Review Article

Frozen Elephant Trunk as an Effective Alternative to Open and Hybrid Two-Stage Procedures for Complex Aortic Disease

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The management of aneurysms involving the aortic arch and descending aorta poses a technical challenge and is an area of ongoing development and innovation. Although one-stage replacement of the aorta is feasible and has been the mainstay of surgical treatment of extensive thoracic aneurysms in the past, the technical complexity and associated morbidity of one-stage procedures has led to the development of two-stage open and hybrid procedures. In this way the operating surgeon or endovascular physician is able to complete the distal aortic reconstruction following the patient's recovery from the first main reconstructive procedure and by accessing the site for intervention away from previous surgery. More recently, and with the advent of endovascular technology, a one-stage complete repair of extensive thoracic aneurysms and dissections has been achieved, aiming at decreasing the cumulative morbidity and mortality of two-stage procedures. The "frozen elephant trunk" technique, which involves the single-stage combination of open antegrade stent graft insertion into the descending aorta and conventional surgical reconstruction of the aortic arch has shown promising results.

The aim of this review is to acquaint the modern cardiovascular physician with the evolution and appraisal of surgical treatments for extensive thoracic aneurysms, with emphasis on the frozen elephant trunk, its technical aspects, current applications and outcomes.

Literature search criteria

An electronic search was performed using MEDLINE (1996 – November 2010), EMBASE and SCOPUS (1996 – November 2010), using the following MeSH terms: "frozen elephant trunk", "stented elephant trunk", "open stent grafting", "aneurysm" and "dissection". Articles were also identified using the function "related articles" in MEDLINE, and automatic term mapping for "frozen elephant trunk". We included in the outcome analysis only series with more than 10 patients undergoing the frozen elephant trunk procedure. Only full papers published in English were included. Additionally, abstracts from national and international cardiovascular meetings were evaluated.

Evolution of surgical treatment of extensive thoracic aneurysms

"Extensive" or "complex" aneurysms describe those aneurysms which involve abnormal enlargement of the ascending aorta, aortic arch and descending aorta to the level of the diaphragm. Graphical representation of the evolution of treatment for this entity is shown in Figure 1. Surgical intervention was commonly performed through midline sternotomy with the use of cardiopulmonary bypass and circulatory arrest. However, pathology that extends beyond the proximal 1/3 of the descending aorta cannot be addressed through the conventional midline sternotomy and the surgeon will have to perform the rather extensive 'clamshell' incision,[1] or a midline sternotomy followed by left thoracotomy. Such unfavourable extensive pathology is found in more than 50% of patients undergoing surgery of the thoracic aorta.[2] It is apparent that both options induce augmented surgical trauma, in addition to the technical complexity of single-step aortic reconstruction involving the descending aorta. Outcomes of one-stage open procedures vary in the literature, depending on the experience of the unit, patient selection and underlying pathology. Important considerations of extensive open repair with prolonged circulatory arrest include brain and spinal cord injury, myocardial protection, renal failure and respiratory compromise.[3] Kouchoukos and colleagues presented a rather satisfactory overall in-hospital mortality of 7.2% in their large cohort of one-stage repairs, which is comparable with the more modern two-stage procedures.[4] However, the reported 50% incidence of prolonged mechanical ventilation (with 13% need for tracheostomy) is rather significant and may be a result of the invasiveness of the bilateral anterior thoracotomy and prolonged operative time for complete repair in a single step.

