

Total arch replacement: Technical pearls



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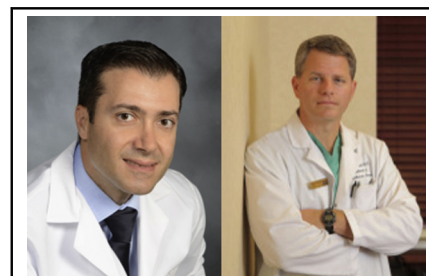
Since its first description by DeBakey and colleagues in 1957,¹ total arch replacement (TAR) has benefited from an ongoing technical evolution leading to ever-improving outcomes.² An ample scrutiny of competing techniques for the procedural steps of TAR has populated the literature with a sizable body of evidence. Having shown the equivalency of cerebral protection strategies,³ herein we share exquisitely technical aspects to tailor TAR to specific scenarios.

DIFFERENT WAYS TO SKIN A CAT: SUPRA-AORTIC TRUNKS REIMPLANTATION

The various techniques for reimplantation of the supra-aortic trunks (SATs) during TAR are equivalent in terms of early and late outcomes.^{4,5} Therefore, the adoption of a certain technique ought to be based on the particularity of each case.

En Bloc Technique

The en bloc technique (EBT), which entails reimplantation of an island of aortic wall containing the ostia of the innominate artery (IA), left carotid artery (LCA), and left subclavian artery (LSA), has certainly withstood the test of time and remains a mainstay of TAR. The small island technical variant, which contemplates en bloc reattachment of the IA and LCA, particularly when they have a common origin (ie, bovine arch), is complemented with a separate bypass to the LSA that in such instances has often a more distant origin. The ideal indication for EBT is the replacement of degenerative aneurysms in elderly patients. In the latter, the risk of leaving behind a rim of aortic tissue that can become aneurysmal over time is minimized by both the absence of connective tissue disease and the shorter life expectancy. Additionally, the reduced time required to perform the Carrel patch is particularly beneficial in elderly patients with a decreased tolerance for prolonged circulatory arrest times.⁶ But there is a caveat: If not given extra care, the Carrel patch can paradoxically produce the opposite effect with bleeding that is difficult to control and will jeopardize the whole concept of limiting operative times for



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CENTRAL MESSAGE

Because evidence does not support a 1-size-fits-all procedural approach to total arch replacement, it is fundamental to be familiar with the entire technical armamentarium to optimize its outcomes.

See Commentary on page 14.

these frail patients. Indeed, bleeding from the posterior aspect of the Carrel patch and of the distal aortic anastomosis is difficult to visualize and treat because of the proximity and orientation of the 2 anastomotic sites. Therefore, we strongly advise investing extra time in making the relative suture lines as hemostatic as possible. To this purpose, after the customary continuous suture line, we meticulously add a crown of interrupted 4–0 polypropylene pledgeted stitches. The latter are preferable to a strip of felt, which is more expeditiously completed but will obscure and make difficult to pinpoint eventual sources of bleeding along the suture lines. Although the pledgets' crown should ideally cover the entirety of the suture lines, sometimes clinical judgment warrants reducing the time under circulatory arrest. In the latter scenario, we advise reinforcing with the crown of pledgets at least the segments of the suture lines that will be obscured to direct vision once the adjacent anastomoses are completed.

Anatomic Branch Technique

The Occam's razor, a principle enunciated by the homonymous 13th century philosopher, states that "entities should not be multiplied without necessity." Applied to TAR, this means that we should forfeit the simplicity of EBT for

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individual implantation of the SAT only if valid reasons like the following apply: to avoid the risk of Carrel patch aneurysm in young patients with connective tissue disease; to re-implant SATs that have widely distant ostia; to reduce the risk of malperfusion and embolization, or simply not to compromise the anastomotic site when the SAT's origin or surrounding aorta are dissected or significantly atheromatous.

