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Endovascular Aortic Arch Repair: Hopes and Certainties

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Abstract For aneurysms and dissections involving the aortic arch, the traditional treatment is open surgical repair requiring cardiopulmonary bypass and deep hypothermic circulatory arrest. Reported mortality rates range from 7% to 17% and neurologic injury rates range from 4% to 12%. Since the first clinical applications of endovascular repair in the early 1990s, this less-invasive treatment modality has evolved steadily. For the treatment of aortic arch pathologies, combined open and endovascular strategies (hybrid procedures) have gained a widespread implementation. Evidence to date proves the feasibility of open surgical branch re-vascularisation followed by endovascular repair into the proximal arch. For hybrid procedures, mortality and stroke rates are given as 0–20%, and 0–8%, respectively. Alternative approaches using fenestrated and branched stent grafts have been considered. Although this technique is challenging and devices are not available widely, it is anticipated that this new technique will expand the range of aortic arch pathologies that can be treated by endovascular means.

Conventional surgical repair of aortic arch pathology is an invasive procedure necessitating arch replacement with cardiopulmonary bypass and deep hypothermic circulatory arrest. Despite advances in surgical techniques, anaesthesia and intensive care management, reported mortality rates range between 7% and 17% and the rate of gross neurologic injury ranges from 4% to 12% with a direct correlation between advanced age and adverse outcome.[1–4] Since the first endovascular application of a self-fixing synthetic prosthesis for the treatment of a traumatic thoracic aortic aneurysm by Volodos and associates[5] in 1988, this less-invasive procedure became an alternative modality to open surgical repair. Although various pathologies such as atherosclerotic aneurysms and dissections often involve the origin of the supra-aortic branches, hybrid techniques (i.e., open/endovascular combination approaches) have extended endovascular treatment options. Alternatively, first experiences with

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fenestrated stent grafts,[6] branched stent grafts[7–9] and the double-barrel technique[10] for preservation of aortic arch branches have been reported. Besides the involvement of aortic arch vessels, endovascular aortic arch repair might be impeded by extreme arch angulations, the high blood flow and the pulsatile movement of the aorta in this area. The imperative of re-vascularisation of arch vessels prior to the stent-graft procedure depends on the required proximal stent-graft attachments, and different technical opportunities are discussed. Although these adjunctive techniques incorporate invasive surgical procedures, it is believed that minimising the procedural invasiveness, by avoiding aortic cross-clamping and/or hypothermic circulatory arrest, morbidity and mortality outcomes can be improved, especially in high-risk patients. Several surgical approaches and techniques have been described for various levels of aortic arch involvement with encouraging early and mid-term results, although the long-term durability of these hybrid surgical—endovascular procedures remains to be defined.

The Frozen Elephant Trunk Technique

Extensive aortic pathologies involving the ascending aorta, aortic arch and the descending aorta remain a challenging issue in aortic repair. The frozen elephant trunk technique (FET), as an advancement of the conventional elephant trunk technique introduced by Borst and collegues[11] in 1983, has been developed as an alternative treatment option.[12–15] In this single-stage procedure, replacement of the ascending aorta and the aortic arch is performed in a conventional fashion with a median sternotomy. It is followed by an antegrade endovascular stent-graft insertion into the descending aorta through the opened aortic arch. Although experience with FET is limited, results reported during the past years seem to be encouraging (Table 1).[16–21] The averaged mortality rate in the analysed series is 5.6%, and the averaged stroke rate and spinal cord injury rate is 6.0% and 5.6%, respectively. However, a high rate of postoperative paraplegia was reported by Flores et al.[21] In their study cohort, lower limb paraparesis or monoparesis was evident in six (24%) patients, and history of abdominal aortic aneurysm repair combined with a distal landing zone of the stent-graft of T7 or greater was the strongest predictor for spinal cord injury (71% vs. 6%, $p = 0.0047$). Further, major complications reported with the FET are left recurrent nerve injury in up to 12.8%,[18] and renal failure requiring dialysis and prolonged ventilation in up to 15% and 12%, respectively.[16] In patients who had computed tomography (CT) follow-up postoperatively, a complete thrombosis of the perigraft space around the stented segment was found in 78—100%.[16,18–20] Shimamurs et al.[17] reported an actuarial freedom from endoleak of 98% and 91.1% for 1 year and 5 years, respectively.

