan et al. (2024) | 12 | 158 | 0.08 | [0.04; 0.13] |
| Lee et al. (2024) | 8 | 100 | 0.08 | [0.04; 0.15] |
| Nakao et al. (2024) | 10 | 353 | 0.03 | [0.01; 0.05] |
| Okamura et al. (2024) | 7 | 150 | 0.05 | [0.02; 0.09] |
| Pfeiffer et al. (2024) | 25 | 243 | 0.10 | [0.07; 0.15] |
| Zhang et al. (2024) | 105 | 1,672 | 0.06 | [0.05; 0.08] |
| Zhu et al. (2024) | 40 | 344 | 0.12 | [0.08; 0.15] |
| Kimura et al. (2025) | 3 | 107 | 0.03 | [0.01; 0.08] |
| Wu et al. (2025) | 23 | 479 | 0.05 | [0.03; 0.07] |
| Yoshitake et al. (2025) | 12 | 435 | 0.03 | [0.01; 0.05] |
| **Common effect model** | | **9,428** | **0.08** | **[0.07; 0.08]** |
| **Random effects model** | | | **0.07** | **[0.05; 0.09]** |
| **Prediction interval** | | | | **[0.01; 0.26]** |

Heterogeneity: $I^2$=88.7%, $\tau^2$=0.5756, $P<0.0001$

**Figure 1** Forest plot: short-term mortality. CI, confidence interval.

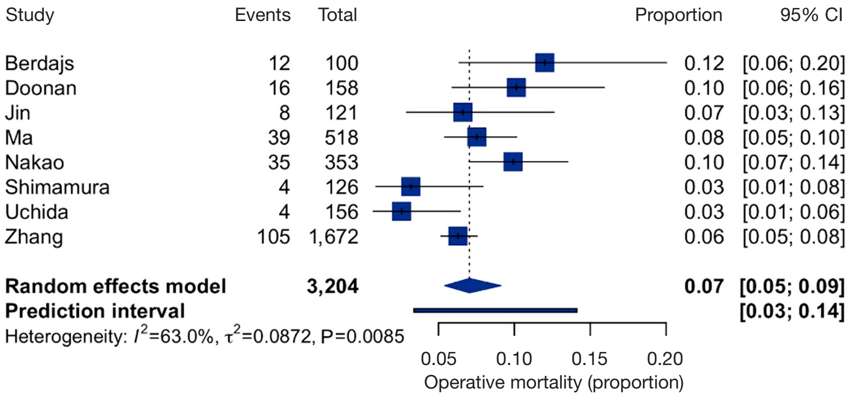


**Figure 2** Forest plot: operative mortality. CI, confidence interval.

**Table 3** Postoperative outcomes

| Parameter | Events/total | N | Weighted pooled estimate (95% CI) | Heterogeneity $I^2$, % |
|---|---|---|---|---|
| Short-term mortality, % | 742/9,428 | 25 | 7.1 (5.7–8.9) | 89 |
| Mortality (operative), % | 223/3,204 | 8 | 7.4 (5.7–9.5) | 63 |
| SCI, % | 228/5,354 | 18 | 3.8 (2.8–5) | 68 |
| ICU length of stay (mean), days | N/A | 13 | 7.2 (3.5–11.0) | 99 |
| CVA, % | 542/7,330 | 21 | 8.2 (6.3–10.7) | 90 |
| ARF—dialysis, % | 690/4,449 | 17 | 11.3 (8.6–14.8) | 91 |

ARF, acute renal failure; CI, confidence interval; CVA, cerebrovascular accident; N, number of studies reported; N/A, not applicable; SCI, spinal cord ischemia.