Performing TAR with anatomic branch technique (ABT)⁷ is facilitated by the utilization of a prefabricated graft, which presents 3 branches for the SATs and a fourth branch to provide distal aortic perfusion (Gelweave Plexus; Vascutek Ltd, Inchinnan, United Kingdom). Upon completion of the distal aortic and LSA anastomoses under circulatory arrest, we clamp the graft proximally to them and restart extracorporeal flow through the perfusion branch to the systemic circulation (via descending aorta) and to the cerebral circulation (via left vertebral artery). Clinical judgment dictates the next step. In the presence of poor cardiac function, we may proceed to complete the proximal aortic anastomosis to expedite coronary reperfusion. Conversely, we prioritize reimplantation of IA and LCA when the limit of a safe ischemic interval for the encephalon is approaching. Compared with Carrel's patch, bleeding after ABT is generally less problematic. Indeed, the individual SAT anastomoses are more hemostatic because the tension of the suture line is better maintained on their smaller circumference; additionally, eventual bleeding is more accessible. Nonetheless, the posterior aspect of the LCA and LSA anastomoses can be difficult to access once the arch regains rigidity after weaning from cardiopulmonary bypass. Therefore, after fashioning the posterior semicircle of the LCA and LSA anastomoses, it may be wise to reinforce it by running endoluminally a second layer of polypropylene 5-0.

Trifurcated Branch Technique

We adopt a nonanatomical reconstruction of the SAT with the trifurcated branch technique (TBT) in some instances, such as when the prefabricated 4-branched graft is not the best fit to the aortic arch (either because of its native configuration or because of previous replacement of adjacent segments), to move proximally the distal aortic anastomosis (either to avoid injury to the recurrent laryngeal nerve, or to perform a type II hybrid TAR), or to adopt alternative iterations of cerebral perfusion.⁸ This technique is facilitated by the adoption of a prefabricated graft with a 12- to 14-mm main body and 8- to 10-mm side branches (eg, Gelweave Trifurcate Arch Graft; Vascutek Ltd). TBT allows surgeons to separate the reconstruction of the SAT and of the aortic arch itself, with many technical variants. One iteration is to anastomose first the SAT to the side branches of the trifurcate graft, whose main body can be then connected to an additional extracorporeal line to deliver cerebral perfusion.⁸

Subsequently, after the arch is replaced with a tubular graft, systemic circulation can be re-established also. Finally, the trifurcated graft is anastomosed end to side to the anterolateral aspect of the reconstructed ascending aorta.

CURVE BALLS: SAT VARIANTS

The branching pattern of the aortic arch varies from the dominant configuration (ie, IA, LCA, and LSA) in 19.1% of cases.⁹ Therefore, it is important to preoperatively plan the strategy for SAT reimplantation, with multiplanar analysis of computed tomography. Below, we review some technical aspects that allow to deal with SAT variants.

Aberrant Left Vertebral Artery

This variant has a prevalence of 2.9%.⁹ When EBT is utilized, the left vertebral artery (LVA) can be often included in the Carrel's patch. Conversely, this variant requires additional preoperative considerations if ABT/TBT are planned. In such cases, a combination of computed tomography and duplex sonography should assess both the right vertebral artery (size, patency, and antegrade flow), and the integrity of the circle of Willis. In the presence of a right vertebral artery able to pressurize the posterior cerebral circulation, we advise reimplanting the LVA during rewarming to save circulatory arrest time. With this sequence, the surgical access to reimplant the LVA in anatomical position may be challenging. Therefore, we suggest either an interposition vein graft to the aortic arch, or direct anastomosis to the LCA. A small aberrant LVA can be sacrificed in the presence of well-compensating right vertebral artery.

Aberrant Right Subclavian Artery

This variant has a prevalence of 0.7%.⁹ An aberrant right subclavian artery (RSA) typically rises from the descending aorta and crosses the midline behind the esophagus to originate the right axillary artery. Anatomical replacement of an aberrant RSA is not practical during TAR via sternotomy. Therefore, the most convenient option is a preemptive right carotid to subclavian bypass with a supraclavicular approach. During this procedure, an important caveat is to ligate the RSA proximal to its vertebral and mammary branches, so that the latter can remain perfused after an eventual second-stage operation that obliterates the origin of the aberrant RSA. Second-stage operations contemplate almost invariably descending thoracic aorta replacement, because either the origin of the aberrant RSA (ie, Kommerell's diverticulum, a wide-mouth dilatation involving the surrounding aorta) or the aorta itself are aneurysmal.

