European Journal of Cardio-Thoracic Surgery 44 (2013) 1076–1083
doi:10.1093/ejcts/ezt252 Advance Access publication 15 May 2013

ORIGINAL ARTICLE

Experience with the conventional and frozen elephant trunk techniques: a single-centre study[†]

Sergey Leontyev*[‡], Michael A. Borger[‡], Christian D. Etz, Monica Moz, Joerg Seeburger, Farhard Bakhtiary, Martin Misfeld and Friedrich W. Mohr

Department of Cardiac Surgery, Heart Center, University of Leipzig, Leipzig, Germany

* Corresponding author. Universität Leipzig, Herzzentrum, Klinik für Herzchirurgie, Strümpellstr. 39, 04289 Leipzig, Germany. Tel: +49-341-865251055; fax: +49-341-8651452; e-mail: sergey.leontyev@med.uni-leipzig.de; serg_leontyev@web.de (S. Leontyev).

Received 25 September 2012; received in revised form 6 February 2013; accepted 14 February 2013

Abstract

OBJECTIVES: The treatment of patients with extensive thoracic aortic disease involving the arch and descending/thoracoabdominal aorta is often performed using an elephant trunk procedure. We retrospectively analysed our results comparing two different techniques: the conventional elephant trunk (cET) and the frozen elephant trunk (FET) operation.

METHODS: Between January 2003 and December 2011, 171 consecutive patients underwent total aortic arch replacement with either a cET ($n = 125$) or FET ($n = 46$) technique. The mean age was 64 ± 13 years and was significantly higher in the FET group ($P < 0.01$). Acute Type A aortic dissection was the indication for surgery in 53.6% of cET and 17.4% of FET patients, and degenerative or atherosclerotic aneurysm accounted for 33.6% of cET and 58.7% of FET patients. The remaining patients were operated on for chronic Type A or acute or chronic Type B dissections with arch involvement.

RESULTS: In-hospital mortality was 21.6 vs 8.7% for cET and FET patients, respectively ($P = 0.1$). Logistic regression analysis revealed Type A aortic dissection (odds ratio (OR) 3.1, $P = 0.01$) as the only independent predictor of hospital mortality. Stroke occurred in 16 vs 13% of cET vs FET patients ($P = 0.4$). Type A aortic dissection was an independent predictor of stroke by multivariable analysis (OR 2.6, $P = 0.03$), and axillary arterial cannulation was protective against stroke (OR 0.4, $P = 0.04$). The occurrence of new-onset paraplegia was significantly higher in the FET group (21.7 vs 4.0%, $P < 0.001$), and aortic repair with the FET technique was an independent predictor for paraplegia (OR 6.6, $P = 0.001$). Among patients receiving FET, a body core temperature during circulatory arrest of ≥28°C in combination with a prolonged circulatory arrest time of >40 min was an independent predictor for permanent spinal cord injury (OR 5.0, 95% CI 1.1–20, $P = 0.038$). The estimated 1-, 3- and 5-year survival were 70 ± 4, 70 ± 4 and 68 ± 4% (cET) and 4 ± 7 and 60 ± 9, 40 ± 1% (FET), with mean survival time 5.2 ± 0.3 vs 3.8 ± 0.5 years (cET vs FET, log-rank $P = 0.9$).

CONCLUSIONS: The FET procedure for extensive thoracic aortic disease is associated with an acceptable mortality rate, but with a higher incidence of perioperative spinal cord injury than cET. Arch replacement with a cET technique should be strongly considered in patients with expected prolonged circulatory arrest times, particularly if operated on under mild or moderate hypothermia. Axillary cannulation is associated with superior neurological outcomes and Type A acute aortic dissection is a risk factor for mortality and poor neurological outcomes in this patient population.

Keywords: Aortic arch surgery • Elephant trunk • Neurological complication

INTRODUCTION

The conventional elephant trunk (cET) procedure, developed by Borst *et al*. [1] in the 1980s, has become the standard approach for patients with extensive pathology of the thoracic aorta involving the arch and the descending/thoracoabdominal aorta. This procedure, however, remains a surgical challenge associated with a significant operative and interval mortality, and a high incidence of neurological complications [2, 3]. In the current endovascular era, new technical solutions have been developed to treat these patients. Since the mid-1990s, endovascular or hybrid operations such as debranching procedures [4] or the frozen elephant trunk (FET) technique [5] have been introduced into clinical practice.

We began to use the FET technique in select patients with extensive thoracic pathology involving the arch and descending aorta in 2006. We compare here the results of the cET approach with the newer FET technique for such patients. The objectives of this study were to: (i) evaluate the clinical characteristics and results of the surgical treatment of patients with extensive aortic pathology after aortic arch replacement; (ii) compare the clinical outcome of patients after cET and FET surgery; (iii) determine predictors of neurological outcome, particularly spinal chord injury, and early and mid-term mortalities after elephant trunk surgery.

[†]Presented at the 26th Annual Meeting of the European Association for Cardio-Thoracic Surgery, Barcelona, Spain, 27–31 October 2012.
[‡]These authors contributed equally.

PATIENTS AND METHODS

Between January 2003 and December 2011, 171 consecutive patients underwent aortic arch/descending aorta replacement with a cET or FET procedure. All patients undergoing total arch replacement with insertion of a graft or stent-graft in the descending aorta during this time period were included in our analysis. Data were prospectively collected in a database and the retrospective review was approved by the local Ethics Committee. Individual patient consent was waived.

Patients were followed annually with a mailed questionnaire or, when needed, by contacting the referring cardiologist or general practitioner. The follow-up was complete in 93% of patients.

Operative technique

Our operative technique for aortic arch replacement, including the methods of cerebral protection, has been previously described in detail [3].

All patients with aortic arch disease and extension into the descending/thoracoabdominal aorta prior to 2006 underwent a cET procedure. cET was performed with a Hemashield graft (Maquet) in accordance with the classic method published by Borst *et al.* [1] in 1983. Since 2006, the cET procedure was used predominantly in patients with extensive distal aortic disease extending into the abdominal aorta. A completion replacement of the distal descending/thoracoabdominal aorta as a second procedure was planned, or felt to be likely in the foreseeable future, in all cET patients.

