Review

Elephant trunk procedure 27 years after Borst: what remains and what is new?

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Summary

The treatment of complex aortic pathology involving both the ascending and descending aortic segments at the same time represents a surgical challenge, with high postoperative morbidity and mortality rates reported. Over the past 27 years, different open surgical and endovascular techniques have been introduced and applied in various two-stage- or one-stage approaches to such cases. Thus, in 1983, Hans Borst significantly changed the traditional two-stage approach by introducing his elephant trunk technique. Leaving a segment of Dacron prosthesis reaching into the descending aorta during the first stage, the second-stage replacement of the residual dilated descending aorta was made far easier. The presence of interval mortality between the two stages, the unaffected need for two large operations to complete aortic repair, and the general failure of some patients to return for the second-stage repair set the scene for the development of one-stage procedures, both open surgical or hybrid surgical and endovascular, such as the frozen elephant trunk. However, the size of the operation, on the one hand, and the risk of spinal cord injury and need for surgical or endovascular completion during follow-up, on the other, have dampened enthusiasm. Recently, the introduction of supra-aortic debranching and endovascular aortic arch stent-graft repair has yet extended treatment to high-risk patients unsuitable to the more aggressive surgery, but mid- and long-term follow-up results are lacking. The lack of randomization and the presence of procedural and complication-related limitations for each technique do not allow for definitive conclusions about the ideal procedure to treat complex aortic pathology. However, the technical revolution experienced over the past 27 years, along with the improvement in perioperative management, has produced outstanding morbidity and mortality results even in this challenging patient population, but the decision regarding which pathology correlates with what operation remains highly debated and dependent also on regional competence.

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1. Introduction

Aortic aneurysms represent the 17th leading cause of mortality in United States, with an incidence of 10/100 000 patient-years [1]. Different aortic segments may be involved at the same time or a second aneurysm can develop later in a patient previously operated on for the same pathology. This is especially true for patients with Marfan syndrome or aortic dissection, who, in time, often require extensive aortic replacement, which presents high complications and mortality rates, due mainly to long or recurrent operative and hypothermic circulatory arrest times [2]. To offset these complications and to allow surgery also in patients with higher risk, different technical solutions have been developed, both surgical, such as the elephant trunk (ET), introduced by Borst in 1983 [3], and hybrid surgical and endovascular, such as the frozen elephant trunk (FET), developed at the mid-1990s by Kato [4] and the aortic arch debranching and stenting techniques, employed for the first time by Buth in 1998 [5].

However, as each approach has shown technical advantages but also complications at follow-up, the ideal technique for treating complex aortic pathology has yet to be determined. As a consequence, the aim of this article is to present and compare the clinical and technical results of the three approaches, focusing especially on complications and follow-up. For each procedure, technical modifications and procedural alternatives are reported.

2. Materials and methods

2.1. Search criteria

A literature search was performed in three steps. First, Ovid and PubMed databases were searched from 1983 to
March 2010 using the combined keywords ((thoracic [TIAB] AND arch [TIAB]) OR (aneurysm [TIAB] AND dissection [TIAB])) AND (surgery [TIAB] OR 'elephant trunk' [TIAB] or stent [TIAB]). The lists of recovered original articles or reviews were cross-searched to not miss pertinent articles not considered in the previous search. Only articles in English language were considered. In the second step, the articles regarding conventional ET and its surgical and hybrid surgical and endovascular alternatives, FET and aortic arch debranching and stent techniques were identified. In the third step, among series followed-up by the same group over the years, for each procedure, only the most recent ones were considered. For each case series including more than five operated patients, the number of patients treated, in-hospital mortality, neurological complications, such as permanent or transient stroke, permanent or transient spinal cord injury (SCI) (paraplegia/paraparesis), and other neurologic dysfunction (e.g., recurrent laryngeal nerve palsy) were extracted and included as percentages in Tables 1—4. In Table 2, for patients, who underwent a one-stage approach, pulmonary complications were also reported. For the ET case series, cumulative neurological complications and mortality rates for first- and second-stage procedures were considered. Given the heterogeneity of case series, no statistical analysis was performed.

3. Results
3.1. Conventional ET technique

Complex aortic pathology, especially in patients presenting with an aneurysm involving the aortic arch and proximal descending aorta, has until the 1990s been approached in one or two stages [6,7]. In the latter case, the aortic arch was replaced first, followed by the remaining affected aorta during a second operation some 4—12 weeks later [6]. Both approaches presented technical challenges, the one-stage operation due to the long duration of the procedure and hypothermic circulatory arrest, and the two-stage operation due to the need for a second operation, which sometimes required another period of hypothermic circulatory arrest to

<table>
<thead>
<tr>
<th>Author</th>
<th>Year</th>
<th>Patients</th>
<th>In-hospital mortality</th>
<th>Stroke (permanent or transient)</th>
<th>Spinal cord injury (permanent or transient)</th>
<th>Other neurologic complications</th>
<th>Pulmonary complications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minale [33]</td>
<td>1994</td>
<td>12</td>
<td>2 (16%)</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Massimo [34]</td>
<td>1997</td>
<td>34</td>
<td>5 (14.7%)</td>
<td>0</td>
<td>3 (8.8%)</td>
<td>1 (2.9%)</td>
<td>5 (14.7%)&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>Beaver [31]</td>
<td>2001</td>
<td>14</td>
<td>2 (14%)</td>
<td>1 (7%)</td>
<td>2 (14%)</td>
<td>0</td>
<td>5 (35%)&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>Doss [28]</td>
<td>2003</td>
<td>15</td>
<td>1 (6.6%)</td>
<td>3 (20%)</td>
<td>0</td>
<td>2 (13.3%)</td>
<td>2 (13.3%)&lt;sup&gt;c&lt;/sup&gt;</td>
</tr>
<tr>
<td>Kouchoukos [29]</td>
<td>2007</td>
<td>69 (24)&lt;sup&gt;*a&lt;/sup&gt;</td>
<td>5 (7.2%)</td>
<td>0</td>
<td>1 (1.4%)</td>
<td>8 (11.6%)</td>
<td>34 (50%)&lt;sup&gt;d&lt;/sup&gt;</td>
</tr>
<tr>
<td>Kouchoukos [30]</td>
<td>2008</td>
<td>51</td>
<td>2 (3.9%)</td>
<td>0</td>
<td>1 (2%)</td>
<td>8 (15.6%)</td>
<td>23 (46%)&lt;sup&gt;e&lt;/sup&gt;</td>
</tr>
<tr>
<td>Okada [32]</td>
<td>2009</td>
<td>16</td>
<td>1 (6.3%)</td>
<td>1 (6%)</td>
<td>1 (6.3%)</td>
<td>1 (6.3%)</td>
<td>3 (18.7%)&lt;sup&gt;c&lt;/sup&gt;</td>
</tr>
<tr>
<td>Total</td>
<td>211</td>
<td>18 (8.5%)</td>
<td>2 (4.2%)</td>
<td>8 (3.8%)</td>
<td>20 (9.5%)</td>
<td>72/199 (36.1%)</td>
<td></td>
</tr>
</tbody>
</table>

