Frozen elephant trunk technique in redo aortic arch surgery: a step-by-step approach

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Frozen elephant trunk (FET) is an established treatment modality for complex aortic arch and proximal descending aortic pathologies. While patients with limited life expectancy are more frequently considered for endovascular treatment options, the FET remains a sustainable platform, especially for younger post-dissection and heritable thoracic aortic disease (HTAD) patients. These patients frequently have undergone previous transsternal operations. A substantial portion require concomitant aortic root or other cardiac procedures. In this manuscript we describe our technique of redo valve sparing aortic root replacement (VSARR) and total aortic arch repair with FET implantation. Our technique combines four main technical aspects: (I) central arterial cannulation is our first option with axillary access being a secondary alternative. Femoral cannulation is only used in bail-out situations or in combination with upper body arterial access. (II) We prefer to revascularize the left subclavian artery (LSA) within the chest during the same procedure. Many alternative options exist for specific anatomical situations. Ideally, the LSA revascularization technique should not add any hypothermic circulatory arrest (HCA) time to the procedure. (III) We liberally address concomitant cardiac pathologies during the same procedure. To avoid long cardiac ischemia times in these complex cases, we employ non-cardioplegic myocardial perfusion during aortic arch repairs where ischemia times of >120 min are anticipated. (IV) During aortic arch preparation we use temporary "flush" retrograde cerebral perfusion (RCP) to reduce the risk of embolization to the supraaortic arteries. After aortic arch preparation bilateral or trilateral selective antegrade cerebral perfusion (SACP) is routinely initiated. The technique allows complex combined cardiac and aortic arch operations to be performed in a standardized and controlled surgical environment. FET implantation will remain an important open surgical tool in the armamentarium of complex aortic arch repair. Creating durable surgical results and minimizing surgical risks have to be the primary goals regarding surgical management.

Keywords: Frozen elephant trunk (FET); redo aortic arch surgery; hereditary thoracic aortic disease; aortic dissection; total arch replacement

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Introduction

Frozen elephant trunk (FET) has become an established treatment modality for complex aortic arch pathologies involving the descending aorta. Despite the technical complexity and inherent perioperative risks, FET can be performed with excellent early and durable long-term results in appropriately selected patients, particularly in certain acute aortic dissection populations, younger patients and those with heritable thoracic aortic disease (HTAD) (1-6). Aortic arch interventions after previous proximal aortic surgery have evolved into a differentiated field with an expanding spectrum of effective treatment options, including open, hybrid, and endovascular approaches (2,3,6-8). In contemporary practice, patient selection is driven less by technical feasibility alone and more by age, life expectancy, connective tissue status, prior index repair, and the anticipated need for durable downstream aortic management. In specialized centers, endovascular or hybrid arch repair has become an acceptable option for selected high-risk patients after previous ascending repair, particularly in older patients, frail patients, and those considered unfit for conventional redo arch surgery (7,8). However, these approaches remain associated with substantial reintervention rates and are not suitable when concomitant root surgery or other intracardiac procedures are needed. By contrast, in younger patients, especially those with HTAD or long-life expectancy after limited prior repair of acute type A dissection, open total arch replacement with FET remains a central reconstructive strategy (9-11). Given that a proximal aortic repair may be exposed to approximately 400 million cardiac cycles over a 10-year period, the need for a durable platform becomes particularly evident in these patients.

The rationale for redo FET in HTAD and post-dissection disease is increasingly supported by institutional experience. In the Hannover Marfan cohort, the main indications for FET are acute and chronic dissection (9). Two thirds of these patients have undergone previous cardiac surgery. More than half require later distal reintervention, underscoring the progressive nature of the disease and the value of durable proximal reconstruction. Similar data was reported from the E-Vita Open registry group (11).

In parallel, the development of branched and trifurcated FET grafts, the proximalization of the aortic anastomosis, and individualization of perfusion and organ-protection strategies have reduced the operative risk of FET procedures (3,4,12). In the context of redo operation this evolving experience facilitates complex procedures, such as combined root and aortic arch repair in one reoperation.

Our current technique reflects an evolution toward a standardized, branched FET-based approach with an individualized organ protection strategy, tailored according to the specific anatomical needs and comorbidities of the patients. The most common scenarios for redo FET procedures are HTAD and post-dissection patients (*Figure 1*).

Preoperative planning

Preoperative computed tomography imaging is mandatory. For redo FET procedures imaging from the neck vessels to the groin is recommended. Meticulous evaluation should address retrosternal distances, arterial and venous access vessels for extracorporeal circulation (ECC), aortic root pathology, coronary anatomy and calcification, as well as anatomical considerations relevant to organ protection management, particularly cerebral perfusion and lower body perfusion.

Preparation and exposition

Preoperative preparation follows current guideline recommendations. We routinely prepare both groins, the bilateral axillary regions, and the entire chest and abdominal wall to preserve flexibility for alternative arterial access, extra-anatomic bypass construction, or emergent peripheral cannulation. The patient is placed in a standard supine position for transsternal access.

