ORIGINAL ARTICLE

The frozen elephant trunk technique: impact of proximalization and the four-sites perfusion technique

Konstantinos Tsagakis[a,*], Anja Osswald[a], Alexander Weymann[a], Aydin Demircioglu[b],
Bastian Schmack[a], Daniel Wendt[a], Heinz Jakob[a] and Arjang Ruhparwar[a]

[a] Department of Thoracic and Cardiovascular Surgery, West German Heart and Vascular Center Essen, University Hospital Essen, Essen, Germany
[b] Department of Diagnostic and Interventional Radiology and Neuroradiology, University Hospital Essen, University of Duisburg-Essen, Essen, Germany

* Corresponding author. Department of Thoracic and Cardiovascular Surgery, West German Heart and Vascular Center Essen, University Hospital Essen, Hufelandstrasse 55, 45147 Essen, Germany. Tel: +49-201-7234901; fax: +49-201-7235451; e-mail: konstantinos.tsagakis@uk-essen.de (K. Tsagakis).

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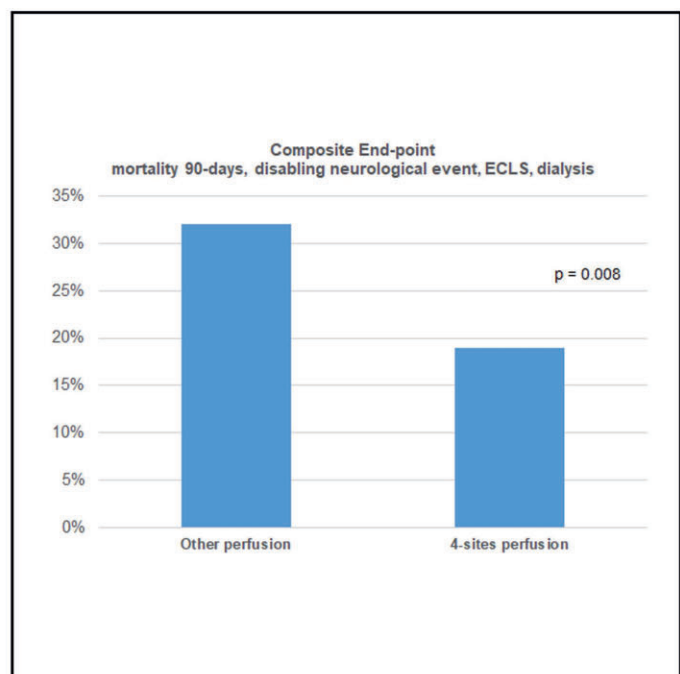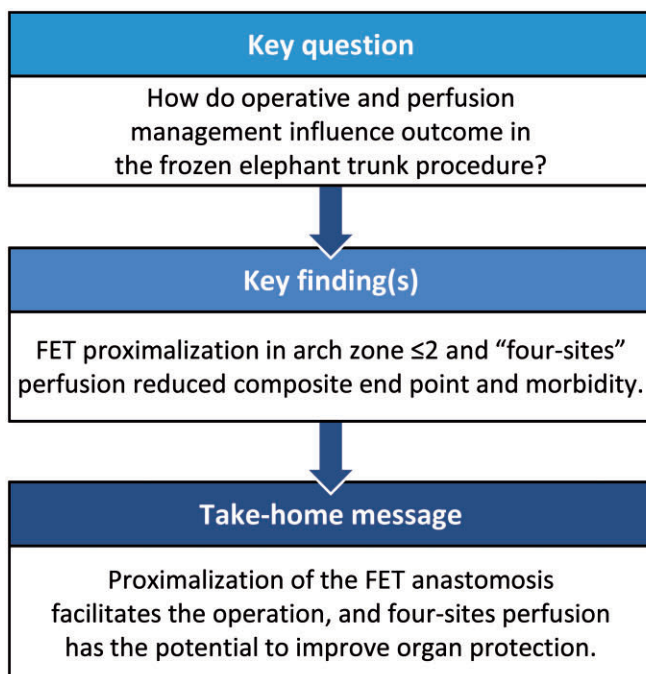
Abstract

OBJECTIVES: To improve organ protection with the frozen elephant trunk (FET) procedure, a so-called four-sites perfusion in combination with proximalization for the distal aortic anastomosis was performed. The impact of these techniques on patient outcome is reported.

METHODS: Between February 2005 and April 2020, a total of 357 patients underwent the FET procedure for acute (54%) or chronic (22%) aortic dissection or aneurysmal disease (24%). The level of the distal FET anastomosis was defined according to aortic arch zones 0–3. Patients were divided into 3 groups according to the intraoperative perfusion strategy: (i) selective antegrade cerebral perfusion (SACP) alone (N = 96, 2 sites); (ii) SACP plus left subclavian artery or distal aorta (N = 84, 3 sites) and (iii) SACP plus left subclavian artery plus distal aorta (N = 177, 4 sites). Early outcome was addressed by a composite end point: occurrence of either a disabling stroke, a disabling spinal cord injury, extracorporeal circulatory support, kidney dialysis or death within 90 days.

