Elephant trunks in aortic surgery: Fresh and frozen

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Aneurysmal diseases are often silent but can cause potentially life-threatening complications in cases of dissection or rupture. Surgical strategies depend on the involved part of the aorta and frequently require extracorporeal circulation and circulatory arrest. From data available from the Centers for Disease Control and Prevention, aneurysm disease is the 18th most common cause of death in all individuals, and the incidence is certain to increase as our population ages. This article discusses different treatment options introduced in the past few decades to address multifocal pathologic conditions of the thoracic aorta. These include the conventional elephant trunk procedure introduced by Hans Borst in 1983, with several modifications, and also hybrid procedures combining open surgical and endovascular techniques: the so-called frozen elephant trunk. Advantages and drawbacks of both techniques will be discussed based on personal and practical perspectives, with specific mention of the elephant trunk procedure in acute aortic dissections. (J Thorac Cardiovasc Surg 2013;145:S98-102)

Originally, physiology focused primarily on human beings, in large part from a desire to improve medical practice. When physiologists first began comparing different species, they sometimes were motivated by simple curiosity but also by a desire to discover basic physiologic principles. The use of model organisms to study specific questions is known as the Krogh principle in honor of the famous Danish physiologist August Krogh. Krogh felt certain that a number of animals were created for such special physiologic research purposes, was afraid that most of them were as yet undiscovered, and suggested that we should “apply to zoologists to find them so that we can lay our hands on them.” We would not be surprised if this twentieth century emphasis on the study of nature in search of solutions to specific medical challenges inspired Hans Borst and his colleagues Walterbusch, and Schaps 30 years ago to introduce the elephant trunk (ET) principle for the treatment of extended aortic diseases.

The acceptance of the ET principle is part of a general understanding that extensive aortic aneurysms that include different parts of the thoracic aorta require individualized therapies based on the extent of the disease, the underlying pathologic condition, and the general condition of the patient. From a technical perspective, the procedure requires us to optimize surgical access, to provide sufficient brain and lower body protection, and to control cardiopulmonary as well as hypothermic circulatory arrest times.

Nowadays, a number of different ET techniques are used, many of them still based on the principles initially described by Borst, Walterbusch, and Schaps in 1983. The purpose of this article is to give a detailed description of fresh insights and the further development of the frozen elephant trunk (FET) concept. Advantages and drawbacks of both approaches will be discussed critically. A specific section will debate the use of ET in acute type A aortic dissection.

THE CONVENTIONAL ELEPHANT TRUNK (CET) PROCEDURE

Before the first cadaver graft implantation in the abdominal aorta in 1951, techniques such as aortic ligation and aortic wrapping with cellophane were used to treat aortic aneurysms. The success of such heroic procedures was quite variable, and so extended aneurysms involving the ascending and the proximal descending aorta were generally considered untreatable. The introduction and subsequent advances in extracorporeal circulation, including the use of hypothermia and the invention of synthetic prostheses, permitted pioneering therapy of thoracic aortic aneurysms. Finally, the implementation of deep hypothermic circulatory arrest by Griep and colleagues improved the strategy, particularly with regard to neuroprotection, and relegated the earlier dismal results to the past.

Despite these tremendous milestones, it took another few years before Borst’s ET procedure became routine in some high-volume centers. Technically, the ET procedure requires the surgeon to invaginate the graft and suture its folded end to the transected aortic arch distal to the left subclavian artery. In the modification described by Crawford, Svensson, and their colleagues, the proximal portion of the graft is then retracted toward the arch and sutured to the head vessels in an island or branched fashion. The distal portion of the prosthesis remains dangling in the descending aorta, awaiting a second-stage operation or the insertion of an endovascular stent graft. For better identification during
a potential interventional second-stage procedure, clips are frequently used as markers at the end of the prosthesis.

The ET procedure offers the advantage of avoiding extensive dissection of scar tissue during the second operation, which may jeopardize the left recurrent laryngeal and vagus nerves, the esophagus, and even the pulmonary artery. Furthermore, clamping the graft distal to the left subclavian artery rather than in the arch facilitates the second stage in a CET repair and avoids periods of hypothermic circulatory arrest.

