General Thoracic and Cardiovascular Surgery (2019) 67:111–117
https://doi.org/10.1007/s11748-018-0911-4

SPECIAL EDITION

Controversies in Surgery for Thoracic Aorta

Is the frozen elephant trunk frozen?

Roberto Di Bartolomeo[1] · Giacomo Murana[1] · Luca Di Marco[1] · Jacopo Alfonsi[1] · Gregorio Gliozzi[1] · Ciro Amodio[1] · Alessandro Leone[1] · Davide Pacini[1]

Received: 17 January 2018 / Accepted: 19 March 2018 / Published online: 28 March 2018
© The Japanese Association for Thoracic Surgery 2018

Abstract
The elephant trunks, either conventional or frozen represent the major technical improvements in the treatment of complex thoracic aortic disease. In the last decades, these useful techniques progressively evolved along with the introduction of new devices to facilitate the procedure and ameliorate post-operative results. The latest multi-branched hybrid FET prostheses give us the opportunity to greatly facilitate graft implantation and reduce operative times. The following review will provide an overview of the FET technique throughout the current available devices, possible surgical indications and principal surgical steps.

Keywords Aortic arch · Frozen · Elephant trunk · Aortic · Cerebral perfusion.

Introduction

The elephant trunk technique (ET) began is bright course more than 30 years ago with the idea to facilitate a second open thoracoabdominal aortic repair at the time of the first open arch procedure [1]. The basic concept of the conventional ET resides in the protrusion of a length of tubing into the down-stream descending aorta during the time of arch reconstruction. Since then, the procedure and the devices greatly improved to facilitate the implantation and ameliorate post-operative results [2–4]. The turning point has certainly been represented by the introduction of endovascular technologies. In 1995 at Stanford University was published the first case of endovascular second stage after ET procedure, using the trunk as proximal landing zone [5]. The natural history of the ET was, therefore, delineated with the antegrade stent graft implantation in the proximal descending thoracic aorta at the time of first operation and the technique renamed as Frozen Elephant trunk (FET) [6]. The benefits of endografts were combined with conventional open surgery to treat extensive aortic aneurysms unsuitable for repair by endovascular therapy alone. The new FET aims to stabilize the maximum extent of the thoracic aorta in one-step procedure and eventually provide an easier landing zone for secondary endovascular aortic repair or open surgery.

State of the art of primary FET prosthesis

Since its first description, different FET prostheses, preassembled or custom-made, have been developed for carrying out this surgery in a broad set of pathologies [7–10]. The proximal portion consists of a Dacron sleeve for conventional surgical handling and the distal part consist of a stent graft. The most used current prostheses are shown in Fig. 1.

In China, Sun introduced the Cronus open stented graft (MicroPort, Shanghai, China), which consists of a regular Dacron vascular tube and interconnected Z-shaped stents [11, 12]. The delivery system consists of a grip handle and a pull wire to make the stent graft expands easily. Epiaortic vessels are reconstructed selectively in a previously assembled four-branched graft.

Later on in Europe, the first commercially available hybrid graft came from Essen and was the E-vita open prosthesis (Jotec Inc., Hechingen, Germany). The hybrid prosthesis consists of a proximal vascular part with zero porosity and a distal self-expandable portion (13 to 16 cm long and 20 to 40 mm in diameter) made of Z-shaped nitinol wire [13, 14]. The stented portion is deployed with

✉ Davide Pacini
davide.pacini@unibo.it

[1] S. Orsola-Malpighi Hospital, Alma Mater studiorum, University of Bologna, Via Massarenti 9, 40138 Bologna, Italy

