Risk factors for stroke after total aortic arch replacement using the frozen elephant trunk technique

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Abstract

OBJECTIVES: This study aimed to analyse risk factors for postoperative stroke, evaluate the underlying mechanisms and report on outcomes of patients suffering a postoperative stroke after total aortic arch replacement using the frozen elephant trunk technique.

METHODS: Two-hundred and fifty patients underwent total aortic arch replacement via the frozen elephant trunk technique between March 2013 and November 2020 for acute and chronic aortic pathologies. Postoperative strokes were evaluated interdisciplinarily by a cardiac surgeon, neurologist and radiologist, and subclassified to each's cerebral territory. We conducted a logistic regression analysis to identify any predictors for postoperative stroke.

RESULTS: Overall in-hospital was mortality 10% (25 patients, 11 with a stroke). A symptomatic postoperative stroke occurred in 42 (16.8%) of our cohort. Eight thereof were non-disabling (3.3%), whereas 34 (13.6%) were disabling strokes. The most frequently affected region was the arteria cerebri media. Embolism was the primary underlying mechanism (n = 31; 73.8%). Mortality in patients with postoperative stroke

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was 26.2%. Logistic regression analysis revealed age over 75 (odds ratio = 3.25; 95% confidence interval 1.20–8.82; \( P = 0.021 \)), a bovine arch (odds ratio = 4.96; 95% confidence interval 1.28–19.28; \( P = 0.021 \)) and an acute preoperative neurological deficit (odds ratio = 19.82; 95% confidence interval 1.09–360.84; \( P = 0.044 \)) as predictors for postoperative stroke.

**CONCLUSIONS:** Stroke after total aortic arch replacement using the frozen elephant trunk technique remains problematic, and most lesions are of embolic origin. Refined organ protection strategies, and sophisticated monitoring are mandatory to reduce the incidence of postoperative stroke, particularly in older patients presenting an acute preoperative neurological deficit or bovine arch.

**Keywords:** Aortic dissection • Frozen elephant trunk • Redo arch surgery • Arch replacement

### ABBREVIATIONS

| Abbreviation | Description |
|--------------|-------------|
| FET          | Frozen elephant trunk |
| mRS          | Modified Rankin scale |
| NIRS         | Near-infrared spectroscopy |
| SACP         | Selective antegrade cerebral perfusion |
| TAR          | Total aortic arch replacement |

### INTRODUCTION

Total aortic arch replacement (TAR) using the frozen elephant trunk (FET) technique was introduced in 2003 [1], and it has since been refined: for one, off-the-shelf hybrid prostheses became available in different modifications and lengths, and secondly, surgical techniques improved as zone 2 distal anastomosis simplified implantation and lowered the incidence of postoperative spinal cord injuries [2, 3]. Accordingly, short- and long-term survival improved over time, but aortic reinterventions are frequently needed [4]. Despite these refinements, stroke-induced neurological impairments remain a major postoperative complication whose mechanisms have neither been adequately analysed nor understood—nor has the stroke rate fallen over the last decade [3].

Aim of this study was to analyse risk factors for postoperative stroke, evaluate its underlying mechanisms and report on the outcome of patients with postoperative stroke after TAR using the FET technique.

### PATIENTS AND METHODS

**Ethics statement**

IRB approval was obtained on 4 February 2021 (No. 20-1302) by the University of Freiburg’s institutional review board and informed consent was waived.

**Patients**

Two-hundred and fifty consecutive patients underwent TAR using the FET technique at the University Heart Centre Freiburg between March 2013 and November 2020 for acute and chronic aortic pathologies including acute and chronic aortic dissection, degenerative aneurysm and penetrating aortic ulcer.

**Data collection and definition of parameters**

Data were collected retrospectively from our centre’s database. Stroke was classified according to the VARC-2 criteria using the modified Rankin scale (mRS) and subclassified as disabling stroke (mRS > 2) and non-disabling stroke (mRS < 3) [5]. A procedure-related stroke was defined as new postoperative deficit without neurological symptoms within 30 days before surgery. The others were defined as disease-related. An acute preoperative neurological deficit occurred within 30 days before surgery. Postoperative strokes were interdisciplinarily evaluated by a cardiac surgeon, neurologist and radiologist, and subclassified to the respective cerebral territory (frontal, parietal, posterior, cerebellar, stem or intracranial bleeding) and to the assumed stroke mechanism (embolic, perfusion/haemodynamic, microangiopathy). Our multidisciplinary team discussed inconsistencies and then made the decision.