<sup>a</sup> Mechanical ventilation >3—4 days.
<sup>b</sup> Five tracheotomies.
<sup>c</sup> Mechanical ventilation >48 h.
<sup>d</sup> Mechanical ventilation >72 h.
<sup>e</sup> Twenty-four atherosclerotic aneurysms.
perform the proximal anastomosis to the distal aortic arch. Furthermore, the approach to the distal aortic arch, usually via a left thoracotomy, was associated with surgical complications related to the densely adherent tissue surrounding the transverse aortic arch prosthesis and the vicinity of vital vascular and nervous anatomical structures, such as the pulmonary artery, the left recurrent laryngeal or vagus nerves, and the esophagus [2].

As a consequence, in 1983, Borst introduced a significant modification to the two-stage technique. In two patients, affected by aneurysms involving the ascending aorta, arch, and descending aorta, during the first stage, a prosthesis was sutured to the proximal transected descending aorta just downstream from the left subclavian artery. This was left reaching antegradely into the descending aorta over 7—8 cm, giving the appearance of an ‘elephant trunk’. A second prosthesis was then sutured proximally to the first graft and descending aorta and employed to reconstruct the aortic arch. During the second stage, performed some weeks later, the remaining dilated descending aorta was replaced using the ET prosthesis for clamping and suturing another graft to

### Table 3. Frozen elephant trunk: case series and results.

<table>
<thead>
<tr>
<th>Author</th>
<th>Year</th>
<th>Patients</th>
<th>Pathology</th>
<th>In-hospital mortality</th>
<th>Stroke (permanent or transient)</th>
<th>Spinal cord injury (permanent or transient)</th>
<th>Other neurologic dysfunction</th>
<th>Endoleaks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mizuno [40]</td>
<td>2002</td>
<td>9</td>
<td>Dissections 9</td>
<td>1 (11.5%)</td>
<td>1 (11.5%)</td>
<td>2 (22%)</td>
<td>0</td>
<td>1 (11.15%)</td>
</tr>
<tr>
<td>Miyairi [41]</td>
<td>2002</td>
<td>19</td>
<td>Aneurysms 17, dissections 2</td>
<td>2 (10.5%)</td>
<td>0</td>
<td>4 (21.1%)</td>
<td>0</td>
<td>1 (5.26%)</td>
</tr>
<tr>
<td>Usui [42]</td>
<td>2002</td>
<td>24</td>
<td>Aneurysms 22, dissections 2</td>
<td>0</td>
<td>1 (4%)</td>
<td>4 (17%)</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Sueda [43]</td>
<td>2004</td>
<td>34</td>
<td>Aneurysms 34</td>
<td>2 (5.9%)</td>
<td>1 (2.9%)</td>
<td>1 (2.9%)</td>
<td>0</td>
<td>1 (2.9%)</td>
</tr>
<tr>
<td>Flores [44]</td>
<td>2006</td>
<td>25</td>
<td>Aneurysms 25</td>
<td>3 (12%)</td>
<td>4 (16%)</td>
<td>6 (24%)</td>
<td>2 (8%)</td>
<td>0</td>
</tr>
<tr>
<td>Baraki [51]</td>
<td>2007</td>
<td>7</td>
<td>Dissections 5, aneurysms 2</td>
<td>0</td>
<td>1 (14.2%)</td>
<td>0</td>
<td>0</td>
<td>1 (14.2%)</td>
</tr>
<tr>
<td>Shimamura [45]</td>
<td>2008</td>
<td>126</td>
<td>Dissections 57, aneurysms 69</td>
<td>7 (5.5%)</td>
<td>7 (5.6%)</td>
<td>8 (6.3%)</td>
<td>12 (9.5%)</td>
<td>5 (3.9%)</td>
</tr>
<tr>
<td>Midorikawa [46]</td>
<td>2008</td>
<td>7</td>
<td>Aneurysms 6, dissection 1</td>
<td>1 (14.2%)</td>
<td>0</td>
<td>1 (14.2%)</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Di Bartolomeo [53]</td>
<td>2009</td>
<td>34</td>
<td>Dissections 27, aneurysms 7</td>
<td>2 (6%)</td>
<td>0</td>
<td>3 (8.8%)</td>
<td>0</td>
<td>6 (17.6%)</td>
</tr>
<tr>
<td>Uchida [47]</td>
<td>2009</td>
<td>58</td>
<td>Aneurysms 58</td>
<td>1 (1.7%)</td>
<td>2 (3.4%)</td>
<td>2 (3.4%)</td>
<td>0</td>
<td>1/50 (2%)</td>
</tr>
<tr>
<td>Uchida [48]</td>
<td>2009</td>
<td>65</td>
<td>Dissections 65</td>
<td>3 (4.6%)</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1 (1.33%)</td>
</tr>
<tr>
<td>Sun [49]</td>
<td>2009</td>
<td>107</td>
<td>Dissections 107</td>
<td>5 (4.67%)</td>
<td>3 (2.8%)</td>
<td>3 (2.8%)</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Tsogakts [54]</td>
<td>2009</td>
<td>41</td>
<td>Dissections 35, aneurysms 6</td>
<td>3 (7%)</td>
<td>5 (12%)</td>
<td>0</td>
<td>0</td>
<td>4 (9.7%)</td>
</tr>
<tr>
<td>Pochettino [55]</td>
<td>2009</td>
<td>7</td>
<td>Dissections 36</td>
<td>5 (14%)</td>
<td>1 (3%)</td>
<td>3 (8%)</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Shimamura [50]</td>
<td>2009</td>
<td>69</td>
<td>Aneurysms 36, dissections 33</td>
<td>5 (7.2%)</td>
<td>4 (5.8%)</td>
<td>2 (2.9%)</td>
<td>0</td>
<td>6 (8.6%)</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>700</td>
<td></td>
<td>45 (6.4%)</td>
<td>35 (5%)</td>
<td>39 (5.6%)</td>
<td>19 (2.7%)</td>
<td>29/479 (6%)</td>
</tr>
</tbody>
</table>