Further modifications include using suture lines at different levels proximal to the left subclavian artery. The advantage of an anastomosis placed in the ascending aorta at the base of the innominate artery, as published by Kuki, Taniguchi, and their associates, lies in a reduction of nerve injury and reduced complications owing to hemorrhage. This technical variation is frequently combined with the use of a branched prosthesis for redirecting the flow into the head vessels. In selected cases in which the descending aorta must be treated first, a reversed or bidirectional ET may facilitate the procedure, especially if second- and third-stage procedures for the arch and the thoracoabdominal aorta are necessary.

**THE FET PROCEDURE**

The idea of combining open arch surgery with aortic endovascular treatment to achieve a single-stage repair has initiated a number of inventions to treat multifocal thoracic aortic diseases. With the so-called open stent-grafting technique, various homemade or prefabricated stented or FET prostheses have been inserted into the downstream aorta. Some of these stents are commercially available, at least in Europe. Basically, these prostheses include a stented portion made of nitinol or stainless steel, sutured to a conventional tube graft. As in the original ET procedure, the device is deployed during a period of hypothermic circulatory arrest using a specific introducer. A stiff wire inserted via the femoral artery can be used to guide the prosthesis: this may be helpful especially in dissections to avoid cannulating the false lumen. In some chronic dissection cases, it seems reasonable to fenestrate the intimal membrane for a length corresponding to the ET prosthesis, leaving true and false lumina perfused, and thereby avoiding malperfusion of visceral arteries.

An accurate estimate of the optimal distal landing zone is sometimes not easy to achieve and is discussed in detail subsequently. When the stented portion is brought into the descending aorta, the graft proximal to the stent is circumferentially sutured to the completely transected aorta. In these cases, careful circumferential mobilization of the proximal descending aorta is necessary to permit a secure and watertight anastomosis because later hemostasis is usually not possible. Leaving the nonstented part invaginated within the stented portion facilitates the procedure further. Whereas initially the suture line was usually constructed distal to the left subclavian artery, more recently surgeons tend to a technically more feasible proximal location of the suture line as already performed in CET repairs. After completion of this anastomosis, different approaches used in CET procedures—such as the island technique or a branched anatomic or extra-anatomic approach to the arch vessels—can be chosen to complete the repair.

Whereas the graft segment of the CET is free-floating in the descending aorta awaiting thrombus formation, the stented part of the FET allows progressive thrombotic occlusion in the perigraft space inasmuch as the distal part of the stent acts effectively like a distal anastomosis. Therefore, a depressurization of the aneurysm reduces wall stress, possibly causing shrinkage of the aneurysm. The suture line in the aortic arch avoids endoleaks as well as migration of the stent, as occasionally seen in isolated aortic stent grafting. The sealing properties of the FET make its use especially appealing in aortic dissection, as discussed subsequently.

**LENGTH OF THE ET**

One of the controversies concerning the ET procedure (independent of whether fresh or frozen) is the question of the optimal length of the free-floating or stented part of the prosthesis in the descending aorta. In the ideal scenario, the graft should be selected so that the distal end of the ET is tightly positioned in the descending aorta to prevent retrograde flow into the perigraft space or flapping of the graft. Unfortunately, multifocal extensions of the aneurysms in conjunction with severe aortic kinking and calcifications may necessitate concessions. In contrast to Borst’s suggestions of 7 to 8 cm, a tendency toward the use of a longer prosthesis has been observed, with cautionary notes by some surgeons who have encountered a higher rate of spinal cord injury when extended grafts have been used. Overall, the incidence of spinal cord injury after FET procedures seems to be higher than expected. This may be due to extensive sacrifice of intercostal arteries jeopardizing collateral blood flow to the spinal cord, combined with imperfect protection during surgery. Therefore Minatoya and coworkers suggest perfusion of the left subclavian artery to provide at least
some blood flow during prolonged periods of hypothermic circulatory arrest. The drainage of cerebrospinal fluid has proven to be effective in experimental and clinical settings and may reduce the incidence of delayed paraplegia, which is sometimes observed in the first 2 days after surgery.\textsuperscript{28}

