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REVIEW ARTICLE

Aortic arch aneurysms and dissection—open repair is the gold standard

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Abstract
The aortic arch repair is one of the most complex surgeries and carries a high risk of complications as well as mortality. Since 1975, when the arch repair was first done by Randall B. Griepp using hypothermic circulatory arrest, many new technologies were introduced. But even with the use of antegrade and retrograde perfusion techniques and improvement of surgical techniques and grafts, the rate of mortality, cerebral, spinal, and visceral damage was much higher as compared to any other cardiac surgeries. With further developments aimed at less invasive approaches, thoracic endovascular aortic repair (TEVAR) along with de-branching of supra-aortic vessels or the frozen elephant trunk was introduced. Here, in this article, we review the myriad of approaches to the aortic arch and have come to a conclusion that while traditional open surgery is considered as the gold standard for treatment of extensive aortic arch pathologies, one school of thought suggests hybrid techniques such as the frozen elephant trunk and aortic arch vessel de-branching as more appropriate procedures for high-risk patients, where co-morbidities may contraindicate cardiopulmonary bypass and longer operative times required for traditional repair. No randomized trials are present to compare between open and hybrid or endovascular procedure in normal or high-risk patients. The meta-analysis of most of the studies defines open surgery as the gold standard for arch pathology because the hybrid procedures did not provide any proven survival benefits or decrease in stroke rate and spinal ischemia when compared to open surgery in early, mid, or long-term results.

Keywords Aortic arch · Aneurysm · Open surgery

Introduction

The arch of aorta is a small segment of the aorta containing the brachiocephalic vessels and is anatomically related to important structures like the phrenic nerve, recurrent laryngeal nerve, vagus nerve, and trachea. It is difficult to access and its surgeries carry a lot of morbidity and mortality. Knowing this, it is horrifying to know that there is an increase in the incidence of aortic aneurysm making aneurysm disease the 18th most common cause of death.

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Treatment of arch pathology remains a challenge in view of cerebral, spinal, and renal protection during its surgery even in this modern age. Although with the improved surgical techniques in cerebral perfusion strategies, the newer grafts, and the peri-operative care, there is a marked reduction of the operative risk associated with the open surgical approach. Yet the mortality and morbidity remain high as compared to other surgeries. So with the advent of the endovascular device, more patients are subjected to TEVAR to avoid conventional surgery. But the decision of the patient cohort for surgical and endovascular therapy remains controversial.

Surgical anatomy

The arch begins just proximal to the origin of the innominate artery and ends just beyond the subclavian artery. The normal aortic arch is of greatest diameter at its origin, averaging 28 mm in its proximal portion and narrowing to 20 mm at the isthmus just distal to the left subclavian artery (Fig. 1) [1].

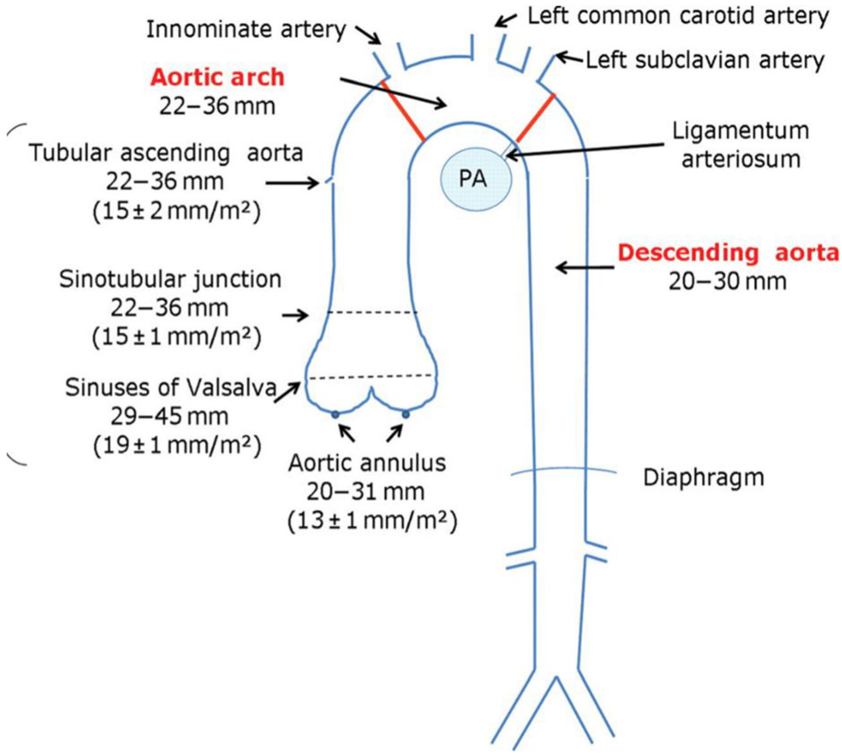


Fig. 1 Dimension of different parts of the aorta

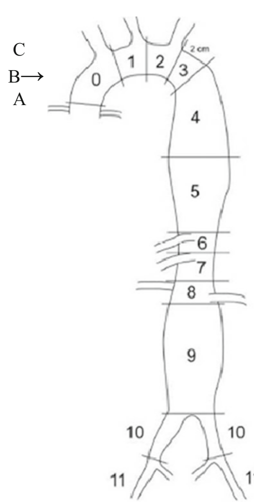
With the advent of endovascular procedure, the aorta is divided into zones (Fig. 2) [2].