In order to overcome some of the technical limitations and optimise postoperative outcomes of the conventional one-stage repair of aneurysms involving the arch and descending aorta, Borst and colleagues proposed a two-stage approach with the use of the 'elephant trunk' technique.[5] The initial procedure involves the transection of the descending aorta at the level just beyond the left subclavian artery. An intussuscepted piece of Dacron graft is inserted into the descending thoracic aorta and secured around its circumference. Once this anastomosis is complete the intussuscepted portion of the graft is retracted, used for the aortic arch reconstruction and then anastomosed proximally to healthy ascending aorta. The distal end of the elephant trunk remains free within the descending aorta (Figure 1d). In cases where the ascending aorta is also involved, conventional graft repair can be performed, which can then be connected to the proximal portion of the elephant trunk, leading to a complete replacement. The use of median sternotomy and limited manipulation within the left hemithorax allows for favourable early postoperative outcomes of this technique. The second stage involves management of the thoracic or thoraco-abdominal aorta. This can be achieved through a left thoracotomy or thoraco-abdominal incision, which is away from the site of previous surgery and avoids some of the associated shortcomings with access, adhesions and wound complications (Figure 1e). Early postoperative results of the elephant trunk appear superior compared to one-stage procedures; however, interpretation of outcomes of this technique should not be limited to the mortality and morbidity figures of each individual step, but also to events occurring during the interval.[6] This may influence outcomes of the follow-up procedure, which may be reflective of a self-selected group with more favourable pathology and co-morbidities. With the advent of endoluminal techniques, the second stage of the elephant trunk can now be accomplished with percutaneous insertion of stent grafts, minimising surgical trauma and associated complications (Figure 1f). The efficacy of this hybrid approach is still awaited, since—with the exception of a few small case series—there is no controlled comparative study to provide the essential evidence.

More recently, the concept of antegrade open stent graft placement into the descending aorta was introduced as an adjunct procedure to conventional aortic arch reconstruction, aiming at a single-stage hybrid repair of extensive aneurysms and dissections. The early experience of this procedure was described by Kato and colleagues[7] and the term "frozen elephant trunk" was proposed by Karck[8] to illustrate the principles of the elephant trunk management of aortic disease with the advantage of the fixed anatomical placement within the aorta (Figure 1g). Although another hybrid approach has been proposed, with retrograde stent graft occlusion of the arch and extra-anatomic bypass of the head and neck vessels, it appears that the frozen elephant trunk is a practical, efficacious and more physiological approach to extensive thoracic aneurysms, commendably combining the advantages of open aortic surgery and endovascular

