



# Are frozen elephant trunks freezing out conventional ones? A systematic review and meta-analysis

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**Background:** The frozen elephant trunk (fET) has become the preeminent choice for aortic arch repair with easier second-stage endovascular solutions compared to the conventional elephant trunk (cET). Traditionally, the major advantage of cET implantation is reduced risk of spinal cord injury (SCI). With increased rates of implantation and refinement in technique, we aim to investigate if previous adverse events of fET, such as SCI, have been reduced to a level comparable to the cET.

**Methods:** Four databases were searched from inception to January 2025. All studies reporting 30-day mortality and SCI in conventional or fETs were identified. Papers that included emergency surgery in a mixed cohort or novel and handmade prosthesis were excluded. Relevant data was extracted, and meta-analysis was conducted using a random effects model.

**Results:** Twenty-eight studies were included with a total of 1,504 patients (122 cET, 1,382 fET). Cohort sizes ranged from 12 to 126 patients. The aggregate mean age was 60.7 years for fET and 65.6 years for cET. The 30-day mortality was 5.4% for fET and 3.9% for cET. There was a signal towards increased SCI for fET at 4.4% compared to 1.2% in cET.

**Conclusions:** In non-emergent total arch replacement, there were similar rates of 30-day mortality. There was a signal towards increased SCI for fETs compared to cETs. Meta-regression identified a non-significant trend towards decreasing rates of SCI in fETs over time.

**Keywords:** Conventional elephant trunk (cET); frozen elephant trunk (fET); spinal cord injury (SCI); mortality



Submitted Mar 24, 2025. Accepted for publication Jul 14, 2025. Published online Jul 28, 2025.

doi: 10.21037/acs-2025-eket-0058

View this article at: <https://dx.doi.org/10.21037/acs-2025-eket-0058>

## Introduction

When the conventional elephant trunk (cET) was introduced by Borst *et al.* in 1983 (1), it represented a major improvement in the management of aortic arch pathologies, allowing for a much more simplified second-stage repair. Benefits included reduced dissection of the distal arch during the second-stage repair, shortened cross-clamp time during open thoraco-abdominal repair, and no need to clamp proximal to the left subclavian artery with resultant reduction in risk of stroke and paraplegia (2). Borst

advocated for a maximal trunk length of 7–8 cm to minimise the risk of complications due to kinking and graft occlusion. It was also suggested by Crawford *et al.* (3) that there was an increased risk of paraplegia associated with longer trunks as a result of clot formation around the graft. However, the cET technique required a second-stage procedure in the open descending thoracic or thoraco-abdominal aorta repair, with associated interval mortality between these two stages.

The frozen elephant trunk (fET) was conceptualised by Suto *et al.* (4) and Kato *et al.* (5), first as a combination of an

arch graft anastomosed onto a stent graft, and then into the modern-day hybrid device, consisting of a combined arch graft and deployable stent graft. Variations of fETs include branched proximal arch grafts, which allow for reduced circulatory arrest times. Examples of these devices include the Thoraflex Hybrid (Vascutek, Inchinnan, Scotland, UK), Evita Open and Open Plus (Jotec GmbH, Hechingen, Germany), J Graft open stent graft (Japan Lifeline, Tokyo, Japan) and Cronus (MicroPort, Shanghai, China). When they were first introduced in 2003, the main advantage was being able to exclude some distal arch aneurysms, or if unable to exclude them, provide an easier landing zone for a second-stage completion endovascular solution. This meant that there was no longer a requirement for a second-stage open operation and a reduction in interval mortality after the first-stage repair. The major downside of the fET was the increased risk of SCI, with early studies demonstrating SCI rates of up to 21.7% (6). These studies demonstrated otherwise acceptable adverse event profiles which were similar or better to the cET technique.

