Eur J Vasc Endovasc Surg (2026) 72, 363—372

EJVES Open Access

Debranching versus Fenestrated Repair for Left Subclavian Artery Revascularisation during Thoracic Endovascular Aortic Repair: The DEFENCE Multicentre Study

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WHAT THIS PAPER ADDS

This multicentre propensity score matched analysis provides the largest matched direct comparison of carotid subclavian bypass thoracic endovascular aortic repair (CSB-TEVAR) and fenestrated thoracic endovascular aortic repair (FTEVAR) for left subclavian artery revascularisation during thoracic endovascular aortic repair. While both approaches achieved excellent technical success and survival, CSB-TEVAR was associated with a significantly higher risk of late re-interventions, whereas FTEVAR offered greater long term durability. These findings highlight the importance of individualised patient selection, emphasise the need for close surveillance after CSB-TEVAR, and support the preferential use of FTEVAR in suitable elective cases.

Objective: To compare the early and midterm outcomes of left subclavian artery revascularization during thoracic endovascular aortic repair (TEVAR) following carotid subclavian bypass/transposition (CSB) *vs*. fenestrated repair when landing in zone 1/2. Propensity score matching (PSM) was applied to adjust for baseline differences.

Methods: DEbranching versus FENestrated Repair for Left SubClavian Artery REvascularisation (DEFENCE) was a retrospective, international multicentre observational study conducted between January 2019 and July 2023 on consecutive patients who underwent open debranching or fenestration of the left subclavian artery before TEVAR for various aortic arch and descending aortic pathologies. PSM (68 pairs) was performed using logistic regression. Primary endpoints included technical success and 30-day outcomes. Secondary endpoints included re-intervention, death, and aortic related complications at 12, 24, and 36 months.

Results: 275 patients were included (198 CSB-TEVAR and 77 FTEVAR). Before PSM, statistically significant differences existed in patient demographics and the distribution of aortic pathology. In the matched cohort, CSB-TEVAR demonstrated higher overall re-intervention rates (15% *vs.* 3%, $p = .031$) and aortic related re-intervention rates (15% *vs.* 3%, $p = .031$) compared with FTEVAR. No statistically significant differences were observed in overall mortality rates (7% *vs.* 13%, $p = .40$) or aortic related mortality rate (3% *vs.* 3%, $p = 1.0$). Kaplan—Meier analysis indicated a statistically significant trend towards increased late re-intervention in the CSB-TEVAR group (log rank $p = .019$). Cox regression revealed that carotid subclavian bypass was associated with a fivefold increased independent risk of overall and aortic related re-interventions (hazard ratio 5.185, 95% confidence interval 1.13 − 23.86, $p = .035$).

Conclusion: CSB-TEVAR and FTEVAR achieved high technical success, long term durability, and similar mortality rates. FTEVAR is a durable, low re-intervention alternative, while CSB-TEVAR remains a practical option in urgent cases despite its higher incidence of peri-operative and access related morbidity.

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https://doi.org/10.1016/j.ejvs.2025.12.008

Keywords: Aortic pathology, Carotid subclavian bypass, Fenestrated thoracic endovascular aortic repair, Left subclavian artery, Propensity score matching, Thoracic endovascular aortic repair
Article history: Received 18 August 2025, Accepted 2 December 2025, Available online 9 December 2025
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INTRODUCTION

Thoracic endovascular aortic repair (TEVAR) has emerged as the preferred treatment modality for distal aortic arch and descending thoracic aortic pathologies.[1,2] Compared with conventional open repair, TEVAR offers lower perioperative morbidity and mortality rates, shorter recovery times, and favourable long term durability. However, achieving an adequate proximal sealing zone remains a major technical challenge, particularly in cases where the disease extends proximally into the aortic arch (Ishimaru zones 1 or 2).[3–5]

In such scenarios, intentional coverage of the left subclavian artery (LSA) is often necessary to obtain a sufficient landing zone. The LSA, however, plays a vital role in maintaining spinal cord, posterior cerebral, and left upper extremity perfusion. Its occlusion may increase the risk of spinal cord ischaemia (SCI), posterior circulation stroke, and upper limb ischaemia.[3–5] As a result, several revascularisation strategies have been developed to preserve LSA perfusion, aiming to balance procedural feasibility with neurological and vascular safety.

Traditional surgical approaches, such as carotid subclavian bypass (CSB) or transposition, have been well established and widely adopted to maintain LSA flow during TEVAR. Fully endovascular solutions, including fenestrated and or branched endografts, have been introduced, offering the potential advantages of avoiding surgical incisions and minimising invasiveness.[6–8] However, these endovascular techniques require careful pre-operative planning and precise intra-operative execution, carrying risks of endoleak or target vessel occlusion.

Despite growing experience with both surgical and endovascular revascularisation, the comparative safety, efficacy, and long term durability of these strategies are still debated. This study, therefore, compared the early and midterm outcomes following carotid subclavian bypass thoracic endovascular aortic repair (CSB-TEVAR) with fenestrated thoracic endovascular aortic repair (FTEVAR) for aortic pathologies requiring proximal landing in Ishimaru zones 1 and or 2.