Endovascular Elephant Trunk Completion

The conventional elephant trunk technique for extensive thoracic aneurysm and dissection repair is an accepted surgical approach. However, mortality of the second stage of the procedure, consisting of completion of distal anastomosis through a left thoracotomy approach, was reported in up to 9.6% in a recent series.[22] Being seen as an opportunity for reduction of the mortality associated with the second stage of the elephant trunk technique, transfemoral endovascular stent-graft implantation was used to complete the distal repair.[23,24] Experiences with this two-stage procedure are limited and operative mortality for the endovascular completion is reported in 0—8.3% in the case series published.[23–25] Moreover, there were no reported cases of permanent paraplegia.

Re-vascularisation of Supra-aortic Branches Prior to Stent-graft Therapy

Successful stent-graft placement and sealing require a satisfactory proximal landing zone of at least 20 mm in length. To overcome the anatomic limitation of proximal landing zones, combined surgical supra-aortic debranching and endovasular techniques as a one-[26] or two-stage procedure have gained an innovative approach for aortic arch repair. According to the Criado classification[27] of the thoracic aortic landing zones, different hybrid procedures are currently the subject of active investigations. The classification provides an uniform nomenclature and is defined as follows: zone 0 is the ascending aorta from the aortic valve including the innominate artery, zone 1 from just beyond the origin of the innominate artery including the left common carotid artery (CCA); zone 2 from just beyond the origin of the left CCA including the left subclavian artery; and zone 3 from just beyond the origin of the left subclavian artery (LSA) to the beginning of the descending thoracic aorta.

Table 1 Results with frozen elephant trunk procedures

Author	Year	Mortality	Stroke	Spinal cord injury
Di Bartolomeo et al.	2009	2/34 (6%)[a]	0/34 (0%)	3/34 (9%)
Shimamura et al.	2008	4/126 (3.2%)[b]	7/126 (5.6%)	8/126 (6.4%)
Baraki et al.	2007	5/39 (12.8%)[a]	5/39 (12.8%)	0/39 (0%)
Liu et al.	2006	2/60 (3.3%)[a]	3/60 (5.0%)	1/60 (1.6%)
Uchida et al.	2006	2/35 (5.7%)[b]	0/35 (0%)	0/35 (0%)
Flores et al.	2006	3/25 (12%)[a]	4/25 (16%)	6/25 (24%)
Total		18/319 (5.6%)	19/319 (6.0%)	18/319 (5.6%)

[a] = inhospital mortality.
[b] = 30-day mortality.

Landing zone 0

For a hybrid approach to arch pathology that encompasses all supra-aortic vessels (zone 0), one relatively standard procedural strategy is debranching of supra-aortic vessels and re-vascularisation of the innominate and left carotid artery by placement of a bifurcated graft in the anterior aspect of the ascending aorta (Fig. 1).[28–35] In contrast to bifurcated grafts, Szeto et al.[36] reported their experience in eight patients with the use of a trifurcated Dacron graft and re-vascularisation of all supra-aortic vessels. As another option, femoroaxillary bypasses as an extra-thoracic approach[27] or the descending aorta as source for a bypass[37] have been also described. After surgical re-vascularisation, stent-graft implantation may be performed simultaneously in the same operating setting with the option for additional surgical measures, such external banding in case of incomplete sealing of the proximal attachment site. Primary banding of the distal segment of the ascending aorta for prevention of further dilation and stent-graft migration has found favour with some surgeons.[30,38]