The distal landing zone being proximal to T7 (7), staged procedures when sacrificing segmental arteries (8), circulatory arrest times (9), and maintaining post-operative blood pressure (10) have been identified as factors affecting SCI rates. There is ongoing investigation into the utility of minimally invasive staged segmental artery coil embolisation (MIS<sup>2</sup>ACE) in reducing the risk of paraplegia post-fET with the PAPAartis trial (11).

We aim to review the literature to determine if advances in spinal cord protection strategies and increases in knowledge and centre expertise around fET implantation have led to a reduction in SCI rates, and if this has nullified one of the biggest advantages of the cET.

## Methods

### Literature search strategy

The methods for this systematic review adhered to the guidelines outlined by the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement (12). Four electronic databases were interrogated to perform the literature searches, encompassing EMBASE, Ovid MEDLINE, PubMed, and SCOPUS. These databases were searched from the date of inception through to January 2025. For the examination of the outcomes for conventional and fETs, a search strategy was generated using the following combination of keywords and Medical

Subject Headings (MeSH): ('conventional elephant trunk' OR cET OR 'elephant trunk') AND ('frozen elephant trunk' OR fET or 'stented elephant trunk' OR 'stent-graft') AND ('spinal cord injury' OR SCI or paraplegi\* OR neuro\* OR "Spinal Cord Injuries"[MeSH] OR "Paraplegia"[MeSH] OR "Neurologic Manifestations"[MeSH]). Predefined selection criteria were applied to assess for inclusion (see inclusion and exclusion criteria below). Each study was independently assessed by at least two of the co-authors (D.K.N., D.D., A.R.W.S., R.O., T.C.) with any conflicts resolved prior to progression through mutual agreement. Where the title and/or abstract provided insufficient detail to assess relevance for inclusion, a full text review was conducted in the first instance.

### Eligibility criteria

Studies were included in the review if they examined the perioperative and postoperative outcomes of interest in patients undergoing aortic arch repair with either a cET or fET. Both comparative studies and single arm studies were included. Studies had to report on 30-day mortality and SCI rates. Emergency surgery, repair of acute Type A and complicated Type B dissections were excluded due to the risk of confounding from the increased mortality and morbidity associated with these pathologies.

Studies were excluded from the review for the following criteria: (I) non-English reporting; (II) less than 10 cases included; (III) abstracts/conference presentations/editorials/reviews; (IV) no mention of perioperative and postoperative results; (V) aggregate data not split between subgroups, preventing analysis; and (VI) full texts not readily available via institutional access. Reference lists of the included studies were reviewed at the completion of the database search to identify any extra, not yet included studies.

### Primary and secondary endpoints

The primary endpoints of analysis were all-cause 30-day mortality, in-hospital mortality and rates of SCI and/or paraplegia/paraparesis. Secondary endpoints were rates of stroke, renal failure, and distal embolic events including mesenteric ischaemia or lower limb ischaemia.

### Data extraction, critical appraisal, risk of bias and quality assessment

Three reviewers (D.K.N., R.O., T.C.) independently

extracted data directly from publication texts, tables, and figures. A fourth reviewer (A.R.W.S.) independently reviewed and confirmed all extracted data. Differing opinions between reviewers were resolved through discussion between all reviewers. Where data was insufficient or indistinct, attempts were made to contact the original authors of the study as required.

Cochrane's Risk of Bias in Non-randomized Studies - of Interventions, Version 2 (ROBINS-I V2) was used to assess the risk of bias for each paper. The Canadian Institute of Health Economics Quality Appraisal score was used as the quality assessment tool (Institute of Health Economics 2016). Studies were categorised as low quality (score <10/19), moderate quality (score  $\geq$ 10/19) or high quality (score  $\geq$ 15/19).

## Statistics

A meta-analysis of proportions or means were performed for categorical and continuous variables, as appropriate, by an independent reviewer (D.D.). A random-effects model was used to account for inevitable between-study variance from sources such as differing regions, surgeon experience, surgical technique and equipment, and management protocols. Means and standard deviations (SDs) were calculated from the median, where reported, using the methods described by Wan and colleagues (13). Pooled data and SDs or standard error (SE) are presented as N (%)  $\pm$  SD or SE with 95% confidence intervals (CIs).

