Keynote Lecture Series

From back table innovation to contemporary application: a review of the frozen elephant trunk technique

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The frozen elephant trunk (FET) technique represents a significant advancement in the surgical management of complex aortic pathologies involving the aortic arch and descending thoracic aorta. This review traces the evolution of the FET procedure from its conceptual origins in the conventional elephant trunk (ET) technique to its current application as a hybrid, single-stage intervention. The FET technique integrates open surgical repair with endovascular technology, allowing for simultaneous aortic arch replacement and stent-graft deployment into the descending aorta. Key indications include acute and chronic aortic dissections, arch aneurysms, and malperfusion syndromes. Surgical considerations such as cannulation strategy, cerebral protection, and spinal cord preservation are discussed in detail, with emphasis on techniques that enhance safety and outcomes. The development of commercially available FET prostheses—such as E-vita Open Neo, Thoraflex Hybrid, and Frozenix—has improved procedural versatility and enabled individualized treatment strategies. Innovations in graft design, including proximalization of distal anastomosis and integration of side branches, have further simplified the procedure and broadened its applicability. Despite variability in outcomes across patient populations, the FET procedure is associated with favorable early and mid-term results, including reduced inter-stage mortality and enhanced aortic remodeling. The technique continues to evolve, driven by advances in device technology and a growing emphasis on tailored, patient-specific surgical approaches.

Keywords: Frozen elephant trunk (FET); hybrid aortic surgery; aortic arch replacement

Submitted Jun 01, 2025. Accepted for publication Jul 14, 2025. Published online Sep 25, 2025.
doi: 10.21037/acs-2025-evet-0105
View this article at: https://dx.doi.org/10.21037/acs-2025-evet-0105

Introduction

The management of extensive aortic pathologies, particularly those involving both the aortic arch and the descending thoracic aorta, presents a severe challenge in cardiovascular surgery. Historically, these complex conditions were addressed through staged surgical interventions, which were often associated with significant morbidity and mortality risks. A transformative approach emerged with the development of the frozen elephant trunk (FET) technique, a hybrid procedure that combines the principles of open surgical aortic arch repair with simultaneous endovascular stenting of the descending thoracic aorta (1). This innovative method has evolved considerably from its conceptualization, marking a significant advancement in the treatment of intricate aortic diseases. The FET technique represents a progression from the conventional elephant trunk (ET) procedure, incorporating endovascular principles to achieve a more comprehensive and often single-stage repair (1).

This review aims to provide a state-of-the-art overview of the FET technique, tracing its journey from its origins to its current applications.

The origin of the ET technique

The foundation for the FET technique was laid with the introduction of the ET procedure by Hans Georg Borst in 1983 (2). The ET procedure was characterized by a two-stage approach. The initial stage involved aortic arch replacement performed through a median sternotomy, leaving a free-floating graft extension, the "elephant trunk", within the descending aorta. The second stage, typically conducted via a left thoracotomy, involved the repair of the descending aorta, utilizing the previously placed graft extension for anastomosis.

The primary rationale behind the ET technique was to simplify the technical demands of the second-stage repair by providing a readily accessible graft for anastomosis, thereby eliminating the need for direct clamping of the descending thoracic aorta. However, the ET technique was not without limitations. Graft-related complications, such as thromboembolism due to the free-floating nature of the graft and kinking or occlusion, were significant concerns (3-5). Furthermore, the two-stage nature of the procedure carried a considerable risk of inter-stage mortality, and a substantial proportion of patients who underwent the first stage never proceeded to the second, often due to death or refusal of further surgery (6). Over time, modifications to the original ET technique were introduced, such as altering the length of the free-floating portion (7). While the ET technique represented a significant step forward in addressing complex aortic pathologies, its inherent two-stage nature presented considerable risks and limitations. The period between the two surgeries was a time of increased vulnerability for patients, and the necessity for a second major operation contributed to overall morbidity and mortality (8). The evolution of the ET technique, with subsequent modifications, demonstrates the continuous efforts in surgical innovation to overcome these shortcomings, ultimately paving the way for the development of the more integrated FET approach (1).

The advent of the FET

The introduction of endovascular technology and the development of specialized arch prostheses served as crucial catalysts in the evolution towards the FET concept. This concept was pioneered in the mid-1990s by Kato and colleagues. The first clinical application of the FET procedure followed in 2003, implemented by Karck and colleagues, which integrated a covered stent component with a conventional vascular graft (6). The FET technique represented a significant departure from the staged ET procedure by offering a one-stage hybrid approach. This method allows for the simultaneous total replacement of the aortic arch and the antegrade delivery of a stent-graft into the descending aorta. The term "frozen elephant trunk" was coined by Karck, drawing inspiration from the static, "frozen" appearance of the stent on postoperative imaging. The initial objectives for performing the FET procedure were multifaceted, including addressing extensive aortic pathology spanning the arch and proximal descending aorta, implementing a tear-oriented surgical strategy for aortic dissections, managing malperfusion syndrome, and promoting favorable aortic remodeling (9).