### Table 4. Debranching of the aortic arch and stenting: case series and results.

<table>
<thead>
<tr>
<th>Author</th>
<th>Year</th>
<th>Patients</th>
<th>In-hospital mortality</th>
<th>Stroke (permanent or transient)</th>
<th>Spinal cord injury (permanent or transient)</th>
<th>Endoleaks (all types)</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inoue [89]</td>
<td>1999</td>
<td>15</td>
<td>0</td>
<td>1 (6.6%)</td>
<td>0</td>
<td>4 (26.6%)</td>
<td>Inoue stent</td>
</tr>
<tr>
<td>Wang [90]</td>
<td>2005</td>
<td>16</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>2 (12.5%)</td>
<td>Single branched stent graft</td>
</tr>
<tr>
<td>Carrer [70]</td>
<td>2005</td>
<td>6</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1 (16.6%)</td>
<td></td>
</tr>
<tr>
<td>Akasaka [69]</td>
<td>2005</td>
<td>12</td>
<td>0</td>
<td>1 (8.3%)</td>
<td>1 (8.3%)</td>
<td>0</td>
<td>Matsui–Kitamura stent</td>
</tr>
<tr>
<td>Bergeron [71]</td>
<td>2006</td>
<td>25</td>
<td>2 (8%)</td>
<td>2 (8%)</td>
<td>0</td>
<td>4 (16%)</td>
<td></td>
</tr>
<tr>
<td>Dagenais [72]</td>
<td>2006</td>
<td>10/18*</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>2 (20%)</td>
<td></td>
</tr>
<tr>
<td>Saleh [73]</td>
<td>2006</td>
<td>15</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Melissano [74]</td>
<td>2007</td>
<td>64</td>
<td>4 (6.3%)</td>
<td>2 (3.1%)</td>
<td>2 (3.1%)</td>
<td>8 (12.5%), early</td>
<td></td>
</tr>
<tr>
<td>Szeto [75]</td>
<td>2007</td>
<td>8</td>
<td>1 (12.5%)</td>
<td>2 (25%)</td>
<td>0</td>
<td>0</td>
<td>Cardiopulmonary bypass</td>
</tr>
<tr>
<td>Balducci [91]</td>
<td>2008</td>
<td>7</td>
<td>0</td>
<td>1 (14.2%)</td>
<td>0</td>
<td>0</td>
<td>Double barrel technique</td>
</tr>
<tr>
<td>Gottardi [76]</td>
<td>2008</td>
<td>73</td>
<td>5 (6.8%)</td>
<td>1 (1.36%)</td>
<td>0</td>
<td>18 (24.6%), early</td>
<td></td>
</tr>
<tr>
<td>Chan [77]</td>
<td>2008</td>
<td>16</td>
<td>0</td>
<td>3 (18.75%)</td>
<td>0</td>
<td>3 (18.75%)</td>
<td></td>
</tr>
<tr>
<td>Kurimoto [92]</td>
<td>2009</td>
<td>104</td>
<td>8 (7.7%)</td>
<td>5 (4.9%)</td>
<td>3 (2.9%)</td>
<td>3 (2.9%)</td>
<td>Fenestrated stent grafts</td>
</tr>
<tr>
<td>Kotels [78]</td>
<td>2009</td>
<td>88</td>
<td>17 (19%)</td>
<td>3 (3.4%)</td>
<td>1 (1.1%)</td>
<td>23 (26%)</td>
<td></td>
</tr>
<tr>
<td>Canaud [79]</td>
<td>2009</td>
<td>34/44b</td>
<td>7 (20.4%)</td>
<td>3 (6.8%)</td>
<td>2 (4.5%)</td>
<td>7 (15.9%)</td>
<td></td>
</tr>
<tr>
<td>Hughes [80]</td>
<td>2009</td>
<td>28</td>
<td>0 (0%)</td>
<td>1 (3.6%)</td>
<td>0</td>
<td>5 (17.8%)</td>
<td>Seven patients stage I elephant trunk completion</td>
</tr>
<tr>
<td>Da Rocha [81]</td>
<td>2009</td>
<td>32/41c</td>
<td>1 (3.4%)</td>
<td>1 (3.4%)</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Younes [82]</td>
<td>2010</td>
<td>35/42d</td>
<td>2 (5.7%)</td>
<td>8 (23%)</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Ydas [83]</td>
<td>2010</td>
<td>9</td>
<td>1 (11%)</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Donas [84]</td>
<td>2010</td>
<td>20</td>
<td>3 (15%)</td>
<td>3 (15%)</td>
<td>0</td>
<td>0</td>
<td>VORTEC technique</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>617</td>
<td>51 (8.3%)</td>
<td>36 (5.8%)</td>
<td>10 (1.6%)</td>
<td>77/478 (16%)</td>
<td></td>
</tr>
</tbody>
</table>

