Progress of the treatment for extended aortic aneurysms; is the frozen elephant trunk technique the next standard in the treatment of complex aortic disease including the arch?

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Received 18 October 2007; received in revised form 11 February 2008; accepted 14 February 2008; Available online 10 April 2008

Summary

Patients with extensive aortic aneurysms involving the ascending aorta, aortic arch, and the descending aorta are still considered to be a challenge for many cardiovascular surgeons. The introduction of the elephant trunk technique by Borst et al. in 1983 has greatly facilitated surgery on this kind of pathology and this technique has been recognized as a standard modality for treatment of extended aortic aneurysms. As a next step, the frozen elephant trunk technique has been introduced in some institutes in the late 1990s. With this technique, surgery is performed through a median sternotomy, and an endovascular stent-graft is placed into the descending aorta in an antegrade fashion through the opened aortic arch. Then the ascending aorta and the aortic arch are replaced conventionally. The frozen elephant trunk technique enables one-stage repair of extended aortic aneurysms in a certain patient cohort with similar operative mortality as with the conventional elephant trunk technique, in which a second-stage operation is a prerequisite. Although the surgical strategy should be adjusted specifically to each patient's individual pathology, the frozen elephant trunk technique may become the next standard treatment for extended aortic aneurysm instead of its conventional variant.

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Keywords: Frozen elephant trunk; Extended thoracic aneurysms; Endovascular stent-graft

1. Introduction

Patients with extensive aortic aneurysms involving the ascending aorta, aortic arch, and the descending aorta are still considered to be a challenge for many cardiovascular surgeons. The relatively proximal segment of the descending aorta (the proximal 1/3 of the descending aorta) can be operated on the median sternotomy, but this one-stage approach is often difficult because of poor and limited operative access combined with an increased risk of bleeding from distant sites [1]. Therefore, many surgeons have preferred a two-stage approach to treat the combined lesions of the aortic arch and the descending aorta, especially when the extent of the aneurysms is beyond the proximal 1/3 of the descending aorta. The introduction of the elephant trunk technique by Borst et al. [2] in 1983 has greatly facilitated surgery on this kind of pathology and this technique has been recognized as the standard modality for treatment of extended aortic aneurysms. The procedure involves the prosthetic replacement of the ascending aorta and the aortic arch with an elephant trunk extension of the arch graft into the descending aorta through a median sternotomy. In a second-stage operation, the elephant trunk can be extended to the desired level through a lateral thoracotomy. However, a well-known disadvantage of this staged approach is that a cumulative mortality, which includes in-hospital mortality for the two procedures and death (commonly from aortic rupture) in the interval between them, is not low [3–5]. To reduce the cumulative risks of the staged approach, some surgeons have preferred a single-stage repair of extensive aortic aneurysms with a clamshell incision [6], a left lateral thoracotomy [7], or combination with a median sternotomy and a left lateral thoracotomy [8]. However, this strategy has been followed in a few institutes only because of its technical difficulties and too much invasiveness.

Since the introduction of endovascular stent-graft technology for thoracic aortic aneurysms by Dake et al. [9] in 1998, it has been considered as an alternative treatment modality for thoracic aortic aneurysms that may be associated with reduced mortality and morbidity. However, repair of the aortic arch only with an endovascular stent-graft is not possible because of the supra-aortic vessels (except for a few experimental approaches). As a next step of the progression in the treatment of extensive aortic
aneurysms, the frozen elephant trunk technique has been introduced [10,11]. In this technique, the operation is performed with a median sternotomy, and an endovascular stent-graft is placed into the descending aorta in an antegrade fashion through the opened aortic arch. Then, the ascending aorta and the aortic arch are replaced conventionally. This technique has a combination of advantages of surgical and interventional approaches, and therefore appears to be promising. However, we know from our own experiences that this technique has some limitations.

