Normothermic frozen elephant trunk surgery without circulatory arrest: is this the future?

Marco Di Eusanio[1], Erlil Mali[1], Pietro Giorgio Malvindi[1], Vincenzo Vento[2], Simone D'Alessio[1], Michele Galeazzi[1]^, Olimpia Bifulco[1], Francesca Spagnolo[1], Emanuele Gatta[2], Paolo Berretta[1]

[1]Cardiac Surgery Unit, Lancisi Cardiovascular Center, Polytechnic University of Marche, Ancona, Italy; [2]Vascular Surgery Unit, Lancisi Cardiovascular Center, Ancona, Italy

Correspondence to: Paolo Berretta, MD, PhD. Cardiac Surgery Unit, Lancisi Cardiovascular Center, Polytechnic University of Marche, Via Conca 71, 60126 Ancona, Italy. Email: p.berretta@icloud.com.

Frozen elephant trunk (FET) repair has expanded the treatment of complex aortic arch pathology but continues to rely on hypothermic circulatory arrest (HCA), which remains a major physiological limitation of the procedure. In this Keynote, we describe our current normothermic FET strategy, designed to perform arch reconstruction under continuous cerebral and systemic perfusion, through the integration of open and endovascular techniques. Retrograde stent-graft deployment and balloon occlusion within the prosthesis allow controlled distal aortic clamping while maintaining uninterrupted systemic circulation. In our initial experience, the technique was technically feasible and associated with acceptable perioperative hemodynamic and metabolic profiles; however, given the limited clinical experience, these findings should be interpreted as preliminary and require further evaluation. Beyond its technical aspects, this approach reflects a conceptual shift in arch surgery from mitigating the consequences of circulatory arrest to pursuing strategies aimed at avoiding it. In selected patients, normothermic FET may represent a physiologically oriented option within the ongoing evolution of contemporary aortic arch repair.

Keywords: Normothermic frozen elephant trunk (normothermic FET); frozen elephant trunk (FET); circulatory arrest; arch surgery

Submitted Mar 28, 2026. Accepted for publication Jul 08, 2026. Published online Jul 31, 2026.
doi: 10.21037/acs-2026-0131-aar
View this article at: https://dx.doi.org/10.21037/acs-2026-0131-aar

Introduction

Over the past decades, aortic arch surgery has progressively evolved through advances in cerebral protection, cannulation strategies, and graft reconstruction techniques, leading to broader treatment options and improved outcomes. Within this evolution, the frozen elephant trunk (FET) technique has further refined the surgical management of complex aortic arch pathology (1). By combining total arch replacement with deployment of a stented graft into the proximal descending thoracic aorta, FET allows treatment of extensive disease extending beyond the distal arch in a single operative stage. Beyond facilitating comprehensive arch reconstruction, the stented component enables more effective management of distal pathology (2). In acute aortic dissection, particularly in patients with distal complex intimal tears, arch rupture, or true lumen compression with malperfusion, FET simplifies arch repair, optimizes distal true lumen perfusion, and promotes false lumen thrombosis and aortic remodeling (3). Despite these advances and the growing experience reported by specialized centers, FET remains a technically demanding operation that requires hypothermic circulatory arrest (HCA) and prolonged extracorporeal circulation (ECC). Although these strategies have enabled complex

^ ORCID: 0000-0002-4238-8838.

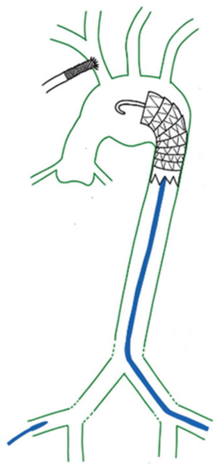

Figure 1 Retrograde transfemoral deployment of the stent graft into the distal aortic arch/proximal descending thoracic aorta.

arch repair to be performed safely, they continue to impose a relevant physiological burden and have been associated with increased operative morbidity and mortality (4-12). In this context, the evolution of arch surgery may increasingly be guided by the objective of preserving continuous cerebral and systemic perfusion throughout reconstruction, with growing attention to strategies that reduce reliance on HCA (13-16). Guided by this objective, we have refined our normothermic arch strategy to maintain uninterrupted cerebral and systemic perfusion during the entire reconstructive phase, thereby eliminating the need for circulatory arrest (17-19). Here, we describe the rationale, operative principles, and initial clinical experience with this approach, and discuss its implications within the ongoing evolution of contemporary aortic arch surgery.