MATERIALS AND METHODS

DEbranching versus FENestrated Repair for Left SubClavian Artery REvascularisation (DEFENCE) was a retrospective, international, multicentre observational study that involved ten investigational centres. The study included all consecutive patients who underwent open LSA debranching or fenestration before TEVAR for various aortic arch and descending aortic pathologies between January 2019 and July 2023. The study was conducted in compliance with the Declaration of Helsinki and its amendments and in accordance with the Strengthening the Reporting of Observational Studies in Epidemiology (STROBE) guidelines.[9] The local ethics committee approved the study (no. 23-0895). Patient consent was waived due to the retrospective nature of the study and the anonymisation of the data.

Study population

Demographic data and baseline characteristics of the patients were collected. Inclusion criteria involved patients with distal aortic arch and descending aortic pathologies requiring proximal sealing in zone 1 or 2, including degenerative aneurysms, acute and chronic type B aortic dissections, type Ia endoleaks, penetrating aortic ulcers, and intramural haematomas.

Patients were assigned to FTEVAR (Supplementary Figure S1) or CSB-TEVAR (Supplementary Figure S2) based on anatomic considerations, urgency of the procedure, availability of fenestrated devices, and institutional expertise. TEVAR was performed using commercially available stent grafts.

Patients who underwent LSA debranching (CSB or carotid subclavian transposition) followed by TEVAR (proximal seal in zone 2) received treatment in either one or in two sittings. Patients who underwent FTEVAR had a custom made fenestration for the LSA only. Endografts with a proximal scallop for the left common carotid artery (LCCA) were included (proximal seal in either zone 1 or 2).

The authors excluded FTEVAR patients with a fenestration for the LCCA or the innominate artery; cases with branches for the LSA; combination with chimneys for the arch vessels; large $>$ 12 mm non-stented fenestrations; and physician modification and *in situ* fenestrations.

Endpoints

The primary endpoints were technical success and 30 day outcomes. Technical success in endovascular treatment was defined as successful endovascular access and stent graft deployment of all devices, including no type I or IIIc endoleak or target vessel occlusion or stenosis persistent at first follow up computed tomography angiogram. Technical success in debranching was defined as successful performance of surgical LSA debranching with successful placement of TEVAR at the desired position and no type I endoleak or target vessel occlusion or stenosis persistent at first follow up computed tomography angiogram.

The 30 day outcomes encompassed both TEVAR and any staged CSB procedures, measured from the date of the first intervention, and included all cause and aorta related death; all cause and aorta related re-intervention; major

adverse events including myocardial infarction, respiratory related events (respiratory failure, re-intubation, prolonged intubation lasting more than 48 hours, and or pneumonia), renal failure, stroke, transient ischaemic attack, and SCI; endoleaks; major adverse outcomes; intra-procedural complications; and 30 day access related complications including nerve injury, haematoma, pseudoaneurysm, thrombosis, infection, and re-intervention. Aortic related re-intervention was defined as being aortic, LSA, LCCA, or CSB related. Secondary endpoints included follow up (12, 24, and 36 months) all cause and aorta related death; all cause and aorta related re-intervention; all cause and aorta related endoleaks; and LSA patency.

Statistics

Data were analysed and processed with IBM SPSS Statistics for Windows Version 29.0 (IBM Corp., Armonk, NY, USA). The normality of the data was tested using the Kolmogorov—Smirnov test. Normally distributed quantitative data were presented as mean ± standard deviation (SD), while non-normal data were presented as the median and interquartile range (IQR). Categorical data were presented in numbers and percentages. Comparative studies for categorical data were carried out using Pearson's correlation and the Fisher's exact test when appropriate. The Bonferroni method was used to adjust p values wherever appropriate. Quantitative data were analysed by Student's t test and Mann—Whitney U test in parametric and non-parametric data, respectively. Time to event outcomes and survival were analysed using Kaplan—Meier (KM) curves and the log rank test, whereas logistic regression analysis was used for multivariable analysis. Variables showing a univariable association with a p value $< .20$ were subsequently entered into the multivariable logistic regression model to identify independent predictors of adverse events. Separate models were constructed for each outcome of interest. Cox regression analysis was used to demonstrate significant differences between the two types of treatment on follow up outcomes. A p value $< .050$ was considered statistically significant.

Propensity score matching (PSM) was employed to reduce selection bias and ensure comparability between the treatment groups. Propensity scores were estimated using logistic regression, incorporating relevant demographic covariables (age, sex, body mass index) and baseline characteristics (coronary artery disease, coronary artery bypass graft, percutaneous coronary angioplasty or stent, chronic heart failure, hypertension, dyslipidaemia, smoking, chronic obstructive pulmonary disease, peripheral arterial disease, diabetes mellitus, renal insufficiency, dialysis, stroke, previous ascending aortic open repair, previous descending thoracic aortic repair, status of pathology, and presenting pathology). All covariables were entered simultaneously (forced entry method), avoiding automated stepwise selection to prevent overfitting. Interaction and non-linear terms were not included to maintain model interpretability, given the limited events per variable ratio. Model discrimination and calibration were assessed using the C statistic (area under the receiver operating characteristic curve) and Hosmer—Lemeshow goodness of fit test, respectively. The model demonstrated good discrimination (C statistic = 0.782, 95% confidence interval [CI] 0.713 — 0.851) and satisfactory calibration (Hosmer—Lemeshow $\chi^2 = 11.497$, $p = .18$). Overlap and common support between groups were confirmed both visually using smoothed density plots and numerically (CSB-TEVAR range = 0.000 — 0.876; FTEVAR range = 0.132 — 0.980).