Landing zone 1

Anchoring of the stent graft in zone 1 requires re-vascularisation of the left CCA, which is most commonly achieved through construction of a right CCA to left CCA bypass.[28–31] This extrathoracic procedure is less invasive than those performed through a median sternotomy. Patency rates of such bypasses were reported in 88% at 3 years and 84% at 5 years with primary-assisted-patency rates exceeding 90%.[39] As an alternate, transposition of the left CCA to the brachiocephalic trunk (Fig. 2) has been claimed to be advantageous compared to bypasses because of avoidance of alloplastic material, and consequently less risk for infection.[33,40] However, this procedure presupposes at least an upper hemi-sternotomy. Depending on individual anatomic variables, the left subclavian artery (LSA) may be re-vascularised or simply covered by the subsequently placed stent graft. As an alternative to simultaneous surgical/endovascular procedures, most interventionalists prefer a staged procedure for endovascular repair due to better technical equipment in the angiosuite. Further advantages are a shorter procedure time and therefore less stress for the patient and avoidance of double burden of the renal function due to blood loss and contrast load.

Landing zone 2

A substantial amount of thoracic aortic pathologies involves the distal arch adjacent to the LSA. Stent-graft repair in this condition will necessitate partial or complete overstenting of LSA origin. In a few series, overstenting of the LSA[41–44] is reported as a feasible and well-tolerated procedure for fixation of the stent graft. In the study group of Görich and co-workers[43] with incomplete overstenting of LSA in four and complete occlusion of the LSA in 19 patients, three (13.6%) patients reported ischaemic arm symptoms but none of the patients had persistent signs of vertebrobasilary insufficiency. More recently, Riesenman et al.[45] reported their experience in 112 patients, out of whom 18 had complete and 10 patients partial coverage of the LSA. The overall incidence of cerebrovascular accident in this study was 4.5%, with a much higher incidence (10.7%) in the group of patients that had partial or complete LSA