Distant or Hostile LSA

Although not due to anatomical variants, there are instances that call for an extra-anatomical reconstruction of the LSA. Firstly, adequate access for anatomical reconstruction can be compromised either by caudal displacement of

the LSA origin, or by dorsal rotation of the aortic arch. Secondly, there are circumstances when we may want to situate the distal aortic anastomosis before the LSA origin. For instance, it can be challenging to anastomose distal to the LSA in an aortic arch that is small because it is acutely dissected but not aneurysmal. Also, we may elect to perform the first stage of an elephant trunk proximal to the point of intersection with the recurrent laryngeal nerve, when the latter is adherent the arterial wall or simply to minimize its postoperative dysfunction (eg, in patients with respiratory compromise). All these scenarios are dealt with ligation of the LSA origin, and performance of an extra-anatomical bypass. If this is foreseen preoperatively, supraclavicular left carotid-subclavian rerouting with either transposition or bypass are suitable options. If the decision arises intraoperatively, an 8- to 10-mm graft is anastomosed to the left axillary artery with an infraclavicular approach, tunneled through the second intercostal space, and anastomosed to the aortic graft directly or to the LCA.

HYBRID TAR

The circulatory arrest required by TAR is a daunting proposition to patients who, for age or comorbidities, are at high surgical risk. Therefore, avoidance of circulatory arrest has been pursued with hybrid TAR, which was first performed by Volodos in 1991.¹⁰ It ought to be specified that, to compare apples to apples, only zone 0 hybrid repair can be deemed equivalent to TAR. Zone 0 hybrid TAR implies SAT reimplantation with the TBT on the native (type I) or prosthetic (type II) ascending aorta.¹¹ Type II hybrid TAR is necessary when the native ascending aorta is either hostile for the end-to-side anastomosis (eg, calcified), or is unsuitable as a landing zone (eg, diameter >40 mm and length <20 mm), or prone to early and late complications (eg, dissected, with increased risk of migration, endoleak, retrograde type A dissection, and rupture). In such cases, replacement of the ascending aorta under circulatory arrest is the necessary step before debranching. The latter is performed similarly to the TBT previously described, with the technical caveat of paying attention to the hypotension–hypertension dichotomy (a problem not present during the circulatory arrest of open TAR). Moderate hypotension is advised during the zone 0 end-to-side anastomosis to avoid complications with the native (eg, dissection or rupture) or the prosthetic (eg, slippage of the clamp) ascending aorta. Subsequently, moderate hypertension is advised while sequentially performing the SAT end-to-end anastomoses (intrathoracic or via separate neck access) to optimize the pressurization of the cerebral vasculature.

With the ostia of the SAT oversewn, the entire aortic arch can be stented anterogradely via an additional side-graft anastomosed to the proximal aorta. After stent deployment, the polyethylene terephthalate side-arm is stapled off with a vascular Gia gun (Covidien, Minneapolis, Minn).

Alternatively, the stent can be deployed retrogradely via the iliofemoral system, concomitant with the debranching or at a second stage.

Lately, even its main proponents candidly admit that hybrid TAR has not delivered the purported advantages in high-risk patients. Indeed, recent risk-adjusted series showed the superior early and late outcomes of open TAR. In their cohort of 238 patients, Joo and colleagues¹² demonstrated that open and hybrid TAR had similar operative mortality, but the latter was plagued by a higher incidence of stroke (12.5% vs 2.9%; $P < .01$). After propensity score matching, a notable difference remained (14.5% vs 2.1%). Ten-year survival was significantly reduced by a hybrid approach in the overall (41% vs 82%; $P < .01$) and matched (43% vs 75%; $P = .04$) samples. Open replacement also presented superior freedom from reintervention at 10 years in the overall (88% vs 37%; $P < .01$) and matched (93% vs 34%; $P < .01$) samples. The argument commonly advocated by proponents of catheter-based procedures (ie, reinterventions are usually minor procedures) cannot be used here: 38% of reinterventions were open conversions in the hybrid group.¹² Analogous series showed similar results, although weakened by a shorter follow-up.^{13,14} Nonetheless, we believe that hybrid TAR has a place in the armamentarium of aortic surgeons. For instance, patients with impaired renal function might benefit from the avoidance of circulatory arrest. Indeed, Preventza and colleagues¹⁵ demonstrated that the hybrid approach had lower incidence of acute renal insufficiency both in the overall (20% vs 9%) and matched (28% vs 12%) cohorts, although the small sample size was not adequate for reaching statistical significance. Therefore, avoidance of circulatory arrest remains among the few benefits of hybrid repair for high-risk patients. In reality, a good portion of patients will have to undergo type II hybrid TAR because of a hostile ascending aorta,^{16,17} with the necessity of circulatory arrest that partially defeats the purpose of the hybrid approach.