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*a* Eight patients without aortic arch debranching of any type.  
*b* Ten patients without aortic arch debranching of any type.  
*c* Nine patients with thoraco-abdominal aortic aneurysms and treated with visceral arteries debranching.  
*d* Seven patients with thoraco-abdominal aortic aneurysms and treated with visceral arteries debranching.
additional graft to reconstruct the aortic arch, Svensson modified the original Borst’s technique. He inverted a tubular graft, placed it in the descending aorta, and sutured the double layer head onto the descending aortic wall. The inner segment could then be retrieved and be used for arch reconstruction as usual, leaving an ET in the descending aorta. This modification allowed tightening of the distal suture line, greater surface area between the graft and the aortic wall, and reduction of circulatory arrest times, by making one anastomosis redundant [8]. Several other technical modifications have since appeared, such as performing the distal ET suture between the left subclavian and left common carotid arteries [9] or just in front of the brachiocephalic trunk, leaving, in this last case, a long ET graft segment reaching into the aortic arch and redirecting flow to the supra-aortic vessels through a four-branched prosthesis [10]. Conversely, other authors reported their experience with short or ‘mini’ ET, with the aim to reinforce and protect the distal aortic anastomosis during aortic arch replacement or surgery for aortic dissection [11]. In addition, as the ET can be applied also to other aortic segments, such as the ascending or thoracoabdominal aorta, some authors have employed it in a reversed or bidirectional way, especially in patients needing emergent treatment of those segments, using the invaginated limb of the ET prosthesis later to treat the remaining proximal or distal aortic aneurysmal segments [12,13].

Table 1 shows the most up-to-date conventional ET case series reports. Even if the cumulative in-hospital mortality and neurological complications including first and second stages are reported, the results are excellent [8,10,12—25]. As confidence grew and technical adjuncts, such as cerebral protection with retrograde and eventually selective antegrade cerebral perfusion during arrest [26] and various supra-aortic vessels reconstruction techniques, were introduced, ET indications were further extended. For example, in patients scheduled for descending or thoracoabdominal aortic surgery, who presented at the same time with a severe coronary artery or valvular disease requiring operation, an ET was placed in the descending aorta to facilitate subsequent aortic repair and similarly, to speak prophylactically, in selected patients undergoing aortic arch replacement with a downstream aneurysm not requiring immediate surgery at the time, but whose diameter and growth pattern, along with patient risk factors and characteristics (e.g., Marfan syndrome and connective tissue disorders, blood hypertension, and young patients) would suggest an unfavorable development toward further dilation and earlier need for operation [13,14,20—22,25]. Evidence for false-lumen obliteration and healing following the use of the ET technique in patients with acute aortic dissection further encouraged its use [10,14—21,24]. Even in aneurysmal disease, some authors have described stabilization or total thromboexclusion using only a long ET. However, in comparison to FET, this protective effect of a simple Dacron vascular trunk is highly dependent on aneurysm extent and diameter and not fully reliable [10].

On the other hand, several complications have been reported, such as kinking or occlusion of the graft in the descending aorta [2], recurrent laryngeal nerve damage [20,22], and SCI, related both to an ET graft longer than 8—10 cm in the descending aorta and to clotting around the graft with a risk of peripheral thrombo-embolism [2,8,10,13—15,18,21—23,25]. In patients undergoing operation for chronic aortic dissection, aortic rupture due to ET graft entrapment in the false lumen and malperfusion of visceral arteries supplied by the false lumen due to selective perfusion of the true lumen have been reported [14,22,27]. To avoid these complications, in all patients operated for a chronic aortic dissection, it was then felt imperative to fenestrate the intimal membrane for a length corresponding at least to the ET prosthesis to leave both the true and false lumen perfused [13,14,16,18,20—22].

The presence of a significant interval mortality between the two stages ranging from 3% to 13%, the fact that only 45% of patients, who underwent first-stage ET, returned for second-stage completion, and the complications related to the second stage have convinced some surgeons to perform, whenever possible, a one-stage repair, through a clamshell [28—30], transmediastinal [31] or left posterolateral thoracotomy approach [32]. As Table 2 shows, lower mortality rates, especially in patients undergoing redo surgery for chronic aortic dissection involving the distal aortic arch and the proximal descending aorta, have thus been reported [28—34]. However, the long operating times associated with extensive one stage or total replacements of the entire aorta [33,34]; the higher pulmonary complication rates, ranging from 15% to 50%; the need to sacrifice both internal mammary arteries; the postoperative pain; and the inability to extend resection to segments downstream from the diaphragm, have limited their applicability and acceptance considerably.

Today, one-stage repair is only performed at a small number of centers. Other surgeons, to shorten the time interval between stages, have propagated hybrid approaches with an endovascular completion of the first-stage ET by implanting covered stent grafts both antegrade [35] or retrogradely [18,21,25,36—39]. This option has been considered particularly appealing, as the ET thus functions as a landing zone for such stent grafts. However, the inability to revascularize the intercostal arteries with the risk of spinal cord ischemia, the presence of a long, kinked, or tortuous ET, mobilization of thrombotic material around the prosthesis during catheter manipulation, and the development of endoleaks at follow-up requiring the need of repetitive endovascular procedures have raised some concerns about this approach [37—39].

3.2. FET technique

Starting from the early 1990s [4], new ET prostheses were developed, still not only to treat concomitant aortic arch and proximal descending pathology in one stage but also to reduce the complications associated with the conventional ET, paving the way for the development of a new technique, named by Borst the ‘frozen elephant trunk technique’. These prostheses exhibited a common funnel, with a covered stent, made of nitinol or stainless steel, sutured to the distal end of a conventional polyester or polytetrafluoroethylene (PTFE) tube graft, and are deployed antegrade through the opened aorta by means of an introducer. The proximal non-stented part is used to fix the prosthesis to the distal aortic arch and to allow for reconstruction of the arch itself. Different prostheses have been developed, both ‘homemade’ [4,40—50] and commercially available, such as the Chavan-
Haverich (Curative Medical Devices GmbH, Dresden, Germany) [51] and the E-vita open (JOTEC GmbH, Hechingen, Germany) [52—54]. Stent grafts already commercially available for treating descending and abdominal aorta pathology, such as the GoreTAG (W.L. Gore & Associates, Flagstaff, AZ, USA), have also been employed, by deploying them antegrade through the open aorta and suturing them to the proximal aortic arch repair, without reconstructing the supra-aortic trunks [55]. Recently, a new ‘homemade’ branched stent graft has been introduced, reconstructing simultaneously the supra-aortic branches and descending aorta, thus further reducing hypothermic circulatory arrest times [50].