The development of the FET technique marked a revolutionary step in the management of complex aortic diseases. By providing a single-stage solution that addresses both the aortic arch and the proximal descending aorta, it effectively eliminated the risks associated with the staged ET approach, potentially leading to improved patient outcomes. The emergence of FET was a direct consequence of the limitations inherent in the ET technique, coupled with the advancements in endovascular technology, highlighting the synergistic relationship between different surgical modalities (10).

The transition from a multi-stage surgical approach to the single-stage hybrid FET procedure signifies a substantial shift in the treatment paradigm for complex aortic diseases. This evolution potentially reduces the overall burden on patients by minimizing the need for multiple major surgeries and the associated risks during the inter-stage period (11). Furthermore, the continuous refinement of the FET technique, evident in advancements in graft design and surgical methodologies, underscores a persistent dedication to enhancing patient outcomes and decreasing morbidity in aortic surgery (9).

Indications for the FET procedure

The FET technique has found broad application in the treatment of a variety of complex aortic pathologies. Its primary indications include extensive aortic diseases involving both the aortic arch and the proximal descending thoracic aorta. FET is frequently employed in the management of both acute and chronic aortic dissections, encompassing Stanford Type A and Type B classifications. Aortic arch aneurysms, regardless of their etiology (degenerative, post-dissection, or inflammatory), also represent a common indication for FET (12).

In the context of aortic dissections, FET is particularly valuable for tear-oriented surgery, especially when the primary entry tear is located within the aortic arch or the proximal descending thoracic aorta (13). The technique is also indicated for the management of malperfusion syndrome, a critical complication of acute aortic dissection. Furthermore, FET plays a crucial role in promoting positive aortic remodeling, facilitating the thrombosis of the false lumen and the expansion of the true lumen in aortic dissections and aneurysms (14). A significant advantage of the FET procedure is its ability to provide a stable proximal landing zone in the descending aorta for potential future endovascular interventions, such as thoracic endovascular aortic repair (TEVAR), addressing residual or progressive disease in the more distal aorta (15). Certain unfavorable anatomical conditions for a purely endovascular approach might favor the use of the FET technique (11). The broad spectrum of indications for the FET technique underscores its versatility and significant impact on the field of aortic surgery. Its applicability across various complex aortic pathologies, from dissections to aneurysms, highlights its importance in contemporary surgical practice. The tear-oriented approach facilitated by FET in aortic dissections emphasizes the critical role of addressing the primary entry tear to prevent further propagation of the dissection and associated complications (14).

Surgical techniques in FET implantation

The standard surgical approach for FET implantation is performed via a median sternotomy, providing access to the aortic arch and proximal descending aorta. The establishment of cardiopulmonary bypass is a critical step, with various cannulation strategies employed depending on the patient's condition and the surgeon's preference. Common arterial cannulation sites include the right axillary artery, brachiocephalic trunk, proximal aortic arch, femoral artery, and right carotid artery (16). In our practice, we favor right axillary artery cannulation due to its safety profile and technical feasibility.

Following aortic arch resection, the FET stent-graft system is then introduced and deployed in an antegrade fashion into the true lumen of the descending aorta, typically over a previously positioned stiff guidewire. The proximal Dacron graft component is then sutured to the descending aorta. The arch vessels are subsequently reimplanted, either using the FET prosthesis graft or separate grafts, employing techniques such as the "island" technique or utilizing branched prostheses. The aortic repair is typically completed with the proximal anastomosis.

Adjunctive strategies for spinal cord protection are often employed, including cerebrospinal fluid (CSF) drainage, maintaining an adequate mean arterial pressure (MAP), and in some cases, performing an extra-anatomic bypass of the left axillary artery (13). Emerging techniques aimed at reducing the duration of circulatory arrest, such as the aortic balloon occlusion technique, are also being explored (17).

The evolution of surgical approaches, such as the branch-first technique, where the arch vessels are addressed before the distal anastomosis, and the strategic selection of cannulation sites, are aimed at optimizing cerebral perfusion and minimizing the overall operative time. Continuous cerebral perfusion during the debranching of the arch vessels can contribute to improved neurological outcomes (18).