Publication bias was examined with funnel plots and by Egger's tests. Heterogeneity amongst studies was assessed using the  $I^2$  statistic. Thresholds for these values were considered as low, moderate, and high heterogeneity as 0–49%, 50–75% and >75%, respectively. Potential sources of heterogeneity were explored through leave-one-out sensitivity analysis conducted to identify studies which reclassified an outcome's heterogeneity threshold significantly upon removal. A linear meta-regression weighted by inverse variance was fitted, with the logit-transformed primary and secondary outcomes and the end year of patient recruitment to examine temporal influences on primary and secondary outcomes.

Two-tailed P values <0.05 were deemed as significant. All statistics were performed using Stata (version 17.0, StataCorp, Texas, USA), R {R Core Team (2021) R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. R Studio [RStudio Team (2020)] in the R Studio environment

(RStudio: Integrated Development Environment for R. RStudio, PBC, Boston, MA, USA)} or MedCalc (Medcalc Software Ltd., Version 23.09, Ostend, Belgium).

## Results

### Quantity of evidence

On application of the search terms, a total of 2,778 papers were identified. After removal of duplicates, 980 papers were identified for screening. Following use of the inclusion and exclusion criteria, 410 articles underwent full text review. Twenty-eight studies were identified for inclusion, with detailed study characteristics provided in *Table 1*. The inclusion and exclusion process are visually presented by the PRISMA flow diagram (*Figure S1*). A total of 1,504 patients (122 cET, 1,382 fET) were included.

### Quality of evidence

All included studies were assessed using the Canadian Institute of Health Economics Quality Appraisal score (42) (*Tables S1,S2*). Twenty-six papers (14–20,23–41) were identified as high-quality papers and 2 papers were identified as moderate-quality papers (21,22).

All included studies were assessed using the Cochrane ROBINS-I V2 assessment for risk of bias (43) (*Figure S2*). All were deemed at low risk of bias except for concerns about uncontrolled confounding, and subsequently included in the meta-analysis.

Assessment of publication bias with Begg's and Egger's tests demonstrated no significant publication bias for any of the primary and secondary outcomes assessed. Funnel plot assessment demonstrated potential over-estimation of the effect of fET on 30-day mortality, but SCI appeared to be well estimated (*Figures S3,S4*).

There is clear favouring of the fET technique, with the majority of contemporary literature publishing on this technique.

### Basic demographics

Baseline patient demographic data and included operative data are presented in *Tables 2,3*. For the fET population, a total of 1,382 patients were included, with a mean age of 60.7 years, of which 72.9% were male. The mean cardiopulmonary bypass time for this population was 200 minutes and the mean aortic cross-clamp time was