Monitoring includes near-infrared spectroscopy (NIRS), along with three arterial lines to assess differential perfusion (radial artery bilaterally, one femoral artery). Transesophageal echocardiography is used routinely. Cerebrospinal fluid (CSF) drainage is not performed routinely. It may be considered in selected patients at high risk for spinal cord injury. If indicated, a CSF drain is placed the day before surgery.

The surgical strategy regarding reopening of the chest, perfusion access points, revascularization of supraaortic arteries and organ protection has to be planned in advance. We follow a policy of central arterial cannulation, if feasible and safe. This includes redo operations. Femoral arterial perfusion is generally avoided (6). It remains a feasible option for rescue situations or may be considered as an additional arterial access together with at least one upper

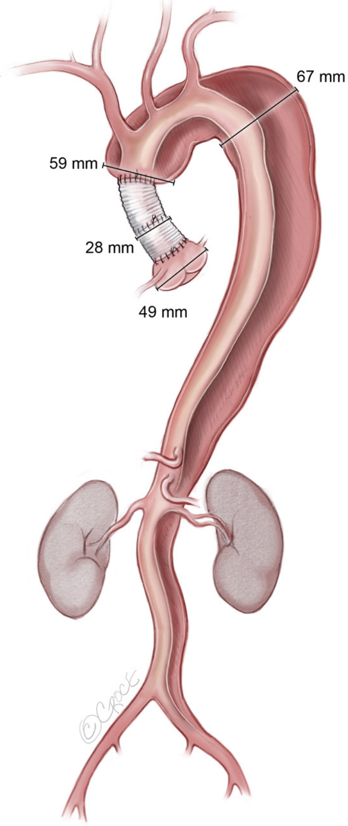

Figure 1 Preoperative anatomy 1.5 years after primary repair of acute type A aortic dissection. The image demonstrates the residual dissection anatomy in a patient with heritable thoracic aortic disease: ascending aortic graft (28 mm), dilated aortic root (49 mm) with moderate aortic regurgitation, aortic arch aneurysm (59 mm), and rapidly enlarging proximal descending aorta (67 mm; growth rate >15 mm/year). A DANE at the distal graft anastomosis is identified as the principal source of persistent false lumen perfusion and the likely driver of progressive distal aortic enlargement. DANE, distal anastomotic new entry.

body arterial perfusion line. The general rule is to avoid retrograde descending aortic flow towards the aortic arch (6) (*Figure 2A,2B*).

We combine central arterial cannulation with temporary "flush" retrograde cerebral perfusion (RCP) during aortic arch preparation (13) and bilateral selective antegrade cerebral perfusion (SACP) (*Figure 2A*). Temporary RCP is only performed in cases where the right axillary artery is not used for arterial perfusion. Our setup allows the use of the cannula in the superior vena cava (SVC) either for RCP or venous drainage.

Regarding the left subclavian artery (LSA) we preoperatively evaluate the anatomical conditions to safely revascularize the LSA within the chest. LSA revascularization should be managed without additional hypothermic circulatory arrest (HCA) times. Our prioritized options are: (I) LSA revascularization after the distal aortic arch anastomosis and under reinitiated lower body perfusion. (II) LSA revascularization during the cooling phase with a separate graft to facilitate later connection with the branched aortic arch graft during the reperfusion/warming phase. (III) If LSA revascularization is deemed too risky or technically cumbersome within the chest, we typically perform an extraanatomic bypass to the left axillary artery. This is either done at the end of the procedure or primarily at the beginning of the operation. In the latter case, the bypass can be used for additional arterial perfusion, as suggested by Tsagakis *et al.* (3) Performing a left carotid-subclavian bypass prior to the FET procedure is another option to facilitate LSA management (14).