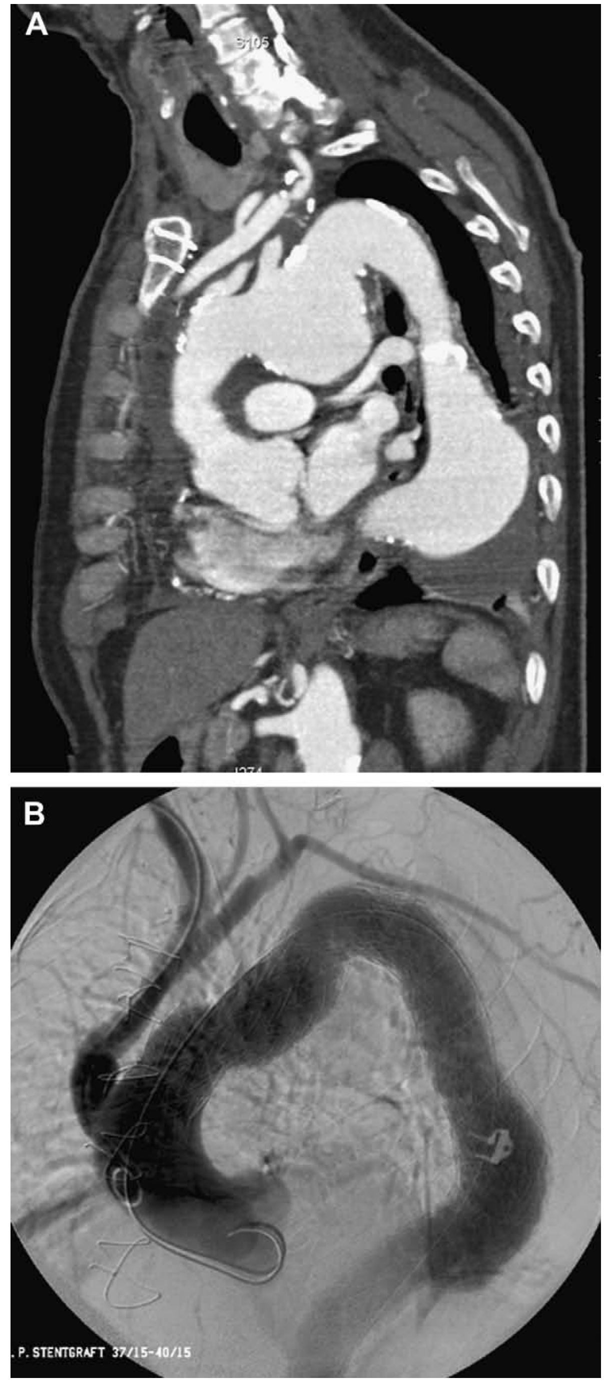

Figure 1 Aortic arch aneurysm necessitating anchoring of the stent-graft in zone 0 and aneurysm of the descending aorta. A total arch rerouting was performed by the use of an inversed bifurcated graft prosthesis with end-to-end anastomosis between the first branch and the brachiocephalic trunk and between the second branch and the LSA. The left CCA was reinserted into the branch of the LSA (A). Successful exclusion of both aneurysms after EVAR (B).

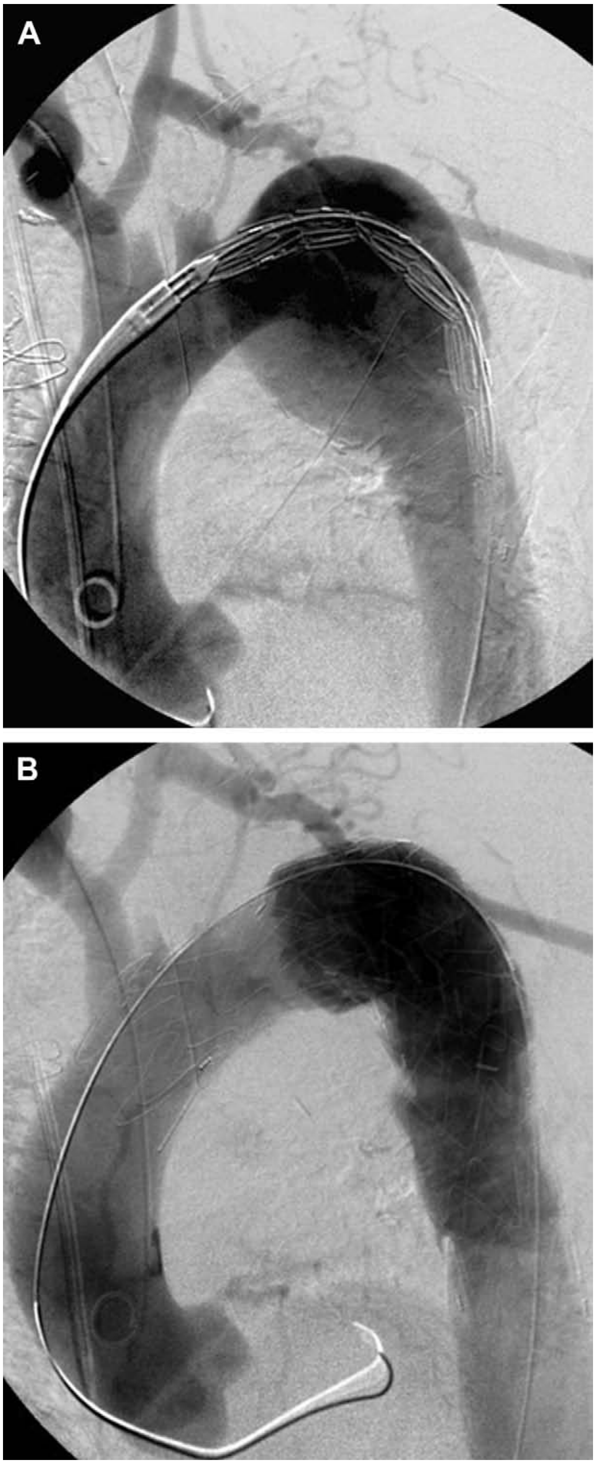

Figure 2 Distal arch aneurysm necessitating anchoring of the stent-graft in zone 1. Transposition of the left CCA and of the LSA was performed prior to EVAR (A). Successful exclusion of the aneurysm after stent-graft implantation (B). Krainz Elfriede.