RESULTS: Preoperative characteristics were similar among the groups. Surgery in group C was characterized by FET proximalization in arch zone ≤ 2, moderate hypothermia at 28°C and shorter periods of extracorporeal circulation, SACP, hypothermic circulatory arrest and cardioplegic arrest ($P < 0.001$, respectively). Occurrence of the composite end point was reduced in group C ($P = 0.008$). The combination of FET proximalization and four-sites perfusion was a protective factor for the composite outcome in multivariable analysis ($P = 0.009$). The 5-year survival was improved in patients who underwent FET proximalization in zone ≤ 2 (hazard ratio 0.7, 95% confidence interval 0.4–1.0; $P = 0.036$).

CONCLUSIONS: FET proximalization in combination with four-sites perfusion has the potential to improve patient outcomes in terms of survival and major events.

Subject collection: 120; 161.

Keywords: Frozen elephant trunk • Aortic surgery • Perfusion • Organ protection

ABBREVIATIONS

AAD	Acute aortic dissection
Ax	Axillary
CPB	Cardiopulmonary bypass
CI	Confidence interval
FET	Frozen elephant trunk
HCA	Hypothermic circulatory arrest
HR	Hazard ratio
LSA	Left subclavian artery
SACP	Selective antegrade cerebral perfusion
SCI	Spinal cord injury

INTRODUCTION

The frozen elephant trunk (FET) procedure is a major operation with substantial risks of morbidity and mortality [1–3]. The fixation of FET in the transition zone between the aortic arch and the descending aorta may represent a surgical challenge, thereby escalating the duration of surgery and the severity of surgical trauma [4].

To facilitate the FET procedure, we previously introduced the proximalization of the distal aortic anastomosis by separating the left subclavian artery (LSA) revascularization from open arch repair [5]. Using this technique, the FET is deployed in the surgically more accessible aortic arch zone 2 after LSA debranching. The surgical access to the LSA enabled the establishment of selective LSA perfusion complementary to bilateral selective antegrade cerebral perfusion (SACP). Considering the risk of spinal cord injury (SCI), selective LSA perfusion maintained the blood supply to the left vertebral and mammary arteries and via communications to the anterior spinal artery. Additionally, implementation of selective distal aortic perfusion directly after FET fixation enabled the completion of the operation under whole-body perfusion [6]. This more comprehensive perfusion, the so-called four-sites perfusion, may improve the cerebral, spinal cord and visceral organ protection in FET surgery.

The combination of FET proximalization by LSA debranching prior to aortic clamping with the four-sites perfusion represents the current standard technique for FET surgery in our department. The goal of the study was to evaluate this technique in terms of early and late patient outcomes.

METHODS

Ethical statement

The institutional review board approved submission and publication of the retrospective study and waived the need for informed patient consent.
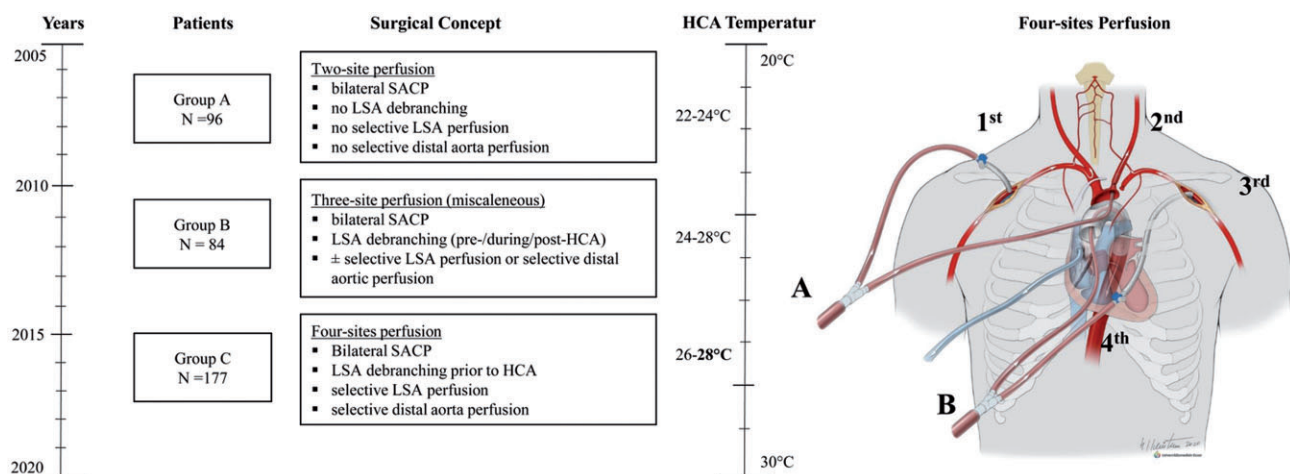

Figure 1: Study design according to the surgical and perfusion concept in chronological order. Drawing illustrates the four-sites perfusion: Main Y-arterial line (**A**) is connected at the right axillary artery (first site) and left common carotid artery (second site) for bilateral cerebral perfusion. A second pump and arterial Y-line (**B**) is used for LSA (third site) and antegrade perfusion of the distal aorta (fourth site). HCA: hypothermic circulatory arrest; LSA: left subclavian artery; SACP: selective antegrade cerebral perfusion.