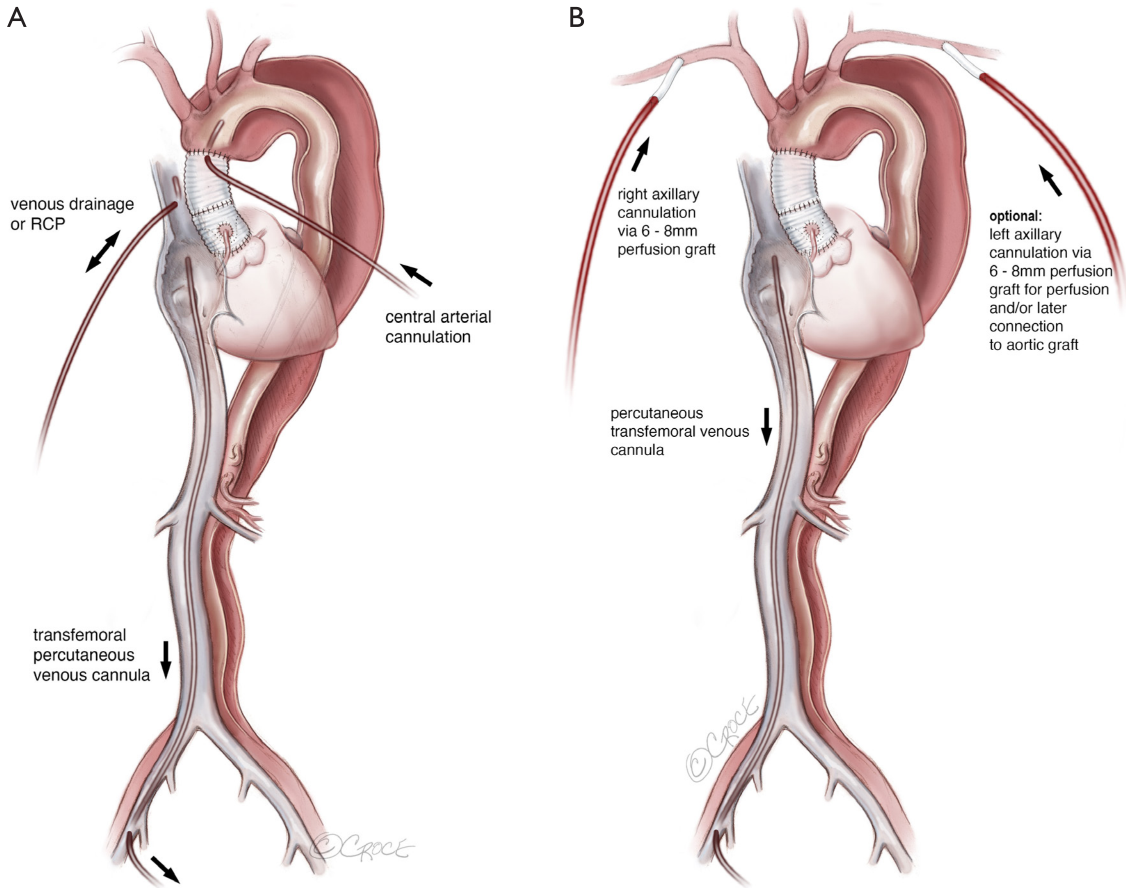

Figure 2 Cannulation strategies for redo aortic arch repair. (A) Venous drainage is established via percutaneous transfemoral cannulation of the right femoral vein and cannulation of the superior vena cava, the latter serving dual purpose for systemic venous drainage and subsequent retrograde cerebral perfusion during hypothermic circulatory arrest. Arterial inflow is achieved through direct cannulation of the pre-existing ascending aortic graft, avoiding the aneurysmal native aortic segments and ensuring controlled antegrade perfusion prior to arch replacement. (B) Alternative arterial cannulation strategies for redo aortic arch repair. Venous drainage is established via percutaneous transfemoral cannulation of the right femoral vein. As the guideline-recommended standard arterial access, right axillary artery cannulation is performed through a 6–8 mm interposition graft, facilitating both systemic perfusion and selective antegrade cerebral perfusion during hypothermic circulatory arrest. Additionally, left axillary artery cannulation via an analogous 6–8 mm interposition graft is depicted as an alternative or complementary option, providing perfusion access while simultaneously serving as the inflow for a potential extra-anatomic bypass to revascularize the left subclavian artery during arch reconstruction. RCP, retrograde cerebral perfusion.

Operation

The operation begins with a standard redo sternotomy. Arterial cannulation for ECC is performed centrally, venous cannulation is achieved in most redo operations transfemorally and in addition via the SVC (*Figure 2A*). Alternatively, right sided or bilateral axillary cannulation may be used for arterial access (*Figure 2B*) (6), depending on anatomical considerations (e.g., deep chest, risk of recurrent laryngeal nerve palsy).

We use two alternative approaches in terms of operative sequence and myocardial protection: (I) in cases with a simple supracommissural aortic connection cardiac protection is managed by standard cardioplegic arrest throughout the procedure. (II) In complex concomitant cardiac procedures with anticipated cardiac arrest times of >120 min, cardiac procedures are performed first, followed

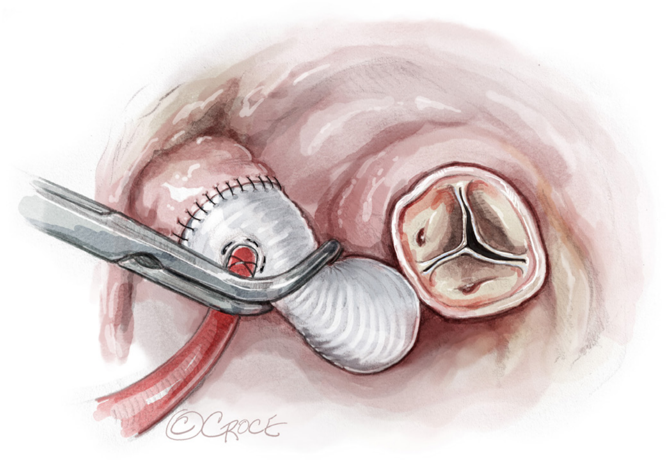

Figure 3 Intraoperative view of the aortic root following cross-clamping and supracommissural transection of the ascending aortic graft. The aortic root demonstrates annuloaortic ectasia with a dilated root geometry and structurally intact, pliable valve leaflets without relevant cusp pathology. This morphology confirms eligibility for valve-sparing aortic root replacement (David procedure), which was pursued despite the added complexity of the concomitant planned frozen elephant trunk repair.

by aortic arch repair under non-cardioplegic myocardial perfusion (i.e., "beating heart arch surgery") (12). This manuscript describes the latter approach.