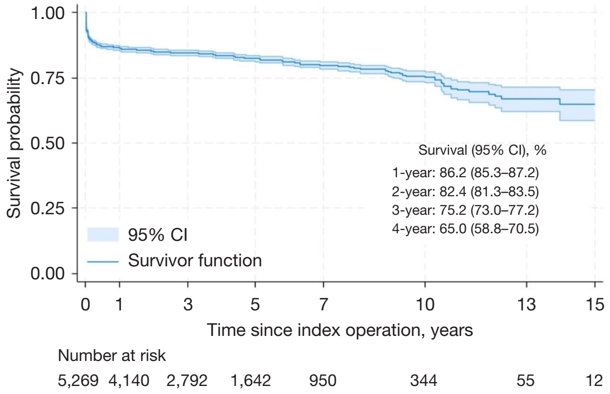


**Figure 3** Overall survival proportion Kaplan-Meier curve. CI, confidence interval.

10 and 15 years was 86.2%, 78.8%, 67.9% and 62.0%, respectively (*Figure 3*). Aggregation of survival in studies that only included patients with acute dissection revealed actuarial survival of 86.2%, 82.4%, 75.2% and 65.0% at the same time intervals (*Figure 4*). Data regarding the freedom from distal re-intervention were available on eight of the included studies. Overall freedom from distal reintervention at 1, 5, 10 and 15 years was 93.9%, 87.4%, 81.5% and 79.4%, respectively (*Figure 5*).

## Study quality and bias assessment

Leave-one-out analysis confirms that no single study materially alters the pooled short-term mortality calculations. Pooled estimates ranged from 6.3% to 7.4% after the omission of individual studies and was most impacted by the omission of Tan *et al.* (7.4%). Heterogeneity was negligibly affected by all omissions ($\Delta I^2=0$) (Figure S6). Visual analysis of funnel plots do not reveal marked asymmetry, suggesting no publication bias for the primary outcome short-term mortality (Figure S7).

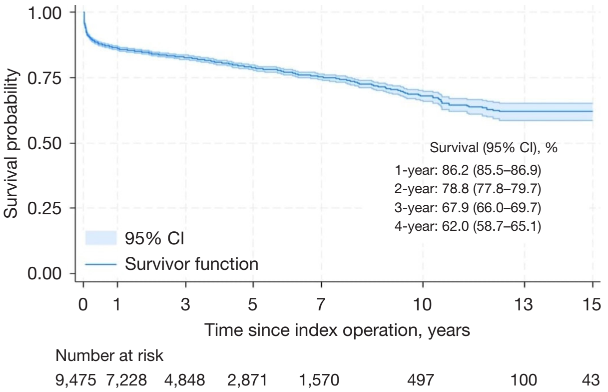


**Figure 4** Overall survival proportion for AAD Kaplan-Meier curve. AAD, acute aortic dissection; CI, confidence interval.

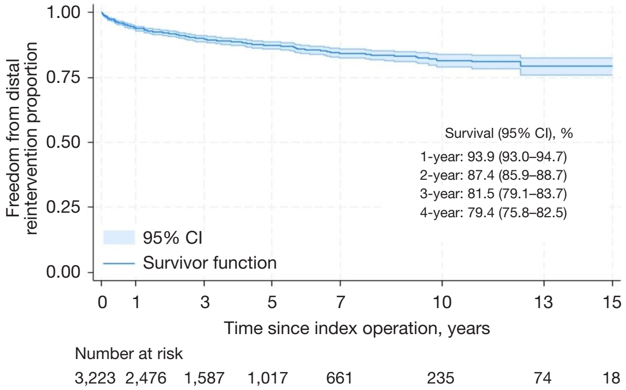


**Figure 5** Overall freedom from distal aortic reintervention Kaplan-Meier curve. CI, confidence interval.

However, completion of weighted regression analysis (Egger's test) revealed statistically significant skew for short-term mortality ($P=8.92\times10^{-6}$, k=25), which is suggestive of a potential publication bias. Trim-and-fill was then performed, and estimated no missing studies for short-term mortality, yielding a pooled proportion identical to the unadjusted value. The ROBINS-I tool was applied to 28 studies, with 14 studies scoring "moderate" in terms of risk of bias. Thirteen studies scored a "serious" risk of bias, and one study scored a "critical" risk of bias, reflecting the largely retrospective nature of the cohort studies included (Figure S8).

In additional analyses, meta-regression by publication year showed no clear temporal trend in short-term mortality (Figure S9). Stratification by region produced pooled short-term mortality estimates of 8.1% (95% CI: 7.3–9.0%) in China, 3.2% (95% CI: 2.3–4.2%) in Japan, 9.5% (95% CI: 8.6–10.4%) in Europe, 8.0% (95% CI: 3.5–15.2%) in other Asia, and 7.6% (95% CI: 4.0–12.9) in Canada, with substantial residual heterogeneity ($I^2=92.9\%$, $\tau^2=0.2160$; $P<0.0004$) (Figure S10). Restricting to studies at ROBINS-I "moderate" risk of bias (k=13; N=5,955) yielded a random-effects pooled short-term mortality of 6.0% (95% CI: 4.0–8.0%), a prediction interval of 2–19%, and persistent heterogeneity ($I^2=88.6\%$, $\tau^2=0.3535$; $P<0.0001$) (Figure S11).