Patients and definitions

Between February 2005 and April 2020, a total of 357 patients (age 60 years, standard deviation 12) underwent the FET procedure for acute aortic dissection (54%, AAD) or chronic aortic dissection (22%) or aneurysmal disease (24%) in our institution. The patients were divided into 3 groups according to the perfusion technique in addition to bilateral SACP (Fig. 1):

Group A: FET surgery without selective LSA perfusion and selective distal aortic perfusion.
Group B: FET surgery with either selective LSA perfusion or selective distal aortic perfusion.
Group C: FET surgery in combination with LSA debranching prior to aortic clamping and four-sites perfusion.

Four-sites perfusion was defined as the simultaneous perfusion of both carotid arteries and both subclavian arteries during arch repair and additional selective perfusion of the distal aorta immediately after FET fixation (Video 1).

In addition to in-hospital deaths, early outcome can be determined by severe organ dysfunction and post-discharge deaths. Furthermore, intraoperative perfusion management may prevent organ dysfunction and improve recovery. In order to evaluate mortality and the severity of morbidity, we defined a composite end point consisting of the occurrence of either a disabling stroke, disabling SCI, extracorporeal circulatory support, kidney dialysis or death within 90 days as the primary end point of the study.

Definitions

- Disabling stroke was indicated by the modified Rankin scale of ≥ 3 (range 0–6, higher scores indicate severe disability) [7]. Cerebral events were defined as transient or permanent, including those patients with new neurological symptoms before the cut-down in case of AAD.
- Disabling SCI was defined as permanent motor dysfunction requiring minor or major assistance. Classification of SCI severity was based on the American Spinal Injury Association Impairment Scale (A–E), whereby A-B-C indicated a disabling condition in terms of the study [8]. Furthermore, SCI was classified as complete in case of loss of motor function; otherwise, it was considered as incomplete.
- Extracorporeal life support included the use of venoarterial or venovenous perfusion postoperatively either for cardio-circulatory or pulmonary failure.
- Persisting renal dialysis was defined as the need for renal replacement therapy 90 days after surgery.

Cerebral and spinal cord events were verified by computed or magnetic resonance tomography and clinical examination. Follow-up was performed 3–6 months postoperatively and annually thereafter.

Surgery: from the first to the current technique

The operative technique was described previously [9]. We used SACP and near infrared spectroscopy for cerebral protection.

Video 1 Four-sites perfusion technique in acute type I aortic dissection.

Patients who were electively operated on underwent cerebrospinal fluid drainage and pressure monitoring (LiquoGuard, Moeller Medical GmbH, Fulda, Germany). FET guidance and deployment were controlled by guidewire and angioscopy [10]. Arch arteries were re-implanted as 3- or 2-island according to the level of the distal FET anastomosis. Otherwise, selective arteries were re-implanted directly or with interposition grafts. The E-vita open and the later E-vita open plus ($N = 354$, Jotec/CryoLife, Hechingen, Germany) or the Thoraflex ($N = 3$, Terumo Aortic, Renfrewshire, UK) was used for the FET graft. Changes in operative management over time were as follows:

- FET proximalization to arch zone ≤ 2 reduced the ischaemic times, and the hypothermic circulatory arrest (HCA) temperature was gradually elevated from 24 to 28°C.
- LSA debranching was performed initially via a median sternotomy under cardiopulmonary bypass (CPB). To gain access to the LSA, a clamp at the LSA origin was used to retract the arch and to obtain exposure to the LSA for an end-to-end artery graft anastomosis. In patients with anatomical complexities, this anastomosis was completed under HCA after arch resection. This technique was changed in 2013 using an extra-anatomic aortoaxillary bypass to separate completely the LSA revascularization from the CPB and HCA.
- Selective distal aortic perfusion was applied initially in selective patients with increased risk for visceral ischaemia. This perfusion was established via the femoral artery after endoclamping the FET stent graft by balloon. Later, a Foley 30-Fr catheter through the opened arch was used routinely as an endoclamp and a perfusion cannula.