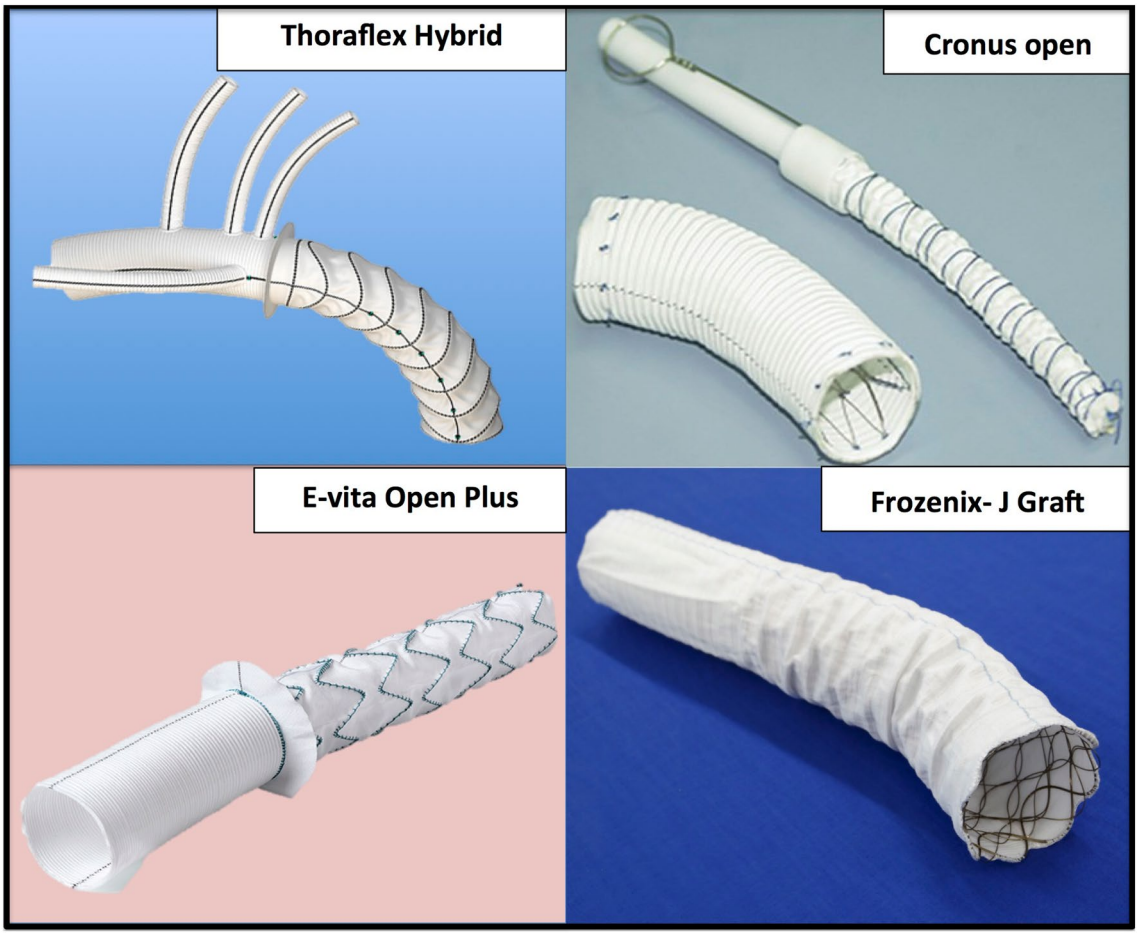

Fig. 1 Current available open stent grafts used in the frozen elephant trunk technique

a squeeze-to-release mechanism, in which the prosthesis is introduced forward into the proximal descending aorta by every "squeeze" of the handle.

The proximal and distal grafts have the same diameter, and a sewing collar is added between them to facilitate the distal anastomosis during arch reconstruction.

The latest evolution of the conventional FET prosthesis is the Vascutek Thoraflex hybrid graft (Inchinnan, Scotland). The unstented portion has four integrated side branches, 3 for the selective anastomosis of the arch vessels and 1 used to restore lower body perfusion after the distal anastomosis [8, 15]. The distal stent stented part is 10 or 15 cm long and 28–40 mm in diameter. It also has radiopaque markers to simplify secondary procedures if needed.

Main advantages of a branched hybrid graft compare to not branched grafts are the reduction of myocardial and lower body ischemia time, the anatomic reconstruction of the epiaortic vessels and the possibility to facilitate the distal suture more proximally in the aortic arch [15, 16].