## Discussion

This systematic review incorporates 28 studies and confirms the FET as a robust strategy for complex arch and proximal descending thoracic aortic disease. The appeal of FET lies in single-stage arch replacement with an antegrade stent graft that secures proximal control, promotes false-lumen thrombosis, and creates a distal landing zone for later endovascular completion. In the setting of type A dissection, the FET technique is utilized as an adjunct to a total arch in the presence of re-entrant tears affecting the distal arch and descending aorta (3). It has a stronger indication in the setting of malperfusion, whereby the FET obliterates the false lumen at the level of the proximal descending thoracic aorta and covers re-entrant tears, potentially pressurizing the false lumen (38). Available long-term data is emerging but suggests that aortic remodeling with partial or complete thrombosis of the false lumen can occur in up to 90% of cases (31,38). The FET can also be employed in chronic aortic disease, whereby it is performed electively for aneurysmal degeneration of the false lumen. These patients are typically survivors of acute dissections undergoing limited proximal repair (39). The pattern of disease can be complex with tears at the distal suture line of the original graft, extension into the head and neck vessels and further re-entrant tears of the distal aorta. The FET may address all these concerns as a single-stage procedure (39).

Our pooled short-term mortality of 7% aligns with other published data and is marginally higher than a recently published meta-analysis demonstrating a 30-day mortality rate of 5.78% (5,40-42). Importantly, this study excluded acute aortic pathology (43). Significant heterogeneity between the cohorts, reflective of the mixed aortic pathologies, was noted. The pooled short-term mortality for those studies where FET was employed for acute dissection was 7.7% which is fractionally higher than the mortality for the overall cohort, however, less than previously reported in literature (43). One such explanation for this is the exclusion of smaller patient cohorts in this study, and therefore the potential exclusion of lower-volume centers. Registry data suggest that short and long-term survival are improved when FETs are performed at higher-volume centers (29).

We observed 10-year survival of 67.9% across indications; this mirrors pooled long-term data from a meta-analysis by Tian *et al.*, demonstrating an actuarial survival of 68% at this time point (6). Notably, significantly more patients in the present analysis were included than in previous studies (6). Interestingly, the 10-year survival of 75.1% for the acute dissection cohort was marginally higher and also consistent with the same meta-analysis (6). Both curves demonstrate early regression in actuarial survival with a sustained trajectory, suggesting that the perioperative period following a FET is the most tumultuous for a patient from a survival perspective. Freedom from distal aortic re-intervention remains robust following an FET, with a 10-year freedom from reintervention of 75.2%. This supports the notion that early false-lumen exclusion and remodeling in the acute phase translate into sustained benefit in the long term (3). It also highlights the importance of patient selection in FET. Those with large aneurysms and connective tissue disorders are more likely to have re-intervention and would warrant closer follow-up and tailored long-term management strategies (44,45). The assessment of these patient cohorts was outside the purview of this systematic review.

Spinal cord ischemia is one of the hazards following FET. In the present cohort, the SCI rate was 4% which is marginally lower than a contemporary meta-analysis by Ng *et al.* (42). Previously published rates of SCI have ranged from 4.7–6.5% (6,46). Spinal cord ischemia event rate has been demonstrated to be higher with stent length greater than 15cm or coverage to T8 or beyond (46). Several developments underlie the trend of reducing SCI. Firstly is the proximalization of the distal anastomoses to zone 1/2, which reduces distal graft coverage (24,28). Secondly, is the design of newer FET prostheses, with an additional limb to allow earlier lower body perfusion after the distal anastomoses (27). Thirdly, the drainage of CSF is key in augmenting spinal cord perfusion pressure and for ongoing monitoring (47).