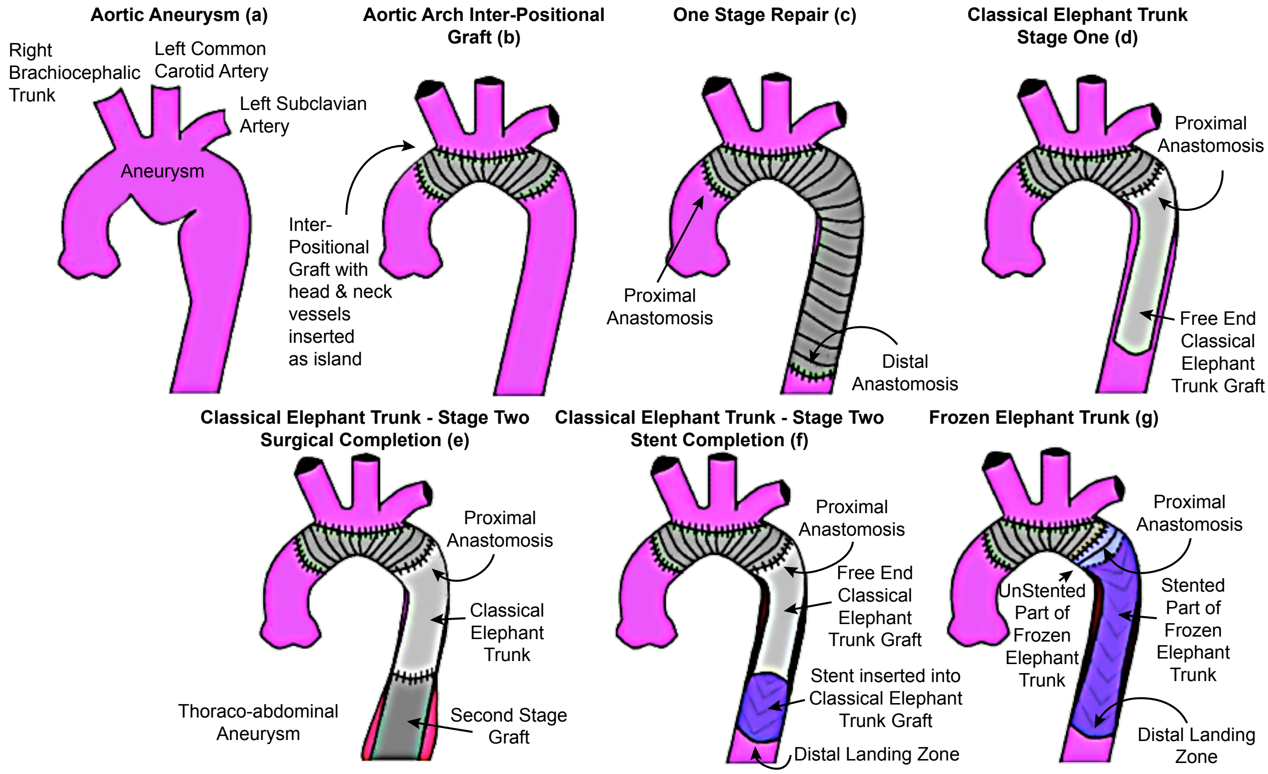

Figure 1. Graphical representation of different techniques for repair of extended thoracic aneurysms.

techniques. As a result, the evolution of treatment for extensive thoracic aneurysms appears to have moved away from the extensive initial single-stage and, more recently, two-stage procedures (elephant trunk), back to single-stage (frozen elephant trunk) with the adjunct of endovascular techniques (Figure 2).

Frozen elephant trunk: technical points and practical considerations

The surgical technique of the frozen elephant trunk involves median sternotomy and establishment of cardiopulmonary bypass with arterial cannulation to the axillary artery (and sometimes femoral or central cannulation depending on the pathology), followed by hypothermic arrest and selective cerebral perfusion. The aorta is then transected just distally to the left subclavian artery and the lumen of the diseased descending aorta is appropriately sized for the antegrade placement of the stent graft. Implantation of the stented portion of the prosthesis is performed through a super-stiff guidewire. Following a few reported cases of aortic perforation due to anatomical variability and friable aortic wall, some groups have used a through-and-through transfemoral technique.[9] The stent is then dilated with appropriate balloon catheters and the tubular portion of the graft sutured circumferentially on the descending aorta. Often, the invaginated component of the non-stented endograft is pulled back and appropriately trimmed for re-implantation of the head and neck vessels, or it is anastomosed directly to another graft that has been used for ascending aortic and/or arch reconstruction.

Certain practical aspects of the procedure will need to be considered for safe and effective implantation of the endograft. Its size should match the size of the aorta just distally to the left subclavian artery in cases of aneurysms and the diameter of the true lumen (and not the whole circumference of the aorta) in cases of dissection. In cases of dissection it is imperative to delineate the perfusion of vital organs through the true or false lumen because their inappropriate exclusion could lead to catastrophic complications.

Current practice regarding the distal landing zone of the stented portion of the frozen elephant trunk dictates placement at the level of T8.[10] Extensive exclusion of the intercostal arteries during stent graft