Operative strategy

In our current practice, this normothermic FET strategy integrates open surgical and endovascular techniques to maintain uninterrupted cerebral and systemic perfusion throughout the entire arch procedure, thereby avoiding the need for HCA.

This is achieved through four essential technical components: (I) combined femoral and innominate/axillary arterial cannulation for cardiopulmonary bypass, allowing continuous lower and upper body perfusion; (II) selective antegrade cerebral perfusion with full brain perfusion during the arch reconstruction phase; (III) retrograde transfemoral deployment of the stent graft into the proximal descending thoracic aorta/distal arch; and (IV) retrograde balloon occlusion within the stent graft to obtain controlled distal aortic clamping without interrupting systemic perfusion.

Surgical technique

The procedure is performed in a hybrid operating theater under general anesthesia. Bilateral radial arterial pressure monitoring and near-infrared spectroscopy are routinely employed. A standard median sternotomy is performed. The supra-aortic vessels are extensively prepared and isolated before opening the pericardium. This facilitates optimal visualization and control of the arch branches in a dry operative field, avoiding interference from pericardial fluid or blood during subsequent dissection. The pericardium is then opened, and the ascending aorta, proximal arch (up to the intended distal anastomosis zone), right atrium, and right superior pulmonary vein are adequately exposed. Both femoral arteries are surgically prepared. After systemic heparinization, cardiopulmonary bypass is established using dual arterial inflow through the innominate (or right axillary) artery and one femoral artery via a Y-connector, ensuring continuous perfusion of both the upper and lower body. Venous drainage is achieved through right atrial cannulation, and the left ventricle is vented via the right superior pulmonary vein.

The intended proximal landing zone of the endograft (zone 1, 2, or 3) is identified and marked with multiple large hemoclips. Through the contralateral femoral artery, an extra-stiff guidewire is advanced under fluoroscopic guidance, and an appropriate stent graft without a free-flow segment is deployed retrogradely, aligning its proximal edge with the hemoclip markers (*Figure 1*).

A compliant balloon is then introduced retrogradely through the same femoral access using a 14 Fr sheath. Under fluoroscopic control, the balloon is inflated within the stent graft to simulate aortic clamping. The inflation volume is recorded and the catheter position marked. The balloon is subsequently deflated and left in place for later use. Cardiopulmonary bypass is initiated with arterial inflow through the innominate or axillary artery. The left subclavian artery is ligated at its origin and anastomosed distally to an 8-mm vascular graft, which is separately perfused using a dedicated cannula for antegrade selective cerebral perfusion (ASCP). Perfusion of the left subclavian artery is initiated at approximately 250 mL/min and adjusted to maintain balanced radial arterial pressures between 40

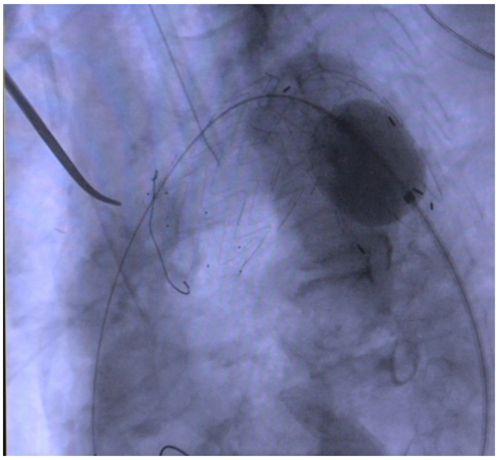

Figure 2 Fluoroscopic image showing distal endoclamping with balloon occlusion within the deployed stent graft.