Evolution of FET graft design

A precursor to the current FET technique was implemented in Vienna in the early 2000s. This approach involved a combined open surgical repair of the ascending aorta and concomitant endovascular stent grafting of the descending aorta for the treatment of acute Stanford type A aortic dissection (19). The initial FET prostheses typically consisted of a conventional vascular graft at the proximal end, to be sutured to the aortic arch, with a covered stent component attached distally, designed for deployment into the descending aorta (1). This design allowed for the combined open surgical repair of the arch and endovascular treatment of the proximal descending aorta in a single procedure.

Beyond the pioneering work in Hannover major contributions to the development and widespread adoption of the FET technique during the 2000s were made by leading centers in Essen and Bologna (20-22). These groups played a pivotal role in refining the surgical methodology and generating influential clinical data, thereby establishing the FET technique as a standard approach in contemporary aortic surgery worldwide.

Over time, several commercially available hybrid FET prostheses have been developed, each with unique features

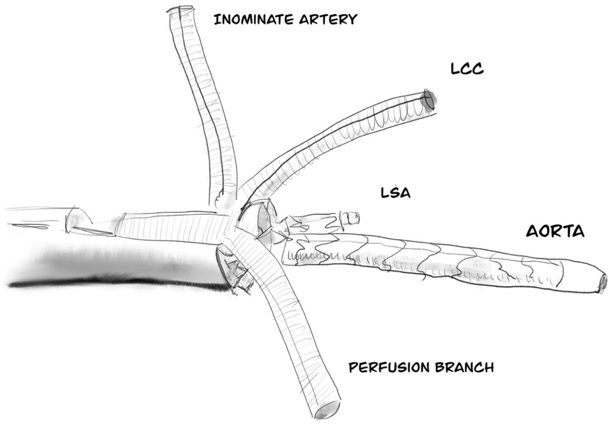

Figure 1 Frozen elephant trunk prosthesis with a stented side branch for the LSA prosthesis showing the LSA side branch stent. LCC, left common carotid; LSA, left subclavian artery.

and delivery systems. These include the E-vita Open series (comprising E-vita Open, E-vita Open Plus, and E-vita Open Neo) manufactured by Jotec, the Thoraflex Hybrid prosthesis produced by Vascutek/Terumo, and the Frozenix, a Japanese-made FET graft characterized by hand-knitted Nitinol stents and a unique delivery system. The E-vita Open, initially known as the Essen I prosthesis, was introduced in 2005 as the first commercially available hybrid prosthesis. It features a polyester fabric covering an endoskeleton made of nitinol Z-stents, along with a proximal non-stented Dacron prosthesis (20). In 2012, the development of the branched E-vita FET device enabled collar anastomosis in zones 1 to 3, along with sequential reimplantation of the supra-aortic vessels. Subsequently, the E-vita Open Neo, introduced in 2020, represented a next-generation advancement. It incorporates a tetra-furcate proximal graft design, facilitating collar anastomosis in zones 0 and 1 (23). Proximalization of the aortic arch to zone 0 using a collar anastomosis in the zone 0/1 configuration has enhanced the accessibility of the FET procedure, particularly for less experienced surgeons. This approach is associated with a reduced risk of recurrent laryngeal nerve injury, a significantly lower incidence of paraplegia, and improved hemostatic control (23).

The Thoraflex hybrid graft, introduced in 2012, is a branched FET prosthesis developed by Terumo Aortic. The device's design includes up to four branches, allowing for individualized reimplantation of supra-aortic vessels and early lower body reperfusion (24,25). Its configuration supports collar anastomosis in zones 0 to 2, enhancing surgical versatility and reducing ischemic times. The Thoraflex Hybrid received Food and Drug Administration (FDA) approval in 2022 and has since been widely adopted in clinical practice.

The third commercially available FET device is the Frozenix prosthesis. Manufactured by Japan Lifeline, it features a non-branched Dacron graft combined with a distal self-expanding nitinol stent-graft. Introduced in clinical practice in the early 2010s and approved in Japan in 2014, Frozenix is widely used in Asia and has demonstrated favorable outcomes in both elective and emergency aortic arch procedures (26). Its streamlined design allows for straightforward deployment and reliable distal fixation, making it a valuable option in hybrid aortic repair strategies.

Key differences among these prostheses lie in the length and design of the stent component, the presence and configuration of side branches, the radial force exerted by the stent, and the characteristics of their respective delivery systems.

A significant trend in the evolution of FET graft design has been the move towards proximalizing the distal anastomosis, with some newer devices facilitating anastomosis in aortic zones 0, 1, and 2, rather than the traditional zone 3, potentially simplifying the procedure and improving safety (23).