After establishing ECC the aorta is clamped and opened and cardioplegia is administered in an antegrade fashion. Retrograde cardioplegia is used only in selected situations. Since total myocardial ischemia times can be limited by non-cardioplegic myocardial perfusion during aortic arch repair, we liberally address concomitant cardiac and aortic root pathologies during these operations. In the presented case, valve sparing aortic root replacement (VSARR) was performed after previous acute type A aortic dissection (AADA) surgery in a HTAD patient (*Figures 3,4*). We favor the David technique with a straight tube graft (David I). Our technique has been described previously (15). Hemostasis and aortic valve function are meticulously taken care of at this stage. The venting catheter is advanced into the left ventricle (LV) under direct vision through the aortic root. Adequate venting of the LV is mandatory for non-cardioplegic myocardial perfusion. Cooling is commenced such that the target circulatory arrest temperature (25–28 ℃) is reached upon completion of the cardiac and aortic root procedures.

Our technique of non-cardioplegic myocardial perfusion (*Figure 5*) during aortic arch repair has been described in detail elsewhere (12). In brief, an aortic root cannula (Medtronic, 11F) with an intraluminal pressure monitoring tip is placed in the aortic root. The heart is thoroughly deaired and the aortic graft clamped distal to the aortic root cannula. Non-cardioplegic myocardial perfusion is then initiated with blood from the main circuit (i.e., cooled blood, 18–26 ℃). Perfusion with normothermic blood has also been described (16). Myocardial perfusion with cold blood is adjusted to a target flow of 150–200 cc/min and a target pressure of 50–65 mmHg. Perfusion parameters vary considerably between individual patients depending on the underlying pathology and myocardial mass. Hypertrophied hearts exhibit higher coronary resistance compared to low-resistance pathologies such as valve regurgitation or HTAD, and therefore require higher perfusion pressures to achieve the target flow. Perfusion pressures are limited to a maximum of 80–85 mmHg. Resistance may also increase gradually during perfusion and is temperature-dependent. Before attention is directed to the aortic arch, adequacy of LV venting and myocardial perfusion must be confirmed (*Figure 5*). Should LV distension occur during perfusion—most likely due to inadequate venting and/or aortic regurgitation—conversion to cardioplegia must be considered. Myocardial perfusion via the aortic root cannula is maintained until the aortic arch and aortic root grafts have been anastomosed (see below).

Prior to initiating HCA, LSA revascularization is performed with a separate graft to avoid additional HCA time (*Figure 6*). We prefer to place the distal aortic arch

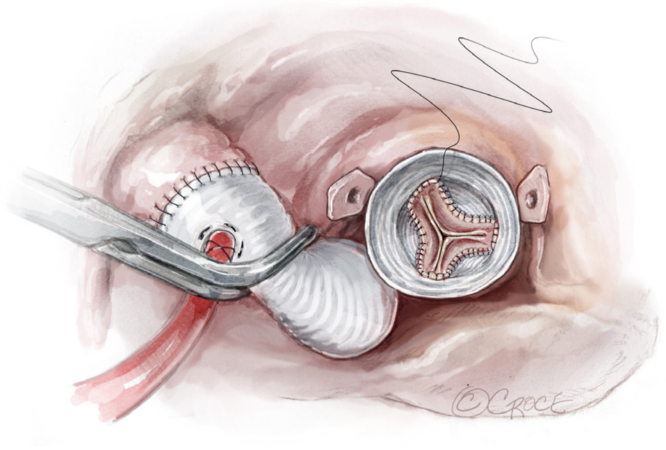

Figure 4 Intraoperative view after aortic valve reimplantation. The aortic valve leaflets demonstrate symmetric coaptation and sufficient alignment. Valve-sparing aortic root replacement was performed using a straight tube graft according to the David I reimplantation technique, which has been the institution's standard approach for three decades. In redo settings with a markedly enlarged aortic root, a Valsalva graft may be considered as an alternative, as the sinus segments can facilitate coronary button reimplantation by reducing tension on the coronary anastomoses.