**Preoperative assessment**

Despite computed tomography angiography (CTA) of the aorta starting in 2018, elective patients underwent additional colour-coded duplex sonography of the carotid arteries and a concomitant or additional computed tomography angiography scan to identify any variants in the circle of Willis that could influence the intraoperative perfusion strategy. A preoperative, new-onset neurological impairment including coma, or a supra-aortic vessel occlusion caused by the acute aortic pathology was not considered reasons to withhold surgery.

**Surgical technique**

Our surgical technique has been described in detail [2, 6–8]. We normally implant the short version of the Thoraflex hybrid-graft (100 mm; Terumo Aortic, Inchinnan, UK); distal anastomoses were routine in zone 2 following zone 3 anastomoses until 2015. The axillary artery is our standard access vessel for arterial cardiopulmonary bypass inflow even if there is a vessel dissection, and all surgeries were performed through a full median sternotomy. Our intended core body temperature is 25 degrees. Bilateral selective antegrade cerebral perfusion (SACP) is our standard cerebral perfusion technique (10 ml/kg/min). Nevertheless, in case of a hypoplastic right vertebral artery, or if the left vertebral artery ends isolated without forming the basilar artery, we usually employ trilateral cerebral perfusion via additional cannulation of the left axillary artery. Bifrontal near-infrared spectroscopy (NIRS) is routine to monitor cerebral oxygenation. We apply cold blood cardioplegia or the beating-heart technique using 300 ml normothermic myocardial perfusion for myocardial protection [7].

**Statistical analysis**

All values are expressed as number (percentage) or median (first quartile; third quartile). IBM SPSS Statistics 27 for Macintosh
Table 1: Descriptive characteristics of the cohort

| Total | No stroke | Stroke | P-value |
|-------|-----------|--------|---------|
| Demographics | n = 250 | n = 208 | n = 42 |
| **Age (years)** | 67 [59–74] | 67 [59–74] | 71 [59–76] | 0.11 |
| Male | 161 (64.4) | 133 (63.9) | 28 (66.7) | 0.86 |
| Chronic health conditions and risk factors | | | |
| Hypertension | 215 (86.0) | 179 (86.1) | 36 (85.7) | >0.99 |
| COPD | 26 (10.4) | 22 (10.6) | 4 (9.5) | >0.99 |
| Cardiac tamponade | 9 (3.6) | 5 (2.4) | 4 (9.5) | 0.047 |
| Coronary artery disease | 74 (29.6) | 61 (29.3) | 13 (31.3) | 0.85 |
| Chronic renal impairment | 33 (13.2) | 25 (12.0) | 8 (19) | 0.21 |
| Bicuspid aortic valve | 11 (4.4) | 10 (4.8) | 1 (2.4) | 0.70 |
| Connective tissue disorder | 23 (9.2) | 22 (10.6) | 1 (2.4) | 0.14 |
| Preoperative neurological state | | | |
| History of stroke | 34 (13.6) | 22 (10.6) | 12 (28.6) | 0.004 |
| Time of previous stroke (months) | 39 [2–92] | 40 [10–61] | 25 [0–210] | 0.75 |
| Coma | 5 (2.0) | 3 (1.4) | 2 (4.8) | 0.13 |
| Hemiparesis | 12 (4.8) | 7 (3.4) | 5 (11.9) | 0.018 |
| Previous cardiac or aortic procedures | | | |
| Time of previous intervention (years) | 5 [1–10] | 5 [1–10] | 5 [3–11] | 0.69 |
| Coronary artery bypass grafting | 8 (3.2) | 7 (3.4) | 1 (2.4) | 0.99 |
| Aortic valve replacement | 28 (11.2) | 24 (11.5) | 4 (9.5) | 0.80 |
| Mitral valve repair | 1 (0.4) | 1 (0.5) | 2 (4.8) | 0.99 |
| Ascending/hemiarch replacement | 78 (31.2) | 69 (33.2) | 9 (21.4) | 0.20 |
| Other | 52 (20.8) | 48 (23.1) | 4 (9.5) | 0.090 |
| Aortic re-do | 95 (38.0) | 85 (40.9) | 10 (23.8) | 0.037 |
| Re-sternotomy | 84 (33.7) | 68 (32.7) | 9 (21.4) | 0.15 |

Data are presented as median (first quartile; third quartile) or as number (%).
COPD: chronic obstructive pulmonary disease.

