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Surgical techniques

IMPACT OF CEREBRAL PERFUSION STRATEGIES ON NEUROLOGICAL OUTCOMES IN AORTIC ARCH REPAIR USING THE FROZEN ELEPHANT TRUNK TECHNIQUE

Shokarovski Marjan, Mehmedovic Nadica, Grazhdani Sonja, Grueva Elena, Papestiev Vasil

University Clinic for Cardiac Surgery, Faculty of Medicine, Ss. Cyril and Methodius University in Skopje, Republic of North Macedonia
e-mail: marjansokar@gmail.com

Abstract

Aim: Spinal cord injury (SCI) leading to paraplegia and/or stroke remains one of the most severe complications following aortic arch repair utilizing the frozen elephant trunk (FET) technique. This study aimed to evaluate the impact of various cerebral perfusion strategies on neurological outcomes, comparing our results on trilateral antegrade cerebral perfusion (tACP) to reported rates from latest literature analysis on bilateral antegrade cerebral perfusion (bACP) and unilateral antegrade cerebral perfusion (uACP).

Methods: A retrospective analysis was performed on 15 patients who underwent surgical intervention at the University Clinic for Cardiac Surgery in Skopje between 2018 and 2023. All patients included had elective chronic aortic dissections. Preoperative evaluation encompassed a detailed medical history, physical examination, diagnostic imaging, and risk stratification using the EuroSCORE II model. Standardized surgical techniques, including trilateral cerebral perfusion, were employed intraoperatively. The primary endpoint was the incidence of major neurological complications, including stroke and SCI, while the secondary endpoint was all-cause mortality.

Results: Major neurological events, including stroke and transient ischemic attack (TIA), were observed in 6.7% of patients, with SCI occurring in a single case (6.7%). These rates are notably lower than previously reported figures of 5-15% for procedural strokes following complex aortic arch repairs employing uACP or bACP. All-cause mortality in our cohort was 20%, compared to the 31% reported in the literature for patients undergoing open aortic arch repair.

Conclusion: In patients undergoing total aortic arch repair with the FET technique, tACP appears to be a viable strategy for cerebral and spinal cord protection. The complication rates observed in our cohort are favorable and support further investigation with larger patient populations to validate these findings.

Keywords: aortic arch surgery, frozen elephant trunk, cerebral protection, spinal cord injury

Introduction

The aorta is the main artery responsible for delivering oxygenated blood from the heart to the body and is susceptible to life-threatening conditions such as aneurysms, dissections, and penetrating ulcers. Aortic aneurysms, most commonly located in the ascending aorta, are defined as a dilation of the vessel wall by 50% or more, though other risk factors may influence the need

for treatment. In about 20% of cases, aneurysms can affect multiple segments of the aorta[1]. Aortic dissections occur when a tear in the inner wall allows blood to split the vessel layers, forming a false lumen. Penetrating aortic ulcers and intramural hematomas also compromise the structural integrity of the vessel. Thoracic aortic aneurysms (TAA) have an incidence of 6–10 cases per 100,000 people annually and are more common in men, while women tend to present atypical symptoms, leading to poorer outcomes[2]. Traditional treatment involves surgical graft replacement, while hybrid techniques like the "frozen elephant trunk" procedure provide effective solutions for complex cases involving the arch and descending aorta[3].

Cerebral protection during aortic surgery requiring circulatory arrest (CA) remains a critical concern, particularly in procedures such as the frozen elephant trunk (FET). Traditionally, deep hypothermia was used to safeguard neurological function; however, the introduction of antegrade selective cerebral perfusion (ASCP) has allowed for safer moderate hypothermia (2°C to 26°C), minimizing risks like organ hypoperfusion and impaired cerebral autoregulation[4]. ASCP has since become the preferred strategy across many centers, yet debate continues over the optimal perfusion method - unilateral *versus* bilateral. Although bilateral ASCP ensures perfusion of both hemispheres, nearly 40% of European centers still favor unilateral ASCP, and existing data show no definitive outcome advantage for either technique. Moreover, heterogeneity in patient profiles, anatomy, and surgical complexity complicates direct comparisons. Recent studies have updated and expanded previous meta-analyses, incorporating more data on CA duration and neurological outcomes[5,6]. In light of persistent concerns regarding spinal cord injury (SCI) and stroke, new approaches such as trilateral ACP (tACP) have emerged. This method involves additional perfusion of the left subclavian artery to enhance vertebral artery flow and mitigate the risk of spinal ischemia. This study aimed to compare our findings with the average rates of neurological complications and mortality reported in the literature among patients who received tACP, with the goal of refining cerebral and spinal protection strategies during aortic arch surgery[4,5].