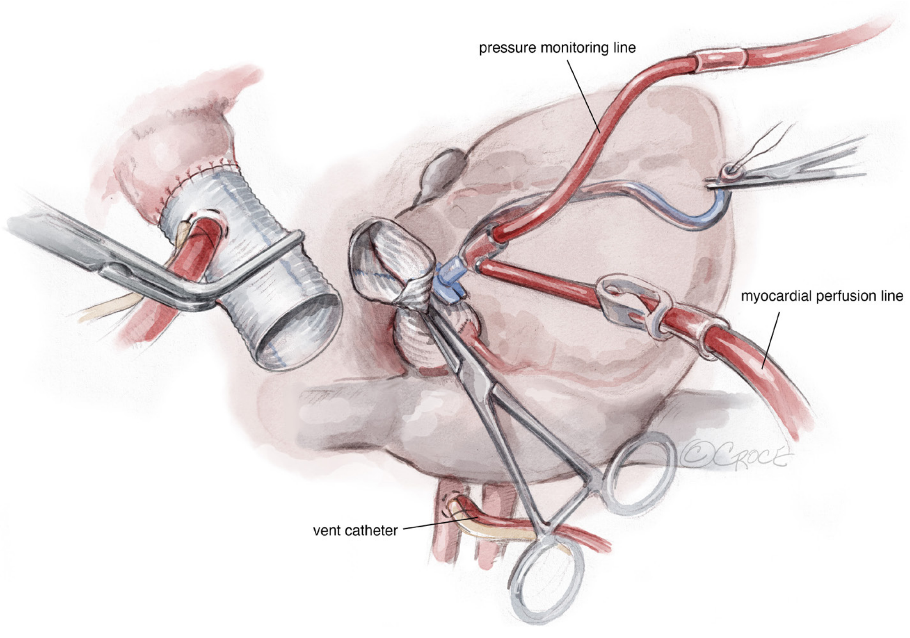

Figure 5 Intraoperative view demonstrating the setup for non-cardioplegic myocardial perfusion. After completing VSARR an 11F aortic root cannula equipped with an intraluminal pressure monitoring line has been inserted into the aortic root to allow controlled antegrade blood perfusion while the heart continues to beat. The ascending graft is clamped distal to the perfusion cannula after deairing the heart in a standard fashion. A vent catheter introduced via the right superior pulmonary vein and advanced into the left ventricle provides continuous cardiac decompression throughout the perfusion period, preventing left ventricular distension. Target perfusion flow is 150–200 mL/min at a perfusion temperature of 26–28 ℃. Perfusion pressure reflects individual coronary vascular resistance: hearts with aortic regurgitation or heritable thoracic aortic disease typically exhibit low resistance and accordingly low perfusion pressures, whereas hypertensive hearts require higher perfusion pressures to maintain adequate myocardial flow. Perfusion parameters are temperature-dependent; some centers

prefer normothermic myocardial perfusion. At our institution, myocardial perfusion is performed at the systemic HCA temperature, and a fibrillating heart is well tolerated throughout the procedure provided adequate left ventricular decompression is maintained via the vent catheter. Most hearts spontaneously convert into sinus rhythm during warming. HCA, hypothermic circulatory arrest; VSARR, valve sparing aortic root replacement.

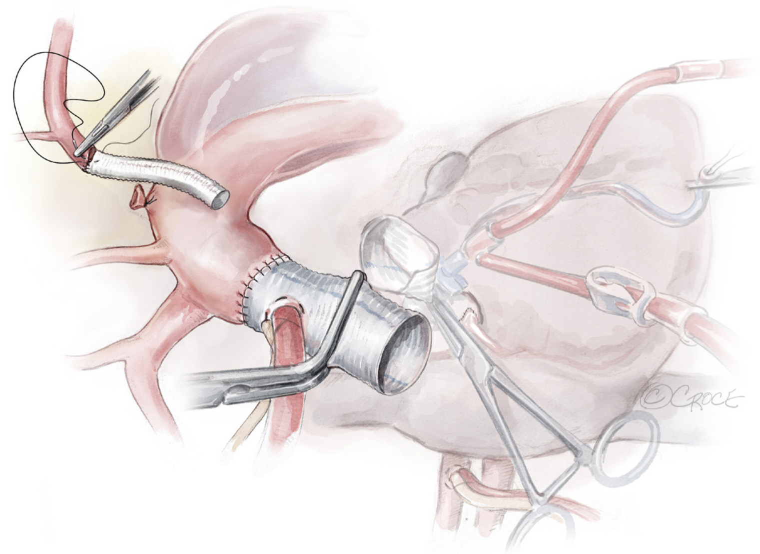

Figure 6 Intraoperative view demonstrating revascularization of the left subclavian artery via a separate 8 mm interposition graft, performed during ongoing antegrade cerebral perfusion through the arch vessels to avoid additional circulatory arrest time attributable to this anastomosis. By completing the left subclavian anastomosis as a separate step prior to frozen elephant trunk deployment and total arch replacement, ischemic time to the left arm and posterior cerebral circulation is minimized while the overall procedural sequence remains uninterrupted.

anastomosis in zone 2. The origin of the LSA is oversewn. Other options to connect the LSA may be used according to the individual anatomy (see above). After LSA connection the graft is clamped temporarily.

HCA is then initiated, the aortic arch opened and RCP is started via the SVC (maximum central venous perfusion pressure of 40 mmHg) during the aortic arch preparation to reduce the risk of air and atherosclerotic particle embolization into the supra-aortic arteries (*Figure 7*). Once aortic arch preparation is completed, trilateral or bilateral SACP is initiated, RCP stopped immediately, and SVC drainage is restored (*Figure 8*). To optimize exposure, four felt-reinforced stay sutures are placed through the aortic wall from outside to inside.