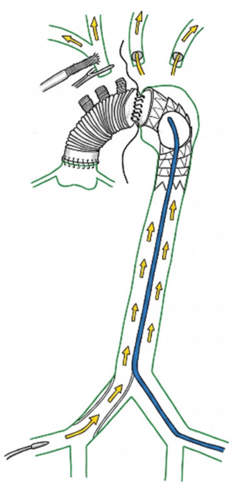

Figure 3 Distal arch reconstruction under continuous perfusion, with lower-body perfusion maintained through the femoral artery and cerebral perfusion maintained by antegrade selective cerebral perfusion. The distal anastomosis incorporates the endograft, native aortic wall, and external reinforcement.

and 80 mmHg. After aortic cross-clamping, myocardial protection is achieved with antegrade administration of cold crystalloid (Custodiol) or Del Nido cardioplegia. The left common carotid artery is ligated at its origin, cannulated distally, and perfused with a second ASCP cannula. Following cardioplegic arrest, the innominate artery is proximally clamped. The aortic balloon is inflated using the previously recorded volume, and femoral arterial inflow is opened to maintain continuous lower body perfusion (*Figure 2*). The aortic cross-clamp is then removed. With uninterrupted cerebral and distal perfusion, the ascending aorta and arch are resected from the sinotubular junction to the proximal edge of the endograft, providing a controlled and bloodless operative field without circulatory arrest. A four-branched vascular graft is anastomosed to the distal aorta. The distal anastomosis incorporates the stent graft internally and is reinforced externally with Teflon felt, creating a three-layer construct consisting of endograft, native aortic wall, and external reinforcement (*Figure 3*). After completion of the distal anastomosis, the arch graft is clamped, the balloon is deflated, and distal perfusion is switched from the femoral line to a side branch of the graft to re-establish antegrade flow. The proximal anastomosis to the aortic root is then completed and myocardial reperfusion is initiated. The supra-aortic vessels are individually reimplanted onto the corresponding branches of the graft, completing the reconstruction.

Special consideration in acute aortic dissection

In acute type A aortic dissection, the technique is reserved for hemodynamically stable patients in whom an adequate distal landing zone can be identified, and the primary entry tear is located within the aortic arch. The cardiopulmonary bypass setup is identical to that described above. After arterial and venous cannulation for ECC, the true lumen is catheterized from the femoral access under combined fluoroscopic and transesophageal echocardiographic guidance to ensure correct guidewire positioning and subsequent endograft deployment. The proximal landing zone is selected according to the location of the primary tear and marked with hemoclips. ECC is initiated, and after ligation at their origins, the left subclavian artery (with interposition graft) and the left common carotid artery are cannulated distally and perfused to establish full ASCP. A long (approximately 60 cm) introducer sheath is advanced through the femoral artery over an extra-stiff guidewire. An appropriate endograft without a free-flow segment is advanced cranially through the sheath and deployed with its proximal edge aligned to the predefined landing zone markers. The delivery system is then removed, and the introducer sheath is advanced further so that its tip is positioned securely within the stent graft. Through the same sheath, a compliant balloon catheter and an arterial cannula connected via a Y-connector to the arterial line supplying the innominate artery are advanced retrogradely into the stent graft. The balloon is inflated to achieve endoclamping, and the femoral arterial line is opened, allowing uninterrupted antegrade perfusion of the distal dissected aorta during arch reconstruction. The operation then proceeds according to the steps previously described. In patients who have previously undergone thoracic endovascular aortic repair (TEVAR), the technique is adapted by using the existing stent graft as the distal landing zone. In these cases, no additional endograft is deployed. A compliant balloon is advanced retrogradely into the previously implanted stent graft and inflated to obtain endoclamping. The distal anastomosis is then performed incorporating the pre-existing stent graft into the three-layer construct, following the same principles described above.

Indications, patient selection and limitations

Patient selection is based on multidisciplinary evaluation by the institutional Aortic Team and careful preoperative computed tomography angiography (CTA) scan assessment. The primary inclusion criterion for this procedure is an adequate landing zone, as it allows secure stent-graft deployment and effective distal aortic control. It is essential to achieve effective endoclamping and to obtain a bloodless operative field at the time of arch opening. In the absence of an appropriate distal landing zone, retrograde flow from the femoral perfusion line cannot be adequately controlled, resulting in persistent back-bleeding into the operative field during distal anastomosis. Exclusion criteria include (I) inadequate distal sealing zone; (II) severe aortic tortuosity; (III) absence of viable vascular access options; (IV) extreme aortic diameters; (V) active endocarditis; and (VI) chronic aortic dissection.