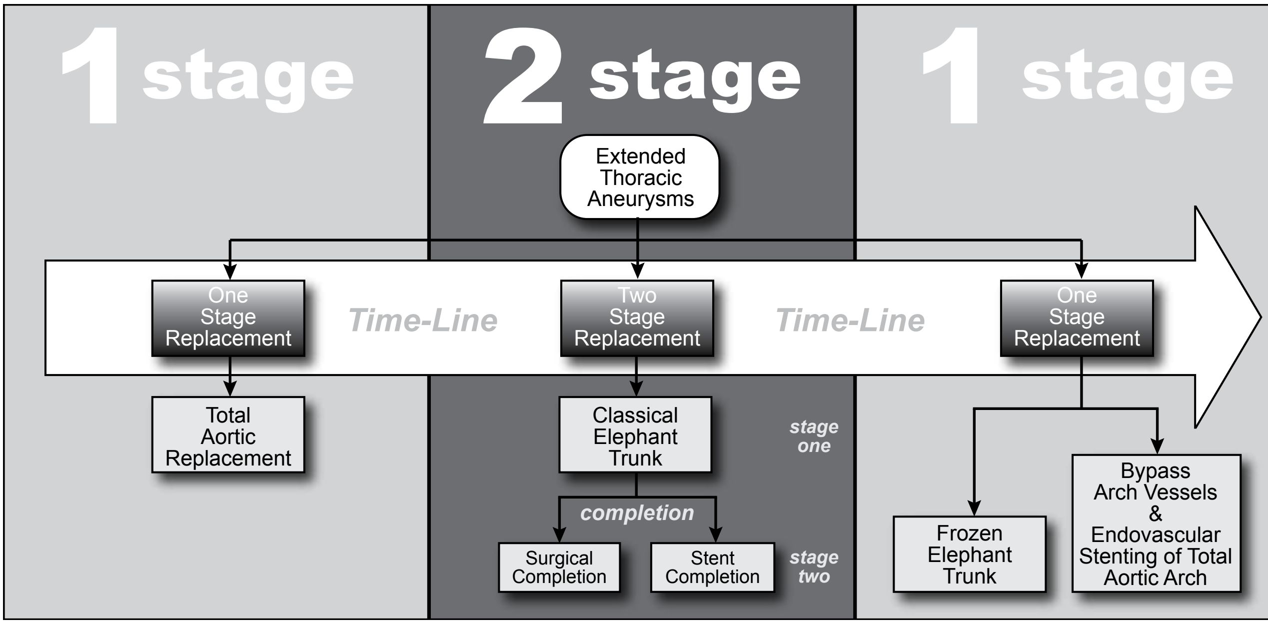

Figure 2. Evolution of the surgical repair of extended thoracic aneurysms.

placement has been implicated in spinal cord ischaemia.[11] This can be more apparent when graft placement extends beyond the level of T9, after which the artery of Adamkiewicz enters the vertebral canal in the majority of patients.[12] Distal placement beyond T8 is also further complicated by the inability of transoesopahgeal echocardiography to delineate the exact positioning and the possibility of graft kinking.[10] A limitation of most commercially available stent grafts is that their length ranges between 15-16 cm. This may be sufficient for the majority of patients; however, in cases of smaller patients a custom-made stent should be considered to avoid extensive deployment into the descending aorta. Another potential limitation of some commercially available hybrid prostheses is that the size of the stented portion is similar to that of the graft tube for the arch anastomosis;[13] this could have technical implications when there is a mismatch between the arch and descending aorta due to variability in the disease process.

Finally, it has to be highlighted that the frozen elephant trunk technique requires the specialist skills of a dedicated operating theatre team that extend beyond the operating surgeon and the assistant. The interventional radiologist is an integral part of the multidisciplinary team responsible for the preoperative assessment of patients with complex aortic disease. Furthermore, the important step of optimal spinal cord and cerebral protection is greatly dependent on the anaesthetist and perfusionist, as well as the synchronisation of the scrub and the responsible circulating nurses. The assistance of a vascular surgeon should also be readily available, especially when abdominal intervention is indicated due to organ malperfusion following graft exclusion of the aortic dissection. The need for a hybrid operating room with fluoroscopic facilities is desirable but not necessary, since the correct positioning of the antegrade stent graft is routinely performed with real time transoesophageal echocardiographic guidance and in the unlikely event of further endovascular intervention this can be performed at a later stage.

Outcomes of the frozen elephant trunk

Studies examining results of the frozen elephant trunk technique are shown in Table 1. Both early and late outcomes should be interpreted cautiously, in the context of the overall cohort size, different underlying aortic pathology and urgency of the procedure. For instance, in the recent study by Pochettino and colleagues 30-day mortality was apparently high at 14%; however, the indication for surgery was acute type A dissection, where outcomes are similar to those for conventional repair without the potential added benefit of managing the downstream aorta.[14] Within the same methodological constraints in cohort heterogeneity, it is apparent that higher volume units pro-

Table 1. Studies examining outcomes of the frozen elephant trunk.