Further advancements include the development of novel FET prostheses incorporating endovascular side branches specifically for the left subclavian artery (LSA), aiming to streamline total arch replacement by facilitating its connection. One such innovative prosthesis features an endovascular side branch for LSA connection, designed to enhance the efficiency of aortic arch replacement (*Figure 1*). Pre-clinical testing in a human cadaver model demonstrated the feasibility of accurate deployment with anatomical orientation towards the LSA ostium, followed by successful stent graft deployment (*Figure 2*) (27). Proximalizing the distal anastomosis to zone 1 simplified the procedure and facilitated its completion. First-in-men experience with this novel FET prosthesis with conditions such as penetrating ulcer, non-A non-B aortic dissection and chronic arch aneurysm showed promising preliminary clinical outcomes (28). Surgeries were performed under high moderate hypothermia (27 ℃), employing bilateral selective antegrade cerebral perfusion and distal aortic perfusion. Anastomosis of the FET prosthesis with the aortic arch occurred in zone 1, followed by separate reimplantation of the left common carotid artery and the brachiocephalic

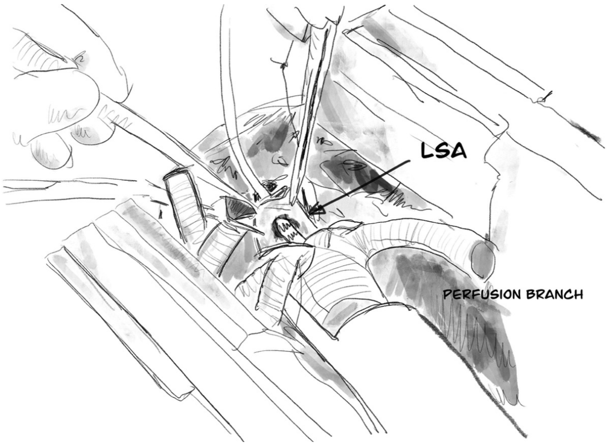

Figure 2 View during implantation showing exact orientation of the side branch towards the LSA ostium. LSA, left subclavian artery.

artery.

The continuous innovation in FET graft design underscores an ongoing commitment to enhancing surgical ease, minimizing complications, and optimizing the long-term remodeling of the aorta. The availability of multiple FET prostheses with diverse features allows surgeons to tailor their approach based on the specific aortic pathology and the individual characteristics of the patient, reflecting a broader movement towards personalized medicine in the field of aortic surgery.

Outcomes and complications of FET surgery

The reported outcomes of FET surgery vary across studies, reflecting differences in patient populations, aortic pathologies, surgical techniques, and institutional experience. In-hospital and 30-day mortality rates have been reported to range from 2.4% to 15.9% (12). Several factors have been identified as influencing the outcomes of FET surgery, including patient-related factors such as age and pre-existing comorbidities, the urgency of the surgical intervention, and the specific aortic pathology being treated (dissection versus aneurysm) (29). Long-term survival rates following FET surgery are generally favorable, with reported 1-year survival around 80–90% and 5-year survival in the range of 60–80% (30). However, a significant proportion of patients may require secondary distal aortic procedures, such as TEVAR or open surgery, during the follow-up period, highlighting the importance of ongoing surveillance (31). Distal stent graft-induced new entry (dSINE) has also been recognized as a potential complication following FET implantation (32). Additionally, intraluminal thrombosis within the stent graft is another potential complication, which can lead to graft occlusion and subsequent distal ischemic events (33). A significant benefit of the FET technique is its ability to promote aortic remodeling, leading to false lumen thrombosis and true lumen expansion in a substantial number of patients (34).

Current best practices and ongoing advancements in FET surgery

Current best practices in FET surgery emphasize the necessity of meticulous surgical skills and adherence to standardized techniques to optimize patient outcomes. Given the complexity of aortic arch surgery, cerebral protection is paramount. Antegrade selective cerebral perfusion (ASCP) is a widely adopted strategy, often combined with moderate to deep hypothermia (ranging from 20 to 28 ℃) (35). Cerebral perfusion can be unilateral or bilateral, depending on the specific technique and the extent of arch involvement. We advocate for moderate hypothermia with bilateral ASCP, as it offers reliable cerebral protection, is straightforward to implement, and is supported by favorable outcomes in the current literature (36). Various strategies are employed to minimize the risk of spinal cord ischemia (SCI), including CSF drainage, maintaining adequate MAP, avoiding the use of excessively long stent grafts, and proximalizing the distal anastomosis site (13). Intraoperative imaging modalities, such as transesophageal echocardiography and angioscopy, are frequently utilized to guide the deployment of the stent graft and to confirm its accurate positioning within the descending aorta (37). A crucial aspect of current practice involves tailoring the selection of the specific FET prosthesis and the surgical technique to the individual patient's anatomy and the precise nature of their aortic pathology (9). While the majority of FET procedures are performed via open sternotomy, advancements in minimally invasive approaches are also being explored. The importance of a multidisciplinary team approach and the establishment of a clear plan for potential distal aortic interventions following FET are increasingly recognized as essential for optimal patient management (38).