The FET technique has been conceived by taking into account lessons learned from previous surgical experience with the conventional ET and from contemporary endovascular technologies, retaining from the first, the concept of placing a prosthesis into the descending aorta, and, from the second, of fixing it with a stent. The ability of an ET to favor aneurysmal or false-lumen thrombosis and obliteration had been already reported by Borst and other authors, especially if long ETs are used [10,14—21,24]. However, its sealing capacity was far from complete, allowing distal perfusion of the aneurysm or false lumen and subsequent expansion and potential rupture. As a consequence, by adding a stent to the distal end of the FET prosthesis, surgeons tried to increase its sealing effect, acting effectively as a distal anastomosis. At the same time, the risk of proximal endoleak and migration was avoided, as the FET prosthesis is sutured to the aortic arch or a more proximal prosthesis [4]. This FET sealing property has made its use particularly appealing in patients with type A aortic dissection, where the presence of a residual patent false lumen after more conservative, tear-oriented surgery for the acute event has been demonstrated to be a risk factor for subsequent aortic enlargement and the need for re-operation [56—59]. In fact, among the 700 FET patients reported in Table 3, more than half (57%) presented with an acute or chronic aortic dissection. By placing a hybrid prosthesis across the intimal tears in the descending aorta, it is possible to exclude the false lumen at this level and depressurize it downstream, facilitating its obliteration and thromboexclusion.

Table 3 shows that, since the first surgical experience by Kato during the mid 1990s [4], different case series have been published, reporting good early and midterm results. In-hospital mortality seems to be improved in comparison to the conventional ET (6.4% vs 10.2%, respectively) [40—55]. In a recent review published in 2008, FET has even been considered the standard treatment for extended aortic aneurysm as an alternative to conventional ET, as it allows for one-stage repair of combined aortic arch and proximal descending aortic aneurysm [60].

However, different complications have been reported with the FET, first being the need for repetitive endovascular or surgical procedures, mainly due to the occurrence of endoleaks, as reported in Table 3, and to false lumen patency downstream from the FET prosthesis in patients operated on for type A aortic dissection, whose incidence has been demonstrated to be between 50% and 90%, due to the presence of abdominal aortic re-entries [48,54]. At follow-up, among E-vita open experiences, Tsagakis reported four (9.7%) endoleaks, one proximal and three distal, requiring three endovascular and one surgical repairs [54]; Di Bartolomeo six (18%) endovascular extensions of the descending thoracic aorta repair for false-lumen patency [53]; and Gorlitzer one thoraco-abdominal repair (14%) in a patient with a patent false-lumen downstream from the stent graft [52]. Among homemade stent-graft experiences, Uchida reported four (6.8%) and one (1.5%) distal re-operations in patients undergoing aortic repair for extensive arteriosclerotic aneurysm [47] and type A acute aortic dissection [48], respectively. Similarly, Shimamura reported five (3.9%) patients presenting with late endoleaks, all requiring endovascular repair, and 10 (7.9%) other patients, affected by aortic dissection, requiring intervention at another aortic lesion (seven endovascular and three surgical repairs) [45]. In addition, among 69 other patients treated recently by the same group with a newly developed branched stent graft, four (5.8%) affected by aortic dissection underwent subsequent endovascular or surgical operations, three at the ascending and thoraco-abdominal and one at the abdominal level. Another six patients showed endoleaks and one stenosis (10.1%) at the cervical stent-graft branch level, requiring subsequent endovascular repair [50].

Pichlmaier first reported an experience with both surgical and endovascular distal aortic re-operations in six patients, who received a FET with the Chavan—Haverich prosthesis, emphasizing several advantages over the conventional ET. In four patients undergoing surgery, the extent of surgical access was reduced, thus avoiding extensive handling of the left lung and rib resections, the FET being longer and not retracted as the ET. Moreover, it was easy to recover and clamp the FET prosthesis without a risk of damaging it and to suture the vascular graft to the stented graft without any additional technical problem, as the false lumen was usually completely thrombosed or obliterated at the distal stent-graft level. In two patients undergoing endovascular repair, the FET prosthesis seemed to offer a better landing zone in comparison to the conventional ET, without any risk of graft kinking and tortuosity [61].

Table 3 shows a higher incidence of temporary or permanent SCI in comparison to the ET series. The mechanisms seem to be multifactorial and far from being completely defined. SCI has been associated with the presence of several preoperative and intra-operative technical risk factors, such as patient age >75 years [41], previous history of aortic abdominal surgery [44], the vertebral level (>T7) of the distal landing zone [44], and presence of a fusiform aneurysm [42]. The possible role of intra-operative body temperature in preventing SCI has not been directly investigated but is being controversially discussed. Thus, in most FET case series, temperatures ranging from 24 to 28 °C have been employed for hypothermic circulatory arrest [45—48,51—56]. This stands in contrast to first-stage ET case series, where lower hypothermic circulatory arrest temperatures but also retrograde cerebral perfusion have usually been employed, associated with very low SCI rates [20,21,24,25]. The SCI rate was higher in the long ET case series, where the only risk factor identified by the authors was distal ET landing level, suggesting obliterated collateral blood flow as the mechanism; however, body temperature had only been lowered to 25 °C [10]. The highest SCI rates
have interestingly been reported in those FET case series where hypothermic circulatory arrest temperatures were in fact lower than 25 °C in addition to using selective antegrade cerebral perfusion [41, 42, 44]. Furthermore, thoracic endovascular aortic repair (TEVAR) case series usually report very low SCI rates at normothermic body temperatures. Finally, during thoraco-abdominal aneurysm repair, maintaining a satisfactory perfusion pressure has been shown to be more important in preventing SCI than reimplanting intercostal arteries or lowering body temperature to deep hypothermic levels. Other major adverse events have been reported, such as stent-graft kinking due to migration, leading to aortic wall perforation [62], coarctation due to tortuosity of the aorta [63], functional stenosis due to compression on the non-stented segment by an expanding false lumen [64], and false-lumen rupture due to impingement of the prosthesis [51]. Similar to ET case series, visceral organ malperfusion syndrome could potentially arise in those patients with chronic aortic dissection, who could present one or more visceral arteries originating and perfused from a patent false lumen. In these patients, before deploying the FET, it appears important to fenestrate the intimal membrane between the true and false lumen for a length corresponding to the stent graft to avoid malperfusion.