**Table 1** Detailed study characteristics

Author	Year of publication	Country	Study type	Operative period	Operation type	Number of fET/cET patients	Risk of bias	Quality of study
Aftab (14)	2017	USA	Single-centre, retrospective	2007–2014	cET	56	Low	High
Arnold (15)	2023	Austria	Single-centre, retrospective	2005–2023	fET	123	Low	High
Beckmann (16)	2020	Germany	Single-centre, retrospective	2012–2018	fET	115	Low	High
Burysz (17)	2024	Poland	Single-centre, retrospective	2016–2024	fET	12	Low	High
Charchyan (18)	2020	Russia	Single-centre, retrospective	2013–2019	fET	20	Low	High
Coselli (19)	2024	USA	Multi-centre, prospective	2016–2018	fET	68	Low	High
Cuko (20)	2023	France	Single-centre, retrospective	2018–2022	fET	43	Low	High
El-Sayed Ahmad (21)	2019	Germany	Single-centre, prospective	2009–2016	fET	38	Low	Moderate
El-Sayed Ahmad (22)	2016	Germany	Single-centre, prospective	2013–2015	fET	14	Low	Moderate
Fiorentino (23)	2021	Netherlands	Single-centre, retrospective	2013–2019	fET	28	Low	High
Furutachi (24)	2023	Japan	Multi-centre, retrospective	2015–2020	fET	12	Low	High
Jakob (25)	2017	Germany	Single-centre, retrospective	2005–2015	fET	82	Low	High
Kim (26)	2024	South Korea	Single-centre, prospective	2021–2023	fET	75	Low	High
Koizumi (27)	2022	Japan	Single-centre, retrospective	2011–2019	fET/cET	60/66	Low	High
Koizumi (28)	2018	Japan	Single-centre, retrospective	2014–2016	fET	30	Low	High
Kozlov (29)	2024	Russia	Single-centre, retrospective	2012–2022	fET	65	Low	High
Kremer (30)	2019	Germany	Single-centre, retrospective	2006–2017	fET	34	Low	High
Liebrich (31)	2021	Germany	Single-centre, retrospective	2009–2020	fET	126	Low	High
Luo (32)	2021	China	Single-centre, retrospective	2009–2019	fET	79	Low	High
Masiello (33)	2022	Italy	Single-centre, retrospective	2017–2020	fET	29	Low	High
Morisaki (34)	2022	Japan	Single-centre, retrospective	2017–2021	fET	44	Low	High
Panfilov (35)	2025	Russia	Single-centre, retrospective	2012–2022	fET	58	Low	High
Qi (36)	2019	China	Single-centre, retrospective	2009–2016	fET	19	Low	High
Sun (37)	2010	China	Single-centre, retrospective	2003–2008	fET	19	Low	High
Sun (38)	2009	China	Single-centre, retrospective	2003–2007	fET	89	Low	High
Suzuki (39)	2023	Japan	Single-centre, retrospective	2016–2021	fET	49	Low	High
Verhoye (40)	2014	France	Single-centre, retrospective	2009–2013	fET	16	Low	High
Zhong (41)	2018	China	Single-centre, retrospective	2010–2016	fET	35	Low	High

Risk of bias, as assessed using the ROBINS-I V2 tool; Quality of study, as assessed using the Canadian Institute of Health Economics quality assessment tool; Low, Low risk of bias except for concerns about uncontrolled confounding. cET, conventional elephant trunk; fET, frozen elephant trunk.

**Table 2** Baseline patient characteristics

Characteristic	fET (n=1,382)		cET (n=122)	
	Pooled weighted estimate (95% CI)	I <sup>2</sup> , % [No. of patients reported]	Pooled weighted estimate (95% CI)	I <sup>2</sup> , % [No. of patients reported]
Age, years	60.7 (57.2–64.2)	99.3 [1,382]	65.6 (48.8–82.3)	98.8 [122]
Males, %	72.9 (67.7–77.7)	76.4 [1,382]	81.5 (74.2–87.8)	NA [122]
Hypertension, %	80.0 (72.9–86.2)	82.8 [840]	96.4 (91.6–101.3)	NA [56]
COPD, %	17.9 (13.1–23.3)	73.2 [844]	25.1 (7.4–48.7)	87.3 [122]
Peripheral vascular disease, %	21.0 (12.9–30.4)	69.5 [290]	NR	NR
Ischemic heart disease, %	21.9 (14.7–30.2)	86.2 [799]	50 (37.9–62.1)	NA [66]
Preoperative CVA or TIA, %	10.4 (6.1–15.5)	74.7 [679]	13.4 (6.9–21.6)	34.7 [122]
Diabetes, %	10.3 (6.5–14.9)	69.6 [688]	5.4 (–0.5 to 11.3)	NA [56]
Smoker (current or previous), %	50.7 (37.2–64.1)	84.4 [343]	NR	NR
Renal insufficiency, %	11.8 (6.4–18.4)	77.9 [518]	12.3 (4.7–22.8)	60.1 [122]
Connective tissue disorder, %	9.2 (6.2–12.7)	63.8 [902]	5.4 (–0.5 to 11.3)	NA [56]
Previous cardiac surgery, %	28.3 (16.8–41.3)	93.0 [760]	78.6 (67.8–89.3)	NA [56]
Aortic aneurysm/dilatation/degeneration, %	65.3 (55.5–74.5)	84.3 [675]	NR	NR
Chronic Type A aortic dissection, %	34.9 (25.2–45.4)	86.9 [687]	5.4 (–0.5 to 11.3)	NA [56]
Chronic Type B aortic dissection, %	45.5 (25.3–66.4)	91.6 [260]	26.8 (15.2–38.4)	NA [56]