A new open stent graft was launched on the Japanese market in July 2014, and the name is Frozenix J graft, which is still waiting to receive the CE-mark approval.

This new hybrid graft is composed by a proximal part consisting of a straight vascular prosthesis of polyester and a distal stented part made of nitinol wire. The two parts are folded and mounted on a shaft within a soft sheath [17].

The diameter of the stent graft ranges from 17 to 39 mm, and three length are available: 60, 90 and 120 mm [18]. The arch vessels are sewn with a separate branched graft during the distal anastomosis on the aortic arch. Compared with other open stent grafts, the J Graft has a unique double-layered oval-shaped nitinol stents that easily conform to the curvature of the aorta.

In some other countries, including the United States, because of the unavailability of the hybrid prosthesis, alternative techniques as been proposed. Pochettino et al. described an antegrade delivery of a stent graft during hypotermic circulatory arrest followed by a complete aortic arch reconstruction with a regular vascular graft [19].

Another example is provided by Roselli at Cleveland Clinic, where a stent graft is delivered in an antegrade insertion more proximally in the aortic arch, followed by the creation of a fenestration in the stent graft to accommodate the arch branch and finally completed by a single proximal anastomosis [9].

Current indications for the use of FET

Due to the great interest on the Frozen elephant trunk technique, the vascular domain of the EACTS felt the need to write a position paper in which, with the help of some other aortic experienced surgeons, tried to provide some recommendations for use of the FET technique [20].

In particular, for which concerns type A dissection, is suggested to perform FET technique to close the primary entry tear in the distal aortic arch or in the proximal descending thoracic aorta to treat or avoid associated malperfusion syndrome (to fully open the compressed true lumen) and to induce thrombosis of the false lumen (Fig. 2) [16, 20, 21].

Taking advantage of the distal stent graft segment of the hybrid prosthesis, a distal anastomosis can be more easily performed proximal to the left subclavian or left carotid arteries avoiding the risk of rupture of the fragile aortic wall [16, 20].

Furthermore, in case of type B dissection, FET procedure was advised when TEVAR is contraindicated or the risk of retrograde type A aortic dissection is too high (Fig. 3) [16, 20, 22]. This may happen when the landing zone is not suitable for the endograft deployment as in concomitant aneurysm of the ascending aorta and arch, or in patients with connective tissue disorders and involvement of the left subclavian artery [22].

Finally, it has been suggested to consider FET technique in patients affected by extensive thoracic or thoracoabdominal aortic disease for degenerative aneurysms or residual aortic dissections when either second open surgery or endovascular treatment are expected [16, 20]. Advantages are to avoid dissection near the distal arch anastomosis, more rapidly performing the distal anastomosis due to the sewing collar and to facilitate second stage operation.

FET technique with a "step by step" approach

The key points for this kind of surgery are an accurate assessment of the aortic anatomy, employment of reliable methods of brain and organ protection during open arch repair and the application of a methodological surgical technique.

The entire aorta has to be carefully investigated before operation, especially in case of acute or chronic dissection, where it is necessary to know the origin of the visceral arteries (true or false lumen) and the presence of the distal reentry sites.

Sizing is based on the diameters of the descending aorta for acute dissections as well as the diameter of the true and false lumen as measured preoperatively using computed tomography (CT) scan. Oversizing is usually avoided in dissected patients to prevent formation of new intimal tears distal to the stent graft [16, 21, 23]. Also in chronic aortic