Material and methods

This study is a retrospective observational case series involving 15 patients (both male and female) who underwent cardiac surgery at the University Clinic for Cardiovascular Surgery in Skopje between 2018 and 2023. The study protocol was approved by the Ethics Committee of the Faculty of Medicine at Ss. Cyril and Methodius University in Skopje (UKIM) and the Ethics Commission of the University Clinic for Cardiovascular Surgery. Ethical approval included clearance for data usage and assessment that the potential benefits outweighed individual risks. Patients with acute aortic syndrome, acute preoperative neurological deficits, end-stage renal disease requiring dialysis, or non-cooperative psychiatric disorders were excluded. Preoperative assessment included a comprehensive evaluation comprising detailed medical history, physical examination, and laboratory testing. Cardiac imaging was performed using transthoracic echocardiography and electrocardiography on multiple occasions during hospitalization. All patients underwent coronary angiography, CT angiography of the full aorta, CT scans of the head, chest, and abdomen, respiratory function tests, and Doppler ultrasound of peripheral and carotid arteries. Pharmacological therapy was optimized preoperatively for all cases. Risk stratification was conducted using the EuroSCORE II system to estimate 30-day surgical mortality. This standardized and comprehensive diagnostic approach ensured consistent patient selection and preparation for surgery. The primary outcome was the occurrence of major neurological complications, specifically stroke and spinal cord injury (SCI), while the secondary outcome was

all-cause mortality. Statistical analysis was expressed in continuous variables presented as mean ± SD, and categorical variables as counts and percentages.

Surgical technique

The surgical procedure is performed under general anesthesia. It begins with preparing the right axillary artery, followed by heparinization and cannulation. A median sternotomy is then performed to access the chest, and the right atrium is cannulated with a two-stage venous cannula; in reoperations, femoral vein cannulation is often used for safety. After preparing the supra-aortic vessels, cardiopulmonary bypass (CPB) is initiated. A Dacron graft is attached to the left subclavian artery to enhance spinal cord perfusion. The patient is cooled to 28°C, and the left ventricle is emptied via a catheter through the pulmonary vein. The ascending aorta is opened and resected, and cerebral perfusion is maintained with reduced flow. Trilateral antegrade cerebral perfusion is obtained through direct perfusion of right subclavian artery, left common carotid artery and left subclavian artery. Cardioplegia is administered directly into the coronary arteries. The supra-coronary vessel ostia are resected for reattachment, either individually or as an island. A stent graft, usually in zone 3, is placed and sutured to the aorta. The proximal anastomosis is then made, and once the heart is de-aerated, the patient is weaned off CPB, cannulas are removed, and bleeding is controlled. The surgical site is closed, and the patient is transferred to ICU for postoperative monitoring.

Results

Preoperative patient characteristics

The average age of patients was 62 years. Specifically, 5 patients were between 50 and 59 years old, 9 patients were aged 60 to 70, and 1 patient was 78 years old. The majority were male (80%). The mean body mass index (BMI) was 30.5 kg/m², ranging from 22.6 to 38.9 kg/m², indicating that, on average, patients fell into the obese category. The distribution of BMI levels is illustrated in Figure 1. In terms of functional status, most patients were classified as NYHA (New York Heart Association) Class II (53.3%), followed by 33.3% in Class I and 13.3% in Class III. The mean EuroSCORE II, used to estimate the risk of cardiac surgery, was 4.84, placing the cohort within the intermediate-risk category (EuroSCORE between 3 and 5), with individual scores ranging from 0.73 to 20.62 (Table 1). Table 1 presents the baseline characteristics, risk factors, and prior surgical history of patients.

Table 1. Baseline characteristics, risk factors, and prior surgical history of patients

Parameters	n=15
Age (years)	62.00 ± 7.50
minimum/maximum	50-78
Gender (n%) male, female	12/80, 3/20
BMI (kg/m2),	30.49 ± 4.56
minimum/maximum	22.6-38.9
BMI category (n%)	
Normal (<25 kg/m2)	2/13.3
Overweight (25-29,9 kg/m2)	4/26.7
Obese (> 30 kg/m2)	9/60.0
NYHA Classification	1.80 ± 0.67
Class I (n/%)	5/33.3
Class II (n/%)	8/53.3
Class III (n/%)	2/13.3
EuroSCORE II	4.84 ± 5.42

minimum/maximum	0.73- 20.62
Present Risk Factors	
Hypertension (n/%)	14/93.3
Dyslipidemia (n/%)	9/60.0
Smoking (n/%)	10/66.7
Diabetes mellitus (n/%)	1/6.7
CVI (n/%)	1/6.7
CKD (n/%)	2/13.3
PVD (n/%)	3/20.0
Carotid artery disease (n/%)	2/13.3
AF (n/%)	2/13.3
CAD (n/%)	7/46.7
Cardiac Comorbidities	
Thoracic aneurysm (n/%)	12/80.0
Abdominal aorta aneurysm (n/%)	7/46.7
Previous CABG (n/%)	2/13.3
Implanted heart valve	3/20.0
Aortic root surgery	3/20.0
Thoracic aorta surgery	4/26.7
Abdominal aorta surgery	1/6.7