Since 2006, we have used the FET technique for patients with aortic disease confined to the arch and descending or proximal abdominal aorta. FET was performed with an E-vita hybrid open stent-graft (Jotec, Hechingen, Germany). The sizing of the stent-graft was done according to the dimension of the native non-diseased aorta or true aortic lumen in patients with acute or chronic aortic dissection, with 5–10% oversizing in order to minimize the chance of a Type Ib endoleak. The technical details of FET surgery have been previously described by Pacini *et al.* [6].

The goal of FET implantation was to either exclude the entire diseased aortic segment with the stent-graft in those patients with disease in the proximal descending aorta, or to use the FET procedure as a bridge to future thoracic endovascular aortic repair (TEVAR) in those patients with disease extending to the distal descending or proximal (i.e. supraceliac) abdominal aorta. FET was not used as a bridge to endovascular aortic repair (EVAR) in patients with extensive thoracoabdominal disease, as we do not routinely perform EVAR in patients with disease of the supra-renal abdominal aorta.

Definitions

In accordance with STS guidelines, *early mortality* was defined as all-cause mortality at 30 days. Operations were considered *emergent* if performed within 24 h of hospital admission for cardiovascular instability and as *urgent* if performed during the same hospital admission.

All patients with suspected neurological complications on physical examination underwent computerized tomography or magnetic resonance imaging. *Neurological complications* were defined as *permanent neurological deficit* (PND) for patients with stroke or paraplegia and *temporary neurological deficit* (TND) for patients with reversible deficits. Stroke was defined as a new postoperative focal neurological deficit that persisted >72 h, or a new focal lesion of the brain detected by computer tomographic scanning. TND was defined as a focal neurological deficit lasting <72 h, or postoperative delirium, agitation, confusion or decreased level of consciousness without any new structural abnormality observed on imaging [7]. *Spinal cord injury* was defined as new-onset transient or permanent paraparesis or paraplegia.

Statistical analysis

Continuous variables are expressed as mean ± SD and categorical data as proportions throughout the manuscript. Categorical variables were compared using the χ^2-test or Fisher's exact test. Independent continuous variables were compared by unpaired Student's *t*-test for comparison of normally distributed data between two groups or Kruskal–Wallis for the comparison of more than two groups test as appropriate.

We examined 24 potential preoperative risk factors for early and late mortality by uni- and multivariate testing (Table 1). Dichotomous adverse outcome events were analysed using a uni- and multivariate logistic regression model with backwards stepwise elimination and were expressed as odds ratios (OR) with 95% confidence intervals (CI). Event-free survival was calculated by Kaplan–Meier methods with 95% CI. Independent predictors of medium-term survival were determined with Cox proportional hazards analysis. *P*-values <0.05 were considered statistically significant. All statistical analyses were performed using SPSS 17.0 (Chicago, IL, USA).

RESULTS

A total of 171 consecutive patients underwent total replacement of the aortic arch using the cET or FET technique during the study period. The majority had suffered from aortic dissection: acute Type A in 43.9% of patients, acute Type B in 7.6%, chronic Type A

Table 1: Preoperative factors used in uni-, multivariate and Cox regression analyses

• Age	• Acute Type A aortic dissection
• Sex	• Acute Type B aortic dissection
• Chronic pulmonary disease	• Chronic Type A aortic dissection
• Peripheral vascular disease	• Chronic Type B aortic dissection operative time
• Preoperative cerebrovascular accident	• Cardiopulmonary bypass time
• Chronic renal insufficiency	• Cross-clamp time
• Diabetes mellitus	• Circulatory arrest time
• Smoker	• Antegrade selective cerebral perfusion
• Surgical timing (elective, urgent and emergent)	• Nasopharyngeal temperature by circulatory arrest
• Redo surgery	• Size of aorta
• Previously EVAR	• Landing zone
• Type of elephant trunk technique	• Oversizing (for FET)
• Aortic aneurysm	

AORTIC SURGERY

Table 2: Demographics and preoperative clinical characteristics

	Total $n = 171$	cET $n = 125$	FET $n = 46$	*P*
Age (years)	63 ± 13	61 ± 13	69 ± 10	0.01
Female	68 (39.8)	45 (36.0)	23 (50.0)	0.1
COPD	14 (8.2)	11 (8.8)	3 (6.5)	0.6
Preoperative renal failure	3 (1.8)	3 (2.4)	0 (0.0)	0.3
Diabetes	25 (14.6)	18 (14.4)	7 (15.2)	0.8
Hypertension	130 (76)	94 (75.0)	36 (78.6)	0.7
Cerebral vasculopathy	9 (5.3)	7 (5.6)	2 (4.3)	0.7
Emergent timing	94 (55)	80 (64)	14 (30.4)	<0.001
Aortic disease				0.004
Degenerative aneurysm	69 (40.4)	42 (33.6)	27 (58.7)	<0.001
Acute Type A aortic dissection	75 (43.9)	67 (53.6)	8 (17.4)	<0.001
Acute Type B aortic dissection	13 (7.6)	6 (4.8)	7 (15.2)	0.02
Chronic Type A aortic dissection	4 (2.3)	3 (2.4)	1 (2.2)	0.9
Chronic Type B aortic dissection	3 (1.8)	2 (1.6)	1 (2.2)	0.8
Downstream aneurysm following acute Type A aortic dissection	5 (2.9)	3 (2.4)	2 (4.3)	0.5
Aneurysm formation following acute Type B dissection	2 (1.2)	2 (1.6)	0 (0)	0.3
Previous TEVAR	7 (4.1)	7 (5.6)	0 (0.0)	0.7
Previous surgery	27 (15.8)	18 (14.4)	9 (19.6)	0.4
CABG	3 (1.8)	2 (1.6)	1 (2.2)	0.8
Valve	8 (4.7)	5 (4.0)	3 (6.5)	0.5
Root	4 (2.3)	3 (2.4)	1 (2.2)	0.9
Abdominal aorta	3 (1.8)	2 (1.6)	1 (2.2)	0.8
Thoracic aorta	14 (8.1)	8 (6.4)	6 (13)	0.2
Aortic diameter				
Ascending	52 ± 15	46 ± 11	50 ± 14	0.6
Arch	46 ± 15	52 ± 16	48 ± 15	0.2
Descending	40 ± 12	42 ± 12	41 ± 12	0.8

Data are presented as numbers of cases unless otherwise indicated.
COPD: chronic obstructive pulmonary disease; TEVAR: thoracic endovascular aortic repair; CABG: coronary artery bypass grafting.

in 2.3% and chronic Type B in 1.8%. A degenerative aortic aneurysm was the indication for surgery in 40.4% of patients.