Chronic aortic dissection represents a limitation for the normothermic FET strategy. In this setting, deployment of a stent graft within the true lumen does not induce effective false lumen collapse. Consequently, once the arch is opened, persistent back-bleeding from the false lumen may occur despite balloon endoclamping of the true lumen.

In acute type A aortic dissection, this approach can be considered in hemodynamically stable patients in whom the primary entry tear is clearly located within the aortic arch, as well as in selected patients who have previously undergone TEVAR. If the primary entry tear is located in the ascending aorta, it cannot be excluded by the stent graft; therefore, persistent false-lumen back-bleeding may occur after arch opening despite balloon endoclamping, making the technique unsuitable.

The distal anastomosis is the most demanding step of the procedure. Incorporation of the stent graft into the suture line requires full-thickness bites through both the endograft fabric and the native aortic wall. The reduced compliance of the endograft makes suture handling more demanding and hemostasis more challenging, resulting in a distal anastomosis that is less straightforward than in conventional open repair.

Finally, this strategy requires advanced expertise in both open arch surgery and catheter-based techniques, as well as a hybrid operating environment and a coordinated aortic team experienced in complex arch procedures integrating open and endovascular approaches.

Initial clinical experience

Between September 2019 and January 2025, 23 aortic arch operations without HCA were performed at our institution, including *de novo* FET procedures and arch reconstructions after previous TEVAR (20). The median age of the patients was 73 (range, 60–83 years), and EuroSCORE II ranged from 1.4% to 10% (median 3.8%). Indications included degenerative aneurysm (n=14), type I endoleak (n=4), acute aortic dissection (n=2), chronic penetrating ulcer (n=2), and Kommerell's diverticulum (n=1). Technical success was achieved in all patients, with successful endograft deployment and completion of the distal anastomosis without the need for circulatory arrest.

Median cardiopulmonary bypass and aortic cross-clamp times were 109 minutes (range, 65–205 minutes) and 56 minutes (range, 42–125 minutes), respectively. Median cerebral perfusion time was 69 minutes (range, 45–130 minutes). Myocardial protection was achieved with Custodiol cardioplegia in 16 patients and del Nido cardioplegia in 7 patients.

Normothermic or mild hypothermic ECC was used in 22 patients, while moderate hypothermia was used in one patient with type A acute dissection. The median peak intraoperative lactate level was 1.8 mmol/L, ranging from 1 to 3.2 mmol/L.

Two in-hospital deaths occurred, due to septic shock and stroke. Major complications included temporary dialysis in four patients, stroke in three patients, and respiratory insufficiency in three patients. No permanent spinal cord injury was observed. The median intensive care unit and hospital stays were 4 and 10 days, respectively. At a median follow-up of 27 months, estimated overall survival at 1, 2, and 3 years was 86.1%, 69.8%, and 69.8%, respectively, and three patients required distal aortic reintervention due to type Ib (n=2) and type II (n=1) endoleaks.

Discussion

HCA remains a major limitation of aortic arch surgery and FET repair. Despite significant advances in cerebral protection and perfusion strategies, systemic hypothermia and interruption of visceral perfusion expose patients to ischemic stress, inflammatory activation, and metabolic imbalance with potential consequences including neurological injury, organ dysfunction, and prolonged recovery (4-12). Evidence suggests that even short periods of circulatory arrest may be associated with measurable cognitive impairment and radiological evidence of brain injury, confirming that no duration of arrest can be considered entirely safe (12). In this context, preserving uninterrupted cerebral and systemic perfusion throughout reconstruction represents a more physiological objective. This approach should be viewed within the broader evolution of arch surgery, in which open reconstruction, endovascular distal control, and continuous cerebral and systemic perfusion are increasingly integrated to reduce the physiological burden of complex aortic repair (17-20).