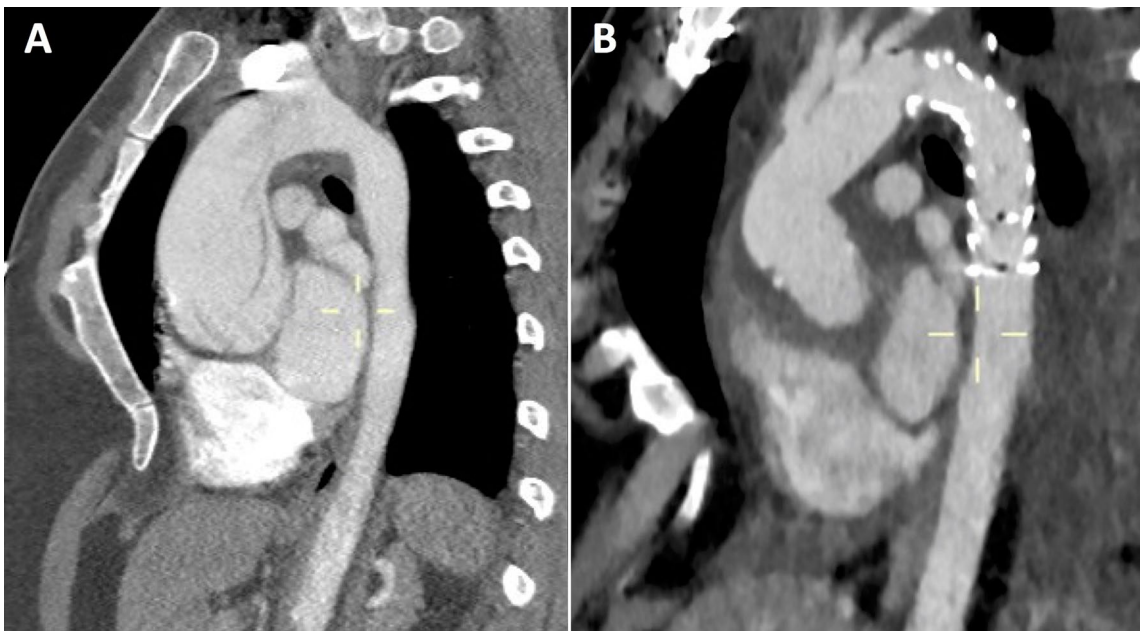

Fig. 2 Type A acute aortic dissection: **a** before and **b** after the Thoraflex 4-branched hybrid graft implantation