The purpose of this review is to summarize the clinical data available in the field of the treatment of extended aortic diseases. Current techniques will be described, and advantages and limitations of each technique will be discussed. To that extent, an extensive literature search was conducted through ‘Pub-Med’ and ‘EMBASE’ using several main key word combinations, including aortic surgery, ascending aorta, aortic arch, descending aorta, elephant trunk, frozen elephant trunk, endovascular stent-graft, single-stage approach, two-stage approach, and more. The search was conducted as far back as 1970 and as recently as July 2007.

2. The conventional elephant trunk technique

The basic principle of the conventional elephant trunk resides in the protraction of a length of tubing into the down stream aorta distal to the actual graft to aortic anastomosis at the level of the left subclavian artery [2]. In the subsequent operation performed through lateral thoracotomy, the graft segment in the descending aorta may be used for further replacing the diseased vessel. More importantly, the difficult and often dangerous dissection of the original distal graft to aortic anastomosis is avoided.

After earlier publications from Borst and co-workers [2,12] and Crawford’s landmark paper published in 1990 [13], this method became more and more popular for treating patients with complex aortic disease [3—5,12,14—24]. Today, the elephant trunk operation is employed in the two classic conditions: aneurysms and chronic dissection of (1) the aortic arch and (2) the descending thoracic aorta involving the respective downstream portions of the vessel. It may also be chosen for selected patients with acute dissection [14,18]. One of the advantages of this technique is that it can be also performed in patients with an extensive aortic aneurysm extending into the thoracoabdominal aorta [3,4,5,12,17].

Meanwhile, several modifications of the original technique have been reported. Coselli and Oberwalder [21] introduced the reversed elephant trunk technique, while Carrel et al. [22,23] described a bidirectional variant for the replacement of the descending aorta, thereby facilitating second- and third-stage procedures for the replacement of the aortic arch and the thoracoabdominal aorta. To avoid increased tension on the suture line distal to the left subclavian artery and to obtain complete hemostasis, further modifications have been prompted by preparing this anastomosis at an upstream and less dilated aortic level. Thus, Svensson et al. have suggested placing the anastomosis in the aortic arch between the left carotid artery and the left subclavian artery [24]. Another, even more radical approach in this regard was published by Kuki et al. [15], who reported a series of 17 patients in whom the elephant trunk anastomosis was made at the base of the innominate artery. While the length of the elephant trunk depends on the extent of the downstream aortic enlargement and should be at least 7—8 cm according to Borst’s original suggestion, the technical modification described by Kuki et al. requires a length of about 15 cm. Here may reside a potential problem of this variant, because a long elephant trunk is more likely to cause complications due to kinking and graft occlusion. This suspicion is supported by Crawford’s finding that there are increased risks of peripheral embolization caused by a flapping action of the elephant trunk and paraplegia as a result of clot formation around the graft, if the trunk is too long [13].

Beside those technical modifications, the main concern with regard to staged repair of extensive thoracic aortic aneurysms using the conventional elephant trunk operation resides in the fact that the risks of two major surgical procedures and the risk during the time interval between the two interventions add up cumulatively. Publications reported on the initial elephant trunk operation with or without secondary staged operation are summarized in Table 1.