3.3. Aortic arch debranching and endovascular exclusion

At the end of the 1990s and as soon as the first midterm results of TEVAR became available [65, 66], different authors began to extend this new technology, first to distal and, subsequently, to more proximal aortic arch pathology [5, 67]. By avoiding the use of cardiopulmonary bypass, aortic clamping, and hypothermic circulatory arrest, the aim was to extend aortic arch repair to patients not previously deemed candidates for conventional surgery, due to concomitant co-morbid conditions, such as old age, previous cardiac operations, chronic obstructive pulmonary disease, and previous cerebrovascular accidents.

The extension of endovascular treatment to the aortic arch added new challenges to those already experienced with the treatment of the descending aorta. Thus, a proximal landing zone at least 2 cm long at the aortic arch level must take into account the presence of supra-aortic vessels and of anatomic and hemodynamic properties peculiar to the aortic arch, such as its curvature, the high blood-flow velocity usually present in this area, and the substantial movement of this portion of the aorta with each heartbeat in comparison to other aortic segments [68]. To create a suitable landing zone for endovascular repair, authors rerouted blood flow to the supra-aortic vessels prior to stent-graft deployment, by introducing different ‘debranching’ techniques, such as surgical extra-anatomic bypasses or transpositions [69—84] and branched or fenestrated stent grafts [85—93]. Stent-graft completion can then be performed immediately or deferred to arch debranching. According to the Criado and Ishimaru classification of aortic arch landing zones [68], patients requiring stent-graft placement at zone 0 usually undergo preemptive total arch rerouting, often through a median sternotomy. Instead, patients requiring stent grafting in zone 1 or 2 undergo double- and single-vessel transposition.

This may be achieved by transposing or bypassing the left carotid from the brachiocephalic artery and the left subclavian from the left carotid artery, and by simply bypassing or transposing the subclavian from left common carotid artery, respectively. Although, in the majority of series, the cardiopulmonary bypass is thus avoided altogether, there are a few authors, who report brief periods of cardiopulmonary bypass to extend hybrid aortic arch repair to as many high-risk patients as possible, such as those with a compromised cardiac function, who would not tolerate the side clamping of the ascending aorta, those who should undergo concomitant cardiac procedures, and those who present a relatively short ascending aorta and where side clamping of the ascending aorta would involve also the sinotubular junction [75]. Other surgical approaches have been proposed by rerouting blood to the supra-aortic vessels from the femoral arteries or the descending aorta [82], but have been rarely employed. Recently, a new sutureless telescoping anastomosis technique has been introduced, called VORTEC (Viabahn Open Rebranching Technique, W.L. Gore & Associates, Flagstaff, AZ, USA), which allows for shorter anastomosing times between the Dacron prosthesis and the supra-aortic vessels, reducing at the same time vessel dissection, manipulation, and ischemia [84].

In contrast to the above surgical debranching, experience with branched and fenestrated stents has been limited by the complex stent-graft deployment and by the risk of stent migration and fracture [85—93]. However, branched stent grafts could potentially allow for total endovascular aortic repair. Inoue treated 14 patients with a single branched stent graft and one patient with a trifurcated stent graft, with primary and secondary success of 60% and 73%, respectively. The need for extensive catheter manipulation with the associated risk of peripheral embolization and the complex stent-graft deployment procedure limited the application of this procedure [89]. Particularly the so-called chimney graft method has the potential to solve a number of the technical problems in endovascular treatment of the arch, but remains to be validated [94].

Furthermore, the presence of aneurysms with a diameter >44 mm, which represents the maximal diameter of available stent grafts, often extending distally to the descending or proximally to the ascending aorta, would preclude endovascular treatment in those patients presenting with complex aortic pathology. Encouraging results have here been obtained by banding the ascending aorta with a Dacron strip during the debranching procedure, which could, in addition, impede further aortic dilation and, if properly marked with clips, guides the surgeon during the subsequent stent deployment. However, extreme banding has been reported to lead to aortic wall necrosis [95]. Other authors have proposed a more aggressive and invasive approach by replacing the ascending aorta with or without the hemiarch using a trifurcated graft and subsequently deploying the stent antegrade through the third branch of the ascending aorta graft or retrogradely through the femoral artery [75, 80, 83].

Recently, concerns have been raised about the suitability of a woven Dacron graft to serve as a landing zone, as Dacron grafts usually dilate over time to some degree. It has even been proposed that radial forces exerted by the stent may
aggravate this process, leading to subsequent type I proximal endoleaks and migration [80].