Author, year	N	Age	Indication	Follow-up	Early mortality	Early morbidity	Late morbidity	Late survival
Orihashi, 2001[31]	15	65.8	80% AA, 20% type B AD	16 months	6.7%	7% neurological deficit	7% endoleak	86.6%
Kato, 2002[25]	19	59.7	Type A AD	2.4 years	5.3%	11% neurological deficit, 11% renal failure, 16% mediastinitis	11% reoperation (seroma and additional stent graft)	82.6% at 3 years (actuarial)
Karck, 2005[32]	22	62	50% type A AD, 18% type B AD, 32% AA	14 months	4.5%	18% neurological deficit, 9% vocal cord paralysis	9% endoleak	100% at 14 months
Flores, 2006[11]	25	73	52% arch (±descending) AA, 48% descending AA	35 months	12%	24% SCI, 16% stroke, 8% vocal cord paralysis	-	70% at 2 years (actuarial)
Liu, 2006[18]	60	53	60% acute type A AD, 40% chronic type A AD	6 months	3.3%	5% stroke, 15% neurological deficit, 5% re-exploration for bleeding	-	100%
Baraki, 2007[9]	39	62	46% AA, 54% AD	22 months	12.8%	12.8% neurological deficit 12.8% re-exploration for bleeding 12.8% vocal cord paralysis	6% endoleak	87%
Shimamura, 2008[10]	126	67.8	33% type A AD, 13% type B AD, 55% AA	60.4 months	5.5%	5.6% stroke, 6.3% SCI, 2.4% re-exploration for bleeding, 4.8% renal failure	3.9% endoleak	63.3% at 5 years (actuarial)
Di Bartolomeo, 2009[33]	34	61.7	56% type A AD, 24% type B AD, 21% AA	8.6 months	6%	12% re-exploration for bleeding 9% SCI, 15% renal failure, 12% pulmonary insufficiency	3% rupture during repair of abdominal aneurysm	90% at 12 months (actuarial)
Tsagakis, 2009[21]	41	60	85% AD, 15% AA	17 months	7%	7% bleeding, 12% neurological insufficiency (7% stroke), 2% renal failure (permanent)	9% endoleak	87%
Usui, 2009[17,34]	24	71	92% AA, 4% AD, 4% penetrating ulcer	85 months	0%	5% stroke, 12.5% spinal cord injury	42% endoleak	68.6% at 5 years
Pochettino, 2009[35]	36	59	All type A AD (acute DeBakey I)	15.9 months	14%	3% stroke, 9% SCI, 17% renal failure, 8% ischaemic bowel	26% downstream endovascular intervention	100%
Tsagakis, 2010[16]	106	57	91% DeBakey I, 9% DeBakey III (involving the arch)	20 months	12%	5% stroke, 3% SCI, 19% re-exploration for bleeding	10% downstream endovascular intervention	88% at 2 years (actuarial)
Gorlitzer, 2010[27]	14	49	All type A AD (24% acute)	21.4 months	0%	14% neurological deficit	-	100%
Uchida, 2010[15]	156	67.9	42% acute type A AD, 17% acute type B AD, 5% chronic type B AD, 36% AA	63.3	3.8%	2.6% stroke, 2% SCI, 2.6% re-exploration for bleeding, 5.1% renal failure, 2.6% mediastinitis	9.4% additional aortic procedure, 1.3% endoleak	80.7% at 8 years

AD – aortic dissection; AA – aortic aneurysm; SCI – spinal cord injury.

duce more favourable outcomes, as seen in the work by Shimamura and Uchida et al.[10,15] It is noteworthy that the observed 12% early mortality in the large cohort of 106 patients with complex aortic dissection in the work by Tsagakis and colleagues is not a single-centre experience, but that of 5 units that fed into the commercial stent graft registry.[16] The combined early morbidity of stroke and spinal cord injury has an incidence between 9% and 16%. Once again, differences in cerebral and spinal cord protection protocols may account for some of the variability in neurological outcomes between studies.

The most common procedural cause of late morbidity appears to be different types of endoleaks. In most cases the incidence was less than 10%. However, in the report by Usui and colleagues[17] endoleak occurred in 10 out of 24 patients (42%) where a custom-made stent graft was utilised. A subsequent technical modification with anchoring of the graft to the native aorta prevented stent migration and graft kinking, and the development of subsequent endoleak.