With regard to the size of the descending aorta, 68.2% of FET patients had a descending aorta diameter of >35 mm (mean diameter 47 ± 10 mm) and 31.8% <35 mm (mean diameter 30 ± 3 mm). In the cET patients, 39.6% had a descending aorta diameter of >35 mm (mean diameter 47 ± 10 mm) and 60.4% <35 mm (mean diameter 30 ± 2 mm).

A cET procedure was performed significantly more often in patients with acute Type A aortic dissection (53.6 vs 17.4%, $P < 0.001$). Patients with acute Type B aortic dissection were more likely to undergo a FET procedure (15.2 vs 4.8%, $P = 0.02$). FET patients were also significantly older than cET patients ($P < 0.001$) (Table 2).

Preoperative neurological deficit was present in 12.0% of patients presenting with acute Type A aortic dissection, while a further 26.7% of these patients were admitted in a critical preoperative state (i.e. resuscitated and/or intubated), making the determination of their preoperative neurological status difficult.

Operative details and postoperative complications

Aortic root replacement or aortic valve replacement/reconstruction was more frequently performed in patients undergoing cET implantation (Table 3). Mean rectal temperature during circulatory arrest was significantly higher in patients undergoing FET surgery ($P = 0.002$, Table 3). The incidence of most early postoperative outcomes was similar between the 2 patient groups (Table 3).

Risk factors for mortality

The 30-day mortality for the entire cohort of patients was 16.4% ($n = 28$), with a trend towards a higher mortality in the cET group (19.2% cET vs 8.7% FET, $P = 0.1$). In-hospital mortality was 18.1% for all patients and was significantly higher in cET patients by univariate analysis (21.6 vs 8.7%, $P = 0.001$) (Table 4).

Patients with urgent and emergent indications for surgery had significantly higher 30-day mortality rates compared with those undergoing elective surgery (7.8 vs 23.4%, $P = 0.006$). For elective patients only, the 30-day mortality was 9.1 vs 6.1% for cET vs FET surgery ($P = 0.2$). For urgent or emergent patients, 30-day mortality occurred in 24.7 vs 15.4% of cET and FET patients, respectively ($P = 0.5$).

Patients with acute Type A aortic dissection had a significantly higher early mortality compared with those without acute Type A dissection (28 vs 7.3%, $P < 0.01$).

Multivariable logistic regression analysis revealed that acute Type A aortic dissection was the only independent predictor for 30-day mortality (OR 4.9, 95% CI 1.9–12, $P < 0.01$). Likewise, acute Type A dissection was the only multivariate risk factor for in-hospital mortality (OR 4.0, 95% CI 1.7–9.3, $P = 0.001$).

Permanent and temporary neurological deficit

PND occurred in 15.2% ($n = 26$) of patients (Table 4). The incidence of PND between cET and FET patients was not statistically significant (16 vs 13%, $P = 0.6$). When analysed according to

Table 3: Operation data

	Total $n = 171$	cET $n = 125$	FET $n = 46$	P
Operation				
CPB time (min)	224 ± 66	225 ± 68	220 ± 61	0.5
Cross-clamp time (min)	116 ± 46	122 ± 47	100 ± 38	0.09
Circulatory-arrest time (min)	44 ± 18	42 ± 19	50 ± 15	0.09
ASCP	141 (82.5)	95 (76)	46 (100)	0.08
ASCP time (min)	44 ± 16	42 ± 19	47 ± 14	0.1
Minimum rectal temperature (°C)	24 ± 3	23 ± 3	25 ± 3	0.002
Axillary artery cannulation	126 (73.7)	89 (71.2)	37 (80.4)	0.2
Reimplantation of supraaortic vessels				
Island	124 (72.5)	89 (71.2)	35 (76.1)	0.5
Separate	47 (27.5)	36 (28.8)	11 (23.9)	0.5
Aortic valve/root intervention				
ARR	55 (32.2)	49 (39.2)	6 (13.0)	0.01
AV Reimplantation (David)	16 (9.4)	15 (12.0)	1 (2.2)	0.05
AV Reconstruction (Yacoub)	4 (2.3)	3 (2.4)	1 (2.2)	0.9
AVR	10 (5.8)	10 (8.0)	0 (0.0)	0.05
Concomitant surgery				
MVR	5 (2.9)	5 (4.0)	0 (0.0)	0.2
CABG	23 (13.5)	15 (12.0)	8 (17.4)	0.4

Data are presented as number of cases unless otherwise indicated.
CPB: cardiopulmonary bypass; ASCP: antegrade selective cerebral perfusion; AVR: aortic valve replacement; AV: aortic valve; ARR: aortic root replacement; CABG: coronary artery bypass grafting; CPB: cardiopulmonary bypass; MVR: mitral valve reconstruction; PND: permanent neurologic deficit; TND: temporary neurological deficit.