(Armonk, NY, USA) was used for statistical analysis. Normality was assessed graphically using Q–Q plots. Group comparison for the univariable analysis was performed using Student’s t-test for continuous variables. For categorical variables, the Chi-squared or Fisher’s Exact test was applied when appropriate. A logistic regression analysis was done to identify independent predictors for postoperative stroke. We selected these clinical covariates and entered them in the model: age over 75, acute type A aortic dissection, dissected supra-aortic vessels, bovine arch, SACP time, cardiopulmonary bypass time, zone 2 distal anastomosis, trilaterial cerebral perfusion, preoperative circle of Willis scan, auxiliary cannulation via Dacron graft, surgery before 2018 and acute preoperative neurological deficit and renal-failure history. The Hosmer–Lemeshow test was used to determine the model’s goodness of fit.

RESULTS

Patients characteristics

TAR was performed in 250 patients (64.4% male). Previous strokes were documented in 34 cases (13.6%) at a 39-month interval (IQR 2–92). Five patients (2%) were referred comatose, and 12 suffered from persisting hemiparesis; both conditions were more frequent in patients with postoperative stroke. Previous aortic interventions or surgeries were frequently observed. Patients characteristics are summarized in Table 1.

Aortic characteristics

Most had undergone surgery for chronic aortic dissections; acute type A aortic dissection was the indication in 35 patients (14%). We identified no differences in underlying pathologies in both groups. Aortic arch variants were observed in 36 (14.4%) patients (isolated offspring of the left vertebral artery n = 10 (4%), bovine arch n = 14 (5.6%) and an aberrant right subclavian artery n = 5 (2%)). Patients with postoperative stroke were more likely to present a bovine arch (14.3% vs 3.8%; P = 0.012). In those with aortic dissection, the dissection membrane extended into the supra-aortic and extracranial vessels in most patients (n = 81; 51.9%), and we diagnosed an occlusion in 16 (10.3%) patients. Computed tomography angiography data are summarized in Table 2.

Surgical characteristics

Concomitant procedures were performed in 99 patients (39.6%), with aortic valve replacement the most common (n = 39; 15.6%). We detected no differences regarding concomitant procedures between patients with and without postoperative stroke. We applied beating-heart technique for myocardial protection in 56 patients (22.4%)—more often in those without stroke. Cardiopulmonary bypass and SACP time were significantly longer in patients with stroke. Indications for aortic valve replacement were moderate or severe aortic stenosis in 2 (0.8%) and 5 (2.0%) patients, respectively, as well as moderate or severe aortic regurgitation in 19 (7.6%) and 13 (5.2%) patients, respectively. Surgical characteristics are summarized in Table 3.

Clinical outcome and follow-up

In-hospital mortality was 10%. A symptomatic postoperative stroke occurred in 16.8% of our cohort. Thirty-three (13.2%) were procedure-related, whereas 2.8% (n = 7) were disease-related or occurred during hospital stay (n = 2; 1 embolic stroke and 1 patient after cardiopulmonary resuscitation). Clinical outcomes and follow-up data are in Table 4. Seven of the procedure-related strokes were non-disabling (2.8%), whereas 26 (10.4%) were disabling strokes. The most frequent stroke-affected area was the arteria cerebri media territory, and embolism was the main underlying mechanism (n = 31; 73.8%). Mortality in patients suffering a postoperative stroke was higher (26.2%; n = 11), and they also underwent tracheostomy, dialysis and prolonged ventilation more often. Two of our 5 comatose patients suffered a disabling stroke (mRS 4) and the others died in hospital. Incidence of stroke in patients with bovine arch was 42.9% (50% thereof of embolic origin). About 16.7% were left-sided, 33.3% were right-sided and 50% were bilateral strokes. Outcomes of patients with stroke are illustrated in Table 4.

Logistic regression analysis

As predictors for postoperative stroke, our logistic regression model identified: age over 75 (odds ratio = 3.25; 95% confidence interval 1.20–8.82; P = 0.021), a bovine arch (odds ratio = 4.96;
95% confidence interval 1.28–19.28; \( P = 0.021 \) and acute preoperative neurological deficit (odds ratio = 19.82; 95% confidence interval 1.09–360.84; \( P = 0.044 \)) as predictors for postoperative stroke. The full model is shown in Table 5.