The device-specific series by Tan *et al.* (27) reported an exceptionally low early mortality (0.6% 30-day mortality), which likely reflects several features of the cohort and study design rather than a true benchmark for all-comers undergoing FET. Their dataset aggregated 931 Thoraflex™ Hybrid implantations drawn from multiple experienced aortic centers and included a substantial proportion of elective or lower-acuity pathology, with only half of the cases being dissection, thereby diluting the early risk profile seen in purely acute cohorts. Moreover, outcomes were compiled from high-volume specialist centers gathered from various aortic centers internationally, a context that could confer lower perioperative mortality. Taken together, the combination of case-mix, center expertise and potential reporting/selection effects inherent to single-device appraisal likely explains why this study sits at the extreme lower bound of our meta-analytic distribution. Importantly, leave-out-one analysis in our review shows that removing Tan *et al.* increases the short-term mortality modestly (from 7.0% to 7.4%) without changing heterogeneity, indicating that our conclusions are robust to this outlier.

This systematic review has several limitations. This review synthesizes exclusively observational evidence—no randomized comparisons of FET versus alternative arch strategies were identified. Accordingly, confounding by indication and center-level practice effects cannot be excluded. Between-study heterogeneity was substantial across most variables, reflecting differences in case-mix (acute *vs.* chronic dissection vs aneurysm), operative strategy (distal anastomosis zone, cerebral perfusion technique, HCA temperature and duration) and device type. When required, medians and IQRs were converted to means and SDs using the Wan *et al.* method (9), such transformations assume approximate symmetry and introduce additional uncertainty for skewed distributions, which may not be fully captured in reported CIs. Our eligibility criteria were chosen to reduce small-study noise and ensure mid- to long-term data, but they favor large high-volume centers and may limit generalizability to smaller programs and early-experience eras. Finally, although we attempted to avoid double-counting by preferring the most complete or up-to-date cohort when centers or registries reported overlapping series, residual overlap and center-correlation cannot be entirely excluded. Not all outcomes were reported by all studies, and loss-to-follow-up was variable described, which may bias both short- and long-term incidence estimates.

## Conclusions

Our long-term data expands on previous literature, demonstrating similar, favorable long-term survival and freedom from re-intervention for the use of FET. The short-term mortality remains consistent with current literature, and the rate of spinal cord ischemia is marginally lower than previously published. The consistent pattern of improved late-survival in acute dissections supports the hypothesis that early false-lumen exclusion and acute remodeling confer long-term benefit. The rate of re-intervention highlights the importance of close follow-up and patient selection.