Table 1
Surgical series of conventional elephant trunk technique

<table>
<thead>
<tr>
<th>Author</th>
<th>Year</th>
<th>Mortality at first-stage ET</th>
<th>Patients underwent second-stage operation</th>
<th>Mortality at second-stage operation</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Safi et al.</td>
<td>2007</td>
<td>16/254 (6.3%)</td>
<td>115/254 (45.3%)</td>
<td>11/115 (9.6%)</td>
<td>[3]</td>
</tr>
<tr>
<td>Coselli et al.</td>
<td>2006</td>
<td>18/148 (12.2%)</td>
<td>76/148 (51.4%)</td>
<td>3/76 (3.9%)</td>
<td>[4]</td>
</tr>
<tr>
<td>Svensson et al.</td>
<td>2005</td>
<td>2/94 (2.1%)</td>
<td>47/94 (50%)</td>
<td>4/47 (8.5%) including 7 pts.</td>
<td>[5]</td>
</tr>
<tr>
<td>Hanafusa et al.*</td>
<td>2002</td>
<td>1/12 (8.3%)</td>
<td>0</td>
<td>0/9 (0%)</td>
<td>[14]</td>
</tr>
<tr>
<td>Kuki et al.</td>
<td>2002</td>
<td>0/17 (0%)</td>
<td>1/17 (52.9%)</td>
<td>0/9 (0%)</td>
<td>[15]</td>
</tr>
<tr>
<td>Takahara et al.</td>
<td>2002</td>
<td>3/37 (8.1%)</td>
<td>0</td>
<td>0/9 (0%)</td>
<td>[16]</td>
</tr>
<tr>
<td>Schepens et al.</td>
<td>2002</td>
<td>8/100 (8%)</td>
<td>44/100 (44%)</td>
<td>NA</td>
<td>[17]</td>
</tr>
<tr>
<td>Kiriki et al.</td>
<td>2002</td>
<td>9/28 (32.1%)</td>
<td>6/28 (66.7%)</td>
<td>2/6 (33.3%)</td>
<td>[21]</td>
</tr>
<tr>
<td>Naka et al.</td>
<td>1999</td>
<td>1/9 (11.1%)</td>
<td>6/9 (66.7%)</td>
<td>2/6 (33.3%)</td>
<td>[22]</td>
</tr>
<tr>
<td>Ando et al.</td>
<td>1998</td>
<td>2/15 (13.3%)</td>
<td>0</td>
<td>NA</td>
<td>[23]</td>
</tr>
<tr>
<td>Heinemann, Borst et al.</td>
<td>1995</td>
<td>10/72 (13.9%)</td>
<td>24/72 (33.3%)</td>
<td>NA</td>
<td>[12]</td>
</tr>
</tbody>
</table>

Total: 70/786 (8.9%) 321/694 (46.3%) 20/268 (7.7%)

* Ten patients with acute type A dissection, two with chronic type A dissection.

b All patients with acute type A dissection.
The summarized early mortality is 8.9% after the first stage operation and 7.7% after the second-stage operation. Because the elephant trunk procedure is performed sometimes for prophylactic purpose as in acute aortic dissection type A, it is difficult to analyze the interval mortality of patients who did not return for the second-stage operation from this summary. However, Safi et al. reported recently that the interval mortality was 16% (7/45 pts.) in their series [3]. This fact indicates clearly the limitations of a staged approach.

3. The first-stage elephant trunk procedure + endovascular completion

The idea of using an elephant trunk prosthesis as a stent-graft, introduced in the descending aorta, was born and popularised by Buffolo’s group [25,26], who employed this approach in a large series of patients with acute type B dissection. Along with the advent of transfemoral stent-grafts for the treatment of descending aortic aneurysms, it became possible to securely anchor a stent-graft in an elephant trunk prosthesis previously placed during arch surgery [9]. Published series of endovascular completion after previous elephant trunk procedure are summarized in Table 2 [27—30]. Although this cohort is relatively small, the procedural results seem to be promising with a low risk for paraplegia. If the anatomical condition is suitable for an endovascular procedure, in other words, if the distal landing zone could be secured, this endovascular completion may be an alternative to conventional second-stage operation.

4. One-stage extensive aortic replacement

To accomplish extensive aortic replacement with a one-stage approach, some operative methods have been devised as following: (1) through a median sternotomy [31], (2) with a median sternotomy + lateral thoracotomy or thoracoabdominal incision [8,32], (3) through a lateral thoracotomy [7], and (4) with a bilateral anterior thoracotomy (clamshell incision) [34—36]. Despite acceptable early results from those reports, this one-stage approach appears not to be widespread. It may be because of complexity and/or too much invasiveness of this approach. The summarized mortality of this one-stage repair is 8.9% as shown in Table 3 [7,8,32,34—36]. However, some variants are listed in this table, each of them with a limited number of patients. Available data indicate that one-stage repair of extensive aortic disease is a complex surgical alternative, and accumulation of a larger number of patients is mandatory for further evaluation.