### Table 2: Computed tomography data

| Underlying pathologies | Total n = 250 | No stroke n = 208 | Stroke n = 42 | \( P \)-value |
|------------------------|--------------|------------------|--------------|--------------|
| Acute aortic dissection |              |                  |              |              |
| Type A                 | 35 (14)      | 26 (12.5)        | 9 (21.4)     | 0.14         |
| Type B                 | 22 (8.8)     | 17 (8.2)         | 5 (11.9)     | 0.39         |
| Non-A non-B            | 20 (8.0)     | 17 (8.2)         | 3 (7.1)      | >0.99        |
| Chronic aortic dissection |          |                  |              |              |
| Residual type B dissection after type A repair | 55 (22) | 50 (24) | 5 (11.9) | 0.10 |
| Type B                 | 14 (5.6)     | 13 (6.3)         | 1 (2.4)      | 0.48         |
| Non-A non-B            | 10 (4.0)     | 10 (4.8)         | 0 (0.0)      | 0.22         |
| Aneurysm               | 72 (28.8)    | 57 (27.4)        | 15 (35.7)    | 0.35         |
| PAU                    | 21 (8.4)     | 18 (8.7)         | 3 (7.1)      | 0.78         |
| Others                 | 2 (0.8)      | 1 (0.5)          | 1 (2.4)      | 0.31         |
| Aortic arch variants   | 36 (14.4)    | 26 (12.5)        | 10 (23.8)    | 0.043        |
| Isolated offspring left vertebral artery | 10 (4)   | 9 (4.3)         | 1 (2.4)      | 0.71         |
| Bovine arch            | 14 (5.6)     | 8 (3.8)          | 6 (14.3)     | 0.012        |
| Aberrant right subclavian artery | 5 (2.0) | 2 (1.0)  | 3 (7.1)  | 0.029    |
| Stenosis of extracranial vessels | 28 (11.2) | 27 (13)   | 1 (2.4)  | 0.050    |
| Dissection's extension in patients with aortic dissection | n = 156 | n = 133 | n = 23 |              |
| Supra-aortic and extracranial vessels | 81 (51.9) | 69 (51.9) | 12 (52.2) | 0.71 |
| Brachiocephalic trunk  | 49 (31.4)    | 39 (29.3)        | 10 (43.5)    | 0.27         |
| Right subclavian artery | 15 (9.6) | 12 (9.0)       | 3 (13.0)    | 0.71         |
| Right common carotid artery | 27 (17.3) | 21 (15.8)   | 6 (26.1)    | 0.27         |
| Left common carotid artery | 38 (24.8) | 32 (24.1) | 6 (26.1)  | >0.99 |
| Left subclavian artery  | 55 (35.3)    | 47 (35.3)        | 8 (38.0)     | >0.99        |
| Left vertebral artery  | 4 (2.6)      | 4 (3.0)          | 0 (0.0)      | >0.99        |
| Right vertebral artery | 1 (0.6)      | 1 (0.8)          | 0 (0.0)      | >0.99        |
| Thoracic descending aorta | 137 (87.8) | 117 (88)     | 20 (87)     | 0.39         |
| Abdominal aorta        | 111 (71.2)   | 95 (71.4)        | 16 (69.6)    | 0.49         |
| Iliac arteries         | 86 (55.1)    | 72 (54.1)        | 14 (60.8)    | >0.99        |
| Occluded supra-aortic and extracranial vessels | 16 (10.3) | 10 (7.5) | 2 (8.7)  | 0.70    |
| Right common carotid artery | 4 (2.6) | 3 (1.4)       | 1 (2.4)     | 0.66         |
| Left common carotid artery | 4 (2.6) | 3 (1.4) | 1 (2.4)  | 0.66 |
| Left subclavian artery  | 1 (0.6)      | 1 (0.5)          | 0 (0.0)      | >0.99        |
| Left vertebral artery  | 2 (1.3)      | 2 (1.0)          | 0 (0.0)      | >0.99        |
| Right vertebral artery | 5 (3.2)      | 5 (2.4)          | 0 (0.0)      | >0.99        |

Data are presented as number (%).

PAU: penetrating aortic ulcer.