Nearest neighbour matching with a one to one ratio and a calliper width of 0.2 SD of the propensity score was used without replacement. A narrower calliper (0.1 SD) was initially explored but resulted in excessive data loss (56 matched pairs). The calliper was therefore widened to 0.2 SD to optimise the balance to sample size trade off, in line with published recommendations.[10] This final model yielded 68 matched pairs (136 patients) with all covariables achieving a standardised mean difference < 0.10, confirming adequate covariable balance. Additionally, visual inspections of balance plots and comparisons of means or proportions confirmed that no statistically significant differences remained between the groups after matching.

RESULTS

General cohort

Two hundred and seventy-five patients (198 CSB-TEVAR and 77 FTEVAR) were included, with a mean age of 67.8 ± 10.9 years and 67.6% men. Technical success was achieved in 99.6% of cases. Intra-procedural, access related, and LSA related complications occurred in 9.8%, 15.6%, and 12.4% of cases, respectively. Respiratory (12.4%) , stroke (7.3%), and SCI related (5.5%) complications were the most common medical events. Median intensive care unit (ICU) and hospital stays were one (IQR 1, 2) and nine (IQR 6, 14) days. Thirty day re-intervention and mortality rates were 11.3% and 6.5%, with aortic related causes accounting for 8.7% and 2.9%, respectively. Over a 17 month mean follow up, aortic related complications occurred in 6.5%, re-interventions in 10.9% (10.5% aortic related), and aortic rupture in three patients (1.1%). LSA patency was 99.3%, and LSA stent or bypass complications occurred in 2.9%. Overall and aortic related mortality rates were 13.1% and 3.6%, respectively (Tables 1 and 2).

Fenestrated thoracic endovascular aortic repair vs. carotid subclavian bypass thoracic endovascular aortic repair

Patients treated with FTEVAR were statistically significantly older than those undergoing CSB-TEVAR (70.8 ± 9.7 years *vs.* 66.6 ± 11.2 years). Comorbidity profiles were similar, although FTEVAR was more commonly used in asymptomatic cases (75% *vs.* 64.1%). Procedurally, FTEVAR had statistically significantly longer fluoroscopy but shorter operating times and required less contrast. Technical success was comparable (100% *vs.* 99.5%), but ICU and hospital stays were longer in the CSB group.

Table 1. Demographics, baseline characteristics, and outcomes of the study cohort (n = 275).

Characteristic	Patients (n = 275)	Thoracic endovascular aortic repair		p value
		FTEVAR (n = 77)	CSB-TEVAR (n = 198)	
Demographics and baseline characteristics				
Age − y	67.8 ± 10.9	70.8 ± 9.7	66.6 ± 11.2	.004
Sex, men	186 (67.6)	51 (66)	135 (68.2)	.77
Body mass index − kg/m^2	27.2 ± 9.0	28.5 ± 13.0	26.3 ± 4.8	.093
Coronary artery disease	54 (19.6)	11 (14)	43 (21.7)	.18
PTCA or stent	21 (7.6)	2 (3)	19 (9.6)	.073
Hypertension	241 (87.6)	72 (94)	169 (85.4)	.069
Dyslipidaemia	104 (37.8)	23 (30)	81 (40.9)	.098
Dialysis	7 (2.5)	0 (0)	7 (3.5)	.20
Aortic details				
Type of pathology				.18
Aneurysm	127 (46.2)	31 (40)	66 (33.3)	
Dissection	97 (35.3)	33 (43)	94 (47.5)	
Penetrating aortic ulcer	33 (12.0)	12 (16)	21 (10.6)	
Intramural haematoma	8 (2.9)	0 (0)	8 (4.0)	
Status				.12
Asymptomatic or elective	185 (67.3)	58 (75)	127 (64.1)	
Symptomatic or urgent	78 (28.4)	16 (21)	62 (31.3)	
Ruptured or emergency	12 (4.4)	3 (4)	9 (4.5)	
Asymptomatic or elective	185 (67.3)	58 (75)	127 (64.1)	.025
Symptomatic or ruptured, urgent or emergency	90 (32.7)	19 (25)	71 (35.9)	.083
Arch type				.54
I	81 (29.5)	31 (40)	50 (25.3)	
II	127 (46.2)	38 (49)	89 (44.9)	
III	67 (24.4)	25 (32)	42 (21.2)	
Bovine arch	31 (11.3)	11 (14)	20 (10.1)	.40
Direct take off of the left VA from aorta	7 (2.5)	1 (1)	6 (3.0)	.68
Predominant left VA	212 (77.1)	61 (79)	151 (76.3)	.74
Patent left VA	271 (98.5)	76 (99)	195 (98.5)	1.0
Cardiac output reduction	125 (45.5)	31 (40)	94 (47.5)	.35
Total operating time − min	197 ± 90	165 ± 80	210 ± 91	<.001
Contrast volume − mL	137 (92, 230)	120 (77, 162)	163 (109, 300)	<.001
Fluoroscopy time − min	19 (13, 27)	23 (17, 31)	18 (12, 24)	.003
Radiation dose − cGy/cm^2	406 (229, 788)	395 (231, 831)	107 (221, 757)	.56
Thirty day outcomes				
Technical success	274 (99.6)	77 (100)	197 (99.5)	1.0
Length of intensive care unit stay − d	1 (1, 2)	1 (0, 2)	2 (1, 3)	.003
Length of total hospital stay − d	9 (6, 14)	6 (4, 8)	10 (7, 15)	<.001
Complications				
Intra-procedural complications	27 (9.8)	6 (8)	21 (10.6)	.65
Medical complications	60 (21.8)	14 (18)	46 (23.2)	.42
Access related complications	43 (15.6)	14 (18)	29 (14.6)	.47
LSA bridging stent, bypass, or transposition related	34 (12.4)	11 (14)	23 (11.6)	.55
Myocardial infarction	2 (0.7)	1 (1)	1 (0.5)	.48
Respiratory related	34 (12.4)	5 (6)	29 (14.6)	.069
Stroke	20 (7.3)	4 (5)	16 (8.1)	.61
Spinal cord ischaemia	15 (5.5)	4 (5)	11 (5.6)	1.0
Renal impairment	22 (8.0)	2 (3)	20 (10.1)	.046
New onset dialysis	4 (1.5)	1 (1)	3 (1.5)	1.0
Endoleak	41 (14.9)	11 (14)	30 (15.2)	1.0
Re-intervention and death				
Overall re-intervention	31 (11.3)	9 (12)	22 (11.1)	1.0
Aortic related re-intervention	24 (8.7)	8 (10)	16 (8.1)	.63
LSA stent or bypass related re-intervention	22 (8.0)	7 (9)	15 (7.6)	.63
Overall mortality rate	18 (6.5)	5 (6)	13 (6.6)	1.0
Aortic related mortality rate	8 (2.9)	1 (1)	7 (3.5)	.45
Follow up outcomes				
Left common carotid artery patency	274 (99.6)	77 (100)	197 (99.5)	1.0
LSA patency	273 (99.3)	77 (100)	196 (99.0)	1.0
LSA stent or bypass complications	8 (2.9)	5 (6)	3 (1.5)	.041
Overall re-intervention	21 (7.6)	2 (3)	19 (9.6)	.073
Aortic related re-intervention	20 (7.3)	2 (3)	18 (9.1)	.072
LSA stent or bypass related re-intervention	7 (2.5)	1 (1)	6 (3.0)	.68