5. The frozen elephant trunk technique

Another way to achieve one-stage repair of extensive aortic disease via median sternotomy evolved in a hybrid procedure combining the concepts of the elephant trunk principle and endovascular stenting of descending aortic aneurysms. It was introduced in the late 1990s as the ‘open stent-grafting’ technique [37,38] and the technique has been improved with the terminology ‘frozen elephant trunk’ [10]. With this approach, a repair of the aortic arch is performed conventionally through a median sternotomy with hypothermic circulatory arrest and antegrade cerebral perfusion. Repair of the descending aorta is performed simultaneously using a home made endovascular stent-graft. The endograft consists of a woven vascular prosthesis with stainless steel stents affixed to the inner aspects at its distal end. The proximal portion of the hybrid prosthesis is non-stented and consists of a Dacron sleeve for conventional surgical handling. The distal landing site of the stent-graft is at or above the proximal half of the descending aorta, and the non-stented Dacron graft segment is sutured circumferentially to the aorta distal to the origin of the left subclavian artery [10]. Whereas the graft segment forming through the conventional elephant trunk is floating freely in the descending aortic lumen thereby impeding thrombus formation between the graft and the aneurysmal vessel wall, the frozen elephant trunk technique allows for progressive thrombus formation in the perigraft space in the descending aorta up to the level of the stent. Thrombotic occlusion of this space is a prerequisite for reduction of wall stress of the aneurysmal vessel.
of postoperative paraplegia [43]. They reported that 3.3%, Flores et al., however, reported a relatively high rate of postoperative paraplegia [43]. They reported that ischemic spinal cord injury was evident in six (24%) patients who experienced lower limb paraparesis or ischemic spinal cord injury was evident in six (24%) patients who experienced lower limb paraparesis or ischemic spinal cord injury was evident in six (24%) patients who experienced lower limb paraparesis or ischemic spinal cord injury was evident in six (24%) patients who experienced lower limb paraparesis or ischemic spinal cord injury was evident in six (24%) patients who experienced lower limb paraparesis or ischemic spinal cord injury was evident in six (24%) patients who experienced lower limb paraparesis or ischemic spinal cord injury was evident in six (24%) patients who experienced lower limb paraparesis or ischemic spinal cord injury was evident in six (24%) patients who experienced lower limb paraparesis or ischemic spinal cord injury was evident in six (24%) patients who experienced lower limb paraparesis or.

effect may prevent subsequent growth of the aortic diameter. Initially, Suto et al. described a patient with an aneurysm of the distal aortic arch and the descending aorta which was replaced via median sternotomy during circulatory arrest by antegrade implantation of a Gianturco stent connected to a conventional vascular prosthesis [37]. Based on Buffalo’s earlier experience of non-stented elephant trunk insertion in patients with acute type B dissection [25,26] and Kato’s description of endovascular covered stent-grafting through median sternotomy [39], Usui et al. reported in 1999 a series of 12 patients who underwent implantation of a covered stent-graft for distal aortic arch aneurysm via median sternotomy under pigtail catheter guidance [38]. Thereafter, this technique has been continuously performed in some institutes with improving results.

### Table 4

<table>
<thead>
<tr>
<th>Author</th>
<th>Year</th>
<th>Mortality</th>
<th>Paraplegia</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baraki et al.</td>
<td>2007</td>
<td>5/39 (12.8%)</td>
<td>0/39 (0%)</td>
<td>[40]</td>
</tr>
<tr>
<td>Liu et al.</td>
<td>2006</td>
<td>2/60 (3.3%)</td>
<td>1/60 (1.6%)</td>
<td>[41]</td>
</tr>
<tr>
<td>Uchida et al.</td>
<td>2006</td>
<td>2/35 (5.7%)</td>
<td>0/35 (0%)</td>
<td>[42]</td>
</tr>
<tr>
<td>Flores et al.</td>
<td>2006</td>
<td>3/25 (12%)</td>
<td>4/25 (16%)</td>
<td>[43]</td>
</tr>
<tr>
<td>Usui et al.</td>
<td>2002</td>
<td>0/24 (0%)</td>
<td>1/24 (4.2%)</td>
<td>[44]</td>
</tr>
<tr>
<td>Mizuno et al.</td>
<td>2002</td>
<td>1/9 (11.1%)</td>
<td>0/0 (0%)</td>
<td>[45]</td>
</tr>
<tr>
<td>Fleck et al.</td>
<td>2002</td>
<td>1/8 (12.5%)</td>
<td>0/0 (0%)</td>
<td>[46]</td>
</tr>
<tr>
<td>Ohrashi et al.</td>
<td>2001</td>
<td>1/15 (6.7%)</td>
<td>1/15 (6.7%)</td>
<td>[47]</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>15/215 (7.0%)</td>
<td>7/215 (3.3%)</td>
<td></td>
</tr>
</tbody>
</table>