Values were calculated using meta-analysis of proportions or means as appropriate with a random-effects model. CI, confidence interval; COPD, chronic obstructive pulmonary disease; CVA, cerebrovascular accident; cET, conventional elephant trunk; fET, frozen elephant trunk; NA, not applicable; NR, not reported; TIA, transient ischemic attack.

119 minutes. Circulatory arrest, lower body circulatory arrest times and antegrade cerebral perfusion times were variably reported. Minimum circulatory temperatures were incompletely reported and averaged 27.0 °C. For the cET population, a total of 122 patients were included, with a mean age of 65.6 years, of whom 81.5% were male. The mean cardiopulmonary bypass time was 234 minutes, and the mean aortic cross-clamp time was 157 minutes. Minimum circulatory temperature averaged 27.6 °C.

### Primary endpoints

The 30-day mortality was greater in the fET population than cET on average, at 5.4% (95% CI: 3.9–7.2%) and 3.9% (95% CI: 1.2–8.0%), respectively. In-hospital mortality (where reported) was measured at 5.1% (95% CI: 3.2–7.4%) and 5.1% (95% CI: 1.0–12.1%) for fET and cET, respectively. There was a signal towards a difference in SCI at 4.4% (95% CI: 3.1–5.9%) and 1.2% (95% CI: 0.0–4.1%)

for fET and cET, respectively. Results are summarised in *Table 4*.

Meta regression analysis of cET primary or secondary outcomes in relation to time was not possible due to paucity of cET data. Non-significant positive correlations were demonstrated for logit proportions of fET 30-day mortality ( $P=0.273$ ) and in-hospital mortality ( $P=0.064$ ) with the end year of patient recruitment. Similarly, there was a non-significant negative temporal correlation in the logit proportions of fET SCI ( $P=0.351$ ).

### Secondary endpoints

The rate of stroke was reported at 5.8% (95% CI: 4.0–7.9%) for fET and 1.8% (95% CI: 0.0–6.4%) for cET, with a similarly stark difference in the rates of renal failure requiring dialysis at 11.5% (95% CI: 7.8–15.7%) for fET and 4.8% (95% CI: 1.8–9.2%) for cET. The rate of renal insufficiency requiring dialysis and not needing dialysis

**Table 3** Pooled operative data

Outcome	fET (n=1,382)		cET (n=122)	
	Pooled weighted estimate (95% CI)	I <sup>2</sup> , % [No. of patients reported]	Pooled weighted estimate (95% CI)	I <sup>2</sup> , % [No. of patients reported]
Preoperative CSF drain, %	46.0 (1.0–96.9)	99.3 [354]	NR	NR
Postoperative CSF drain, %	2.4 (0.4–5.8)	39.9 [226]	NR	NR
Operation time, minutes	386 (354.7–417.0)	95.4 [579]	446 (420.8–471.2)	NA [66]
Cardiopulmonary bypass time, minutes	200 (188.6–212.2)	95.6 [1,370]	234 (223.5–245.1)	NA [66]
Aortic cross-clamp time, minutes	119 (104.6–134.2)	98.5 [1,087]	157 (149.5–164.5)	NA [66]
Circulatory arrest time, minutes	44 (36.2–51.7)	98.7 [642]	66 (62.1–70.5)	NA [66]
Antegrade cerebral perfusion time, minutes	67 (50.3–83.8)	99.8 [876]	57 (51.5–63.1)	NA [56]
Lower body circulatory arrest time, minutes	43 (37.0–49.4)	96.3 [577]	57 (51.5–63.1)	NA [56]
Temperature cooled to, °C	27.0 (25.1–29.0)	99.7 [396]	27.6 (27.5–27.8)	NA [66]
ICU length of stay, days	5.6 (3.4–7.8)	98.4 [437]	3.9 (3.2–4.7)	NA [56]
Hospital length of stay, days	17.6 (11.7–23.5)	99.1 [381]	9.0 (7.0–11.0)	NA [56]
Return to theatre for any reason, %	9.7 (7.4–12.3)	32.1 [848]	6.06 (0.3–11.8)	NA [66]
Return to theatre for bleeding, %	10.2 (7.6–13.3)	14.5 [531]	8.9 (1.5–16.4)	NA [56]