Table 1-*continued*

Characteristic	Patients (n = 275)	Thoracic endovascular aortic repair		p value
		FTEVAR (n = 77)	CSB-TEVAR (n = 198)	
Overall mortality rate	36 (13.1)	11 (14)	25 (12.6)	.70
Aortic related mortality rate	10 (3.6)	2 (3)	8 (4.0)	.73

Data are presented as n (%), mean ± standard deviation, or median (interquartile range). FTEVAR = fenestrated thoracic endovascular aortic repair; CBS-TEVAR = carotid subclavian bypass thoracic endovascular aortic repair; PTCA = percutaneous coronary angioplasty; VA = vertebral artery; LSA = left subclavian artery.

Although overall 30 day complications, re-intervention (12% *vs.* 11.1%), and mortality rates (6% *vs.* 6.6%) were similar, respiratory complications were more frequent in the CSB-TEVAR group (14.6% *vs.* 6%, p = .069). The nature of 30 day re-interventions differed, with CSB-TEVAR having more extensive surgical revisions and access complications.

During follow up, LSA related complications were more common after FTEVAR (6% *vs.* 1.5%, p = .041), yet CSB-TEVAR had none significant more overall (9.6% *vs.* 3%) and aortic related (9.1% *vs.* 3%) re-interventions (p = .073 and p = .072, respectively). Death during follow up remained similar between groups (14% *vs.* 12.6%). CSB-TEVAR follow up re-interventions were notably more complex, involving multiple endovascular and surgical procedures, whereas FTEVAR cases were limited to minor extensions.

The 30 day re-interventions in FTEVAR (n = 9) included two TEVAR extensions (one proximal with LCCA *in situ* fenestration and one distal), two relining of LSA stents (one due to occlusion and one due to type Ic endoleak), one LCCA stenting for partial coverage, one neck swelling and bleeding, one pneumothorax, one left upper limb acute ischaemia, and one right lower limb access bleeding. In CSB-TEVAR, 30 day re-interventions (n = 22) included nine CSB revisions (five haematomas, three bleedings, one stenosis), four lower limb access complications, three TEVAR extensions (one for distal stent graft induced new entry (SINE), one for type III endoleak, and one for type Ia endoleak), one bypass removal secondary to infection, one LCCA stenting for partial coverage, one LSA extra coiling for type II endoleak, one renal artery embolisation secondary to bleeding, one left upper limb acute ischaemia, and one haemothorax.

The 30 day mortality rate in the FTEVAR group (n = 5, 6%) included one cardiac arrest, one cranial haemorrhage, one pneumonia, and two multiorgan failure and sepsis. For CSB-TEVAR, the 30 day mortality rate (n = 13, 6.6%) included two aortic ruptures, two cerebral haemorrhages, one bleeding duodenal ulcer, one bilateral stroke, four multiorgan failure and sepsis, one asystole and bradycardia in the ICU, one mediastinal abscess, and one acute respiratory failure.