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## Footnote

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## References

1. Borst HG, Walterbusch G, Schaps D. Extensive aortic replacement using "elephant trunk" prosthesis. Thorac Cardiovasc Surg 1983;31:37-40.
2. Kato M, Ohnishi K, Kaneko M, et al. New graft-implanting method for thoracic aortic aneurysm or dissection with a stented graft. Circulation 1996;94:II188-93.
3. Acharya M, Sherzad H, Bashir M, et al. The frozen elephant trunk procedure: indications, outcomes and future directions. Cardiovasc Diagn Ther 2022;12:708-21.
4. Karck M, Chavan A, Hagl C, et al. The frozen elephant trunk technique: a new treatment for thoracic aortic aneurysms. J Thorac Cardiovasc Surg 2003;125:1550-3.
5. Tian DH, Wan B, Di Eusanio M, et al. A systematic review and meta-analysis on the safety and efficacy of the frozen elephant trunk technique in aortic arch surgery. Ann Cardiothorac Surg 2013;2:581-91.
6. Tian DH, Ha H, Joshi Y, et al. Long-term outcomes of the frozen elephant trunk procedure: a systematic review. Ann Cardiothorac Surg 2020;9:144-51.
7. Moher D, Liberati A, Tetzlaff J, et al. Preferred reporting items for systematic reviews and meta-analyses: the PRISMA statement. PLoS Med 2009;6:e1000097.
8. Guyot P, Ades AE, Ouwens MJ, et al. Enhanced secondary analysis of survival data: reconstructing the data from published Kaplan-Meier survival curves. BMC Med Res Methodol 2012;12:9.
9. Wan X, Wang W, Liu J, et al. Estimating the sample mean and standard deviation from the sample size, median, range and/or interquartile range. BMC Med Res Methodol 2014;14:135.
10. Akbulut M, Ak A, Arslan O, et al. Comparison between Arch Zones in Modified Frozen Elephant Trunk Procedure for Complex Thoracic Aortic Diseases. Braz J Cardiovasc Surg 2020;35:934-41.
11. Arnold Z, Geisler D, Aschacher T, et al. Long-Term Results with 187 Frozen Elephant Trunk Procedures. J Clin Med 2023;12:4143.
12. Berdajs DA, Koechlin L, Reid G, et al. Modified frozen elephant trunk procedure as standard approach in acute type A aortic dissection: A propensity-weighted analysis. J Thorac Cardiovasc Surg 2022;163:1754-1761.e3.
13. Biancari F, Lega JR, Mariscalco G, et al. Aortic arch surgery for DeBakey type 1 aortic dissection in patients aged 60 years or younger. BJS Open 2024;8:zrae047.
14. Chiu PH, Cheng YT, Chang FC, et al. Outcomes of Frozen Elephant Trunk for Type 1A Acute Aortic Dissection: A Nationwide, Population Based Study. Eur J Vasc Endovasc Surg 2025. [Epub ahead of print]. doi: 10.1016/j.ejvs.2025.07.003.
15. Dohle DS, Pfeiffer P, Buchholz V, et al. Proximalization of the Distal Anastomosis in Frozen Elephant Trunk Surgery. Thorac Cardiovasc Surg 2024;72: S1-68.
16. Doonan RJ, Senanayake E, Claridge M, et al. Distal Repair After Total Aortic Arch Replacement With Frozen Elephant Trunk in Patients With Chronic Multilevel Thoracic Aortic Disease. Eur J Vasc Endovasc Surg 2024;68:73-81.
17. Jin M, Ma WG, Liu S, et al. Predictors of Prolonged Mechanical Ventilation in Adults After Acute Type-A Aortic Dissection Repair. J Cardiothorac Vasc Anesth 2017;31:1580-7.
18. Kimura T, Tsuneyoshi H, Setozaki S, et al. Mid-term morphological changes in Frozenix. Interdiscip Cardiovasc Thorac Surg 2025;40:ivaf104.
19. Lee KFL, Bhatia I, Chan TLD, et al. Proximalization of