Values were calculated using meta-analysis of proportions or means as appropriate with a random-effects model. CI, confidence interval; cET, conventional elephant trunk; CSF, cerebrospinal fluid; fET, frozen elephant trunk; ICU, intensive care unit; NA, not applicable; NR, not reported.

**Table 4** Primary and secondary postoperative outcomes

Outcome	fET (n=1,382)		cET (n=122)	
	Pooled weighted estimate (95% CI), %	I <sup>2</sup> , % [No. of patients reported]	Pooled weighted estimate (95% CI), %	I <sup>2</sup> , % [No. of patients reported]
30-day mortality	5.4 (3.9–7.2)	42.7 [1,382]	3.9 (1.2–8.0)	NA [122]
In-hospital mortality	5.1 (3.2–7.4)	50.9 [898]	5.1 (1.0–12.1)	51.7 [122]
Clinically significant SCI (all)	4.4 (3.1–5.9)	35.7 [1,382]	1.2 (0.0–4.1)	16.8 [122]
Clinically significant SCI (permanent)	2.9 (1.6–4.6)	0 [450]	0.4 (0.1–2.3)	0 [122]
Clinically significant SCI (temporary)	5.8 (2.5–10.4)	59.1 [382]	1.2 (0.0–4.1)	17.8 [122]
Postoperative stroke	5.8 (4.0–7.9)	56.6 [1,382]	1.8 (0.0–6.4)	49.7 [122]
New renal failure (requiring dialysis)	11.5 (7.8–15.7)	67.2 [809]	4.8 (1.8–9.2)	0 [122]
New renal insufficiency (not requiring dialysis)	11.1 (7.3–15.5)	18.5 [307]	7.6 (1.2–14.0)	NA [66]
Distal embolic events	2.5 (0.8–5.2)	60.5 [498]	1.5 (–1.4 to 4.5)	NA [66]

Values were calculated using meta-analysis of proportions or means as appropriate with a random-effects model. CI, confidence interval; cET, conventional elephant trunk; fET, frozen elephant trunk; NA, not applicable; SCI, spinal cord injury.

within the fET cohort was 11.5% (95% CI: 7.8–15.7%) and 11.1% (95% CI: 7.3–15.5%), respectively. There was a low rate of distal embolic events in the fET cohort, reported at 2.5% (95% CI: 0.8–5.2%). For the cET cohort, the rate of renal insufficiency requiring dialysis was reported at 4.8% (95% CI: 1.8–9.2%) and rate of renal insufficiency and distal embolic events was only reported in one paper, at 7.6% and 1.5%, respectively.

Meta-regression revealed no temporal correlation in logit proportions of stroke ( $P=0.960$ ), as well as weak negative temporal correlation for rates of renal failure ( $P=0.748$ ) and a non-significant positive temporal correlation for renal insufficiency ( $P=0.416$ ). Finally, meta-regression analysis for logit proportions of distal embolic events and end year of patient recruitment revealed a non-significant positive correlation ( $P=0.220$ ).