Follow up re-interventions after FTEVAR (n = 2) included one extension of the LSA stent for type Ic endoleak, and one TEVAR distal extension for SINE. CSB-TEVAR patients (n = 19) had five CSB revisions (one secondary to occlusion and upper limb claudication, one for stenosis, one for lymphocele, and two for bleeding), nine TEVAR (two had TEVAR extensions proximally and distally for type Ia and type Ib endoleaks, two had proximal extensions only, one had distal extension for distal SINE, three had TEVAR relining of whom one had concomitant left iliofemoral bypass and another right renal artery stenting with the stent assisted balloon induced intimal disruption and relamination in aortic dissection repair [STABILISE] technique, and one with supra-aortic debranching and further proximal TEVAR extension), one had fenestrated TEVAR (fenestration for the LCCA), one false lumen occlusion and fenestrated endovascular aortic repair, one type II endoleak who underwent further LSA embolisation, and two frozen elephant trunks (one had retrograde type A aortic dissection and received total aortic reconstruction along with the coronaries, and the other had aneurysmal changes proximal to TEVAR and had concomitant renal artery embolisation).

The follow up mortality rate recorded in the FTEVAR group (n = 11) included two cardiac related (one arrest and one failure), two pneumonia, one retrograde type A aortic dissection, one urosepsis, and five unknown reasons. In the CSB-TEVAR group, follow up deaths (n = 25) included seven aortic related, one aortic rupture, one cerebral haemorrhage, one mesenteric ischaemia, and 15 unknown reasons (Table 1).

Propensity score matching analysis

After PSM, 30 day respiratory complications were statistically significantly more common in the CSB-TEVAR group (p = .045), while renal impairment (p = .055) and follow up LSA stent or bypass complications (p = .058) showed no statistically significant difference between groups. CSB-TEVAR remained associated with higher overall and aortic related re-intervention rates (p = .031 for both), whereas mortality outcomes did not differ statistically significantly after matching.

The absolute re-intervention risk was 15% for CSB-TEVAR *vs.* 3% for FTEVAR (acute respiratory disease 11.8%), corresponding to a number needed to harm ≈ 9 (1/0.118 = 8.47), indicating that for approximately every nine patients treated with CSB-TEVAR instead of FTEVAR, one additional re-intervention occurred during follow up (Table 3).

Table 2. Aortic pathology, past aortic history, medication, details of aortic dissection, operative details, and additional outcomes of fenestrated thoracic endovascular aortic repair (FTEVAR) and carotid subclavian bypass thoracic endovascular aortic repair (CSB-TEVAR) treatment.

Characteristic	Patients (n = 275)
Past aortic history	
Ascending aorta open repair	34 (12.4)
Descending aorta treatment	37 (13.5)
Open repair	24 (8.7)
Endovascular	13 (4.7)
Medication	
Aspirin	136 (49.5)
Clopidogrel	56 (20.4)
Direct oral anticoagulant	28 (10.2)
Warfarin	10 (3.6)
Lipid lowering	119 (43.3)
β blockers	172 (62.5)
Calcium channel blockers	114 (41.5)
Aortic pathology	
Type of pathology	
Dissection	127 (46.2)
Aneurysm	97 (35.3)
Penetrating aortic ulcer	33 (12.0)
Intramural haematoma	8 (2.9)
Type Ia endoleak	6 (2.2)
Traumatic	4 (1.5)
Largest aortic diameter − mm	56 ± 17
Aortic dissection (n = 127)	
Onset	
Acute	49 (38.6)
Subacute	20 (15.7)
Chronic	58 (45.7)
Complicated	
Uncomplicated	102 (80.3)
Complicated	25 (19.7)
Type of endovascular intervention	
FTEVAR	77 (28.0)
CSB-TEVAR	198 (72.0)
Flushing of device	
Regular	114 (41.5)
CO_2	82 (29.8)
120 mL saline	79 (28.7)
Femoral access	
Percutaneous	208 (75.6)
Cutdown	67 (24.4)
Iliac conduit	3 (1.1)
Cardiac output reduction	125 (45.5)
Drug induced	36
Inferior vena cava occlusion	14
Munich Valsalva implantation technique	16
Rapid pacing	6
Valsalva	53
Main TEVAR system − F	21 ± 2
Low profile device	105 (38.2)
Proximal endograft diameter − mm	37 ± 5
Distal endograft diameter − mm	35 ± 6
Length of aortic coverage − mm	192 ± 70
Spinal drainage	8 (2.9)
Estimated blood loss − mL	200 (100, 425)
Follow up period − mo	17 ± 15
FTEVAR details (n = 77)	
Scallop for left carotid artery	40 (52)
LSA diameter, 15 mm after take off − mm	10 ± 2
Size of endograft fenestration − mm	9 ± 2
Upper extremity access	
Percutaneous	51 (66)
Cutdown	26 (34)
Upper extremity access artery	
Brachial	75 (97)
Axillary	2 (3)
LSA stent diameter − mm	10 ± 2
LSA stent length − mm	39 ± 11
LSA bare stent relining	6 (8)
CSB-TEVAR details (n = 198)	
Staged procedure	74 (37.4)
Time between carotid subclavian bypass and TEVAR − d	9 (3, 28)
Type of debranching	
Carotid subclavian bypass	189 (95.5)
Subclavian transposition	9 (4.5)
Type of conduit	
Polyester	175 (92.6)
PTFE	13 (6.9)
Vein	1 (0.5)
Additional findings	
30 d gastrointestinal complication requiring resection	1 (0.4)
Follow up endoleak	20 (7.3)
Follow up aortic rupture	3 (1.1)

Data are presented as *n* (%), *n*, mean ± standard deviation, or median (interquartile range). FTEVAR = fenestrated thoracic endovascular aortic repair; CBS-TEVAR = carotid subclavian bypass thoracic endovascular aortic repair; TEVAR = thoracic endovascular aortic repair; LSA = left subclavian artery; PTFE = polytetrafluoroethylene.