Table 4: Postoperative clinical characteristics for cET vs FET patients and for patients with and without Type A aortic dissection

	Total $n = 171$	cET $n = 125$	FET $n = 46$	P
Postoperative outcome				
PND	26 (15.2)	20 (16.0)	6 (13.0)	0.6
TND	27 (15.8)	23 (18.4)	4 (8.7)	0.1
Paraplegia	15 (8.8)	5 (4.0)	10 (21.7)	<0.001
Respiratory failure	76 (44.4)	57 (45.6)	19 (41.3)	0.6
Renal failure	34 (19.9)	23 (18.4)	11 (23.9)	0.4
Reoperation for bleeding	30 (17.5)	24 (19.2)	6 (13.0)	0.3
30-day mortality	28 (16.4)	24 (19.2)	4 (8.7)	0.1
In-hospital mortality	31 (18.1)	27 (21.6)	4 (8.7)	0.053
	Total $n = 171$	Type A $n = 75$	Non-type A $n = 96$	P
Postoperative outcome				
PND	26 (15.2)	20 (16.0)	6 (13.0)	0.08
TND	27 (15.8)	13 (17.3)	14 (14.6)	0.6
Paraplegia	15 (8.8)	7 (9.3)	8 (8.3)	0.8
Respiratory failure	76 (44.4)	36 (48.0)	40 (41.7)	0.4
Renal failure	34 (19,9)	22 (29.3)	12 (12.5)	0.006
Reoperation for bleeding	30 (17,5)	15 (20.0)	15 (15.6)	0.4
30-day mortality	28 (16,4)	21 (28)	7 (7.3)	<0.001
In-hospital mortality	31 (18.1)	22 (29.3)	9 (9.4)	0.001

Data are presented as number of cases unless otherwise indicated.

surgical timing, the PND rate for the two groups remained non-significantly different (19.8 vs 15.4% for cET vs FET, $P = 0.1$ in urgent/emergent cases and 6.8 vs 12.1% for cET vs FET, $P = 0.4$ in elective cases).

The risk of PND was significantly higher in patients presenting with acute Type A aortic dissection (22.7 vs 9.4%; $P = 0.01$). The overall incidence of TND was 15.8% ($n = 27$), and was not different between patients undergoing cET and FET surgery ($P = 0.1$).

Acute Type A aortic dissection was identified as an independent predictor of PND by multivariate analysis (OR 2.6 95% CI 1.07–6.6, $P = 0.03$). The use of axillary arterial cannulation was protective against the development of PND (OR 0.39, 95% CI 0.16–0.9, $P = 0.04$).

AORTIC SURGERY

Paraplegia

The overall rate of paraplegia was 8.8% ($n = 15$) and was significantly higher for FET ($n = 10$) compared with cET patients ($n = 5$) (21.7 vs 4%, $P < 0.01$). When surgical timing was accounted for, the incidence of paraplegia continued to be significantly higher for FET compared with cET: 23.1 vs 4.9%, $P = 0.02$ for urgent/emergent cases and 7.4 vs 10.4%, $P = 0.5$ for elective cases.

Multivariate analysis identified the use of FET as an independent risk factor for permanent paraplegia (OR 6.6, 95% CI 2.2–20.7, $P < 0.01$).

Among FET patients, multivariate analysis identified a body core temperature during circulatory arrest of 28°C or higher in combination with a duration of circulatory arrest >40 min as an independent predictor of permanent spinal cord injury (OR 5.0, 95% CI 1.1–20, $P = 0.038$).

The presence of acute or chronic aortic dissection, oversizing of the prosthesis, size of the descending aorta or level of landing zone were not identified as factors influencing paraplegia after FET.

Predictors of medium-term survival

The estimated mean follow-up time for all patients was 5.4 ± 0.3 years (range, 0–7.7 years), with a total follow-up of 333.2 patient-years. The unadjusted 1-, 3- and 5-year survival for the entire group were 73.3 ± 3.5, 69.2 ± 3.3 and 66.7 ± 4.4%, respectively. One-, 3- and 5-year survival for cET and FET patients was 70 ± 4, 70 ± 4 and 68 ± 4% and 74 ± 7, 60 ± and 40 ± 1%, respectively ($P = 0.9$).

The type of elephant trunk performed did not have a significant influence on mid-term survival (5.5 ± 0.3 (cET) vs 3.8 ± 0.5 years (FET); log-rank $P = 0.9$) (Fig. 1). Unadjusted survival of patients with acute Type A aortic dissection was worse than patients without acute Type A dissection (log-rank $P = 0.02$, Fig. 2).

Cox proportional hazards analysis revealed the following independent predictors of mid-term survival: age (hazard ratio (HR) 1.04, 95% CI 1.02–1.07, $P = 0.002$), preoperative renal insufficiency (HR 8.4, 95% CI 1.8–38.3, $P = 0.005$) and acute Type A aortic dissection (HR 2.6, 95% CI 1.4–4.7, $P = 0.001$).

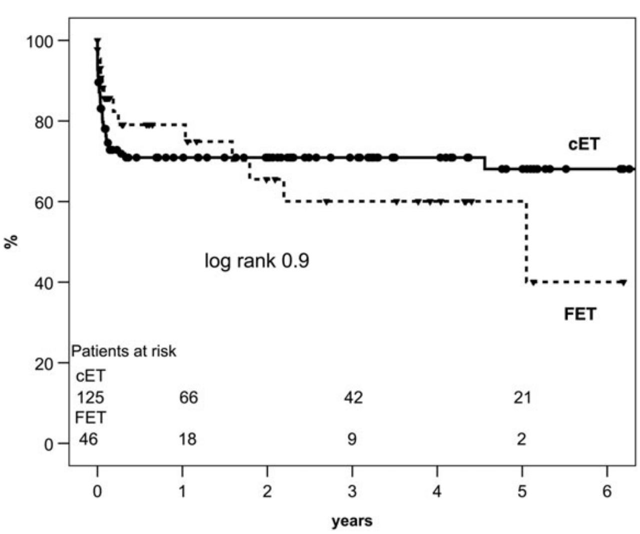

Figure 1: Kaplan–Meier survival curve for patients undergoing cET and FET surgery.