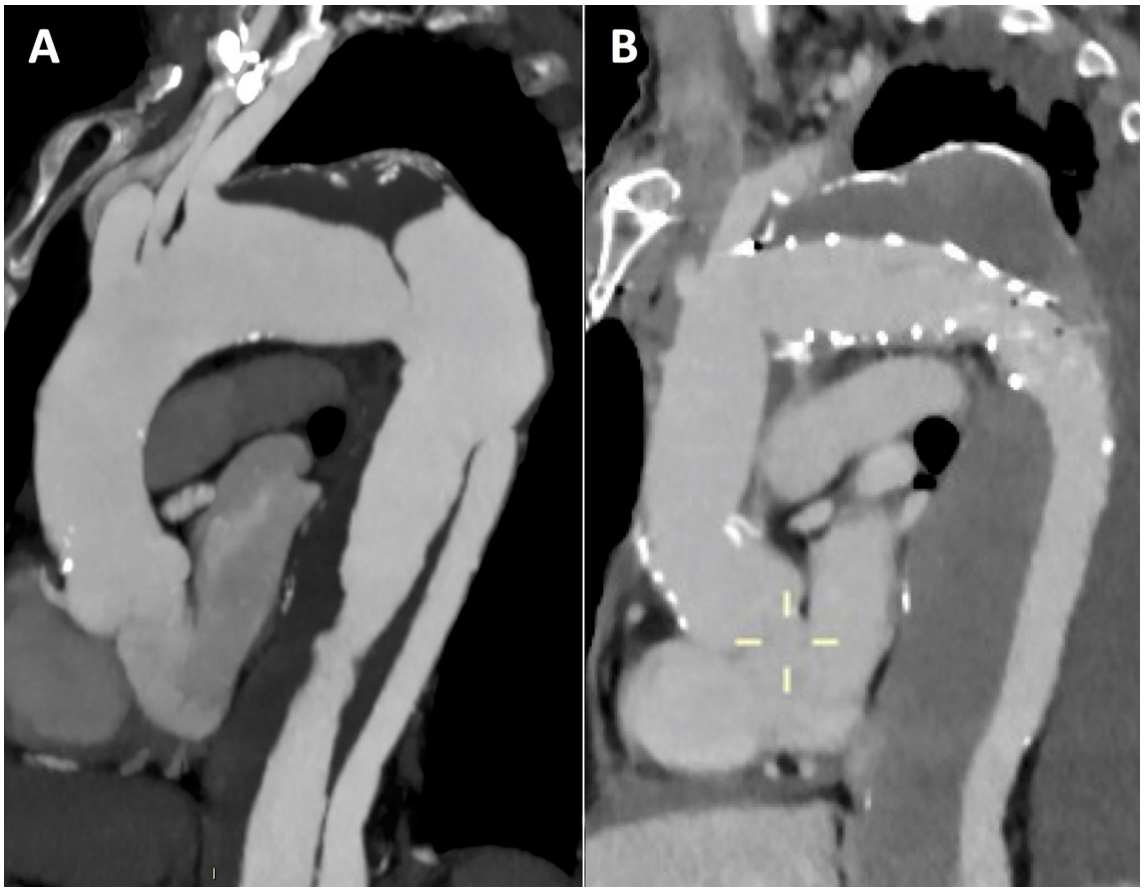

Fig. 3 Chronic Type B aortic dissection: **a** before and **b** after FET implantation

aneurysms is very important to know the exact diameters of the distal landing zone in the descending thoracic aorta to decide the correct size of the stent graft.

In our experience, for myocardial protection we use the modified Bretschneider solution (Custodiol; Koehler Chemie, Alsbach-Haenlein, Germany) in a single dose, which guarantees 3 h of safe myocardial protection [21]. As method of cerebral protection is usually recommended a bilateral antegrade selective cerebral perfusion under moderate systemic hypothermia.

As arterial line inflow we use the axillary, innominate or carotid arteries to achieve antegrade systemic perfusion and at the same time the right hemisphere during the circulatory arrest. The left side hemisphere is perfused through a cannula inserted in the left common carotid artery and left subclavian artery. To protect abdominal organs and the spinal cord we routinely use moderate hypothermia at 26 °C of nasopharyngeal temperature.

In all patients, near-infrared spectroscopy is necessary to monitor cerebral perfusion.

Is also recommended, in all elective patients, to insert 1 day before surgery (to be also maintained 48 h after the procedure) an intrathecal catheter for spinal-cord fluid drainage.

Technical steps for the implantation of hybrid grafts are as follow:

1. *Guidewire positioning* After systemic heparinization a guidewire is inserted through the femoral artery in the thoracic aorta under transesophageal echocardiography (TEE) guidance. This is necessary to facilitate the subsequent stent graft release and above all in case of dissection to identify the true lumen.
2. *Central arterial cannulation* Achieved using the axillary, innominate and carotid arteries.
3. *Hypothermic circulatory arrest* At the target temperature, 25 to 26 °C of nasopharyngeal temperature, we reduce the arterial flow at 800 ml and, after clamping the proximal innominate artery, the perfusion of right cerebral hemisphere is obtained. At this moment, we open the aortic arch and we cannulate directly the left common carotid artery and, whenever it is possible, the left subclavian artery to guarantee a more physiologic cerebral and spinal-cord perfusion.
4. *Aortic wall reinforcement* Is usually preferred to reinforce the distal suture line in both aortic dissections and chronic aneurysm. During the circulatory arrest

the aortic stump is prepared using an external Teflon felt fixed with some (usually four) internal pledgeted U-stitches.