coverage. Contemporary data from the European Valiant registry,[46] including 180 patients, reported stroke and paraplegia rates of 3.8% and 3.3%, respectively. Six out of seven patients, who suffered from stroke, had a fixation of the stent graft proximal to the LSA, and the stroke rate in patients with LSA occlusion was 9% compared with 0.8% of patients with no coverage or re-vascularisation of the LSA. Recently, a report from the EUROSTAR registry[47] of 606 patients stated that occlusion of the LSA was associated with a higher risks of neurological complications. In the study group reported by Schoder et al.,[48] only two (25%) of eight patients with complete occlusion of the overstented LSA were without symptoms at any time. Furthermore, in the study by Reece et al.,[49] four (20%) out of 20 patients developed late symptoms between 3 and 26 months after a stent-graft procedure with occlusion of the LSA.

Therefore, to minimise the risk for ischaemic complications, one should evaluate the carotid and vertebral arteries, as well as the circle of Willis before intentional LSA occlusion. Anatomic variants, such as origin of the left vertebral artery at the arch or a non-existing fusion of the vertebral arteries to the basilary artery, an inadequate contralateral vertebral artery (VA) and presence of a left internal mammary artery bypass, do not allow LSA occlusion without previous re-vascularisation. Furthermore, prophylactic LSA re-vascularisation should be kept in mind in young patients, in left-handed professionals or in case of previous abdominal aortic surgery to prevent paraplegia. However, management of the LSA, including previous elective re-vascularisation, remains a debated issue.[29,41–51]

Results

Evidence to date proves the feasibility of arch vessel re-vascularisation followed by endovascular repair into zone 0 and 1 of the aorta (Table 2). However, there exist no controlled studies, and the decision to embark on a hybrid strategy depends on the clinician's individual judgment. Presence of endoleaks with respect to different landing zones and the length of proximal anchoring zone were evaluated in the study by Melissano et al.[29] Stent-graft placement into zone 0 was performed in 14 patients with a mean length of the proximal landing zone (PLZ) of 43.9 mm after supra-aortic vessel debranching. In zones 1 and 2, the mean PLZ reached 28.4 mm and 30.4 mm, respectively. A type I or III endoleak in zones 0 and 2 occurred in 7.1% and 7.9%, respectively, whereas in zone 1, having the shortest landing zone, the rate of type Ia endoleaks was 33.3%. Furthermore, after stent-graft anchoring in zone 0, a higher risk of cerebrovascular accident was observed (14.3% compared with 0% in zones 1 and 2). Similar findings were reported by Freezor et al.[50] who found a significant higher incidence of strokes with proximal extent of repair. Seven (78%) of nine patients who had a stroke had coverage of zone 0–2, while 2 (22%) had anchoring of the stent graft distal to the LSA. Out of all patients suffering from stroke, six had posterior circulation stroke associated with coverage of zones 0–2, and only one of the patients had carotid–subclavian bypass prior to stent-graft placement. From the data thus obtained, it might be presumed that re-vascularisation of the LSA is a crucial point in endovascular arch repair. In the latter study, the rate of posterior circulation stroke decreased from 5.5% to 1.2% after adoption of head and neck imaging prior to aortic arch repair.

Table 2 Results after hybrid arch procedures including landing zones 0 and 1

Author	Year	Mortality	Stroke	Spinal cord injury	EL Ia
Weigang et al.	2009	4/26 (15.4%)	0/26 (0%)	0/26 (0%)	0/26 (0%)
Melissano et al.	2007	2/26 (7.7%)	2/26 (7.7%)	0/26 (0%)	5/26 (19,2%)
Czerny et al.	2007	2/27 (7.4%)	0/27 (0%)	0/27 (0%)	4/27 (14,8%)
Bergeron et al.	2006	2/25 (8%)	2/25 (8%)	1/25 (4%)	3/25 (12%)
Saleh et al.	2006	0/15 (0%)	0/15 (0%)	0/15 (0%)	0/15 (0%)
Schumacher et al.	2006	5/25 (20%)	1/25 (4%)	0/25 (0%)	3/25 (12%)
Total		15/144 (10.4%)	5/144 (3.5%)	1/144 (0.7%)	15/144 (10.4%)

EL Ia = endoleak at proximal landing zone.