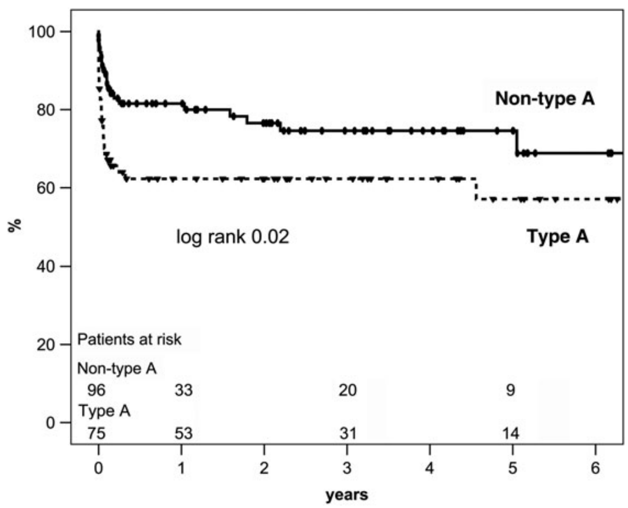

Figure 2: Kaplan–Meier survival curve for patients undergoing cET or FET surgery presenting with and without acute Type A aortic dissection.

During the follow-up, 17 cET patients underwent reoperative thoracoabdominal aortic surgery for remaining downstream disease (11 planned, 6 after disease progression/new onset of symptoms) after an interval of 1.7 ± 2.4 years (range 17 days to 8.5 years). One patient was operated on emergently for rupture of the descending aorta. One patient with previous FET implantation underwent open reoperative repair for stent-graft infection. TEVAR was performed during the follow-up in 9 patients. Five such patients had previously undergone FET surgery and 4 cET surgery.

DISCUSSION

The current study summarizes our 9-year institutional experience with a group of high-risk patients with extensive aortic disease undergoing aortic arch repair with an elephant trunk technique. In the majority of patients, the conventional, 'classic' elephant trunk implantation was performed as described by Borst *et al.* in 1983 [1]. The 'frozen' elephant trunk technique, including a hybrid stent-graft prosthesis, was introduced into clinical practice at our institution in 2006. All patients treated with an FET implantation received an E-vita hybrid prosthesis in the current study.

In-hospital mortality reported for patients undergoing cET surgery varies depending on aortic pathology, ranging between 10.6 and 20% [8, 9]. The international E-vita open registry reported in 2011, the results from 274 FET patients, with an in-hospital mortality rate of 15% [10].

The 30-day mortality observed in our study—19.2% for cET and 8.7% for FET—is comparable with other case series reported in the literature. Our observed trend ($P = 0.1$) towards a lower rate of mortality for FET patients must be interpreted with caution, given the fact that significantly less FET patients presented with acute Type A aortic dissection and that acute Type A dissection was the only significant predictor of mortality by multivariable analysis. This observation is in line with our previously published results of aortic arch surgery (partial and total aortic arch replacement), whereby we identified acute Type A aortic dissection as an independent predictor for 30-day mortality [3].

Neurological complications: PND

Neurological complications have a significant impact on patient outcomes after cardiac—and in particular aortic—surgery. PND and stroke are particularly devastating complications associated with prolonged ventilation times and intensive care unit/hospital stays, increased resource utilization, and reduced patient quality of life and long-term survival [3, 11, 12].

The incidence of PND in patients undergoing aortic arch surgery has generally been reported to range between 1.1 and 9.8% [2, 12, 13]. In our series, the rate of PND was higher (16% after cET vs 13% with FET). However, it is important to note that a large proportion (44%) of our patients underwent emergent surgery for acute Type A aortic dissection—representing a high-risk population often presenting with unclear neurological status prior to emergency surgery [14].

Numerous studies have identified independent predictors of stroke after aortic arch repair: urgent status [2, 11, 15], acute Type A aortic dissection [16], age, history of previous 'central neurological event' [16], renal insufficiency [2], operation time [2], prolonged circulatory arrest [2] and prolonged selective cerebral perfusion. PND was observed in 15% of our patients with increasing age, duration of circulatory arrest time and extent of aortic arch repair identified as independent predictors. The postoperative PND rate was nearly twice as high among patients who had presented with acute Type A aortic dissection.

The optimal arterial cannulation site during aortic arch surgery is still a subject of debate and might have a significant impact on PND and stroke rates [12]. The distal ascending aorta, the brachiocephalic trunk and the inner curvature of the transverse arch are three possible options for direct aortic cannulation. Femoral and axillary cannulations are further options for vascular access during aortic arch surgery. Femoral arterial cannulation has been reported to have a higher in-hospital mortality [2] and worse neurological outcome. One possible reason for worse outcomes is retrograde cerebral embolization, although selection bias is hard to exclude in these retrospective studies. Several publications have demonstrated that axillary cannulation is associated with improved neurological outcome in patients undergoing circulatory arrest [12]. At our institution, axillary cannulation has become the standard access for aortic arch surgery for the last 10 years. Multivariate analysis revealed axillary cannulation to independently be protective against stroke in our patient population. In our opinion, axillary cannulation allows for safe and secure antegrade cerebral perfusion during circulatory arrest, and allows optimal de-airing of the aortic arch during reinstitution of full cardiopulmonary bypass flow.

Neurological complications: spinal chord injury

Ischaemic spinal cord injury is one of the most dreaded complications after thoracoabdominal aortic surgery, but particularly shattering after primary aortic arch repair. Paraplegia is a historically rare complication after cET surgery. The reported incidence of permanent or transient spinal cord injury after cET implantation ranges between 0.4 and 2.8% [8, 9, 17].

The reported incidence of spinal cord injury in patients undergoing FET appears to be significantly higher. Data from the international E-vita registry on 274 FET patients revealed an 8% rate of spinal cord injury [10], and a recent multicentre study reported a 9% incidence of this dreaded complication [6]. In a meta-analysis of FET studies, Ius et al. [18] estimated the incidence of spinal chord injury to be 5.6%. Single-centre studies have reported incidences as high as 21–24% after FET implantation [19–21]. Miyairi et al. [19] attributed their observed episodes of post-FET paraplegia to spinal cord ischaemic times of >60 min in 3 of 4 cases, which was additionally aggravated by haemodynamic instability after cardiopulmonary bypass in one patient. Mizuno et al. [20] reported 2 cases of paraplegia in their series of nine FET patients without any identifiable risk factor, but their average lower-body arrest time was quite long (54 ± 10 min). In both cases of paraplegia, the distal arrest time was >40 min.