5. *Stent graft release* Advancement of the hybrid system in the descending thoracic aorta over a guidewire that has been retrogradely positioned. The stent graft release could be with a squeezing mechanism like for the E-vita or with a pullback system like for the thoraflex prosthesis.
6. *Angioscopy* Is recommended to use it during the procedure. Before the deployment of the hybrid prosthesis to have a clear vision of the aortic anatomy, and after to asses the correct position and opening of the stent.
7. *Distal anastomosis* The collar if incorporated or directly the prosthesis is sutured to the previously reinforced distal aorta. It can be performed in zone 3, 2, 1 or even in zone zero. It is clear that the more proximal this anastomosis is, the easier it can be performed and the lower is the risk to damage the left recurrent nerve. We began to deploy and fixate the graft in Zone 2 between the left carotid and subclavian arteries. Thus, the distal arch remains in place and the orifice of LSA is sacrificed by 2–0 polypropylene U-stitches after transection of the LSA.
8. *Reperfusion of the lower body* Immediately after distal anastomosis is necessary to restart CPB (and rewarming of the patient) through the side branch of the tetrafurcated Thoraflex device or directly through a previously assembled new vascular prosthesis.
9. *Epiaortic vessels reimplantation* After the distal anastomosis is performed, there are two different options for the epiaortic vessels reimplantation according to the type of hybrid prosthesis. In the E-vita is necessary to use the en-block technique and only after epiaortic vessels reimplantation is possible to proceed with the proximal anastomosis. In case of Thoraflex Hybrid implantation is possible to reimplant the left subclavian artery first and then perform the remaining left carotid and innominate arteries anastomosis under the beating heart to reduce the myocardial ischemia.
10. *Proximal anastomosis* The proximal prosthesis-to-aorta or prosthesis-to-prosthesis anastomosis (in case of aortic root replacement) completes the procedure.

Results in Bologna

Since 2007, 250 patients (male: 82.8%; mean age: 61.5 ± 11 years) underwent extensive thoracic aorta surgery using the FET approach with an E-vita open ($n = 164$) or the Thoraflex Hybrid ($n = 86$) prosthesis. The most frequent indications for surgery included residual type A chronic dissection (40%), extensive degenerative aneurysm of the thoracic aorta (27%), acute type A (12%) and type B (4%) aortic dissection and chronic type A (5%) and type B aortic dissection (12%). Figure 4 shows a case of FET implantation in a patient with a distal aortic arch aneurysm involving the descending thoracic aorta. Fifty-two patients had already undergone cardiac/aortic interventions through a median sternotomy. A total of 101 associated procedures were performed, with 50.0% on the aortic root.

Overall hospital mortality was 17.2% including emergency cases and reoperations.

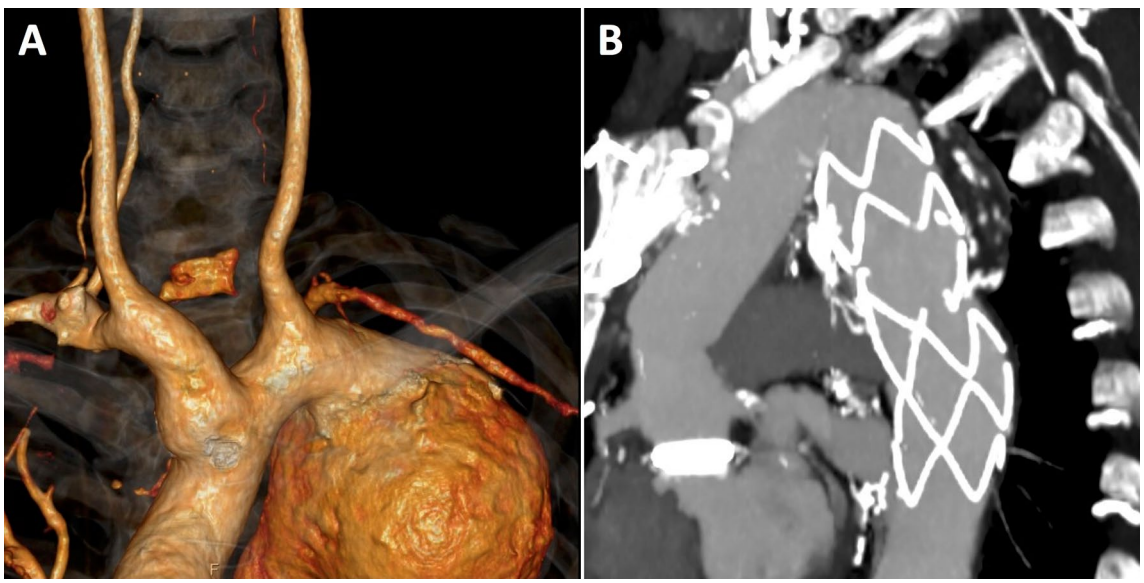

Fig. 4 Angio-CT showing a degenerative distal aortic arch aneurysm: **a** before and **b** after the E-vita hybrid graft implantation

Major post-operative events were neurological complications as permanent neurological disease in 25 patients (10.0%) and spinal cord deficits like paraplegia/paraparesis (4.8%) that we observed more frequently at the beginning of our experience with the use of the E-vita prosthesis. At the moment, with the use of branched grafts paraplegia was never observed.