Frozen Elephant Trunk Procedure: Zone 0 or 1 versus Zone 2 or 3 Arch Repair. Thorac Cardiovasc Surg 2024;72:89-95.
20. Leone A, Beckmann E, Martens A, et al. Total aortic arch replacement with frozen elephant trunk technique: Results from two European institutes. J Thorac Cardiovasc Surg 2020;159:1201-11.
21. Li J, Li L, Wang M, et al. Comparison of Prognosis Between Hybrid Debranching Surgery and Total Open Arch Replacement With Frozen Elephant Trunk for Type A Acute Aortic Syndrome Patients. Front Cardiovasc Med 2021;8:689507.
22. Ma WG, Chen Y, Zhang W, et al. Extended repair for acute type A aortic dissection: long-term outcomes of the frozen elephant trunk technique beyond 10 years. J Cardiovasc Surg (Torino) 2020;61:292-300.
23. Nakao T, Tsuda S, Hoshino S, et al. Single-center retrospective cohort study on long-term outcomes of Zone 1 arch repair with frozen elephant trunk using Frozenix: up to 9.5 years of follow-up. J Vis Surg 2024;10:23.
24. Okamura H, Azuma S, Kitada Y, et al. Outcomes of fenestrated frozen elephant trunk technique in 150 patients with acute type A aortic dissection. JTCVS Tech 2024;27:1-8.
25. Shimamura K, Kuratani T, Matsumiya G, et al. Long-term results of the open stent-grafting technique for extended aortic arch disease. J Thorac Cardiovasc Surg 2008;135:1261-9.
26. Shrestha M, Martens A, Kaufeld T, et al. Single-centre experience with the frozen elephant trunk technique in 251 patients over 15 years. Eur J Cardiothorac Surg 2017;52:858-66.
27. Tan SZCP, Jubouri M, Mohammed I, et al. What Is the Long-Term Clinical Efficacy of the Thoraflex™ Hybrid Prosthesis for Aortic Arch Repair? Front Cardiovasc Med 2022;9:842165.
28. Tsagakis K, Osswald A, Weymann A, et al. The frozen elephant trunk technique: impact of proximalization and the four-sites perfusion technique. Eur J Cardiothorac Surg 2021;61:195-203.
29. Tsagakis K, Pacini D, Grabenwöger M, et al. Results of frozen elephant trunk from the international E-vita Open registry. Ann Cardiothorac Surg 2020;9:178-88.
30. Uchida N, Katayama A, Tamura K, et al. Long-term results of the frozen elephant trunk technique for extended aortic arch disease. Eur J Cardiothorac Surg 2010;37:1338-45.
31. Wada T, Yamamoto H, Takagi D, et al. Aortic remodeling, reintervention, and survival after zone 0 arch repair with frozen elephant trunks for acute type A aortic dissection: Midterm results. JTCVS Tech 2022;14:29-38.
32. Wu Q, Jiang D, Shen Y, et al. Ten Years' Experience of Surgical Treatment With Modified Triple-Branched Stent Graft for Type A Aortic Dissection. Ann Thorac Surg 2025. [Epub ahead of print]. doi: 10.1016/j.athoracsur.2025.03.006.
33. Xue Y, Pan J, Cao H, et al. Different aortic arch surgery methods for type A aortic dissection: clinical outcomes and follow-up results. Interact Cardiovasc Thorac Surg 2020;31:254-62.
34. Yoshitake A, Kinoshita O, Gyoten T, et al. Ten-Year Single-Center Experience With a Japanese Frozen Elephant Trunk Graft (FROZENIX) for Treating Thoracic Aortic Disease in 435 Patients. Circ J 2025. [Epub ahead of print]. doi: 10.1253/circj.CJ-25-0013.
35. Yu A, Zhang M, Wang Z, et al. Elephant Trunk Stent Fenestration for Acute Type A Aortic Dissection. Ann Thorac Surg 2021;112:747-54.
36. Zhang K, Qiu J, Wu J, et al. Long-term outcomes in total arch replacement combined with frozen elephant trunk for acute type A aortic dissection. J Thorac Cardiovasc Surg 2024;S0022-5223(24)01106-1.
37. Zhu QY, Lv XS, Li SM, et al. Prognostic analysis of acute type A aortic dissection after different surgical interventions: a cohort study. J Thorac Dis 2024;16:8709-23.
38. Di Bartolomeo R, Pantaleo A, Berretta P, et al. Frozen elephant trunk surgery in acute aortic dissection. J Thorac Cardiovasc Surg 2015;149:S105-9.
39. Roselli EE, Bakaeen FG, Johnston DR, et al. Role of the frozen elephant trunk procedure for chronic aortic dissection. Eur J Cardiothorac Surg 2017;51:i35-9.
40. Rezaei Y, Bashir M, Mousavizadeh M, et al. Frozen elephant trunk in total arch replacement: A systematic review and meta-analysis of outcomes and aortic proximalization. J Card Surg 2021;36:1922-34.
41. Papakonstantinou NA, Antonopoulos CN, Baikoussis NG, et al. Frozen Elephant Trunk: An Alternative Surgical Weapon Against Extensive Thoracic Aorta Disease. A Three-Year Meta-Analysis. Heart Lung Circ 2019;28:213-22.
42. Chakos A, Jbara D, Yan TD, et al. Long-term survival and related outcomes for hybrid versus traditional arch repair-a meta-analysis. Ann Cardiothorac Surg 2018;7:319-27.
43. Takagi H, Umemoto T; ALICE Group. A Meta-Analysis of Total Arch Replacement With Frozen Elephant Trunk in Acute Type A Aortic Dissection. Vasc Endovascular

Surg 2016;50:33-46.

44. Beckmann E, Martens A, Krueger H, et al. Total aortic arch replacement with frozen elephant trunk in patients with Marfan syndrome. Ann Cardiothorac Surg 2025;14:303-8.
45. Ma WG, Zhang W, Zhu JM, et al. Long-term outcomes of frozen elephant trunk for type A aortic dissection in patients with Marfan syndrome. J Thorac Cardiovasc Surg 2017;154:1175-1189.e2.
46. Preventza O, Liao JL, Olive JK, et al. Neurologic complications after the frozen elephant trunk procedure: A meta-analysis of more than 3000 patients. J Thorac Cardiovasc Surg 2020;160:20-33.e4.
47. Murana G, Campanini F, Fiaschini C, et al. Spinal cord injury after frozen elephant trunk procedures-prevention and management. Ann Cardiothorac Surg 2023;12:500-2.

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