ELEPHANTS, SOMETIMES WITH SKIRTS

The distal anastomosis of TAR requires additional considerations in patients who are either already in need of descending aorta replacement (ie, mega-aorta carriers), or who will likely require it (ie, dissection carriers). In such instances, the surgeon will be kind to the patient and him/herself if during TAR he or she paves the way for a smoother second-stage operation. In 1982, to this purpose Borst and colleagues¹⁸ introduced the concept of elephant trunk: a graft that, anchored to the distal TAR anastomosis, freely floats in the descending aorta. This initial iteration contemplated suturing an inner tube (ie, the graft) within the closed confines of an outer tube (ie, the aorta).¹⁸ The required suturing at a difficult angle exerted a significant tension on the aortic wall, with microtears that were probably responsible

for fatal delayed ruptures at the anastomotic site.¹⁹ The invagination technique, as ultimately described by Svensson in 1992,²⁰ obviated such concerns by allowing a comfortable open distal aortic anastomosis to the invaginated polyethylene terephthalate graft. Here we delve into a few tenets to optimize it. Firstly, the smaller the aortic lumen (eg, acute dissection) is, the shorter the elephant trunk should be. Indeed, peri-elephant trunk thrombosis is conceivably more probable when the space between graft and aortic wall is minimal, with consequent obliteration of the intercostal arteries and delayed spinal cord injury, per early reports.¹⁹ Secondly, inserting a long stay suture to the proximal edge of the graft greatly facilitates later evagination, especially from aortas of small circumference. Thirdly, in selected dissection cases we condone the practice of obliterating the false lumen with 4 to 5 mattress pledgeted 4–0 sutures on the luminal side and a strip of felt on the adventitial side.^{21,22} This practice creates a solid substrate for the distal aortic anastomosis, by reinforcing the friable acutely dissected wall, or by collapsing the indurated intimal flap of the chronically dissected aorta [Figure 1](#).

The invagination technique does not address satisfactorily some instances, which we prefer to tackle employing the skirted graft that was conceived by Neri and colleagues in 2004.²³ Indeed, mega-aortas may present such large diameters of the distal arch that even anastomosing the biggest conventional graft with the invagination technique would lead to anastomotic tension. In this scenario, the skirt of the graft is trimmed to match the aortic circumference, allowing a tension-free anastomosis. Another scenario suited for the skirted graft is when ABT and elephant trunk are required concomitantly because it is not practical to invaginate and then retrieve a quadrifurcated graft. In either instance, after the trimmed skirt is anastomosed under circulatory arrest, we connect the dedicated perfusion branch to the cardiopulmonary bypass circuit, and de-air. Subsequently, the main body of the graft is clamped proximal to the perfusion branch, and the lower body is reperfused while performing either EBT with the Siena Ante-Flo, or ABT with the Siena Plexus (Gelweave Grafts, Vascutek Ltd).