BMI-Body Mass Index, NYHA-New York Heart Association, EuroSCORE II-European System for Cardiac Operative Risk Evaluation, CVI-Cerebrovascular Incident; CKD-Chronic Kidney Disease, PVD-Peripheral Vascular Disease; AF-Atrial Fibrillation, CAD-Coronary Artery Disease, CABG-Coronary Artery Bypass Grafting

Intraoperative characteristics

All 15 patients underwent right subclavian artery cannulation with trilateral cerebral protection. The mean cardiopulmonary bypass time was 185.53 minutes, cardiac ischemia lasted 83.67 minutes, and antegrade circulatory perfusion averaged 42.46 minutes. Intubation time averaged 73 hours. Associated procedures were performed in 5 patients, including valve interventions, a Bentall procedure, and CABG in 3 patients (20%). One patient underwent simultaneous left carotid and subclavian artery intervention. Intraoperative inotropes were administered in 80% of patients, vasopressors in the ICU in 73.3%, with a mean postoperative serum lactate of 3.69 mmol/L and an average transfusion of 2.53 blood units per patient.

Neurologic complications

Table 2. Major neurologic complications

Parameters	**n=15**
CVI (n/%)	1/6.7
Paraplegia (n/%)	1/6.7
Neurologic deficit (n/%)	
Temporary/permanent	0/1(6.7)

Major neurologic complications observed in the cohort included cerebrovascular incident (CVI) and spinal cord injury, manifesting as paresis, paresthesia, or paraplegia. Among the 15 patients, one patient (6.7%) experienced a CVI, and one patient (6.7%) developed paraplegia postoperatively. The patient with paraplegia underwent an extended course of intensive physical

rehabilitation, after which partial motor recovery was achieved. However, the patient continues to experience persistent paraparesis. Despite the severity of these events, the low incidence reflects a generally favorable neurologic outcome profile within this high-risk surgical cohort.

All-cause mortality

All-cause in-hospital mortality was observed in 3 out of 15 patients (20%) who underwent the frozen elephant trunk (FET) procedure. The timing of death varied, occurring on postoperative days 2, 3, and 45, representing both early and delayed postoperative mortality.

Discussion

The frozen elephant trunk (FET) technique continues to demonstrate strong clinical value in the management of complex aortic pathologies, particularly those involving the aortic arch and descending thoracic aorta. In line with our findings, the latest guidelines from the European Association for Cardio-Thoracic Surgery (EACTS), published in February 2024, recommend the FET procedure as a preferred approach for such conditions[2]. Our experience with 15 patients at the University Clinic for Cardiac Surgery in Skopje supports the effectiveness of this technique, especially in cases of degenerative aneurysms and chronic dissections. The integration of advanced perfusion strategies such as trilateral cerebral perfusion has further contributed to improved neurological and hemodynamic outcomes. While this approach has shown promise, current literature on its application in FET procedures remains sparse.

Notably, Salem *et al*., are the only in the literature up to date to evaluate trilateral cerebral perfusion. Although their results were non-specific and did not clearly demonstrate the superiority of bilateral over trilateral antegrade cerebral perfusion, both methods were found to be safe and effective, highlighting the need for further research of the strategy for cerebral protection[7]. Angeloni *et al.* proved that antegrade cerebral protection was superior to retrograde, but failed to prove significant difference between the unilateral and bilateral antegrade cerebral protection, although the bilateral protection was favored in longer circulatory arrest times[8]. Angleitner *et al*., examined the difference between unilateral and bilateral cerebral protection and showed improved overall survival, particularly in patients requiring cerebral perfusion durations of 50 minutes or longer[9]. Furthermore, Tsagakis *et al.,* described a four-site perfusion technique, involving distal aorta perfusion in addition to trilateral antegrade cerebral perfusion, which proved to be a protective strategy regarding serious neurologic complications[10].

In our study, major neurological events - comprising stroke and transient ischemic attack (TIA) - were identified in 6.7% of patients, with spinal cord injury occurring in a single case. These incidences are notably lower than the 5-15% range reported in previous studies for procedural strokes following complex aortic arch repairs utilizing unilateral or bilateral antegrade cerebral perfusion[2-6]. Additionally, the overall all-cause mortality rate in our cohort was 20%, which is lower than the 31% survival rate reported in the literature for patients undergoing open aortic arch repair. These findings suggest a potentially favorable neurological and survival profile associated with our approach, though further comparative analysis is warranted.

Conclusion

Our positive results underscore the potential benefits of integrating such sophisticated cerebral perfusion techniques during FET procedures. Nonetheless, given the limited number of studies and the sparse data currently available, larger patient populations and multicenter studies are needed to validate these findings and establish optimized protocols for cerebral and spinal cord

protection in complex aortic surgery. These initial outcomes support further investigation into the wider application of tACP in this setting, aiming to improve the safety and long-term results of extensive aortic repairs.

Conflict of interest statement. None declared.

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