In the review by Ius and coworkers,\textsuperscript{23} the paraplegia rate in CET procedures was between 0\% and 8\% (mean, 2\%), with a high rate in those with long ET. In the case series of FET, the rate ranged between 0\% and 24\% (mean, 5.6\%), but 57\% of the latter were operated on for dissections, which have an intrinsic increased risk of spinal cord injury. Other risk factors for the occurrence of paraplegia have been identified and collected by Ius and colleagues\textsuperscript{23}: advanced patient age\textsuperscript{29}; a history of downstream aortic surgery\textsuperscript{30}; a distal landing zone below T7\textsuperscript{30}; and the presence of a fusiform aneurysm.\textsuperscript{31}

In addition to uncertainties relating to graft size, kinking, graft occlusion, intracavity thrombus formation, and peripheral embolic events are feared complications, especially when using the CET technique. Oversizing of a FET may cause rupture or dissection. The ultimate fate of the descending aorta at the distal end of a FET stent remains unclear.

**THE SECOND-STAGE PROCEDURE**

In planning the second stage of CET surgery, one must weigh an adequate recovery time after initial surgery against the risk of descending thoracic aortic rupture. The optimal interval depends on the underlying pathologic condition of the aorta, the general condition of the patient, and the extent of the planned procedure.\textsuperscript{32} Pulmonary function testing helps determine whether patients can tolerate a second surgical procedure or should preferably be treated with an endovascular graft. A reason for postponing a second stage may also be that the diameter of the descending or thoracoabdominal aorta poses only a small risk of dissection or rupture.

However, what are the indications for the second intervention? In their review, Ius and coworkers\textsuperscript{23} collected 1311 patients operated on for stage 1 of a CET because of true aneurysms or dissections. The in-hospital mortality for this procedure was 10\%. Only 45\% had second-stage surgery, with a daunting overall interval mortality of 9\%. Of 700 patients treated with a FET with a mortality rate of 6.4\%, 6\% had significant endoleaks. Stage 2 operations or interventions were mainly necessary owing to a growing diameter of the aorta distal to the repair, persisting perigraft perfusion, and/or late endoleaks. Inasmuch as both CET and FET techniques are associated with complications requiring further interventions, it is not completely justifiable to promote the FET as a reliable 1-stage procedure.

**ETS AND STANFORD TYPE A ACUTE AORTIC DISSECTION**

In contrast to elective surgery for aneurysms, a Stanford type A acute aortic dissection (AADA) is an emergency operation. The major goal of surgery is the prevention of intrapericardial rupture.\textsuperscript{33} This can be achieved in the majority of cases by replacing the ascending aorta, thereby excising the proximal entry tear. Further goals are the correction of diseases of the aortic root, the coronary ostia, and the distal aorta and elimination of distal malperfusion.\textsuperscript{34} In the following discussion, we focus on the question of what is the best treatment for the distal aorta.

Thus far, no randomized studies are available to answer the question whether a more aggressive approach toward replacement of the entire aortic arch is associated with an increased mortality.\textsuperscript{35} Furthermore, the effects of arch replacement on the need for eventual reoperation have also not been analyzed. Therefore, most of the available data are reports of (consecutive?) cases from centers with differing policies and strategies and experience with the treatment of AADA. Multicenter and registry data may also help in getting some idea concerning the best treatment strategy for the distal aorta.

In a recent publication, the German Registry for Acute Aortic Dissection Type A (GERAADA) focused on 658 patients with a type I DeBakey aortic dissection.\textsuperscript{36} Patients with hemiarch replacement were compared with those who underwent at least a total arch replacement (n = 140; 48 with a FET). The authors conclude that the more aggressive approach is not associated with a significantly higher perioperative risk, but they have no data beyond the 30-day-mortality. In 2008, Jakob and coworkers\textsuperscript{37} presented their experience with 45 type I DeBakey aortic dissections. Although patients with conventional surgery and those with FETs had the same outcomes up to 4 years, the presence of the stent reduced the size and rate of occurrence of a persistent false lumen. The group from the University of Pennsylvania published their experience in 78 patients: although no short-term differences were seen, there was a greater need for later reintervention in patients subjected to conventional repair.\textsuperscript{38} Uchida and coworkers\textsuperscript{39} also found that survival and event rate for the thoracic aorta were significantly lower using a FET than with a classic ascending/hemiarch repair.