One of the factors thought to have an impact on spinal cord injury is the level of the distal landing zone for the stent graft, as a marker of the number of segmental arteries occluded with graft deployment. Flores et al. [21] demonstrated that a distal landing zone beyond T7 is associated with a significantly higher incidence of spinal cord injury. They reported a 24% incidence (6 of 25 patients) of ischaemic spinal cord injury in their series, with distal deployment of the stented-graft being a significant risk factor by multivariate analysis. Similarly, Mizuno et al. [20] in their early series, reported that the distal landing zone was at the T8 level in both patients suffering postoperative paraplegia in their small series.

Interestingly, the combination of a distal landing zone of T7 or lower and a history of previous abdominal aortic aneurysm repair was the strongest predictor for spinal cord injury (71 vs 6%, $P = .0047$) in the study from Flores et al. [21] This observation suggest an important role of distal inflow to the paraspinous arterial *Collateral Network* via the hypogastric arteries. Recent experimental studies on spinal cord blood flow, however, suggest that spinal perfusion is not acutely compromised by serial segmental artery sacrifice in a cranio-caudal direction down to a level of T11/12. Such findings are supported by the reasonably low paraplegia or paraplegia rates of 3.8% in clinical series of descending thoracic and Crawford type I thoracoabdominal aortic aneurysm repairs [22]. The Collateral Network Concept [17] has been used to explain this phenomenon. FET procedures, however, have the potential to impact on both inflow pathways simultaneously: segmental artery perfusion and upper inflow to the Collateral Network via the vertebral artery. This might be the reason for the increased occurrence of paraplegia and the significantly higher incidence as compared with cET procedures.

In the present study, we failed to find a significant correlation between the level of the distal landing zone/segmental arteries covered by the stent graft and the rate of spinal cord ischaemic injury. In 6 of 10 patients suffering spinal cord injury, the stent-graft landing zone was at level T8 or above. Similarly, Pacini and Miyairy [6, 19] failed to find a significant correlation between the distal FET landing zone level and the incidence of acute ischaemic spinal cord injury. Interestingly, Pacini et al. [6] identified the diameter of the false lumen in patients with chronic aortic dissection as an independent predictor for spinal cord injury. In the current study, we failed to find an association between chronic aortic dissection and neurological outcome.

The incidence of post-FET spinal cord injury in the present study was 21.4%, being on the higher end of those reported in the literature. Multivariate logistic analysis identified only one factor as an independent predictor for paraplegia within the FET subgroup: body core temperatures of >28°C during circulatory arrest times of >40 min. Half of the patients (5 of 10) who suffered ischaemic spinal cord injury had circulatory arrest times of >40 min at 28°C or warmer. The influence of temperature on spinal cord ischaemic tolerance has been thoroughly investigated by Griepp's group [17, 23, 24]. Temperature during circulatory arrest, regardless of distal arrest duration, did not significantly influence functional spinal cord integrity in our cohort. Similar to our observations, Pacini *et al.* [6] failed to find a significant correlation between spinal cord injury and time of antegrade cerebral perfusion, despite distal arrest times of 75 ± 22 min. However, postoperative haemodynamics might play an important role if a large number of segmental arteries are occluded [25].

In our opinion, the occurrence of spinal cord injury is multifactorial and mostly influenced by a combination of acute ischaemic injury during distal circulatory arrest at mild to moderate hypothermia, and postoperative haemodynamics fluctuations after extensive segmental artery occlusion. Protective adjuncts, such as spinal fluid drainage and the preservation of the left subclavian artery may attenuate the deleterious effects of these insults. However, none of these factors alone revealed a statistically significant influence on spinal cord injury in our study. Based on the results of our multivariable analysis, the only recommendation that we can currently make is that the FET procedure should not be performed under mild hypothermia, particularly if a prolonged circulatory arrest time is expected. Further studies in this area should be performed in order determine if our observed increased risk of paraplegia for the FET procedure is a true phenomenon, and if neuroprotective adjuncts may somehow mitigate this risk.

Study limitations

The current study is limited by several weaknesses. First, its retrospective and non-randomized nature makes it susceptible to selection bias. Secondly, the patient cohort is somewhat inhomogenous, with several different aortic pathologies. However, it reflects the clinical reality of this new hybrid surgical approach in patients undergoing aortic arch surgery with elephant trunk implantation.

In conclusion, the surgical treatment of patients with extensive aortic arch pathology continues to be a surgical challenge associated with significant mortality and neurological complications. The FET procedure can be performed with a relatively low mortality rate, but is associated with an increased incidence of permanent paraplegia due to ischaemic spinal cord injury. Prolonged distal arrest times of >40 min, particularly in combination with a core body temperature of >28°C, is an independent predictor of paraplegia in FET patients. More pronounced hypothermia should be used during FET surgery, particularly in patients with expected prolonged circulatory arrest times.

Conflict of interest: none declared.

REFERENCES

[1] Borst HG, Walterbusch G, Schaps D. Extensive aortic replacement using 'elephant trunk' prosthesis. Thorac Cardiovasc Surg 1983;31:37–40.

[2] Khaladj N, Shrestha M, Meck S, Peterss S, Kamiya H, Kallenbach K *et al.* Hypothermic circulatory arrest with selective antegrade cerebral perfusion in ascending aortic and aortic arch surgery: a risk factor analysis for adverse outcome in 501 patients. J Thorac Cardiovasc Surg 2008;135:908–14.

[3] Misfeld M, Leontyev S, Borger MA, Gindensperger O, Lehmann S, Legare JFMohr FW. What is the best strategy for brain protection in patients undergoing aortic arch surgery? A single center experience of 636 patients. Ann Thorac Surg 2011;93:1502–8.

[4] Buth J, Penn O, Tielbeek A, Mersman M. Combined approach to stent-graft treatment of an aortic arch aneurysm. J Endovasc Surg 1998;5: 329–32.