Left subclavian artery debranching by aortoaxillary bypass

Prior to the sternotomy, both axillary (Ax) arteries were exposed for a T anastomosis with an 8-mm graft. The right Ax graft was connected to the main pump Y-line for CPB. The free end of the left Ax graft was ligated after flushing with heparin solution. After the sternotomy and initiation of CPB, the left Ax graft was retrieved via the first intercostal space into the mediastinum and connected to a second arterial Y-line. After cardioplegic arrest, clamping of the brachiocephalic trunk initiated SACP. The aortic arch was resected in zone 2 and the left common carotid artery

Table 1: Preoperative characteristics

Groups	Previous concepts			Current concept	
	A	B	Sum A + B	C	*P*-value
Patients	96	84	180	177	
Age (years), mean ± SD	59 ± 12	61 ± 11	60 ± 11	60 ± 12	0.90
Male gender, *n* (%)	72 (75)	56 (67)	128 (71)	119 (67)	0.49
Emergency, *n* (%)	66 (69)	51 (61)	117 (65)	110 (62)	0.58
Aortic dissection, *n* (%)					
Acute type I–III	58 (60)	47 (56)	105 (58)	87 (49)	0.090
Chronic type I–III	22 (23)	13 (16)	35 (19)	43 (24)	0.31
Aneurysm, *n* (%)	16 (17)	24 (29)	40 (22)	47 (27)	0.39
Arch/descending	10 (10)	9 (11)	19 (11)	17 (10)	0.86
Crawford type I–II	6 (6)[a]	15 (18)	21 (12)	30 (17)	0.17
Previous operations, *n* (%)					
Thoracic aorta/cardiac	20 (21)	14 (17)	34 (19)	32 (18)	0.89
TEVAR	5 (5)	7 (8)	12 (7)	11 (6)	1.00
Abdominal aorta	6 (6)	3 (4)	9 (5)	4 (2)	0.26
Marfan	6 (6)	2 (2)	8 (4)	6 (3)	0.79
Cardiac comorbidities, *n* (%)					
Coronary artery disease	29 (30)	23 (27)	52 (29)	48 (27)	0.72
EF <40%	0	2 (2)	2 (1)	5 (3)	0.28
AV regurgitation ≥II°	45 (47)	38 (45)	83 (46)	84 (48)	0.83
MV regurgitation >II°	6 (6)	9 (11)	15 (8)	16 (9)	0.85
Other comorbidities, *n* (%)					
COPD	18 (19)	26 (31)	44 (24)	46 (26)	0.81
Creatinine >1.5 mg/dl	17 (18)	22 (26)	39 (22)	33 (19)	0.51
Diabetes mellitus	7 (7)	7 (8)	14 (8)	10 (6)	0.53
Peripheral artery disease	17 (18)	15 (18)	32 (18)	24 (14)	0.31
Previous St.p. stroke	10 (10)	9 (11)	19 (11)	19 (11)	1.00

AV: aortic valve; COPD: chronic obstructive pulmonary disease; EF: ejection fraction; MV: mitral valve; SD: standard deviation; TEVAR: thoracic endovascular aortic repair.

was cannulated. Ligation of the origin of the LSA initiated the selective LSA perfusion via the left Ax graft. Completion of arch repair in zone 2 and proximal aortic repair were followed by end-to-site implantation of the left Ax graft in the proximal graft on the beating heart. The length and position of the Ax graft were designed to avoid graft kinking and positioning close to the sternum.

Four-sites perfusion

Extracorporeal perfusion was implemented with a centrifugal pump between the venous reservoir and the oxygenator as the main pump for body perfusion and bilateral SACP (main Y-line). By adding a roller pump after the oxygenator, a second circuit (second Y-line) was established for selective perfusion of the LSA and the distal aorta under HCA [7]. This set-up enabled us to adjust perfusion flow and pressure at the different perfusion sites. Arterial blood pressure was measured in both radial arteries and 1 femoral artery. SACP pressure (50–60 mmHg) was controlled at the tip of the left common carotid artery balloon cannula (Gundry RCSP, Medtronic, Minneapolis, MN, USA). Selective LSA perfusion (300–400 ml/min) was adjusted to 50 mmHg at the left radial artery. HCA was initiated at 28°C bladder temperature. Just before HCA, the blood temperature was reduced to 22°C for the SACP and LSA perfusion. Rewarming was started just before completion of the FET fixation, so that selective distal perfusion (~1800 ml/min) was performed at 28°C. A low pressure at the femoral artery was tolerated to avoid the administration of adrenergic drugs during the period of SACP. Completion of arch repair was

accompanied by stepwise rewarming. Four-site selective perfusion was finished by clamping the arch graft and re-establishing the systemic perfusion, usually via the right Ax artery.