HOW TO CATCH 2 BIRDS WITH 1 STONE: FREEZE THE TRUNK

Although the elephant trunk facilitates a second-stage repair of the descending aorta, it does not directly incorporate it in the initial operation. This leads to a nonnegligible mortality between the 2 stages.^{24,25} Additionally, a considerable number of patients are lost to the second operation,⁵ paving the way to late complications inherent to the natural history of degenerative and dissecting aneurysms.²⁶ The frozen elephant trunk (FET) represented a further evolution to obviate such problematics, by performing synchronously TAR and antegrade thoracic endovascular aortic repair

(TEVAR). When dedicated hybrid frozen elephant trunk devices are not available, a spurious iteration of this concept combines proximal aortic replacement and antegrade TEVAR. Although the proximal repair has been mostly limited to a hemiarch in the pertinent literature,^{15,27,28} here we only describe the technicalities of concomitant TAR and antegrade TEVAR. It is advisable to employ a device that is both malleable and fully covered, as free-flow bare stent endings will prevent the incorporation of the endograft in the suture line as described below. Such an endograft (eg, Conformable GORE TAG; W.L. Gore & Associates, Newark, Del) is manually bent according to the patient anatomy. The latter also dictates the stent length, which should be 10 or 15 cm, with the latter as upper limit to reduce the risk of spinal cord injury.²⁹ The endograft should be oversized ~10% to 15%, with the usual cautions and limitations in the presence of an acutely dissected aorta, which is measured according to the long axis of the true lumen in zone 3. Under circulatory arrest and with the native arch resected, a bronchoscope is utilized to visualize the descending aorta before and after stent deployment to exclude theoretical pitfalls (eg, wire breaching the false lumen of dissected aortas). A soft glide wire is inserted into the true lumen and exchanged it over a catheter for a stiff wire (eg, Lunderquist extra-stiff wire; Cook Medical LLC, Bloomington, Ind) that is advanced ≤ 20 cm. The endograft is then deployed over the stiff wire, with the upper limit of zone 3 as proximal landing zone. Delivery of warm saline over the endograft favors its complete expansion in a hypothermic body. We condone conforming the endograft to the aortic wall with the 30 mL balloon of a soft Foley,²⁷ especially against the hardened flap of chronic dissections, but not in the fragile true lumen of acute dissections. The stent graft is adapted and secured to the gentle concavity of zone 3 upper edge with a couple of 4–0 polypropylene pledgeted stitches. The distal aortic anastomosis is then performed by incorporating both the surgical graft and the endograft in the suture line along the lesser curvature of the arch. The procedure is then completed by carrying out the TAR. This technique will inevitably leave behind a triangular portion of aorta (hypotenuse corresponding to the convexity of upper zone 3) that, although small, conceivably opens to the possibility of type IA endoleaks. The latter are virtually impossible with a dedicated FET hybrid device, which was introduced in 2003 by Krack and colleagues³⁰ combining a proximal conventional graft to a distal covered stent. Since initial commercialization in 2007, off-the-shelf FET devices have evolved to provide a comprehensive solution that optimizes not only concomitant treatment of the descending aorta, but also the previously discussed concepts of SAT reimplantation and distal aortic anastomosis. We will delve on a few technical caveats regarding the utilization of the different E-Vita (Jotec GmbH, Hechingen, Germany) and Thoraflex (Vascutek) models. To reduce

type IB endoleaks, ideally their stented portion should be oversized $>10\%$ the aortic diameter, aiming at a sealing zone >30 mm in healthy aorta (provided the total covered aorta is <150 mm to reduce spinal cord injury).³¹ The catheterization of the aortic arch with an extra-stiff guidewire via femoral artery ought to be planned preoperatively with computed tomography (eg, to identify the best access and route to the true lumen in dissections), and confirmed intraoperatively with transesophageal echocardiogram. Under circulatory arrest the aortic arch is resected, the endograft portion of FET device is inserted into the descending aorta over the guidewire and deployed according to the specific steps indicated by each manufacturer. Subsequently, the distal aortic anastomosis is performed utilizing the skirted portion of the hybrid graft, which is a useful feature of both E-Vita and Thoraflex devices. Reimplantation of the SAT with EBT can be performed with either the dedicated E-Vita (the older Open Plus model does not have a perfusion branch, which is included in the latest Open Neo Straight model) or Thoraflex (Ante-Flo model, which has a perfusion branch) devices. Reimplantation with ABT can be pursued with the E-Vita Open Neo Branched or the Thoraflex Plexus devices, which both present individual branches for the SAT and a fourth perfusion

branch. If there is an interest in moving the distal aortic anastomosis to zone 0 to 1 and/or pursuing reimplantation with TBT, the E-Vita Open Neo Trifurcated presents a trifurcated branch for the SAT with the addition of a perfusion branch.