[5] Kato M, Ohnishi K, Kaneko M, Ueda T, Kishi D, Mizushima T *et al.* New graft-implanting method for thoracic aortic aneurysm or dissection with a stented graft. Circulation 1996;94:II188–93.

[6] Pacini D, Tsagakis K, Jakob H, Mestres CA, Armaro A, Weiss G *et al.* The frozen elephant trunk for the treatment of chronic dissection of the thoracic aorta: a multicenter experience. Ann Thorac Surg 2011;92:1663–70.

[7] Ergin MA, Galla JD, Lansman L, Quintana C, Bodian C, Griepp RB. Hypothermic circulatory arrest in operations on the thoracic aorta. Determinants of operative mortality and neurologic outcome. J Thorac Cardiovasc Surg 1994;107:788–97.

[8] Safi HJ, Miller CC III, Estrera AL, Villa MA, Goodrick JS, Porat E *et al.* Optimization of aortic arch replacement: two-stage approach. Ann Thorac Surg 2007;83:S815–8.

[9] Palma JH, Almeida DR, Carvalho AC, Andrade JC, Buffolo E. Surgical treatment of acute type B aortic dissection using an endoprosthesis (elephant trunk). Ann Thorac Surg 1997;63:1081–4.

[10] Jakob H, Tsagakis K, Pacini D, Di Bartolomeo R, Mestres C, Mohr F *et al.* The International E-vita Open Registry: data sets of 274 patients. J Cardiovasc Surg 2011;52:717–23.

[11] Goldstein LJ, Davies RR, Rizzo JA, Davila JJ, Cooperberg MR, Shaw RK *et al.* Stroke in surgery of the thoracic aorta: incidence, impact, etiology, and prevention. J Thorac Cardiovasc Surg 2001;122:935–45.

[12] Immer FF, Moser B, Krahenbuhl ES, Englberger L, Stalder M, Eckstein FS *et al.* Arterial access through the right subclavian artery in surgery of the aortic arch improves neurologic outcome and mid-term quality of life. Ann Thorac Surg 2008;85:1614–8.

[13] LeMaire SA, Carter SA, Coselli JS. The elephant trunk technique for staged repair of complex aneurysms of the entire thoracic aorta. Ann Thorac Surg 2006;81:1561–9.

[14] Conzelmann LO, Hoffmann I, Blettner M, Kallenbach K, Karck M, Dapunt O *et al.* Analysis of risk factors for neurological dysfunction in patients with acute aortic dissection type A: data from the German Registry for Acute Aortic Dissection Type A (GERAADA). Eur J Cardiothorac Surg 2012;42: 557–65.

[15] Di Eusanio M, Schepens MA, Morshuis WJ, Di Bartolomeo R, Pierangeli A, Dossche KM. Antegrade selective cerebral perfusion during operations on the thoracic aorta: factors influencing survival and neurologic outcome in 413 patients. J Thorac Cardiovasc Surg 2002;124:1080–6.

[16] Di Eusanio M, Wesselink RM, Morshuis WJ, Dossche KM, Schepens MA. Deep hypothermic circulatory arrest and antegrade selective cerebral perfusion during ascending aorta-hemiarch replacement: a retrospective comparative study. J Thorac Cardiovasc Surg 2003;125:849–54.

[17] Etz CD, Plestis KA, Kari FA, Luehr M, Bodian CA, Spielvogel D *et al.* Staged repair of thoracic and thoracoabdominal aortic aneurysms using the elephant trunk technique: a consecutive series of 215 first stage and 120 complete repairs. Eur J Cardiothorac Surg 2008;34:605–14.

[18] Ius F, Hagl C, Haverich A, Pichlmaier M. Elephant trunk procedure 27 years after Borst: what remains and what is new? Eur J Cardiothorac Surg 2011;40:1–11.

[19] Miyairi T, Kotsuka Y, Ezure M, Ono M, Morota T, Kubota H *et al.* Open stent-grafting for aortic arch aneurysm is associated with increased risk of paraplegia. Ann Thorac Surg 2002;74:83–9.

[20] Mizuno T, Toyama M, Tabuchi N, Wu H, Sunamori M. Stented elephant trunk procedure combined with ascending aorta and arch replacement for acute type A aortic dissection. Eur J Cardiothorac Surg 2002;22:504–9.

[21] Flores J, Kunihara T, Shiiya N, Yoshimoto K, Matsuzaki K, Yasuda K. Extensive deployment of the stented elephant trunk is associated with an increased risk of spinal cord injury. J Thorac Cardiovasc Surg 2006;131: 336–42.

[22] Coselli JS, Bozinovski J, LeMaire SA. Open surgical repair of 2286 thoracoabdominal aortic aneurysms. Ann Thorac Surg 2007;83:S862–4; discussion S890–862.

[23] Strauch JT, Lauten A, Spielvogel D, Rinke S, Zhang N, Weisz D *et al.* Mild hypothermia protects the spinal cord from ischemic injury in a chronic porcine model. Eur J Cardiothorac Surg 2004;25:708–15.

[24] Etz CD, Luehr M, Kari FA, Lin HM, Kleinman G, Zoli S *et al.* Selective cerebral perfusion at 28 degrees C—is the spinal cord safe? Eur J Cardiothorac Surg 2009;36:946–55.

[25] Etz CD, Luehr M, Kari FA, Bodian CA, Smego D, Plestis KA *et al.* Paraplegia after extensive thoracic and thoracoabdominal aortic aneurysm repair: does critical spinal cord ischemia occur postoperatively? J Thorac Cardiovasc Surg 2008;135:324–30.

APPENDIX. CONFERENCE DISCUSSION

Dr R. Di Bartolomeo *(Bologna, Italy)*: This study compared the short- and mid-term outcomes of patients undergoing a conventional or a frozen elephant trunk technique for extensive aortic disease of the thoracic or thoraco-abdominal aorta. Overall, an acute dissection was the indication for surgery in about half of the patients.