6. Review of the surgical series with the frozen elephant trunk technique

Meanwhile eight published series from groups using the frozen elephant trunk technique could be found in PubMed and EMBASE. Those eight series are summarized in Table 4 [40–47]. The average mortality in the analyzed series is 7.0%. This is considered to be acceptable in comparison with mortality of 8.9% after first-stage of the conventional elephant trunk procedure. The summarized rate of paraplegia after implantation of frozen elephant trunk is 3.3%, Flores et al., however, reported a relatively high rate of postoperative paraplegia [43]. They reported that ischemic spinal cord injury was evident in six (24%) patients who experienced lower limb paraparesis or monoparesis. There was a significant difference (p = 0.0043) regarding the mean value of the thoracic vertebral level, where the distal end of the frozen elephant trunk was deployed between those patients with (T8.0 ± 0.6) and without (T6.5 ± 1.1) spinal cord injury. Their findings are very important regarding the limitation of the frozen trunk technique. In our own series, no paraplegia was observed [40]. We consider the main reason for this difference may reside in the indication for implantation of a frozen elephant trunk, which was limited to patients with extended pathology of the first half of the descending aorta only. Furthermore, stent-graft fabrication was adjusted specifically to each patient’s individual pathology. On the other hand, distal malperfusion was not documented in any reports [40–47]. However, we consider that the use of the frozen elephant trunk would not be advisable when the lower extremity or visceral organs are perfused through the false lumen or the false lumen contains substantial thrombus in cases of chronic aortic dissection. Endoleak was seen in two patients in our series as previously described [40].

One patient with chronic aortic dissection exhibited a small endoleak into the false lumen at the origin of the left subclavian artery. The patient refused a reintervention. In the other patient with chronic aortic dissection type A, the stented segment of the graft could not be anchored successfully in a previous implanted thoracoabdominal aortic stent-graft, giving rise to a distal endoleak, which was treated 2 weeks later by transfemoral endograft-implantation. An endoleak appears to be treatable by additional endograft implantation, but it should be adjusted specifically to each patient’s individual pathology. Hybrid endografts for implantation as a frozen elephant trunk are commercially available. Even though we did not find any accidents due to the use of ‘home made’ prosthesis in our literature search, the same reluctance is advisable as with any kind of other ‘home made’ medical implants and should be applied in this context, too. Although this technique may require more costs than the conventional stage one elephant trunk operation, we believe that the frozen elephant trunk technique can improve surgical results in the treatment of complex aortic disease including the arch and downstream. When compared to the completed two-stage elephant trunk procedure, it may even reduce costs.

7. Practical comment

From a personal and practical perspective after 50 procedures, the seven keys to successful implantation of a hybrid prosthesis are as follows:

1. Careful mobilization at the dorsal circumference of the aortic arch prior to induction of circulatory arrest or shortly thereafter allows for identification of the course of the recurrent laryngeal nerve as a prerequisite for its protection in most instances.
2. Stable positioning of the tips of the perfusion cannulae for selective antegrade cerebral perfusion in the ostia of the brachiocephalic artery and the left common carotid artery avoids delay caused by their occasional incidental dislocation while working in the depth of the operating field.
3. During selective antegrade cerebral perfusion temporary occlusion of the left subclavian artery by a balloon catheter or by use of a clamp prevents disturbing backflow while suturing the circumferential distal anastomosis between the hybrid endograft and the proximal descending aorta.
4. Sufficient circumferential mobilization of the proximal descending aorta facilitates secure deployment and subsequent suturing of the graft. It is imperative to mobilize the adventitia of the false lumen in patients with aortic dissection to an extent that allows for subsequent tension free adaptation of the three ‘layers’ adventitia, dissection membrane and hybrid graft.
5. The diameter of the hybrid graft should match precisely the diameter of the aorta distal of the left subclavian artery. In case of dissection this applies to the diameter of the true lumen and not the dissected aorta as a whole. Deployment of an oversized graft may cause harmful tears in the aortic wall prior to the actual suturing.

6. It is much easier to implant the hybrid prosthesis into the descending aorta with the non-stented segment still invaginated in the stented segment, because the circumferential edge created by invagination allows for facilitated suturing and handling.

7. The circumferential anastomoses for fixation of the graft in the descending aorta distal to the left subclavian artery and for reimplantation of the supra-aortic branches must be completely hemostatic in the first place. It is advisable to use a strip of Teflon felt to reinforce the suture lines. Additional sealing with biological glues should be considered.

8. Bypass of the supra-aortic vessels + endovascular stenting of the total aortic arch

Recently, several reports on a technique combining the implantation of an extra-anatomic bypass to the supra-aortic vessels with endovascular stenting of the aortic arch have been published. The results are listed in Table 5 [48—53]. This novel modality might reduce operative mortality and morbidity including major stroke. At present, the summarized mortality is 11.1%, which is not less than calculated after the conventional or frozen elephant trunk technique. Moreover, the aortic root and the ascending aorta cannot be treated with this method. So far this technique might become a meaningful alternative after further technical evolution. At present the indication of this method should be strongly limited to otherwise inoperable patients.

9. Conclusion

Several methods for treatment of extended aortic aneurysms are reviewed in this article. In comparison with the conventional elephant trunk technique, the frozen elephant trunk technique appears to be advisable because (1) operative mortality is almost same in both methods, (2) one-stage repair is possible with the frozen elephant trunk in patients with an aneurysm involving up to the first half of the descending aorta, (3) the distal end of the frozen elephant trunk offers a secure landing zone for additional endovascular treatment, if needed, and (4) second-stage operation is also possible in patients with an extended thoracoabdominal aneurysm. Other one-stage approaches with diverse incisions may also be an alternative for treatment of extended aortic aneurysms. However, the frozen elephant trunk technique seems advantageous because it can be performed through median sternotomy, which enables all simultaneous manipulations on the heart without limitation. The hybrid approach combining bypass of the supra-aortic vessels and endovascular stenting of total arch has higher mortality than speculated and it seems as yet to be experimental.

The issue of the acute type A aortic dissection should be discussed separately. Although there have been many reports on favorable results of total arch replacement with or without elephant trunk procedure [14,18,54—56], it is still controversial [57—59]. Rampoldi et al. demonstrated in their large multi-center analysis involving 682 patients with acute type A aortic dissection that the partial arch replacement was associated with reduced mortality [57]. Shiono et al. analyzed a total of 134 consecutive patients with type A dissection operated as hemiarch replacement (n = 105) and total arch replacement (n = 29), and found that there were no differences of late survival and freedom from reoperation between the groups. When a false lumen terminates within the first half of the descending aorta, the frozen elephant trunk may offer a perfect result with complete exclusion of the false lumen. In other cases, however, the benefit of the frozen elephant trunk technique should be compared not only with the conventional elephant trunk, but also with the hemiarch replacement.

In conclusion, the frozen elephant trunk technique enables one-stage repair of extended aortic aneurysms in a certain patient cohort with similar operative mortality as the conventional elephant trunk technique, in which staged surgery is mandatory in many patients. Although the operative strategy should be adjusted specifically to each patient’s individual pathology, the frozen elephant trunk technique may become the next standard treatment for complex aortic disease including the arch instead of its conventional variant in this meaning.

References