The effect of the frozen elephant trunk on false lumen thrombosis in dissections, as well as on the rate of regression of aneurysms, is difficult to delineate within the large spectrum of acute and urgent pathologies, their different anatomical location, the different types of endoprostheses used and variable CT imaging follow up. In the multi-centre report by Tsagakis and colleagues, 97% of patients with acute dissection and 89% of those with chronic dissection had full thrombosis of their false lumen within the follow up of 20 months.[16] This is similar to the report of Liu and colleagues, with false lumen thrombus obliteration in 92% and 85%, respectively.[18] With respect to arteriosclerotic aneurysms, application of the frozen elephant trunk caused a reduction in size in 68% of patients and complete obliteration in 18%.[19] It had no effect, however, in 12%, whereas in 2% of patients aneurysms increased in size.

Although the main objective of the frozen elephant trunk is to address the complex aortic pathology in a single-stage procedure, there are limited cases where disease progression may necessitate re-intervention in the distal thoracic and abdominal aorta following previous frozen elephant trunk. In a small case series by Pichlmaier and colleagues, technical considerations and clinical outcomes were assessed in 6 frozen elephant trunk patients who required reoperation for progressive distal aneurysms and dissections.[20] Endovascular stenting was performed in cases where the celiac axis was not involved and open replacement was reserved for more extensive thoraco-abdominal pathology. It appears that proximal clamping of the stented aorta does not distort the fixed hybrid stent and that the anastomosis of the new tube graft onto the stent graft is feasible and safe.

Discussion

The development of the frozen elephant trunk technique was led, to a great extent, by the efficacy of the open elephant trunk and the concomitant evolution of modern endovascular techniques. It comes as a more practical and, potentially, safer alternative to extensive single-stage procedures and two-stage procedures involving either an open or endovascular completion stage.

The main indication for the frozen elephant trunk involves aneurysms proximal and distal to the left subclavian artery. It can be utilised in type B dissections as well as type A dissections extending to the descending thoracic aorta. There have been reports of frozen elephant trunk in acute type A dissections with satisfactory results.[9,10,15,21-27] However, conventional practice, with standard ascending aortic replacement leading to exclusion of the entry point of the dissection, has proven to be efficacious in terms of early and long-term survival, while the need for intervention in the descending aorta remains very low.[28] Whether the addition of a frozen elephant trunk in the management of acute type A dissection is superior to isolated ascending aortic surgery could only be determined through appropriately designed controlled studies and currently remains an area of debate.

One of the potential advantages of the frozen elephant trunk is that the use of the stented graft in the descending aorta expedites thrombus formation, whereas in the conventional elephant trunk there is residual perfusion in the perigraft space, leading to delayed thrombus formation and progressive aneurysmal dilatation.[29] It has also been reported that the flapping action of the downstream portion of the elephant trunk may be responsible for peripheral embolisation.[30]

It is evident from the published reports that operative and early mortality rarely exceeds 12%. This appears more favourable compared to both stages of the conventional elephant trunk.[6] Moreover, the outcomes of the staged approach should not only be viewed as the cumulative operative mortality of the first and second procedure, but also include interval mortality, which in some series is in the region of 16%.[2] In an attempt to ameliorate morbidity associated with cardiopulmonary bypass and deep hypothermic arrest and surgical trauma due to extensive dissection and manipulation of the aorta, several groups have postulated endovascular treatment of the arch after debranching and extra-anatomic bypass of the head and neck vessels.[6] This staged approach has been used with early success in limited cases; however, it does not offer a complete reconstruction of the diseased aorta, which often involves its ascending portion, and data on flow and long-term patency of the bypass grafts are still sparse.

In conclusion, the therapeutic approach to the management of extensive aortic disease has evolved, from complex and traumatic single-stage surgery followed by improved two-stage procedures (that sometimes involve endovascular completion), to the "frozen elephant trunk", which effectively combines endovascular technology with open surgery. The innovation behind this hybrid approach in the management of complex aortic disease runs alongside other aspects of cardiovascular pathology, such as aortic valve disease (transcatheter implantation) and heart failure (Impella pump). It is imperative for cardiovascular physicians and surgeons to continue to work collaboratively, drive and implement technology and innovation, and, ultimately, provide patients with safer and more effective treatments.

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