The lack of a stent graft designed specifically for the aortic arch has been another major concern for surgeons performing endovascular aortic arch repair [68]. All series in Table 4 have employed commercially available stents designed and used for the ascending aorta, where anatomy and hemodynamic forces are quite different to the aortic arch. These stents and especially the first-generation ones are rigid and, as a consequence, unable to conform to the aortic arch. This lack of conformity, especially at the proximal stent-graft end, can provoke a progressive collapse of the stent during systole and re-expansion during diastole, leading to fracture or collapse [96]. In addition, the risk of type III endoleaks increases with the number of stents employed, especially in those patients, who present with extensive aortic pathology. Concerns have also been raised about the available delivery systems that can be too short to reach the aortic arch, too rigid to adapt to its curvature and the three-dimensional angulation between the aortic arch and the descending thoracic aorta not allowing precise deployment in this area at high blood flow. Damage to the aortic valve has been another concern [68]. As a consequence, different safeguards have been employed to offset these problems, such as bending the distal end of the introducer, lowering blood flow by using hypotension or rapid pacing, and modifying available or using more flexible stent grafts, such as the Matsui–Kitamura stent (Kitamura Inc., Kanazawa, Japan) [69], which presents a more flexible skeleton than the Z-shape stents.

These continuous improvements in surgical procedures and stent design for endovascular aortic arch repair have led to ever-improving postoperative and short-term results with this technique, even in a high-risk surgical population, with in-hospital mortality, stroke, and SCI rates comparable to conventional ET and FET case series, as reported in Table 4. However, long-term results are lacking.

4. Discussion

During the past 27 years, new techniques have repeatedly been considered to be an ideal solution to treat complex aortic pathology, but enthusiasm partially waned as mid- and long-term follow-up results became available. In addition, until now, no randomized controlled trial has been performed and, as such, no scientific and statistic-based conclusion could be drawn as to which technique can be considered the most successful in treating complex aortic pathology. Comparisons between techniques by analyzing the retrospective and prospective case series reported in this article may even be considered futile, due to the different observation periods, patient surgical-risk profiles, surgical indications, and events and morbidity reporting. For example, most patients, who underwent a conventional two-stage ET procedure, were operated on during the mid-1980s to 1990s, and relatively few case series of patients affected by acute aortic dissection were reported (Table 1). On the contrary, the FET technique has been developed during the mid-1990s and widely applied only recently, especially in patients presenting with acute or chronic aortic dissection (Table 3). During the time elapsed from the most recent review on this topic [60], 10 new case series with FET have been reported [45–50,52–55], but only three with conventional ET [10,24,25]. As a consequence, newer technical adjuncts, such as antegrade cerebral perfusion, were more commonly and uniformly employed in patients undergoing FET. Furthermore, among FET case series, different stent-graft prostheses have been employed, both homemade and commercially available, making any conclusion even more questionable.

Indeed, some interesting conclusions can be drawn by comparing the case series reported in Tables 1 and 3. First, the FET technique should not strictly be considered a one-stage procedure, as several authors have reported the need for a second operation, both surgical and endovascular, during follow-up. These additional operations should be considered a second-stage operation in the traditional sense and their cumulative mortality, complication, and interval mortality rates must be reported. As a consequence, results in Table 3 should be compared more appropriately to the first-stage results of the conventional ET and not to the cumulative ones given in Table 1. At least three reasons justify this statement. First, endoleaks, as previously reported, cannot be completely avoided, independent of the generation of graft. Second, complex aortic pathology involves different segments simultaneously but the FET stent graft can cover only a given part of the descending aorta related to its length, requiring subsequent surgical or endovascular procedures to complete aortic repair. Third, the initial conception of preventing distal enlargement beyond the stented segment of the descending aorta has not been confirmed and, even if false-lumen thromboexclusion around the stent graft is achieved, this could not prevent distal re-operations during follow-up, as for example, residual distal patent false lumen favors aortic enlargement [56–59]. Moreover, the extensive use of more aggressive surgical procedures, such as total arch replacement with or without an ET or FET extension to the descending aorta in acute aortic dissection, has been recently questioned by some authors [97,98], who perform a more conservative surgery, by replacing the ascending aorta with or without the hemiarch, as in some patients, especially the older ones, aortic growth rates related to false-lumen patency seem to be slower, probably due to the presence of a stiffer and less elastic aortic adventitia [99].

A novel technique, to be considered as a valuable alternative, should not present complications, mortality rates, and follow-up results in excess of those of an already validated procedure. However, by comparing the results in Tables 1 and 3, the FET seems to present a higher postoperative SCI risk than the conventional ET, of 5.6% versus 1.2% (first stage) and 2.0% (cumulative between first and second stage), respectively. This complication can be reduced by improving patient preoperative selection, identifying those patients at higher risk of SCI, according to the risk factors previously reported, and employing technical adjuncts, such as perioperative cerebrospinal fluid drainage and perfusion of the left subclavian artery, reducing clamp and hypothermic circulatory arrest times, and limiting the length of the descending aorta covered by the stent graft to the vertebral T7 level. However, shortening the stent graft obviously would reduce the number of patients, who could
effectively undergo one-stage repair, as aneurysms can involve longer segments of the descending aorta.

The same concepts reported for the conventional and frozen ET techniques could be extended to the endovascular repair of the aortic arch. The favorable early morbidity and mortality rates, reported in Table 4, especially in patients unsuitable for conventional surgery and presenting high American Society of Anesthesiology (ASA) scores, along with a satisfactory technical success [70,73,74], have led some authors to propose this technique as an alternative to open surgery. However, once again, no randomized studies exist, and case series are not comparable because of population characteristics and different operative indications. For instance, no patient presenting with acute aortic dissection has been treated with this new technique, and this indication alone increases operative risks and postoperative morbidity rates in open surgery case series. Furthermore, authors sustaining the validity and feasibility of this new technique compare its postoperative morbidity and mortality rates to quite old open surgical repair case series results [73,76,77,83].