### Heterogeneity analysis

Substantial between-study variability was present for the majority of pooled estimates, particularly for baseline and intraoperative data. Heterogeneity was often unable to be assessed for the cET cohort as data were often only available from one paper. For primary and secondary postoperative outcomes, moderate heterogeneity was present for in-hospital mortality in cET and fET populations. This was also the case for rates of temporary SCI, stroke, renal insufficiency requiring dialysis and distal embolic events in the fET population. Removal of Arnold (2023) and Beckmann (2020), the two largest studies for fET in-hospital mortality, lowered the rate to 4.5% and heterogeneity to 36.6% and 38.1%, respectively (15,16). Sun (2009) disproportionately contributed to heterogeneity, with the fET temporary SCI rate increasing to 6.8% ( $I^2=7.7\%$ ) when removed (38). No individual studies were found to disproportionately drive heterogeneity for postoperative stroke rates or new renal insufficiency requiring dialysis in the fET population. Lastly, removal of Fiorentino (2021) decreased both heterogeneity and the rate of distal embolic events to 45.7% and 1.8%, respectively (23).

### Discussion

Solutions to aortic arch disease continue to remain a challenge in the modern age, with high risk of mortality and morbidity despite improvements in perioperative and surgical strategies. After its introduction in the 1990s, the fET has become the elephant trunk of choice conceptually

due to being the most complete primary repair possible (44), as well as providing a secure landing zone for second-stage procedures, both open and endovascular (45).

The cET has been relegated to niche scenarios such as where the sizing required for the distal anastomosis is not available in a fET device or in kinked or tortuous aortas (46). Adopters identified the reduced mortality associated with fETs, but were wary of adverse events. In particular, SCI was identified as a major downside of fETs.

The present meta-analysis pooled results from 28 institutional series reporting on fETs for total arch replacement in non-emergent aortic arch surgery. There is a paucity of data on cET meeting our criteria, with only two papers being identified (14,27). Therefore, we were unable to carry out statistical analysis between cET and fET.

This study demonstrated a 30-day mortality rate of 5.78% for fETs, a similar but reduced mortality rate compared to similar studies which demonstrated rates of between 7.7% and 7.9% (47-49), although it should be noted that those studies included acute Type A and Type B dissections in their populations, which we have excluded from our study.

cETs have been associated with higher mortality rates, with meta-analyses demonstrating 30-day mortality rates between 10.4% and 14.8% (47-49) again with the caveat of the inclusion of acute dissections. Our analysis demonstrated an early mortality rate of 3.87% in a patient population excluding acute dissections. However, this result should be interpreted with caution as only two papers were included for analysis, significantly underpowering the result.

The benefit of fET in mortality may be related to the complete repair of the dissected or aneurysmal arch, and in allowing for second-stage completion at an earlier time if required. The improved ease of deployment of second-stage endovascular solutions also allows patients to avoid a more invasive open second-stage via thoracotomy, further reducing mortality. The cET traditionally carried both a higher early mortality and higher interval mortality between first and second-stage operations or in patients who decline a second-stage procedure (2). The addition of a branched prosthesis to the fET arsenal may also have helped to reduce visceral ischaemic times, which could in turn have led to lower mortality rates.

It should be noted that our study has only assessed early mortality up to 30 days after intervention, with no data extraction or analysis of 1 year or long-term survival. The results cannot be extrapolated to suggest long term survival benefits of either treatment.

Regarding SCI, this has been the domain of superiority for the cET. Our meta-analysis demonstrates an SCI rate of 4.58% for fETs, similar to the reported 4.0% to 5.0% in previous meta-analyses (47-49). In comparison, cETs have been identified as having SCI rates of between 1.8% and 2% (47-49). Our study demonstrated an even lower SCI rate for cET at 1.15%.

Our results suggest a reduced risk of stroke for the cET population. Previous studies had demonstrated no significant difference but numerically higher risk for fET (49) and cET (48) respectively. Variations in cerebral protection and timing may have influenced results, with longer selective antegrade cerebral perfusion times noted in our fET population. However, differing strategies in perfusion such as bilateral or unilateral cerebral perfusion, or the usage of axillary cannulation may account for the differences in stroke outcomes. Other risk factors for stroke, such as carotid vessel stenoses and age have also not been accounted for.