A final cautionary note to discern whether to use elephant trunk or FET. By choosing the latter, we accept a higher risk of spinal cord injury³² hoping to reduce further distal interventions. But such rationale becomes questionable when we realize that, even in the best hands, the overall reintervention rates after elephant trunk and FET are similar.⁵ Therefore, when the natural history predicts a high probability of late reinterventions (eg, young patients with connective tissue disease or extensive dissection), the classical elephant trunk would appear to be the most cautious approach.

CONCLUSIONS

Substantial technical developments have improved the outcomes of TAR over the past few decades. Nonetheless, current evidence does not support the superiority of specific techniques in performing the procedural steps of TAR. Because the selection of the appropriate technique for each specific scenario is left to clinical judgment, it is

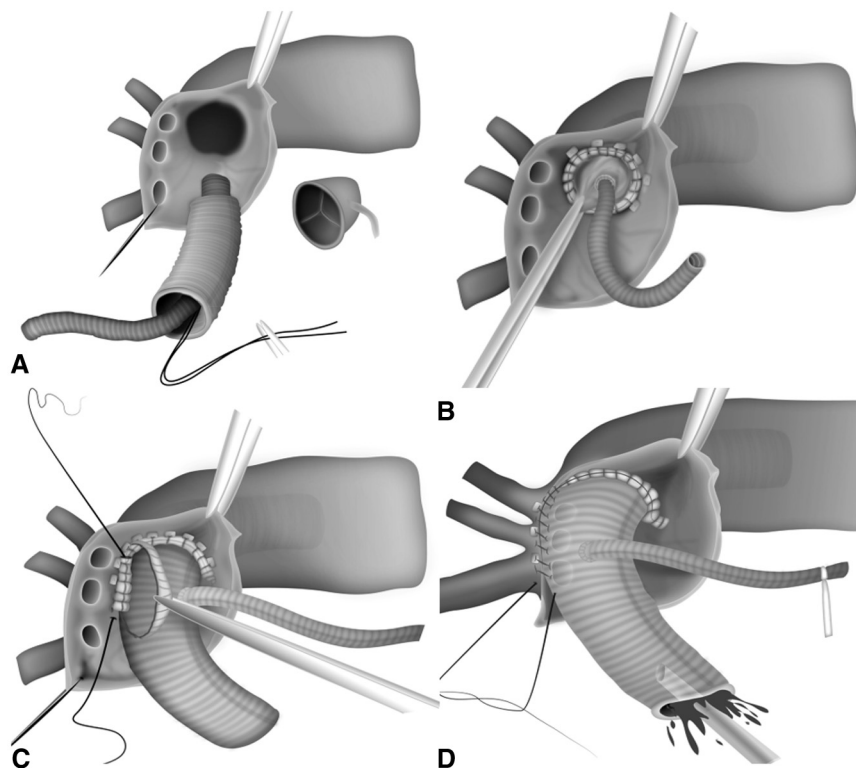


FIGURE 1. Total arch replacement with elephant trunk. A, After insertion of a stay suture to the proximal edge to facilitate retrieval, the large-diameter aortic graft is invaginated. The depicted small-diameter graft represents a perfusion branch. B, The distal aortic anastomosis is fashioned with polypropylene, firstly as a continuous suture line and subsequently as interrupted mattress pledgeted sutures. C, After evagination of the graft, the Carrel patch containing the supra-aortic trunks is anastomosed en bloc. D, The perfusion branch is connected to extra-corporeal flow, and de-airing performed before completing the proximal aortic anastomosis.

important for surgeons to be familiar with the whole technical armamentarium of TAR.

Conflict of Interest Statement

The authors reported no conflicts of interest.

The *Journal* policy requires editors and reviewers to disclose conflicts of interest and to decline handling or reviewing manuscripts for which they may have a conflict of interest. The editors and reviewers of this article have no conflicts of interest.

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