Statistical analysis

Categorical variables were presented as counts and percentages and were compared using the two-sided Fisher's exact test. Continuous variables were expressed as mean and standard deviation or as median and 25th–75th interquartile range. Assumption of normality was assessed visually using Q–Q plots and the Shapiro–Wilk test. Continuous data were compared using the two-sided Student's *t*-test or the Mann–Whitney *U*-test based on the data distribution. Statistical comparisons were performed between group C and the summary of groups A and B (sum A + B) for reasons of simplicity. A multivariable logistic regression based on bootstrap resampling with 1000 repeats was used to evaluate the effect of four-sites perfusion on the occurrence of the composite end point outcome in addition to patient characteristics. Variables entered into the model were age, gender, emergency surgery, coronary artery disease, aortic valve insufficiency, mitral valve insufficiency, chronic obstructive pulmonary disease, creatinine >1.5 mg/dl, diabetes, peripheral artery disease, stroke, previous St.p. aortic/cardiac surgery and four-sites perfusion. Overall survival was estimated using the Kaplan–Meier method, and group differences were tested for statistical significance by the log-rank test. Hazard ratios (HRs) were computed by Cox regression, where the proportional hazards assumption was checked visually by log–log plots. A *P*-value below 0.05 was considered statistically significant. No adjustment

Table 2: Intraoperative data

| Groups | Previous concepts | | | Current concept | |
	A	B	Sum A + B	C	P-value
Patients	96	84	180	177	
Cannulation, n (%)					
Right Ax artery	39 (41)	56 (67)	95 (53)	138 (78)	<0.001
Left Ax artery	0	1 (1)	1 (1)	15 (9)	<0.001
Ascending aorta	53 (55)	24 (29)	77 (43)	11 (6)	<0.001
Other	4 (4)	3 (4)	7 (4)	13 (7)	0.17
FET fixation, n (%)					
Zone 0	0	1 (1)	1 (1)	4 (2)	0.21
Zone 1	0	0	0	9 (5)	0.002
Zone 2	9 (9)	64 (76)	73 (41)	164 (93)	<0.001
Zone 3	87 (91)	19 (23)	106 (59)	0	<0.001
Arch arteries, n (%)					
Island 3-arteries	42 (44)	9 (11)	51 (28)	0	<0.001
Island 2-arteries	6 (6)	41 (49)	47 (26)	120 (68)	<0.001
Separately	48 (50)	34 (41)	82 (46)	57 (32)	0.012
LSA debranching, n (%)					
Aorta−LSA origin	3 (3)	46 (55)	49 (27)	24 (14)	0.002
Aorta−left Ax artery	6 (6)	21 (25)	27 (15)	151 (85)	<0.001
Carotid-subclavian	0	3 (4)	3 (2)	2 (1)	1.00
LSA-debranching time, n (%)					
Prior to aortic clamp	0	31 (37)	31 (17)	177 (100)	<0.001
During HCA	2 (2)	26 (31)	28 (16)	0	<0.001
During reperfusion	7 (7)	13 (16)	20 (11)	0	<0.001
Selective perfusion, n (%)					
Bilateral SACP	95 (99)	80 (95)	175 (97)	177 (100)	0.061
LSA	0	57 (68)	57 (32)	177 (100)	<0.001
Distal aorta	0	47 (56)	47 (26)	177 (100)	<0.001
Proximal repair, n (%)					
Ascending aorta	93 (97)	78 (93)	171 (95)	164 (93)	0.39
Bentall	9 (9)	15 (18)	24 (13)	24 (14)	1.00
AV sparing root surgery	19 (20)	23 (27)	42 (23)	42 (24)	1.00
AV isolated replacement	7 (7)	6 (7)	13 (7)	11 (6)	0.83
MV repair or replacement	4 (4)	4 (5)	8 (4)	4 (2)	0.38
CABG	27 (28)	20 (24)	47 (26)	35 (20)	0.17
Times, median (IQR)					
CPB	243 (208–296)	248 (206–278)	244 (206–286)	220 (177–251)	<0.001
Cardioplegic arrest	142 (118–177)	141 (106–170)	141 (113–174)	116 (93–141)	<0.001
SACP	67 (55–78)	61 (51–73)	63 (51–78)	53 (46–64)	<0.001
HCA	77 (58–87)	48 (35–63)	61 (47–78)	32 (27–38)	<0.001
Bladder (°C)	25 (24–26)	27 (25–28)	25 (24–28)	28 (28–28)	<0.001

AV: aortic valve; Ax: axillary; CABG: coronary artery bypass grafting; CPB: cardiopulmonary bypass; FET: frozen elephant trunk; HCA: hypothermic circulatory arrest; IQR: interquartile range; LSA: left subclavian artery, MV mitral valve; SACP: selective antegrade cerebral perfusion.

for multiple testing was applied. Statistical analysis was performed using SPSS version 26.0 statistical software (IBM Corporation, New York, NY, USA).

RESULTS

Preoperative characteristics were statistically similar among the groups (Table 1). In patients with AAD, the clinical status was statistically similar according to the Penn Classification [11] and the malperfusion sites (Supplementary Material, Table S1). Operative procedures are presented in Table 2.