Accordingly, our normothermic FET strategy was refined to maintain continuous perfusion during the entire reconstructive phase. Several alternative strategies have pursued the same physiological objective through different technical pathways. Touati *et al.* (14) described totally normothermic arch replacement using separate cerebral, systemic, and myocardial perfusion with distal aortic occlusion, whereas Matalanis and Shi (16) reported a branch-first continuous-perfusion technique avoiding deep hypothermia and circulatory arrest. Compared with these strategies, our technique combines retrograde stent-graft deployment and balloon endoclamping with continuous cerebral and systemic perfusion throughout arch reconstruction.

A key technical element of this technique is the retrograde deployment of the stent graft performed before initiation of cardiopulmonary bypass, followed by balloon occlusion within the prosthesis to obtain distal aortic control. In contrast to techniques based on antegrade endoballoon positioning, retrograde occlusion within the stent graft allows controlled distal clamping without interrupting systemic circulation at any stage of the procedure (15,19). By preserving continuous cerebral, spinal cord, and visceral perfusion under normothermic conditions, the operation avoids global ischemia and may reduce the physiological burden associated with circulatory arrest. In our strategy, the left subclavian artery is routinely perfused during arch reconstruction and then reimplanted, with the aim of preserving collateral spinal cord inflow during distal aortic coverage (21).

From a physiological perspective, maintaining uninterrupted systemic perfusion throughout the procedure may have relevant implications. Rather than relying on metabolic suppression through hypothermia, this strategy seeks to preserve organ perfusion and metabolic stability during the entire reconstructive phase. Although the observed hemodynamic and metabolic stability is consistent with the physiological rationale of the technique, the series is exploratory and cannot establish clinical benefit, reduction in organ injury, or superiority over standard FET with HCA (20).

Careful patient selection remains essential when considering a normothermic FET strategy. Anatomical suitability is a prerequisite, particularly the presence of an adequate distal landing zone that allows secure stent-graft deployment and effective endoclamping. Chronic aortic dissection represents a limitation, as incomplete false lumen exclusion may result in persistent back-bleeding once the arch is opened. In acute type A dissection, this approach should be reserved for hemodynamically stable patients in whom the primary entry tear is located within the arch, and a safe landing zone can be clearly defined.

The development of this strategy reflects the broader evolution of contemporary arch surgery toward hybrid integration. Increasing familiarity with catheter-based techniques has redefined the operative skill set of the aortic surgeon, allowing more flexible and tailored solutions in complex reconstructions. The convergence of open surgical and endovascular skills within a dedicated aortic team represents a key element for the safe and effective implementation of such approaches. For this reason, the normothermic FET strategy should be considered within centers with established experience in advanced arch surgery and endovascular aortic repair.

Conclusions

Our normothermic FET strategy enables aortic arch reconstruction under continuous cerebral and systemic perfusion through integration of open and endovascular techniques. In selected patients and experienced centers, it may represent a feasible approach aimed at minimizing global ischemia and reducing reliance on HCA. Although its definitive role remains to be established, continuous perfusion strategies may contribute to the ongoing evolution of contemporary aortic arch surgery.

Acknowledgments

None.

Footnote

Funding: None.

Conflicts of Interest: The authors have no conflicts of interest to declare.