Kaplan—Meier and Cox regression analysis

In the unmatched cohort, KM survival analysis demonstrated no statistically significant difference in overall and aortic related mortality and re-intervention rates between the CSB-TEVAR and FTEVAR groups. In Cox regression analysis, CSB-TEVAR was associated with a non-significant increased risk of overall and aortic related re-interventions (hazard ratio [HR] 3.376, 95% CI 0.79 — 14.53, p = .10 and HR 3.201, 95% CI 0.74 — 13.83, p = .12, respectively).

After PSM, KM analysis revealed a statistically significant trend towards increased late re-intervention in the CSB-TEVAR group regarding overall and aortic related re-interventions (log rank p = .019). Additionally, Cox regression revealed that CSB was associated with a fivefold increased independent risk of overall and aortic related re-interventions (HR 5.185, 95% CI 1.13 — 23.86, p = .035) (Figs 1 and 2; Supplementary Figures S3 — S5)

Uni- and multivariable analysis

Univariable analysis results are summarised in Supplementary Table S1, identifying several patient related and procedure related factors associated with early and follow up outcomes. Multivariable analysis confirmed

Table 3. Outcomes after propensity score matching analysis between the 68 pairs of the two treatment groups.

Characteristics	Thoracic endovascular aortic repair		*p* value
	FTEVAR (n = 68)	CSB-TEVAR (n = 68)	
In hospital and 30 day outcomes			
Intra-procedural complications	6 (9)	11 (16)	.30
Any complications	24 (35)	28 (41)	.60
Medical complications	12 (18)	16 (24)	.52
Myocardial infarction	1 (1)	0	1.0
Respiratory	3 (4)	11 (16)	.045
Stroke	3 (4)	5 (7)	.72
Spinal cord ischaemia	4 (6)	3 (4)	1.0
Renal impairment	2 (3)	9 (13)	.055
New onset dialysis	1 (1)	1 (1)	1.0
Endoleak	10 (15)	13 (19)	.65
Access complications	11 (16)	12 (18)	1.0
LSA stent, bypass, or transposition complications	10 (15)	6 (9)	.43
Overall re-intervention	8 (12)	6 (9)	.78
Aortic related re-intervention	7 (10)	5 (7)	.76
LSA stent or bypass re-intervention	6 (9)	4 (6)	.74
Overall mortality rate	4 (6)	2 (3)	.68
Aortic related mortality rate	1 (1)	1 (1)	1.0
Follow up outcomes			
Left common carotid artery patent	68 (100)	67 (99)	1.0
LSA patent	68 (100)	66 (97)	.50
LSA stent or bypass complications	5 (7)	0	.058
Overall re-intervention	2 (3)	10 (15)	.031
Aortic related re-intervention	2 (3)	10 (15)	.031
LSA stent or bypass re-intervention	1 (1)	2 (3)	1.0
Overall mortality rate	9 (13)	5 (7)	.40
Aortic related mortality rate	2 (3)	2 (3)	1.0

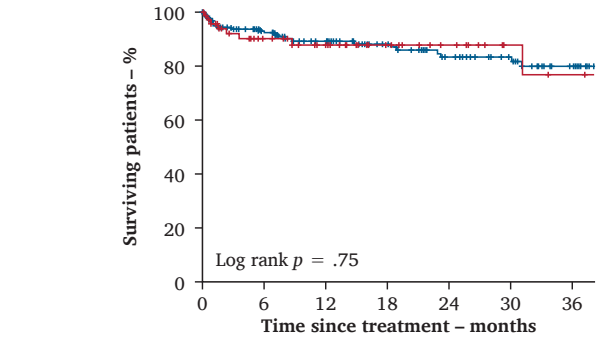
Data are presented as n (%). FTEVAR = fenestrated thoracic endovascular aortic repair; CBS-TEVAR = carotid subclavian bypass thoracic endovascular aortic repair; LSA = left subclavian artery.

that low baseline estimated glomerular filtration rate, symptomatic or ruptured status, and longer aortic coverage independently predicted respiratory complications. Renal impairment was significantly associated with stroke, low estimated glomerular filtration rate, and rupture. FTEVAR and female sex (borderline) were associated with follow up LSA complications. Longer operating time increased the risk of 30 day re-interventions. Stroke, rupture, and large aortic diameter were strong predictors of 30 day and follow up death, while previous percutaneous coronary angioplasty or stent was linked to follow up aortic re-interventions (Supplementary Tables S1 and S2).