Composite end point

The composite end point occurred in 91 (25%) of the entire study population and was less in group C (19%) in comparison to group A + B (32%); $P = 0.008$ (Table 3). FET proximalization and

four-sites perfusion management reduced the composite end point in patients with AAD (17/87, 19% vs 34/105, 32%; $P = 0.050$), in chronic aortic dissection (6/43, 14% vs 9/35, 26%; $P = 0.25$) and in aneurysm (11/47, 23% vs 14/40, 35%; $P = 0.25$) patients. Multivariable logistic regression analysis revealed age, emergency surgery, previous St.p. aortic/cardiac surgery and peripheral artery disease as risk factors for the composite end point and the proximalization concept with four-sites perfusion as the protective factor (Table 4 and Supplementary Material, Table S2).

Other postoperative results

The 30-day mortality was 11% in group C versus 15% in group A + B ($P = 0.27$). Total cerebral events were significantly less in group C (12% vs 21%; $P = 0.031$), particularly the severe cerebral events (Rankin scale 5–6, 5% vs 11%; $P = 0.051$). New cerebral ischaemic events (4% vs 8%; $P = 0.18$), new SCI (3% vs 6%; $P = 0.29$) and permanent complete SCI (1% vs 3%; $P = 0.28$)

Table 3: Study end point and postoperative events

Groups	Previous concepts				Current concept
	A	B	Sum A + B	C	P-value
Patients	96	84	180	177	
Composite end point, n (%)	32 (33)	25 (30)	57 (32)	34 (19)	0.008
Mortality at 90 days	14 (15)	20 (24)	34 (19)	26 (15)	0.32
Disabling cerebral event	17 (18)[a]	9 (11)	26 (14)	13 (7)	0.041
Disabling spinal cord event	5 (5)	3 (4)	8 (4)	2 (1)	0.10
ECLS	3 (3)	10 (12)	13 (7)	8 (5)	0.37
Permanent dialysis	4 (4)	0	4 (2)	2 (1)	0.68
Mortality, n (%)					
Thirty-day	9 (9)	18 (21)	27 (15)	19 (11)	0.27
In-hospital	11 (12)	19 (23)	30 (17)	20 (11)	0.17
Cerebral events, n (%)					
Total	22 (23)	15 (18)	37 (21)	21 (12)	0.031
New ischaemic	10 (10)	4 (5)	14 (8)	7 (4)	0.18
Preoperative	11 (12)	6 (7)	17 (9)	7 (4)	0.055
Haemorrhage	1 (1)	5 (6)	6 (3)	7 (4)	0.78
Modified Rankin scale					
0	3 (3)	3 (4)	6 (3)	2 (1)	0.28
1–2	2 (2)	3 (4)	5 (3)	6 (3)	0.77
3–4	5 (5)	1 (1)	6 (3)	4 (2)	0.75
5–6	12 (13)	8 (10)	20 (11)	9 (5)	0.051
Spinal cord events, n (%)					
Total	6 (6)	8 (10)	14 (8)	6 (3)	0.10
New	4 (4)	6 (7)	10 (6)	5 (3)	0.29
Preoperative	2 (2)	2 (2)	4 (2)	1 (1)	0.37
Spinal cord symptoms, n (%)					
Permanent complete	3 (3)	3 (4)	6 (3)	2 (1)	0.28
Permanent incomplete	2 (2)	2 (2)	4 (2)	0	0.12
Transient	1 (1)	3 (4)	4 (2)	4 (2)	1.00
Other events					
Bowel ischaemia, n (%)	4 (4)	9 (11)	13 (7)	4 (2)	0.044
Limb ischaemia, n (%)	4 (4)	2 (2)	6 (3)	0	0.030
Re-exploration for bleeding, n (%)	16 (17)	10 (12)	26 (14)	10 (6)	0.008
Intubation (days), median (IQR)	4.00 (1.0–24)	2.00 (0.6–5.0)	3.00 (0.8–17.8)	0.75 (0.4–2.2)	<0.001
Temporary renal replacement therapy, n (%)	32 (33)	26 (31)	58 (32)	42 (24)	0.078
Sternal infection, n (%)	4 (4)	2 (2)	6 (3)	6 (3)	1.00

ECLS: extracorporeal life support; IQR: interquartile range.

decreased in group C without statistical significance. Bowel ischaemia (*P* = 0.044), limb ischaemia (*P* = 0.030) and re-exploration for bleeding (*P* = 0.008) were significantly less in group C. The duration of intubation was shorter in group C (*P* < 0.001).

The overall 10-year survival (follow-up median 3.9, interquartile range 6.9–1.6) was 53.4% (Fig. 2A). The 5-year survival was improved in group C (73.3%) compared to group A + B (63.9%) (*P* = 0.092) [HR 0.7, 95% confidence interval (CI) 0.5–1.1] (Fig. 2B). Subsequent analysis revealed a significant increase in the 5-year survival by using the FET proximalization concept (72.9%) in comparison to the zone 3 arch repair technique (59.5%; *P* = 0.036) (HR 0.7, 95% CI 0.4–1.0) (Fig. 2C).