At follow-up 46 patients (18.4%) necessitated a secondary intervention. Of them, 82.2% were endovascular procedures for distal aneurysms extension or to treat endoleaks; the remaining 17.8% were open thoracoabdominal procedures.

Final remarks

Extensive thoracic aortic disease with simultaneous involvement of different aortic segments requires sequential approaches with cumulative surgical trauma and interval mortalities [3, 24–27]. The classic ET approach established the basis for the treatment of this type of aortic disease. Some authors modified the surgical principles introducing the concept of the FET in which a stent graft became part of the procedure.

This hybrid approach allowed a complete repair of the arch and descending intra-thoracic aorta in one stage operation not precluding the possibility treat the remaining thoracoabdominal aorta in a second step.

Of course the refinement of the technique and devices have strongly contributed to reduce major post-operative complications [16, 27].

The latest introduction among the trunk prostheses concerned the branched-FET graft. It is now considered the most worthwhile among the classical and frozen elephant trunk procedures, because offers the flexibility of (1) easier distal arch anastomosis, (2) quick distal organ reperfusion, and (3) individual epiaortic vessel reimplantation [16]. These features contributed to shorten myocardial, spinal cord and visceral ischaemia times.

In conclusion, anterograde stenting of the thoracic aorta broadened indications and simplifies treatment of complex arch pathologies. The concept of obtaining most complete primary repair is effective and facilitates secondary intervention. In experienced centers, the early and also initial long-term results are really encouraging, and therefore, in a near future, with the possibility to simplify the FET implantation, this procedure would continue to gain popularity.

Funding None.

Compliance with ethical standards

Conflict of interest The authors have declared that no conflict of interest exists.