Thus it seems—in the absence of randomized studies—that the stented ET technique does not increase operative mortality and morbidity despite higher cardiopulmonary bypass and hypothermic circulatory arrest times. However, a greater risk of spinal cord ischemia as well as malperfusion symptoms is a major drawback of this technique. Enhanced thrombosis of the false lumen and a lower reoperation rate, however, are likely advantages.\textsuperscript{40} Tsagakis and coworkers\textsuperscript{41} present the data from the International...
E-vita Open Registry: among 68 patients with AADA who underwent a complete arch repair with a hybrid stent graft prosthesis, initial complete or partial thrombosis along the stent was present in 86% at 1 year and 94% at 2 years. Complete or partial false lumen thrombosis distal to the stent increased from 61% to 82% during follow-up.

Appropriate sizing may be important in reducing complications associated with stent grafts. Hoffman and coworkers postulate that the risk of spinal cord injury can be reduced if complete obliteration of the false lumen is achieved by sizing the stent to the total diameter of the aorta, with a landing zone at the level of T10-12. In 32 patients, they had no 30-day mortality and no cerebral or spinal cord injury. This is in contrast to suggestions by others who advise sizing the stent graft to the true lumen and not extending the landing zone beyond T7.16,43

Close follow-up after AADA repair is mandatory, regardless of whether or not an ET is used.44 If distal aortic growth occurs and requires further aortic repair, this can be performed with a low mortality and morbidity in experienced centers.22,45-47

SUMMARY AND CONCLUSIONS

Today, ET procedures are used in a few classic situations: for the multifocal thoracic aortic aneurysm, the acute or chronic type A or sometimes even type B dissection, and for perforated aortic ulcer. Independent of the type of pathologic condition, the ET procedure offers the option of median sternotomy access in treating complex diseases. However, surgeons should be aware that even the FET is often not a single-stage procedure, with additional surgical or endovascular interventions required. This fact, as well as the significant interval mortality between stage 1 and 2 in CET repairs, supports the necessity of close ongoing surveillance of these patients.

Different technical modifications allow tailoring of both approaches on the basis of individual patient needs and specific anatomic conditions. In this context, preoperative planning is essential: 3-dimensional computed tomographic reconstructions are invaluable in devising optimal surgical strategies. During these often time-consuming operations, adequate protection of the brain and also other organs (such as the spinal cord, kidney, liver, and gut) are often decisive for the success of the procedure. Selective cerebral perfusion of the brain and in some instances the lower body may improve the outcome, especially when higher temperatures rather than profound hypothermia are used.

It seems that the stented part of the FET allows more rapid progressive thrombotic occlusion in the perigraft space, offering an advantage over the free-floating conventional unstented graft, especially in cases with extended aneurysms. Furthermore, complications such as kinking, occlusion of the graft, and thrombembolic events seem to be more frequent in patients undergoing a CET procedure. Finally, it seems reasonable to suppose that a FET provides a safer endovascular landing zone than its conventional counterpart: this is important inasmuch as the tendency toward endovascular approaches for stage 2 will further increase as more and more patients’ significant comorbidities are treated.

There is evidence that the FET in chronic aortic dissection may reduce reoperations by causing thrombosis of the false lumen, but ischemic spinal cord injury remains a concerning complication. The impact of stent-graft sizing and the optimal landing zone remain unclear. Moreover, a careful evaluation of the thoracoabdominal aorta is required if visceral arteries arise from the false lumen.

In AADA, the optimal treatment of the distal aortic arch and the proximal descending aorta remain controversial. From the data published thus far, it seems justifiable to implant a FET in type I DeBakey dissections in centers with an expertise in the treatment of aortic diseases, but it should be borne in mind that patients receiving only a partial replacement of the aorta can undergo reoperation on the distal aorta if further enlargement occurs with an acceptable mortality and morbidity. Close surveillance and optimal medical therapy are mandatory. Improved surgical techniques in end-organ protection and generally better outcomes in the treatment of patients with AADA may allow more frequent use of the FET in years to come.

References
Panel 2

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