### Table 3: Surgical characteristics of the cohort

| Concomitant cardiac and vascular procedures | Total n = 250 | No stroke n = 208 | Stroke n = 42 | \( P \)-value |
|--------------------------------------------|--------------|------------------|--------------|--------------|
| Concomitant cardiac and vascular procedures | 99 (39.6) | 81 (38.9) | 18 (42.9) | 0.73         |
| Aortic root conduit                        | 19 (7.6) | 17 (8.2) | 2 (4.8) | 0.75         |
| Valve-sparing aortic root replacement       | 16 (6.4) | 14 (6.7) | 2 (4.8) | >0.99        |
| Aortic valve replacement                    | 4 (1.6) | 3 (1.4) | 1 (2.4) | 0.66         |
| Coronary artery bypass grafting            | 35 (14.0) | 27 (13.0) | 8 (19.0) | 0.33         |
| Thoracic endovascular aortic repair        | 9 (3.6) | 6 (2.9) | 3 (7.1) | 0.18         |

Data are presented as median (first quartile; third quartile) or as number (%).

CPB: cardiopulmonary bypass; min: minutes; SACP: selective antegrade cerebral perfusion.
DISCUSSION

Stroke after TAR using the FET technique remains problematic, and most lesions are of embolic origin. Refined organ protection strategies and sophisticated monitoring are mandatory to reduce the incidence of postoperative stroke, particularly in older patients with an acute preoperative neurological deficit or bovine arch. Although our cohort’s demographics and medical histories are in line with other large FET trials, our patients seem older than in other studies [9, 10]. Our study reveals that an acute preoperative neurological deficit is a predictor for a perioperative one. Other trials, and a large nationwide analysis after cardiac or aortic surgery in the USA also arrived at this finding [11]. These are patients tending to have widespread cerebrovascular disease, whose cerebral blood flow may be impaired and likely to trigger atherosclerotic or thrombotic embolism [12]. This fact is also supported by our results, as the stroke incidence was notably higher in patients with degenerative aortic aneurysms than with chronic aortic dissections. However, another working group that investigated the postoperative stroke risk dependent on the presence or not of previous embolism in patients with infective endocarditis detected no differences in neurological outcome [13]. Since these strokes occurred in different territories, the authors attributed the procedure and manipulation themselves as having played the primary role. Note that we were unable to enter coma in our analysis due to the small number of patients.

Table 4: Clinical outcome and follow-up characteristics of the cohort

| Clinical outcome | Total n = 250 | No stroke n = 208 | Stroke n = 42 | P-value |
|-----------------|--------------|------------------|--------------|---------|
| In-hospital mortality | 25 (10.0) | 14 (6.7) | 11 (26.2) | 0.001 |
| Stroke | | | | |
| Procedure-related | 33 (13.2) | | 33 (78.6) | |
| Disabling | 26 (10.4) | 26 (61.9) | | |
| Non-disabling | 7 (2.8) | 7 (16.7) | | |
| Disease-related or during hospital stay | 9 (3.6) | 9 (21.4) | | |
| Disabling | 8 (3.2) | 8 (19.1) | | |
| Non-disabling | 1 (0.4) | 1 (2.4) | | |
| mRS | | | | |
| 0 | 2 (4.8) | | | |
| 1 | 6 (14.3) | | | |
| 2 | 2 (4.8) | | | |
| 3 | 7 (16.7) | | | |
| 4 | 8 (19) | | | |
| 5 | 7 (16.7) | | | |
| 6 | 10 (23.8) | | | |
| Cerebral territory* | | | | |
| Left-sided | 8 (19.0) | | | |
| Right-sided | 13 (30.9) | | | |
| Bilateral | 21 (50.0) | | | |
| Frontal | 32 (73.8) | | | |
| Parietal | 30 (71.4) | | | |
| Posterior | 20 (47.6) | | | |
| Cerebellar | 20 (47.6) | | | |
| Stem | 7 (16.7) | | | |
| Intracranial bleeding | 6 (14.3) | | | |
| Assumed stroke cause | | | | |
| Embolic | 31 (73.8) | | | |
| Perfusion/haemodynamic | 6 (14.3) | | | |
| Microangiopathy | 1 (2.4) | | | |
| Undetermined | 4 (9.5) | | | |
| Symptomatic SCI | 3 (1.2) | 2 (1.0) | 1 (2.3) | 0.43 |
| Bleeding | 37 (14.8) | 32 (15.4) | 5 (11.9) | 0.64 |
| Dialysis | 31 (12.4) | 20 (9.6) | 11 (26.2) | 0.008 |
| Ventilation time (hours) | 21 [15–48] | 21 [15–39] | 43 [19–132] | 0.012 |
| Tracheostomy | 20 (8) | 12 (5.8) | 8 (19.0) | 0.009 |
| ICU stay (days) | 6 [4–12] | 6 [3–10] | 12 [6–19] | <0.001 |
| Hospital stay (days) | 17 [13–24] | 17 [13–24] | 19 [8–24] | 0.84 |
| Follow-up data | n = 225 | n = 194 | n = 31 | |
| Follow-up (years) | 1.2 [0.3–2.8] | 1.5 [0.4–2.9] | 0.7 [0.2–2.4] | 0.78 |
| Follow-up mortality | 23 (10.2) | 20 (9.6) | 3 (7.1) | 0.020 |
| Aortic reintervention | 78 (34.7) | 73 (35.1) | 5 (16.1) | 0.70 |
| Open surgery | 4 (1.8) | 4 (1.9) | 0 (0.0) | 0.003 |
| Endovascular extension | 63 (28) | 59 (28.4) | 4 (12.9) | |
| Hybrid approach | 11 (4.9) | 10 (4.8) | 1 (3.2) | >0.99 |