Retrograde dissection after stent grafting of the arch is reported in various series.[48,52,53] The anatomy of the arch might obviate the stent graft to accommodate, and the limited flexibility of the devices might produce forced wall stress at the outer curvature leading to intimal injuries.

Stent-Graft Repair Without Surgical Supra-aortic Vessel Re-vascularisation

Endovascular repair of aortic arch pathology by means of branch artery stenting, fenestrated and branched stent grafts have been reported as case reports or small case series.[6–10,54–56]

Branch artery stenting

This technique was first described as a bail-out procedure to treat inadvertent coverage of the left carotid artery.[57] Criado[58] has reported a series of eight patients who were treated with a bare metal stent after inadvertently over-stenting of the left carotid artery in six and the LSA in two patients. In this series, stent placement was technically successful in all patients without neurological complications or death. Besides an emergency use of this technique in four patients, Baldwin et al.[10] reported elective stenting of the innominate artery combined with bypass surgery or vessel transposition in three cases and stenting of the LSA in one patient. Stenting of arch vessels was performed without periprocedural complications and no endoleak was observed during follow-up. Although this technique seams feasible, one must be aware that this technique provides additional proximal fixation length but not an additional sealing zone except in aortic pathologies, which are limited to the lesser curvature.

Branched stent grafts

First experiences with branched stent grafts were reported by Inoue et al.[56] in 1999 but primary success rate was only 60% with failures attributed to endoleaks and access site issues. Furthermore, major complications were provoked by multiple cerebral emboli in the vertebral artery and occlusion of the left carotid artery. A further report by this group noted promising results after single-branched stent-graft implantation in aortic aneurysms and dissections involving the LSA.[8] Out of 17 patients one suffered from paraparesis, but none of the patients had a cerebrovascular embolic event. Proximal attachment site endoleaks were found in two patients, and one out of them could be treated by implantation of a double-branched stent graft. Branched stent-graft delivery from a transfemoral access site into the aortic arch is challenging due to the length and tortuousity of the route. As an alternate, device implantation through the ascending aorta was performed.[31] However, this access site is not free of risks, especially in a diseased ascending aorta. Chuter et al.[7] preferred a single branch from the stent graft to the innominate artery in combination with bypass grafts and a transcarotid access route.

Fenestration of stent grafts

Repair of the distal arch with additional fenestration of the stent graft to maintain blood flow into the LSA was reported by McWilliams et al.[55] Fenestration was performed with the back end of a small-gauge guidewire and the hole was enlarged by using a series of cutting balloons. Finally, the fenestration was stented with a balloon-expandable stent. Kawaguchi et al.[6] reported a series of 288 patients who were treated with homemade fenestrated stent grafts. The cerebral infarction rate was 5.5% (16 cases) with a serious outcome in 1.7%, but no complications have resulted from thrombosis of arch vessels. Further complications were paraplegia in 2.6%, aortic injury in 1.2% and iliac—femoral artery injury in 6%.

Conclusion

Endovascular prostheses, which are currently in use, were not designed for the treatment of arch pathologies. Therefore, incomplete alignment, type 1 endoleaks, and retrograde type A dissections may occur. However, the combined endovascular and surgical treatment of aneurysms and dissections involving the aortic arch has proven to reduce the morbidity and mortality rate in comparison to a full open surgical approach. The development of more flexible or curved stent grafts is under way. Branched stent grafts are in their infancy but are needed. Due to the complex anatomic variations of the arch anatomy, the use of single-branched stent grafts is more realistic. Therefore, if combined procedures may be still required, including carotid—carotid and carotid—subclavian bypass or transposition surgery but without the need for upper sternotomies. Endovascular treatment of type A dissections is feasible and has been reported if the primary entry tear is located in the middle of the ascending aorta.[59] However, the majority of entry tears are close to the aortic valve and coronary arteries which may need replacement of the ascending aorta and aortic valve by a composite graft. In conclusion, the endovascular therapy of aortic arch pathologies has proven to be a less-invasive way of treatment but needs further refinement of devices.

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