Another major concern with supra-aortic debranching and subsequent endovascular stent-graft repair is the problem of endoleaks, with an overall incidence of 16% as reported in Table 4. This technical complication entails two important consequences. First, as the presence of an endoleak of any type often requires endovascular repair, this new procedure cannot be considered strictly speaking a one-stage technique. In addition, given the notorious tendency of the aorta to dilate and the presence of different concomitant aneurysmal segments, additional endovascular procedures will be required during follow-up. As a consequence, as reported for the FET technique, cumulative complication and success rates must be reported, if a comparison to the two-stage conventional ET technique is made. Second, the need of repetitive endovascular repairs raises a concern about durability and long-lasting benefits for patients compared with open surgical repair. Even if feasibility of this technique has been demonstrated, long-term durability and survival results are lacking. Data from TEVAR case series could be extrapolated to endovascular aortic arch repair. In their case series of patients treated between 1992 and 1997 with a homemade, first-generation stent graft, Demers reported an 8 years’ freedom from aortic re-intervention and treatment failure of 70% ± 6% and 39% ± 8%, respectively [100]; but long-term TEVAR durability results could certainly be improved by the introduction of newer stent grafts. By contrast, the long-term survival benefits of stent-graft technology over medical [101] and surgical [102] alternatives are still debated. In the INSTEAD (Investigation of Stent Grafts in Patients With Type B Aortic Dissection) trial, for example, which enrolled patients with uncomplicated chronic Type B dissection, no survival benefit of endovascular over medical therapy was found at 2-year follow-up [101]. Similarly, in a recent meta-analysis of endovascular aortic repair versus open surgical repair for descending thoracic aortic disease, TEVAR failed to show a survival benefit over surgery at follow-up, although all-cause mortality at 30 days was significantly reduced [102]. Recently, the role of stent grafts in treating aortic aneurysms has even been questioned by some authors, who maintain that placement of a stent into the aorta could not impede its natural tendency toward dilation, as the aorta seems to dilate at a mean rate of 0.1 cm year\(^{-1}\) and 0.3 cm year\(^{-1}\) at the ascending and descending aorta levels, respectively, and that this could be particularly aggravated by the stent graft’s radial force, which tends to displace the aortic wall outward, and by the presence of patent intercostal or lumbar arteries, which could keep on perfusing the aneurysmal sac [1,103].

As a consequence, endovascular treatment of complex aortic and, especially, aortic arch pathology requires strict imaging follow-up and, until its long-term durability is confirmed, extension of its employment to good surgical candidates may even seem hazardous. In addition, patient psychological stress associated with repetitive controls and procedures must be taken into account, as well as cumulative procedural costs.

5. Conclusions

Since 1983, different surgical and endovascular techniques have been introduced to treat such a challenging pathology as complex thoracic aortic aneurysms. Every technique showed advantages and drawbacks and, unfortunately, none can be considered the ideal solution for every patient. In addition, the continuous development and introduction of new procedures and the heterogeneity of the pathology treated make randomization near-impossible and comparison difficult. However, an overall conclusion can be drawn from the data gathered here. Over the past 27 years, technical development, both open surgical and endovascular, has undoubtedly made the treatment of an ever-growing percentage of patients possible, including those at high surgical risks and not previously considered surgical candidates. Early and late mortality, postoperative morbidity, and freedom from aortic-related events have shown an outstanding improvement over the years and the results are continuing to do so. It is, however, important that surgeons be aware of the limitations of each technique, to avoid undue ‘exuberance’ in their application [103]. These 27 years have surely represented a technical ‘revolution’ in aortic surgery, and Borst’s ET should certainly be considered one of the most important individual events.

References


Keywords: Aorta; Great vessels; Elephant trunk; Rerouting

uncomplicated. The authors of this article[1, in this issue], outstanding concepts are maintained straightforward and three decades ago. As often in surgery and science, thoracic aortic diseases was introduced by Hans Borst almost time, lucid idea of the elephant trunk to treat extensive cardiothoracic surgical field? This brilliant and, at the same course, the elephant trunk. Who had ever thought that the proboscis, an elongated, mobile appendage from the head used for feeding, sucking, or drinking. The most famous is, of course, the elephant trunk. Who had ever thought that the elephant’s most important and versatile appendage would become the subject of a particular operation within the cardiothoracic surgical field? This brilliant and, at the same time, lucid idea of the elephant trunk to treat extensive thoracic aortic diseases was introduced by Hans Borst almost three decades ago. As often in surgery and science, outstanding concepts are maintained straightforward and uncomplicated. The authors of this article [1, in this issue], not coincidentally partially from the same school as the father of this concept, give us now an extensive and comprehensive overview of the surgical treatment of complex aortic diseases. They start with the initial basic ideas, go through some modifications, and end with recent new perspectives, such as the frozen elephant trunk and aortic arch debranching plus stenting in high-risk patients. They analyze the pros and cons of each technique; for example, they highlight in the conventional elephant trunk technique the necessity to resect the dissection flap in chronic dissection to position the trunk above the resected membrane to allow for perfusion of both the true and false lumen. It is strange that this basic concept is deliberately ignored in the frozen elephant trunk technique. The authors inform us about the points of concern related to the elephant trunk, irrespective of which surgical technique is used: the interval mortality between stage one and two, the failure of some patients to return for the second stage and the ‘prophylactic’ application of the elephant trunk in patients, who do not require immediate downstream repair. The latter subject warns us about the extensive use of too-aggressive surgical procedures of which the indications can sometimes be questioned. They stress that the second stage after the conventional elephant trunk can be completed also by endovascular ways, if the pathology allows for using the trunk as the landing zone. The surgical elephant trunk procedure evolved faster than the proboscis itself. By introducing the frozen elephant trunk, in the early 1990s, surgeons tried, among other things, to increase the sealing capacities in the descending aorta, certainly a very appealing concept in aortic dissection, aiming to reduce subsequent downstream problems that often determine the future of the patient. A major point of concern remains, however; the relative high incidence of spinal cord problems and renal dysfunction. Is this related to a different temperature management during surgery or to the fact that the frozen elephant trunk is deliberately located within the true lumen with occlusion of the false lumen? The authors alert us correctly that the frozen elephant trunk is mostly not a single-stage operation, something that is often ignored by the advocates of this technique and used as a persuasion. In the late 1990s, the aortic debranching concept was launched mostly aiming at avoiding cardiopulmonary bypass in high-risk patients. However, it became clear very rapidly that these interventions certainly are not ‘minimal invasive’