Data are presented as median (first quartile; third quartile) or as number (%). *Multiple nomination possible.

ICU: intensive care unit; mRS: modified Rankin scale; SCI: spinal cord injury.
clinical outcomes provided they had undergone surgery immediately (mortality was 14%, 86% of the cohort recovered consciousness and the majority could engage in daily activities) 

Acute type A aortic dissection was not predictive for postoperative stroke in our study. Nevertheless, our selection of patients with acute type A aortic dissection contributes to the numerically higher stroke incidence in these patients since only those with an arch-entry tear or supra-aortic vessel occlusion undergo TAR in our centre, whereas the others undergo hemiarch replacement. Controversially, our logistic regression model revealed that dissection of the supra-aortic or extracranial vessels was not significant—potentially attributable to the few patients with acute type A aortic dissections. In contrast to our findings, there is evidence that a common carotid artery dissection and carotid true lumen flow impairment are predictive for stroke, but not mortality [15, 16]. Our experience is that dissected supra-aortic vessels do not influence outcomes or cause cannulation difficulties in the right axillary artery when done routinely. Interestingly, a bovine arch has proven to be predictive for postoperative stroke. Dumfarth et al. and Kreibich et al. made this finding, but no conclusive explanation for bovine arch being predictive for postoperative strokes [17, 18]. Right axillary cannulation might contribute to a higher incidence of embolic strokes especially in patients with acute type A aortic dissection. Consequently, the San Donato group founded the CILCA registry to further investigate the bovine arch’s relevance for sustaining cerebral protection during aortic arch replacement. While the antegrade manner of perfusion is widely used, there is ongoing debate as to whether uni-, bi- or trilateral selective cerebral perfusion is ideal. Of note, Zierer et al. [20] demonstrated that bilateral SACP correlated with a higher stroke incidence in elective cases (acute type A aortic dissections were excluded) with regard to more manipulation, other researchers observed no significant difference in neurological outcomes between uni- and bilateral perfusion techniques in patients with acute type A aortic dissection [21]. They detected perfusion safety functionally via transcranial Doppler [22]. Moreover, the efficacy of monitoring intracerebral oxygenation by relying on adequate blood perfusion remains debatable. Most centres in Europe use NIRS. But studies have shown that NIRS does not sufficiently monitor the entire cortex’s oxygenation—rather, only a small part of the frontal lobe. NIRS may therefore only indicate a cannula’s malposition or regional hypoperfusion—it cannot detect embolic events. There is no solid evidence that it predicts any postoperative neurological events [23]. In fact, it seems that we currently lack the means to monitor cerebral perfusion adequately despite the obvious urgency of doing so. Our group is currently evaluating the clinical benefits of multichannel NIRS. With this tool, more than 50 electrodes demonstrate the oxygenation of the entire cortex including the posterior territory.