DISCUSSION

The management of distal aortic arch and descending aortic pathologies has shifted significantly, with TEVAR now being the standard of care due to its lower morbidity and mortality rates compared with open surgery.[1,11] A critical requirement for TEVAR success is an adequate proximal landing zone; if lacking, zone 2 or zone 1 coverage may be necessary.[3–5] One of TEVAR's most feared complications is SCI,[6,12] with the LSA playing a vital role in spinal cord perfusion. LSA revascularisation, particularly in cases with a dominant left vertebral artery or incomplete circle of Willis, reduces the risk of stroke and SCI.[7,13–16] Gaudino *et al.* highlighted the benefit of preserving LSA perfusion in reducing SCI.[12]

Before adjustment, CSB-TEVAR was associated with higher overall and aortic related re-intervention rates, but with similar mortality outcomes. These results support the long term durability advantage of FTEVAR as shown in previous studies.[17,18] Konstantinou *et al.* noted that CSB-TEVAR requires an additional procedure that can introduce graft related complications.[16,18] Similarly, Dias-Neto *et al.* found that FTEVAR is associated with fewer re-interventions, although its availability is limited by the need for custom made devices.[19] CSB-TEVAR patients experienced more respiratory complications and longer ICU and hospital stays, probably due to surgical complexity, echoing findings from Squiers *et al.* and Cooper *et al.*[7,20] This study's outcomes align with the recent literature,[21–23] with CSB-TEVAR showing higher procedural complexity and long term re-intervention risk. Although CSB-TEVAR required a longer overall operation duration due to the surgical bypass component, fluoroscopy time was greater in the FTEVAR group. This probably reflects the meticulous imaging required for fenestration alignment, target vessel catheterisation, and bridging stent deployment. Conversely, CSB-TEVAR, despite a shorter fluoroscopy phase, involved higher contrast use because of repeated angiographic checks during both the surgical and endovascular stages of



CSB-TEVAR					
No. at risk	187	130	106	61	30
Survival – %	100	92.1	89.1	83.2	79.8
SE	.008	.021	.025	.035	.041
FTEVAR					
No. at risk	70	43	32	16	6
Survival – %	100	90.1	87.8	87.8	87.8
SE	.014	.039	.044	.044	.110

Figure 1. Cumulative Kaplan–Meier estimate of overall survival in the unmatched cohort comparing the carotid subclavian bypass thoracic endovascular aortic repair (CSB-TEVAR) and fenestrated thoracic endovascular aortic repair (FTEVAR) groups. SE = standard error.

the hybrid procedure. These complementary findings indicate that total procedural time and fluoroscopy exposure are influenced by different workflow components in each strategy. While endoleak rates were comparable, this study's SCI rates confirmed that SCI risk relates more to aortic coverage than LSA revascularisation strategy. Longer hospital stays and consistent with other studies, increased respiratory complications were also more common in the CSB-TEVAR group.[7,23]

PSM eliminated baseline differences and ensured comparability between groups. CSB-TEVAR maintained significantly higher rates of both overall and aortic related re-interventions, where the sustained difference may reflect CSB-TEVAR's intrinsic limitations, including prosthetic conduit risks and less durable proximal sealing compared with FTEVAR.[18,24] KM analysis confirmed a higher aortic related re-intervention rate in CSB-TEVAR, consistent with other reports.[14,25] Additionally, PSM analysis revealed that 30 day respiratory complications, which were only borderline significant in the unmatched cohort, became statistically significant after matching, indicating a true procedural effect of CSB-TEVAR. Conversely, the loss of significance for renal impairment and LSA stent and bypass complications after matching suggests that these findings in the unmatched analysis were primarily influenced by baseline renal function and patient selection rather than treatment type. The significance of respiratory complications persisting after matching probably reflects a true procedural effect associated with the surgical exposure and longer operation times inherent to CSB-TEVAR.

Although FTEVAR offers better long term outcomes, its use is constrained by custom device logistics and limited availability.[26] Branched thoracic endovascular aortic repair is emerging as a promising alternative, while CSB-TEVAR remains more accessible for urgent cases. Importantly, operator expertise significantly influences FTEVAR outcomes, as noted by Spinelli *et al.*,[27] suggesting that high volume centres may achieve better results. Additionally, the improved sealing performance of FTEVAR may partly reflect the use of scalloped configurations that enhance proximal apposition while maintaining LCCA perfusion. The median follow up period of 17 months was sufficient to demonstrate significant midterm differences in re-intervention rates. However, the continued divergence of the KM curves for re-intervention suggests that the advantage of fenestrated repair may become even more pronounced with longer follow up. Extended surveillance at five and ten years will be crucial to confirm these trends and to establish the true long term durability of both approaches.

This study's strength lies in the PSM analysis and multivariable regression, which confirmed CSB-TEVAR's association with increased follow up LSA complications and overall and aortic related re-interventions. Cox regression similarly identified CSB-TEVAR as a predictor of late re-interventions (HR 5.185). These findings reinforce the need for long term surveillance and support the preferential use of FTEVAR in suitable patients.

Limitations of study

Despite this multicentre study's strengths, several limitations should be acknowledged. The retrospective nature of the study introduces inherent selection biases despite the use of PSM. There was no significant time trend affecting the allocation of patients to FTEVAR or CSB-TEVAR, as both techniques were employed throughout the study period. However, the authors acknowledge that centre specific preferences, expertise, and device availability may have influenced the choice of CSB-TEVAR *vs.* FTEVAR, representing a potential source of selection bias.

Furthermore, although the PSM incorporated detailed anatomic and procedural variables, unmeasured factors such as subtle plaque morphology at the LSA origin or aortic wall quality may still have influenced device or technique selection. Institutional and surgeon volume were not included as covariables due to incomplete standardisation across centres, and procedural urgency was classified categorically rather than by exact timing (hours from presentation to repair). These factors could have introduced residual confounding beyond the scope of statistical adjustment.