The FET is then implanted in a standard fashion as described previously (2,16). A guide wire is used only in selected cases to aid deployment (e.g., severe kinking of the distal aortic arch). After FET stent graft deployment, early distal perfusion via a Foley catheter may be initiated in selected cases to further reduce HCA time. This is typically not feasible in chronic dissections with significant false lumen backflow, as in the present case. The distal aortic anastomosis is performed as a running suture between the native aorta and the sewing collar of the graft (*Figure 9*). A felt strip may be used to reinforce the anastomosis. The perfusion branch is then cannulated, the distal aorta deaired, the side branches clamped, distal perfusion re-established, and rewarming initiated.

The prosthesis-to-prosthesis anastomosis between the aortic arch graft and the aortic root graft is then performed (*Figure 10*), or—if aortic root surgery was not required—the proximal anastomosis is placed at the sinotubular junction

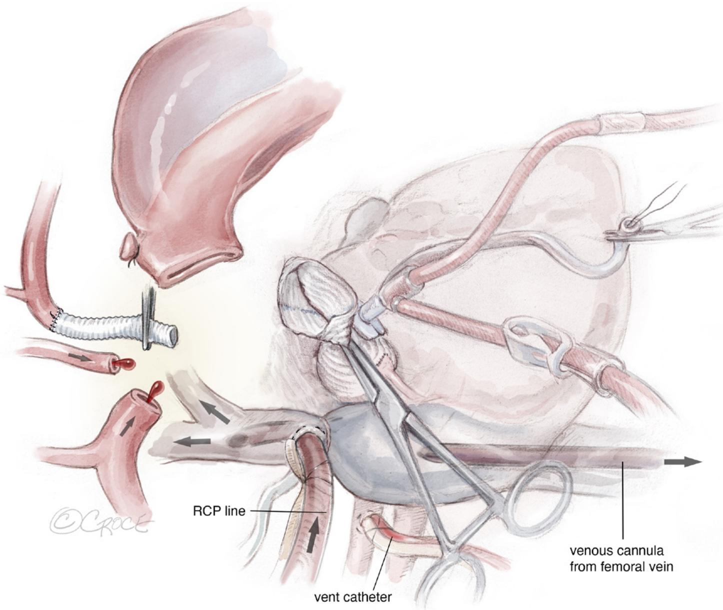

Figure 7 Intraoperative view after initiation of hypothermic circulatory arrest and preparation of the aortic arch. Following cessation of systemic extracorporeal circulation, the arch is opened and RCP is established via the superior vena cava cannula. Backflow of blood through the supra-aortic vessels is visible, serving to flush air and atherosclerotic debris from the supraaortic arteries and reducing the risk of embolization during the open arch phase. Throughout this period, myocardial perfusion is maintained uninterrupted via the aortic root cannula, ensuring continued cardiac protection independent of the cerebral perfusion strategy. RCP, retrograde cerebral perfusion.

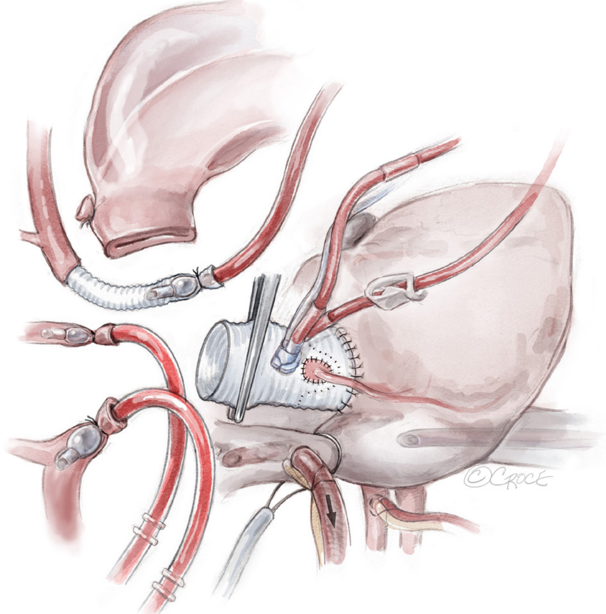

Figure 8 Intraoperative view following preparation of the aortic arch and establishment of trilateral SACP. Perfusion cannulas have been placed into the innominate artery, left common carotid artery, and left subclavian artery via the interposition graft. Retrograde cerebral perfusion is immediately discontinued and the superior vena cava cannula is converted to venous drainage, restoring full systemic venous return. SACP, selective antegrade cerebral perfusion.