DISCUSSION

The ability of FET devices to exclude aneurysmal cavities as well as entry tears and to prevent bleeding and progression of the descending aortic pathology has expanded the use of the technique in all kinds of aortic arch diseases [12–14]. Furthermore, FET treatment is durable up to the mid-descending aorta in most patients and initiates positive remodelling in the residual dissection downstream [15–18]. Aside from these promising characteristics,

the FET technique is still associated with substantial mortality and morbidity, and new techniques are mandatory to improve results, especially, in multimorbid patients.

Three procedures were followed to make FET treatment safer, starting with the introduction of angioscopy to control the distal landing zone and FET deployment. Secondly, separating LSA revascularization from repair of the aortic arch reduced the scope of the operation [5]. Consequently, the proximalization of FET in arch zone ≤2 has made the FET anastomosis easier and faster. Thirdly, the use of an aortoaxillary bypass for LSA revascularization enabled access to the left Ax artery prior to CPB and enabled selective LSA perfusion during arch repair complementary to SACP. This step towards improved organ protection was completed by the selective distal body perfusion immediately after the distal FET anastomosis, the so-called four-sites selective perfusion [6].

The combination of FET proximalization with four-sites perfusion represents a 'take no chances approach' and so far constitutes the final stage of the evolutionary development of the treatment of aortic arch disease at our centre. This approach has improved our results within the entire patient population. It proved to be a protective factor against composite mortality and severe adverse events. Moreover, the significant reduction of abdominal and peripheral complications and the reduction of rethoracotomies for bleeding and the accelerated weaning from

Table 4: Multivariable analysis for composite end point

Variables	B	SE	OR	BCa 95% CI	*P*-value
Age	0.036	0.016	1.034	1.004–1.083	0.017
Emergency	0.792	0.346	2.077	1.093–5.409	0.015
Previous St.p. aortic/cardiac surgery	0.981	0.474	2.635	1.038–7.250	0.023
Peripheral artery disease	0.960	0.433	2.484	1.158–7.121	0.016
Four-sites perfusion	-0.682	0.297	0.529	0.299–0.791	0.009

B: coefficient; BCa: bias corrected and accelerated; CI: confidence interval; OR: odds ratio; SE: standard error.
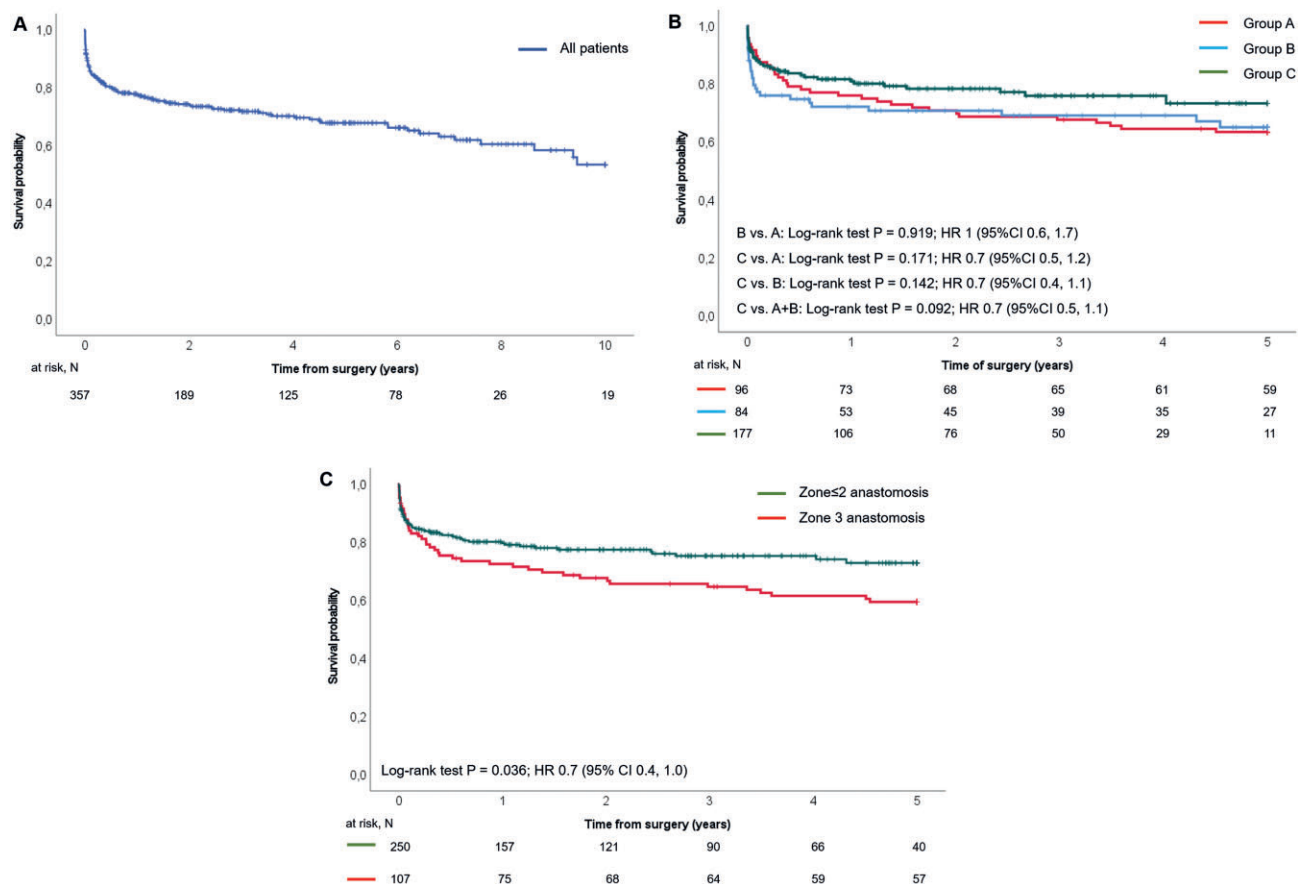
Figure 2: Kaplan–Meier curves demonstrate overall 10-year survival (**A**) and 5-year survival in groups A, B and C (**B**) and according to the frozen elephant trunk proximalization technique (**C**). CI: confidence interval; HR: hazard ratio.