Contemporary best practices in FET surgery underscore a patient-centric approach, characterized by meticulous preoperative planning, precise surgical execution, and individualized strategies for the protection of vital organs.

Recognizing the inherent complexity of the procedure and the significant variability in aortic pathologies among patients, a standardized yet highly personalized approach is considered paramount for achieving the best possible outcomes. Furthermore, ongoing advancements in both surgical techniques and the design of FET devices continue to refine the procedure, with the overarching goals of further reducing the incidence of complications and improving the long-term durability of the repairs (27). The development of new prosthetic designs and the optimization of surgical strategies demonstrate the dynamic and evolving nature of this specialized field within cardiovascular surgery.

Future directions in FET technology and application

The future of FET technology and its application in aortic surgery is poised for continued evolution and refinement. A key focus will likely be on the development of next-generation FET devices that incorporate improved features designed to facilitate easier implantation, enhance procedural safety, and ultimately lead to better patient outcomes. There is a growing emphasis on personalized approaches to FET surgery, where the choice of prosthesis and surgical technique are tailored even more precisely to the individual patient's unique aortic anatomy and specific pathology.

A persistent area of research and development is the further investigation into strategies aimed at preventing SCI, a significant complication associated with FET. Optimizing the distal landing zone of the stent graft and refining stent-graft sizing techniques are also crucial areas of focus to prevent complications such as dSINE (13).

The role of FET in combination with other endovascular techniques for achieving comprehensive aortic repair is an area of increasing interest. This integrated approach leverages the strengths of both open surgical and endovascular modalities to address complex aortic diseases that may extend beyond the reach of either technique alone. Continued research into the long-term outcomes and the durability of FET repairs is essential to fully understand the benefits and limitations of this technique over extended periods (32).

Finally, there is potential for expanding the indications for FET to encompass other complex aortic conditions as our understanding of the technique and its outcomes continues to grow. The development of a modified FET prosthesis with a stented LSA side branch shows promise in simplifying total aortic arch replacement by proximalizing the distal anastomosis into zone 1 and by shortening spinal and lower body hypothermic circulatory arrest times (28).

The trajectory of FET surgery points towards an increasingly personalized approach, driven by advancements in device technology and a deeper understanding of the long-term results. The integration of FET with other endovascular strategies suggests a future where hybrid approaches become more prevalent in the management of extensive and complex aortic diseases.

Conclusions

The FET technique represents a significant evolution in the surgical treatment of complex aortic pathologies involving the aortic arch and descending thoracic aorta. Originating from the conventional ET procedure, the integration of endovascular stent-graft technology has transformed the management of these challenging conditions, often allowing for a single-stage repair. Key advancements in FET graft design, surgical techniques, and our understanding of postoperative outcomes have continuously improved the safety and efficacy of this procedure.

The FET procedure stands as a vital tool in the contemporary surgical armamentarium for addressing intricate aortic arch and descending aorta pathologies. However, ongoing research and innovation remain crucial to further enhance patient outcomes, mitigate the risk of complications such as spinal cord injury, and expand the applications of this promising technique. The future of FET surgery will likely be characterized by a greater emphasis on personalized medicine, continued refinements in device technology, and a more comprehensive understanding of long-term durability. Ultimately, the FET technique has had a transformative impact on aortic surgery, offering a powerful approach to treat complex aortic diseases and holding significant potential for continued advancement in the years to come.

Acknowledgments

None.

Footnote

Funding: None.

Conflicts of Interest: M.G. has a consultant agreement with

Artivion. The other author has no conflicts of interest to declare.

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Cite this article as: Weiss G, Arnold Z, Folkmann S, Aschacher T, Tauber S, Harrer ML, Winkler B, Stabernak J, Gorlitzer M, Grabenwöger M. From back table innovation to contemporary application: a review of the frozen elephant trunk technique. Ann Cardiothorac Surg 2025;14(5):335-342. doi: 10.21037/acs-2025-evet-0105