As reported, 30-day mortality was 16.4%, and permanent neurological dysfunction and paraplegia occurred in 15.2% and 8.8% of patients respectively. Focusing on the frozen elephant trunk patients, Dr Leontyev reported a 30-day mortality of 8.7%, with disappointing rates of permanent neurological deficit and paraplegia of 13% and 21.7% respectively. It should be recalled that such results, and in particular the adverse neurological outcomes, strongly deviate from those reported from the International E-vita Registry which revealed 7% spinal cord injury, with 6% PND. I share your conclusions that neurological outcome can be significantly improved by keeping core temperature between 24–26 degrees centigrade and the duration of circulatory arrest below 35 min.

Second, the elephant trunk and frozen elephant trunk patients were remarkably different and therefore hardly comparable. Elephant trunk patients had more acute aortic dissection and more thoraco-abdominal aortic aneurysms. Furthermore, more profound levels of hypothermia were used in elephant trunk patients as compared to FET patients. Thus, comparative short- and mid-term results and the surgical implications should be considered with great caution.

Dr Leontyev: I think the comparison between the two groups, the conventional and the frozen elephant trunk technique, is indeed very important and showed that frozen elephant trunk implantation may be associated with a significantly increased rate of neurological complications. And in my opinion, it is actually the only way to show all the options for treating patients with extensive thoracic aortic disease. This is the reason I do not completely agree with you that it isn't possible or appropriate to compare the two patient groups.

Dr M. Borger *(Leipzig, Germany)*: I'd just like to say, I don't think we should shoot the messenger here. We have a large aortic programme in our centre and these operations were all done by experienced aortic surgeons.

What I think is important is for other people to learn from our results. We have a reputation as a centre that presents its results honestly, whether they're good or bad. And in this case we found a problem. For example, if I see a patient now that has thoracic aortic disease down to T10, which I know can be completely treated with a frozen elephant trunk operation in one procedure, where you can insert it all the way in and completely seal the aneurysm, I would be a little bit hesitant about doing that now. I think if you still want to do a frozen elephant trunk operation, then use the shorter version of the graft and then later perform a second staged TEVAR procedure from below; with such a two-staged approach probably you will have a lower risk of paraplegia.

But I want to echo Malakh Shrestha's comment in that we're presenting our results here honestly and that there is also a precedent in the literature for a slightly higher paraplegia rate with the frozen elephant trunk (despite what Roberto said) compared to the conventional elephant trunk operation. That data is already out there in the literature.

Dr C. Hagl *(Munich, Germany)*: What about CSF drainage, do you use that? Do you think that would help, especially in the early phase of the operation?

Dr Leontyev: Yes, it is indeed very important to protect the spinal cord to prevent neurological complications. In the last two years, all patients who underwent the frozen elephant trunk technique had a CSF drain. Only for the first 20 patients was data on CSF drainage not available, as previously it was not a standard protocol in our clinic. But we believe it is important to prevent neurological complications.

Dr Hagl: I have a second comment. I think the blood pressure is something which is very important in the phase after the operation. And it is our feeling that the patients who have problems with bleeding, for example, and low pressure over a long time, have more problems with the spinal cord compared to other patients.

Dr Leontyev: I believe that paraplegia is basically a multifactorial problem, and that blood pressure is a very important factor. We believe another important factor is hypothermia and CSF drainage. I think we have to examine our clinical data further, and then the next step will be to experimentally look at the perfusion of the spinal cord during and after elephant trunk implantation with different protocols of antegrade cerebral perfusion.

Dr T. Sioris *(Tampere, Finland)*: With the paraplegia issue, what was your policy regarding the left subclavian artery, meaning perfusion and reimplantation, noticing that you really had many, many cases of acute type A dissection that you helped with this procedure?

Dr Leontyev: That is a very important point. Our hospital policy is to try to reimplant the left subclavian artery in all patients. In the 10 patients with paraplegia, we did reimplant the left subclavian artery. However, perfusing the left subclavian artery is not our standard protocol; we did this only in one patient. Despite perfusion of the left subclavian artery, this patient developed late paraplegia. However, the patient had undergone previous surgery for an abdominal aortic pathology and, as we know from many publications, this has been proposed as an independent predictor for the development of paraplegia after thoracic aortic surgery, possibly because of a compromise of the distal collateral inflow from the hypogastric artery.

Dr K. Tsagakis *(Essen, Germany)*: Reporting the details of the patients with paraplegia will help in our understanding of the pathogenesis of spinal cord injury after frozen elephant trunk. However, I have a question. In all these patients, did the paraplegia occur after the frozen elephant trunk procedure, or after additional interventions on the descending aorta, like stent graft extension or reoperation on the descending aorta?

Dr Leontyev: The 21.7% paraplegia rate occurred in the frozen elephant trunk group after surgery.

Dr M. Karck *(Heidelberg, Germany)*: I'm still not 100% satisfied with this 20% paraplegia rate. Don't you think that 28 degrees (you identified the risk factor yourself) is maybe a little bit too warm for these patients?

Dr Leontyev: Yes, it's too warm, I agree with you. And we changed our strategy and basically we now cool down our patients to 24 or 22 degrees, depending on the extent of the aortic pathology.

AORTIC SURGERY

European Journal of Cardio-Thoracic Surgery 44 (2013) 1083–1084
doi:10.1093/ejcts/ezt191 Advance Access publication 15 May 2013

EDITORIAL COMMENT

Frozen elephant trunk surgery: where do we go from here?

Marco Di Eusanio*

Department of Cardiovascular Surgery, Sant'Orsola-Malpighi Hospital, University of Bologna, Bologna, Italy

* Corresponding author. Department of Cardiac Surgery, Pad.25, Policlinico Sant'Orsola-Malpighi, Università di Bologna, Via Massarenti 9, 40128 Bologna, Italy. Tel: +39-051-6364505; fax: +39-051-345990; e-mail marco.dieusanio2@unibo.it (M. Di Eusanio).

Keywords: Aortic arch surgery • Elephant trunk • Neurological complication

In a recent review published in this journal by Ius *et al.* [1], one of the main conclusions was that it is difficult (one of my esteemed surgeons would add 'worthless' [2]) to compare the outcomes after the conventional Elephant Trunk (cET) and the Frozen