References

1. Eranki A, Downes D, Muston B, et al. Mid-to-long-term outcomes of the frozen elephant trunk procedure in aortic pathology: a systematic review and meta-analysis. Ann Cardiothorac Surg 2025;14:319-29.
2. Weiss G, Arnold Z, Folkmann S, et al. From back table innovation to contemporary application: a review of the frozen elephant trunk technique. Ann Cardiothorac Surg 2025;14:335-42.
3. Berretta P, Di Eusanio M. Descending endograft for DeBakey type 1 aortic dissection: pro. Ann Cardiothorac Surg 2016;5:222-6.
4. Nakamura K, Onitsuka T, Yano M, et al. Risk factor analysis for ascending aorta and aortic arch repair using selective cerebral perfusion with open technique: role of open-stent graft placement. J Cardiovasc Surg (Torino) 2006;47:659-65.
5. Khaladj N, Shrestha M, Meck S, 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.
6. Di Eusanio M, Berretta P, Cefarelli M, et al. Total Arch Replacement Versus More Conservative Management in Type A Acute Aortic Dissection. Ann Thorac Surg 2015;100:88-94.
7. Mousavizadeh M, Daliri M, Aljadayel HA, et al. Hypothermic circulatory arrest time affects neurological outcomes of frozen elephant trunk for acute type A aortic dissection: A systematic review and meta-analysis. J Card Surg 2021;36:3337-51.
8. Czerny M, Krähenbühl E, Reineke D, et al. Mortality and neurologic injury after surgical repair with hypothermic circulatory arrest in acute and chronic proximal thoracic aortic pathology: effect of age on outcome. Circulation 2011;124:1407-13.
9. Svensson LG, Crawford ES, Hess KR, et al. Deep hypothermia with circulatory arrest. Determinants of stroke and early mortality in 656 patients. J Thorac Cardiovasc Surg 1993;106:19-31.
10. Cao L, Guo X, Jia Y, et al. Effect of Deep Hypothermic Circulatory Arrest Versus Moderate Hypothermic Circulatory Arrest in Aortic Arch Surgery on Postoperative Renal Function: A Systematic Review and Meta-Analysis. J Am Heart Assoc 2020;9:e017939.
11. Tian DH, Wan B, Di Eusanio M, et al. A systematic review and meta-analysis on the safety and efficacy of the frozen elephant trunk technique in aortic arch surgery. Ann Cardiothorac Surg 2013;2:581-91.
12. Hughes GC, Chen EP, Browndyke JN, et al. Neurocognitive Dysfunction After Short (<20 Minutes) Duration Hypothermic Circulatory Arrest. Ann Thorac Surg 2025;119:343-50.
13. Malvindi PG, Alfonsi J, Berretta P, et al. Normothermic frozen elephant trunk: our experience and literature review. Cardiovasc Diagn Ther 2022;12:262-71.
14. Touati GD, Marticho P, Farag M, et al. Totally normothermic aortic arch replacement without circulatory arrest. Eur J Cardiothorac Surg 2007;32:263-8.
15. Sun X, Guo H, Liu Y, et al. The aortic balloon occlusion technique in total arch replacement with frozen elephant trunk. Eur J Cardiothorac Surg 2019;55:1219-21.
16. Matalanis G, Shi WY. An Australian experience with aortic arch replacement: a novel approach without circulatory arrest or deep hypothermia. Heart Lung Circ 2011;20:163-9.
17. Di Eusanio M, Gatta E. Frozen Elephant Trunk Without Circulatory Arrest in Acute Aortic Dissection. Ann Thorac Surg 2021;112:e143-5.

18. Di Eusanio M, Cefarelli M, Alfonsi J, et al. Arch Surgery for Type Ia Endoleak: How to Remain Normothermic and Avoid Circulatory Arrest. Ann Thorac Surg 2020;110:e139-41.
19. Di Eusanio M, Cefarelli M, Alfonsi J, et al. Normothermic frozen elephant trunk surgery without circulatory arrest: how we do it in Ancona. Ann Cardiothorac Surg 2020;9:244-5.
20. Berretta P, D'Alessio S, Malvindi PG, et al. Frozen elephant trunk in normothermia without circulatory arrest: initial experience. Ann Cardiothorac Surg 2025;14:291-302.
21. Orozco-Sevilla V, Coselli JS. Management of the left subclavian artery during aortic arch replacement using a frozen elephant trunk approach: a review. Cardiovasc Diagn Ther 2023;13:736-42.

Cite this article as: Di Eusanio M, Mali E, Malvindi PG, Vento V, D'Alessio S, Galeazzi M, Bifulco O, Spagnolo F, Gatta E, Berretta P. Normothermic frozen elephant trunk surgery without circulatory arrest: is this the future? Ann Cardiothorac Surg 2026;15(4):46. doi: 10.21037/acs-2026-0131-aar