Although PSM balanced the cohorts, the sample sizes of the groups remained relatively small, potentially affecting statistical power. Additionally, PSM is a compensatory measure but not a replacement for randomisation. Despite statistical adjustments, residual confounding cannot be completely excluded due to potential variations in patient selection and procedure execution.

As this was a retrospective observational study, no formal sample size or power calculation was performed.

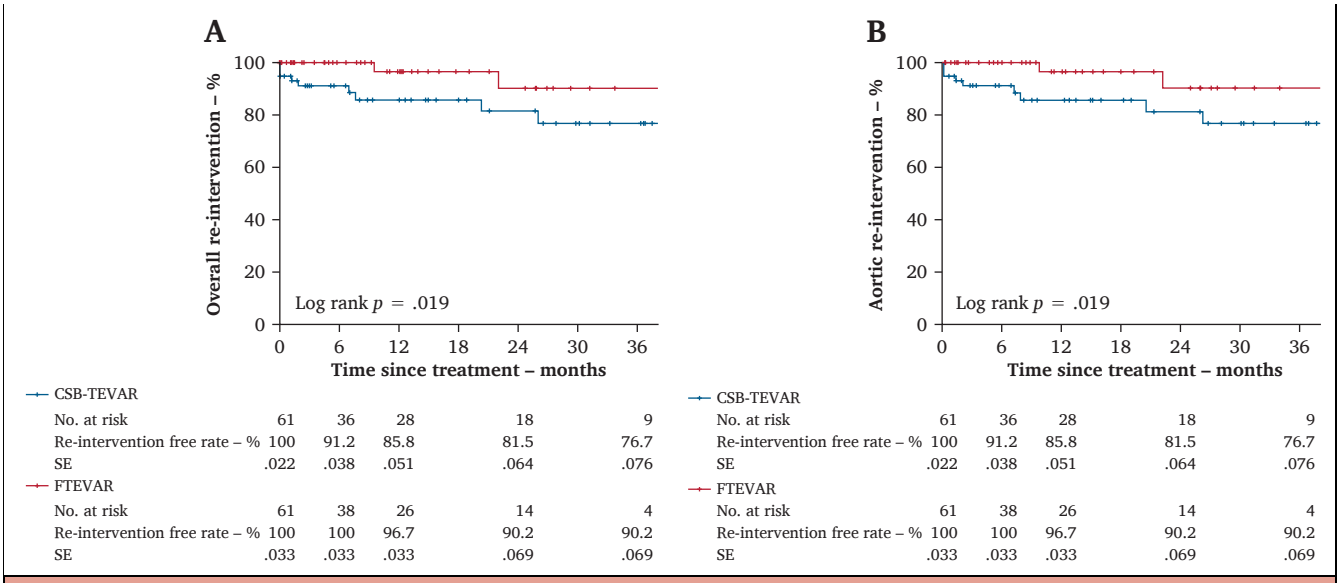


Figure 2. Cumulative Kaplan–Meier estimates of (A) overall re-interventions and (B) aortic re-interventions in the matched cohort comparing the carotid subclavian bypass thoracic endovascular aortic repair (CSB-TEVAR) and fenestrated thoracic endovascular aortic repair (FTEVAR) groups. SE = standard error.

Given the relatively low event rates for several secondary outcomes, the study may be underpowered to detect small but clinically relevant differences. Furthermore, although the post-PSM analysis demonstrated a statistically significant increase in re-intervention after CSB-TEVAR, the wide CIs indicate limited precision due to the modest number of events. To provide clinical interpretability, the authors calculated the absolute risk difference and corresponding number needed to harm, highlighting the practical magnitude of this effect while underscoring the need for cautious interpretation.

The median follow up period of 17 months was sufficient to demonstrate statistically significant midterm differences in re-intervention rates but remains inadequate to determine the true long term durability of either technique. The continued divergence of the KM curves for re-intervention suggests that outcome differences between CSB-TEVAR and FTEVAR may become more pronounced with longer surveillance. Accordingly, extended follow up over five to ten years is warranted to validate these trends and to more comprehensively define the durability of each approach.

While midterm outcomes were assessed, longer follow up is necessary to confirm durability and detect late complications. Further research, preferably in the form of prospective randomised trials, is needed to solidify these findings and establish optimal treatment guidelines for subclavian revascularisation strategies during TEVAR.

Conclusion

CSB-TEVAR and FTEVAR achieved high technical success, long term durability, and similar mortality rates. FTEVAR is a durable, low re-intervention alternative, while CSB-TEVAR remains a practical option in urgent cases despite its higher incidence of peri-operative and access related morbidity. These findings emphasise the need for individualised patient selection and close follow up, particularly for patients undergoing CSB-TEVAR.

CONFLICTS OF INTEREST

N.T. and D.A. are proctors and receive an institutional grant from Cook Medical. C.C.N. is a proctor for Cook Medical, Gore Medical, Medtronic, and Terumo Aortic. The remaining authors have no conflicts of interest.

FUNDING

None.

ACKNOWLEDGEMENTS

None.

APPENDIX A. SUPPLEMENTARY DATA

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ejvs.2025.12.008.

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