The largest meta-analysis to date of studies (covering 3154 patients) reporting on post-FET procedure outcomes revealed a 7.6% incidence of postoperative stroke, but failed to identify any potential risk factors for stroke after total arch replacement. A major limitation in their study is the study design with limited access to essential variables. Other single-centre studies or registries reported an incidence of 7–11.6% [9, 10, 24, 25]. Of note, they often only mention permanent deficits, and their stroke definitions are not comparable to our study’s. If one made a comparison our procedure-related disabling stroke incidence 10.4% would be the most applicable. Nevertheless, we perceive a slight difference in postoperative stroke rates that may have something to do with the prostheses’ design (island vs multi-branch prosthesis) leading to more surgical manipulation (supported by the numerous embolic strokes in our study). However, other influencing factors, especially technical or perfusion differences among centres, cannot be ruled out [9, 10, 24].

Limitations

This is a retrospective single-centre study with all the limitations associated with such a study design. Therefore, we could only analyse our protection strategy, and were unable to compare different hypothermic or perfusion settings. As no NIRS data were collected, no analysis of a drop in saturation was possible. No primary analysis was defined. Many tests were conducted without adjusting for multiple testing. Therefore, analyses were exploratory in nature and inferences drawn from them may not be reproducible.

CONCLUSIONS

Stroke after TAR using the FET technique remains a difficult issue. Whereas most lesions in our patients were of embolic origin, we identified no clear distribution pattern corresponding to their cerebral territory. An acute preoperative neurological deficit, a

| Table 5: Logistic regression model for stroke |
|---------------------------------------------|
| Logistic regression model                  |
| Odds ratio       | 95% CI          | P-value |
| Acute preoperative neurological deficit     | 19.82           | (1.09–360.84) | 0.044 |
| Age over 75 years                             | 3.25            | (1.20–8.82)   | 0.021 |
| Trilateral cerebral perfusion                | 3.43            | (0.97–12.18)  | 0.057 |
| Zone 2 distal anastomosis                     | 0.82            | (0.29–2.35)   | 0.71  |
| Bovine arch                                   | 15.19           | (1.30–177.84) | 0.021 |
| Supra-aortic vessel dissection                | 0.69            | (0.23–2.12)   | 0.26  |
| Axillary cannulation via dacron graft         | 1.44            | (0.54–3.84)   | 0.47  |
| Surgery before 2018                           | 1.95            | (0.59–6.47)   | 0.27  |
| Acute type A aortic dissection                | 3.18            | (0.90–11.22)  | 0.073 |
| Cardiopulmonary bypass time                  | 1.01            | (0.99–1.01)   | 0.24  |
| Selective antegrade cerebral perfusion time   | 0.99            | (0.98–1.01)   | 0.11  |
| History of renal failure                     | 1.57            | (0.45–5.45)   | 0.48  |
| Preoperative Circle of Willis scan           | 1.15            | (0.28–4.68)   | 0.85  |

CI: confidence interval.
bovine arch and age over 75 years were our cohort's only risk factors for postoperative stroke. No morphology or procedure-related factors contributed to the postoperative stroke risk. Refined organ protection strategies and sophisticated monitoring are mandatory in order to reduce stroke after TAR using the FET technique.

Conflict of interest: Martin Czerny and Bartosz Rylski are consultants to Terumo Aortic and shareholders of Ascense Medical. Martin Czerny is consultant to Medtronic, Endospan and NEOS, received speaking honoraria from Cryolife-Jotec and Bentley and is shareholder of TEVAR Ltd.

Data availability statement: The data underlying this article cannot be shared publicly due to our institutional review board's requirements. The data will be shared on reasonable request to the corresponding author.

**Author contributions**

Tim Berger: Conceptualization; Formal analysis; Methodology; Writing—original draft. Maximilian Kreibich: Supervision; Validation; Writing—review & editing. Felix Mueller: Data curation; Formal analysis; Writing—original draft. Lara Beurer-Kellner: Data curation; Methodology; Writing—review & editing. Bartosz Rylski: Supervision; Writing—review & editing. Stoyan Kondov: Conceptualization; Visualization; Writing—review & editing. Holger Schröfel: Writing—review & editing. Clarence Pingpoh: Validation; Writing—review & editing. Friedhelm Beyersdorf: Project administration; Supervision; Writing—review & editing. Matthias Siepe: Methodology; Project administration; Supervision; Writing—review & editing. Martin Czerny: Conceptualization; Methodology; Supervision; Validation; Writing—review & editing.

**Reviewer information**

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