the respirator further indicate the improvement of end-organ protection and the patient's postoperative recovery. The results improved independently from the underlying aortic disease including AAD.

This technique resulted in fewer cerebral events and less severe neurological sequelae after a stroke. Bilateral SACP is an established concept worldwide [19, 20]. An argument for additional selective LSA perfusion is the perfusion of the left vertebral artery, which can be beneficial in patients with an incomplete circle of Willis and in patients without preoperative cerebral imaging. Furthermore, LSA perfusion interrupts the steal phenomenon via the left vertebral artery and may improve a stable perfusion pressure in all cerebral lobes.

Spinal cord ischaemia represents a major adverse event after FET surgery [21]. The cause for SCI seems to be multifactorial,

including the influence of stent graft length, the level of hypothermia and the duration of HCA [4, 22–24]. The continuous blood supply to the anterior spinal artery via cervical and left thoracic artery collaterals under LSA perfusion may improve spinal cord protection under HCA [25]. Moreover, the additional selective distal body perfusion reduced the duration of HCA [26, 27]. Our results demonstrate a lower incidence of SCI under four-sites perfusion and the reduction of severe permanent events to 1%. The aggregate small number of SCI events should be taken into consideration when interpretating the lack of statistical significance.

Proximalization of FET and selective perfusion techniques improved survival at the midterm follow-up, especially, the arch repair in zone ≤2. Other researchers have also reported favourable results after supra-aortic debranching in combination with

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FET [28, 29]. A combination of debranching with FET and the use of 4 separate perfusion sites may be suggestive of additional surgical complexities, but is a logical manoeuvre to counter possible complications of an otherwise major operation. The additional small skin incision and preparation of the left Ax artery prior to sternotomy for LSA perfusion and debranching became a routine in our institution, as did the debranching and selective perfusion of the carotid arteries prior to HCA in case of complex carotid arteries findings. Thus, our operative philosophy changed from the initial radical intention to 'remove the arch pathology' to the current intention to 'simplify arch repair' leaving the distal arch to be treated by the stent graft from inside. Complications related to the aortoaxillary graft in the midterm follow-up were 1 graft infection and 5 late graft occlusions (6/178; 3%). The graft infection was treated successfully via a left thoracotomy, graft resection and carotid-subclavian bypass surgery. Three of the late graft occlusions were asymptomatic, and 2 patients underwent uncomplicated carotid-subclavian bypass surgery.

In our opinion, the extended variety of new FET stent grafts as well as the debranching techniques facilitating anastomosis proximalization up to zone 0 may allow for a more patient-tailored approach and improve the results, especially in multimorbid patients. The four-sites perfusion could be an additional tool to increase safety.

Limitations

The reported progress of the FET technique was performed stepwise over the study period, resulting in our current perfusion concept in group C. The surgical steps and perfusion techniques in groups A and B were less standardized. The increasing surgical experience over the years as well as the statistical limitations arising from the use of a composite end point should be considered when interpreting the results [30].

SUPPLEMENTARY MATERIAL

Supplementary material is available at *EJCTS* online.

Conflict of interest: Heinz Jakob was a consultant to JOTEC GmbH during the study period. All other authors declared no conflict of interest.

Author contributions

Reviewer information

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