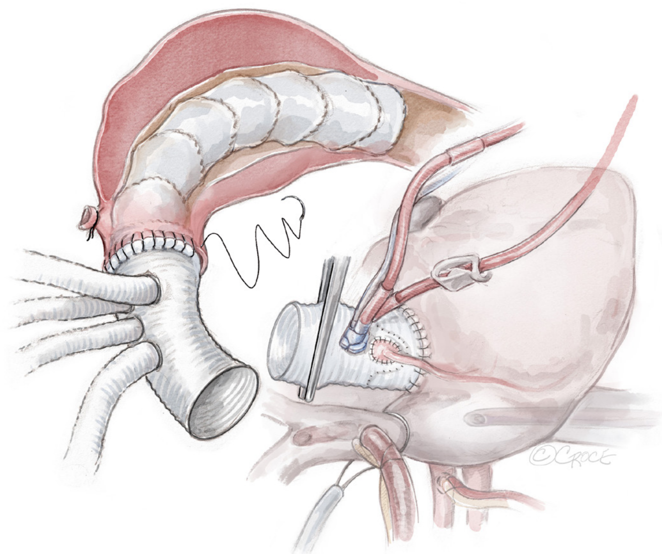

Figure 9 Intraoperative view of the near-completed distal aortic anastomosis in zone 2 following deployment of the frozen elephant trunk into the true lumen of the descending aorta. Prior to anastomosis, exposure of the distal arch in zone 2 is optimized by four felt-pledgeted stay sutures placed through the collar of the frozen elephant trunk prosthesis and tied down, creating a controlled overlap between the native aortic wall and the prosthetic collar. This configuration allows the distal anastomosis to be completed in a straightforward manner using a standard running suture technique with or without additional felt reinforcement.

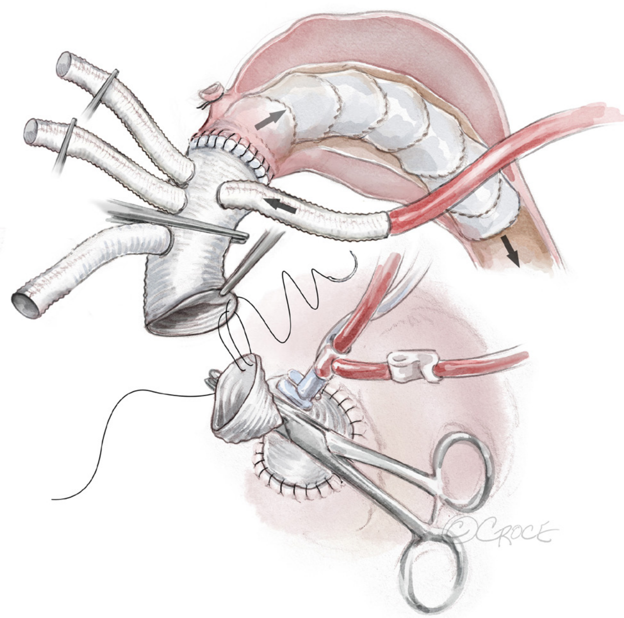

Figure 10 Intraoperative view of the prosthesis-to-prosthesis anastomosis between the aortic arch graft and the aortic root graft following completion of the distal aortic anastomosis, cannulation of the perfusion side branch of the branched FET graft, deairing of the aorta, and establishment of distal perfusion. Rewarming is initiated at this point, allowing efficient use of the remaining anastomotic time. The supra-aortic vessels continue to receive selective antegrade cerebral perfusion. Prior to completion, both prostheses are thoroughly deaired and the aortic clamps are released. Isolated aortic root perfusion via the root cannula is discontinued, with the cannula retained for continued deairing. Myocardial perfusion is subsequently maintained via the arch graft in the standard fashion. FET, frozen elephant trunk.