References

1. Borst HG, Walterbusch G, Schaps D. Extensive aortic replacement using ''elephant trunk'' prosthesis. Thorac Cardiovasc Surg. 1983;31:37–40.
2. Schepens MA. Aortic arch replacement: the conventional 'elephant trunk' technique. Multimed Man Cardiothorac Surg. 2007;1;2007(102).
3. Castrovinci S, Murana G, de Maat GE, et al. The classic elephant trunk technique for staged thoracic and thoracoabdominal aortic repair: long-term results. J Thorac Cardiovasc Surg. 2015;149(2):416 – 22.
4. Shrestha M, Martens A, Kruger H, et al. Total aortic arch replacement with the elephant trunk technique: single-centre 30-year results. Eur J Cardiothorac Surg. 2014;45:181–6.
5. Fann JI, Dake MD, Semba CP, et al. Endovascular stent-grafting after arch aneurysm repair using the "elephant trunk". Ann Thorac Surg. 1995;60(4):1102–5.
6. Karck M, Chavan A, Hagl C, et al. The frozen elephant trunk technique: a new treatment for thoracic aortic aneurysms. J Thorac Cardiovasc Surg. 2003;125:1550–3.
7. Sun L, Qi R, Zhu J, et al. Total arch replacement combined with stented elephant trunk implantation: a new ''standard'' therapy for type a dissection involving repair of the aortic arch? Circulation. 2011;123:971–8.
8. Shrestha M, Pichlmaier M, Martens A, et al. Total aortic arch replacement with a novel four-branched frozen elephant trunk graft: first-in-man results. Eur J Cardiothorac Surg. 2013;43:406 – 10.
9. Roselli EE, Rafael A, Soltesz EG, et al. Simplified frozen elephant trunk repair for acute DeBakey type I dissection. J Thorac Cardiovasc Surg. 2013;145:S197-201.
10. Ma WG, Zheng J, Sun LZ, et al. Open stented grafts for frozen elephant trunk technique: technical aspects and current outcomes. Aorta (Stamford). 2015;3(4):122–35.
11. Liu ZG, Sun LZ, Chang Q, et al. Should the "elephant trunk" be skeletonized? Total arch replacement combined with stented elephant trunk implantation for Stanford Type A aortic dissection. J Thorac Cardiovasc Surg. 2006;131:107–13.
12. Sun LZ, Ma WG, Zhu JM, et al. Sun's procedure for chronic Type A aortic dissection: to- tal arch replacement using a tetrafur- cate graft with stented elephant trunk implantation. Ann Cardiothorac Surg. 2013;2:665–6.
13. Jakob H, Tsagakis K, Leyh R, et al. Development of an integrated stent graft-Dacron prosthesis for intended one-stage repair in complex thoracic aortic disease. Herz. 2005;30:766–8.
14. Jakob H. Facilitated surgical strategy in total arch replacement and descending aorta stent grafting with the E-vita open hybrid prosthesis. Ann Cardiothorac Surg. 2013;2:663–4.
15. Shrestha M, Kaufeld T, Beckmann E, et al. Total aortic arch replacement with a novel 4-branched frozen elephant trunk prosthesis: single-center results of the first 100 patients. J Thorac Cardiovasc Surg. 2016 Jul;152(1):148–59.e1.
16. Di Bartolomeo R, Murana G, Di Marco L, et al. Frozen versus conventional elephant trunk technique: application in clinical practice. Eur J Cardiothorac Surg. 2017 Jan;51(suppl 1):i20-i28.
17. Kato M, Kuratani T, Kaneko M, et al. The results of total arch graft implantation with open stent-graft place- ment for Type A aortic dissection. J Thorac Cardiovasc Surg. 2002;124:531–40.
18. Uchida N, Katayama A, Higashiue S, et al. A new device as an open stent graft for extended aortic repair: a multicentre early experience in Japan. Eur J Cardiothorac Surg. 2016;49:1270–8.
19. Pochettino A, Brinkman WT, Moeller P, et al. Antegrade thoracic stent grafting during repair of acute DeBakey I dissection

prevents development of thoracoabdominal aortic aneurysms. Ann Thorac Surg. 2009;88(2):482–9 (**discussion 489–90**).
20. Shrestha M, Bachet J, Bavaria J, et al. Current status and recommendations for use of the frozen elephant trunk technique: a position paper by the vascular domain of EACTS. Eur J Cardiothorac Surg. 2015;47:759–69.
21. Di Eusanio M, Pantaleo A, Murana G, et al. Frozen elephant trunk surgery-the Bologna's experience. Ann Cardiothorac Surg. 2013;2(5):597–605.
22. Weiss G, Tsagakis K, Jakob H, et al. The frozen elephant trunk technique for the treatment of complicated type B aortic dissection with involvement of the aortic arch: multicentre early experience. Eur J Cardiothorac Surg. 2015;47(1):106 – 14; (**discussion 114**).
23. Di Marco L, Pantaleo A, Leone A, et al. The frozen elephant trunk technique: European association for cardio-thoracic surgery position and bologna experience. Korean J Thorac Cardiovasc Surg. 2017 Feb;50(1):1–7.
24. Murana G, Castrovinci S, Kloppenburg G, et al. Open thoracoabdominal aortic aneurysm repair in the modern era: results from a 20-year single-centre experience. Eur J Cardiothorac Surg. 2016;49(5):1374–81.
25. Di Bartolomeo R, Pacini D, Savini C, et al. Complex thoracic aortic disease: single-stage procedure with the frozen elephant trunk technique. J Thorac Cardiovasc Surg. 2010;140:S81-5 (**discussion S86–91**).
26. Shrestha M, Beckmann E, Krueger H, et al. The elephant trunk is freezing: the Hannover experience. J Thorac Cardiovasc Surg. 2015;149(5):1286–93.
27. Di Marco L, Pacini D, Leone A, et al. The frozen elephant trunk technique for the treatment of complex lesions of the thoracic aorta. G Ital Cardiol (Rome). 2017;18(9):631–7.