There was also a higher numerical risk of renal failure requiring dialysis in patients undergoing fET. Interestingly, this occurred despite shorter operation times, bypass times and circulatory arrest times. A previous meta-analysis identified non-significant differences in relative risk of renal failure (49).

We hypothesised that rates of SCI would be reduced with increasing research into methods of improving spinal cord protection, as well as increased operative experience. However, there is an inherent risk associated with the occlusion of spinal arteries by a stented graft. We conducted further analysis of rates of SCI in relation to the end date of patient recruitment to investigate if there had been any improvement over time. There was a signal towards decreasing proportions of SCI, however, it was statistically insignificant ( $P=0.351$ ) (Figure S5). Further analysis could be performed in the future by stratifying the publications based on self-reported experience in fET surgery, and determining if there were decreased rates of SCI with increasing experience within a centre. Variable adoption of perioperative cerebrospinal fluid drainage may also have confounded our results, and further investigation into relationship between cerebrospinal fluid drainage, graft length, and rates of SCI could be considered. Similarly, meta-regression analysis was applied to 30-day mortality in fETs, with no significant correlation with the end year of recruitment (Figure S6). This is likely attributable to the inherent risks associated with aortic arch surgery.

## Limitations

This systematic review has several significant limitations. All included trials are retrospective observational studies, with no randomised controlled trials having been performed in this field. They are also relatively small populations, ranging from 12 to 126 patients. As a result, it is difficult to make recommendations and come to conclusions based on this limited data. Secondly, only two of the included papers were two-armed studies comparing cETs to fETs, with the majority of them being single armed and looking at fETs in isolation. This was hindered by a lack of literature regarding cETs meeting inclusion criteria. Findings from this study are therefore also not applicable in dissections, inhibiting the application of these results from being applied in graft selection in the acute dissection population. Thirdly, reporting between papers greatly varied in detail regarding circulatory arrest temperatures, neuroprotective measures, cerebrospinal fluid drainage protocols and stent graft lengths used. The experience and volume of the surgical centres were also not analysed. These are critical factors in evaluating the risk of mortality and SCI, and future research should look at analysing outcomes based on these data points. Finally, only early mortality was assessed during this study, and therefore long-term survival benefits cannot be interpolated.

## Conclusions

This systematic review and meta-analysis compared cET and fET in non-emergent total aortic arch replacement. Although statistical analysis and comparison could not be performed between the two due to paucity of data in the cET arm, numerical comparison could be performed. The fET achieves comparable early mortality outcomes compared to the cET (5.4% *vs.* 3.9% in cET), suggesting that the evolution of surgical technique and perioperative management has resulted in fET outcomes similar to those of the cET, making it a suitable and effective approach for many patients.

However, despite advances in cerebral and spinal cord protection strategies, there is still a more frequently reported incidence of SCI in the fET cohort (4.4% *vs.* 1.2% in cET). Notably, meta-regression analyses identified non-significant trends over time, including a decline in SCI rates, and stable 30-day mortality rates amongst fET patients. These signals suggest that there are improved outcomes with improved surgical and perioperative proficiency over

the past decade.

A complete freeze out and succession beyond the original elephant trunk is not yet complete, and there remains a role of Borst's original technique in the arsenal of the thoracic aortic surgeon.

## Acknowledgments

None.

## Footnote

*Funding:* None.

*Conflicts of Interest:* The authors have no conflicts of interest to declare.

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**Cite this article as:** Ng DK, Downes D, Osborn R, Chauraya T, Wilson-Smith AR. Are frozen elephant trunks freezing out conventional ones? A systematic review and meta-analysis. *Ann Cardiothorac Surg* 2025;14(4):247-257. doi: 10.21037/acs-2025-0058