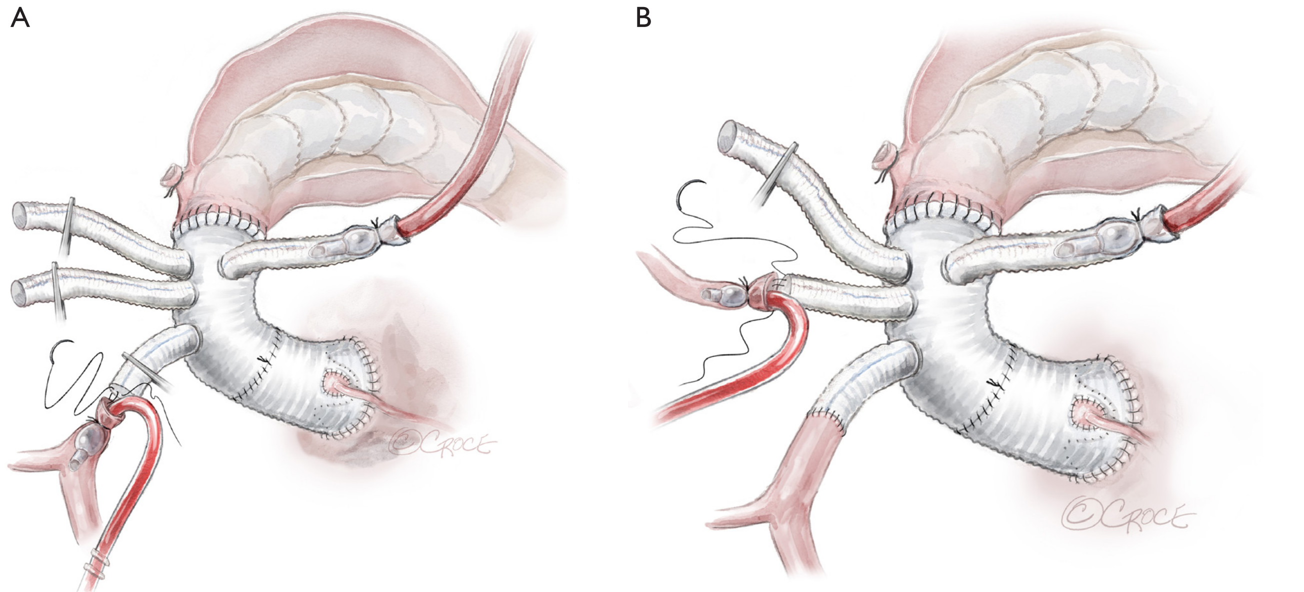

Figure 11 Intraoperative views of the sequential revascularization of the supra-aortic vessels via the side branches of the aortic arch graft. (A) Completion of the anastomosis of the first side branch to the IA. (B) Completion of the anastomosis of the second side branch to the LCCA. IA, innominate artery; LCCA, left common carotid artery.

(STJ). Following thorough deairing of both grafts, the aortic clamps are released and isolated cardiac perfusion via the aortic root cannula is discontinued. From this point onward, myocardial perfusion continues via the aortic arch graft. The aortic root cannula is used for continuous deairing.

Finally, supra-aortic vessels are anastomosed to the corresponding side branches of the aortic arch graft in a standard sequential fashion (*Figure 11A,11B*). The LSA side branch is connected to the previously placed LSA interposition graft (*Figure 12*).

After rewarming and hemostasis, the patient is weaned from bypass. Prolonged reperfusion times are not required, as continuous myocardial perfusion was maintained throughout aortic arch repair.

Comments

Since 2001, over 400 FET procedures have been performed at Hannover Medical School. Since 2012, branched FET grafts have been our predominant approach to total aortic arch repair (2,5,9). FET implantation is used in various pathologies, including acute and chronic dissections and degenerative aneurysms. Compared to other FET series, we follow a liberal policy regarding concomitant cardiac procedures, which account for more than 50% of our cases. Non-cardioplegic myocardial perfusion has been instrumental in reducing cardiac ischemia times in these complex operations and has contributed to improved cardiac outcomes (12,17). Nevertheless, open aortic arch repair remains a technically demanding procedure with substantial operative risks (2,5,9,18). With the expanding availability of endovascular treatment options, catheter-based repair has become the preferred strategy in high-risk surgical patients with limited life expectancy. However, in selected patient cohorts, particularly young post-dissection and HTAD patients, FET implantation remains the standard for durable aortic arch reconstruction. It also provides an optimal landing zone for second stage endovascular completion procedures (19). The creation of safe prosthetic landing zones has also enabled sustainable endovascular aortic repair in HTAD patients and has helped to reduce overall treatment risks in this patient population. FET implantation remains a valuable and indispensable open surgical tool within the growing armamentarium for managing complex aortic arch pathologies (6).

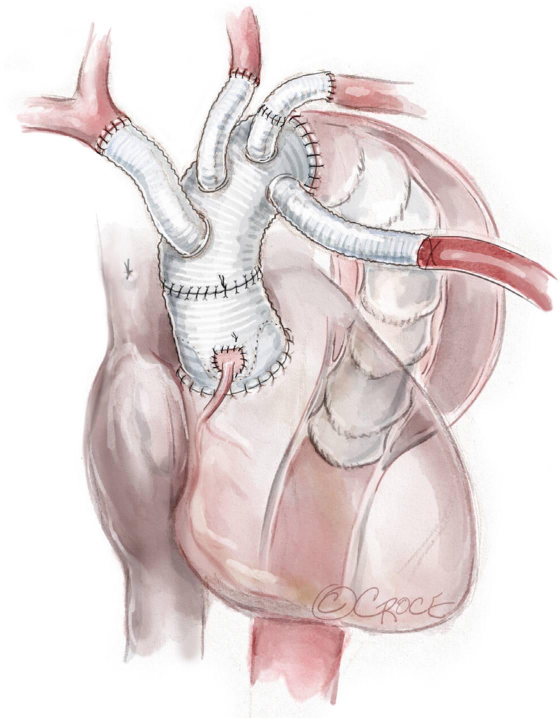

Figure 12 Intraoperative view of the completed aortic arch and root reconstruction. The third side branch of the aortic arch prosthesis has been anastomosed to the interposition graft of the left subclavian artery, completing supra-aortic revascularization. In cases of challenging anatomical conditions, revascularization of the left subclavian artery may alternatively be accomplished via a transthoracic extra-anatomic bypass from the right axillary artery, avoiding direct subclavian dissection and anastomosis in a difficult operative field.

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Footnote

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