An indication of aortic arch surgery

An aortic arch aneurysm is far less common than ascending and descending aneurysm, and in most cases, arch aneurysms represent extensions from ascending or descending aneurysm, so there is no specific criterion.

Symptoms associated with aortic arch aneurysms such as hoarseness resulting from stretching of the left recurrent laryngeal nerve, dysphagia, dyspnea, and chest or back pain are indications for operative intervention for patients with arch aneurysms unless life expectancy is quite limited [3]. Suitability for operative intervention involves a similar risk assessment to that of an aneurysm or other disorders of the ascending aorta and aortic root [4].

According to AHA 2010, endovascular stent grafts have not been approved by the US Food and Drug Administration



A. Below sinotubular junction
B. Sinotubular junction to mid ascending
C. Mid ascending to distal ascending
D. Zone 1 (between innominate and left carotid)
E. Zone 2 (between left carotid and left subclavian)
F. Zone 3 (first 2 cm. distal to left subclavian)
G. Zone 4 (end of zone 3 to mid descending aorta ~ T6)
H. Zone 5 (mid descending aorta to celiac)
I. Zone 6 (celiac to superior mesenteric)
J. Zone 7 (superior mesenteric to renals)
K. Zone 8 (renal to infra-renal abdominal aorta)
L. Zone 9 (infrarenal abdominal aorta)
M. Zone 10 (common iliac)
N. Zone 11 (external iliacs)

Fig. 2 Zones of aorta used in endovascular surgery for the treatment of aneurysms or other conditions of the aortic arch. Therefore, open conventional treatment remains the recommended treatment of choice for arch pathology [4].

Recommendation for symptomatic patient

Class I

1. Patients with symptoms suggestive of expansion of a thoracic aneurysm should be evaluated for prompt surgical intervention unless life expectancy from comorbid conditions is limited or quality of life is substantially impaired.
2. If the separate tear is present in the arch.

Recommendation specific to the arch aneurysm

Class IIa

1. For thoracic aortic aneurysms also involving the proximal aortic arch, partial arch replacement together with ascending aorta repair using right subclavian/axillary artery inflow and hypothermic circulatory arrest is reasonable.
2. Replacement of the entire aortic arch is reasonable for acute dissection when the arch is aneurysmal or there is extensive aortic arch destruction and leakage.
3. Replacement of the entire aortic arch is reasonable for aneurysms of the entire arch, for chronic dissection when the arch is enlarged, and for distal arch aneurysms that also involve the proximal descending thoracic aorta, usually with the elephant trunk procedure.
4. For patients with low operative risk in whom an isolated degenerative or atherosclerotic aneurysm of the aortic arch is present, operative treatment is reasonable for asymptomatic patients when the diameter of the arch exceeds 5.5 cm.
5. For patients with isolated aortic arch aneurysms less than 4.0 cm in diameter, it is reasonable to reimage using computed tomographic imaging or magnetic resonance imaging, at 12-month intervals, to detect enlargement of the aneurysm.
6. For patients with isolated aortic arch aneurysms 4.0 cm or greater in diameter, it is reasonable to reimage using computed tomographic imaging or magnetic resonance imaging, at 6-month intervals, to detect enlargement of the aneurysm.

Goals of aortic arch surgery

- Organ protection—cerebral, spinal and visceral
- Determining pathology-related extent of surgery
- Hemostasis

Pre-operative surgical planning is essential and crucial; however, in the case of acute, unstable condition, the planning may be limited to essential examination. We at our center follow the below-mentioned protocol for work-up and monitoring.

Pre-operative work-up includes

- Blood investigation—Hemogram, liver function test, renal function test, prothrombin time, and viral markers
- Non-contrast computed tomography (NCCT) of head
- Peripheral Doppler
- Echocardiogram
- Carotid Doppler
- CT angiography of the entire aorta if renal function is normal
- Coronary angiogram if male patient above 40 years and non-menstruating female above 45 years

In the pre-operative state, medication is given to control hypertension. In the case of dissection, we use labetalol as the choice of antihypertensive.

Peri-operative medication and monitoring

In the peri-operative setting, we use methylprednisolone at a dose of 7 mg/kg, and thiopental at a dose of 10–15 mg/kg as a part of neuroprotection measures. Mannitol at a dose 0.3–0.4 g/kg is either added in the pump or given intravenously to decrease cerebral edema and flush the kidneys. Furosemide can be added to maintain the urine output and decrease fluid accumulation.

The complexity of aortic arch surgery requires a multimodality monitoring. The standard peri-operative monitoring during aortic arch surgery consists of central venous pressure, pulmonary artery catheter, transoesophageal echocardiography, and invasive blood pressure measurement at different sites. Monitoring blood pressure at different sites is essential; most centers prefer to use one site proximal to and one site distal to the arch to detect malperfusion adequately. At our center, the arterial line is established at both radial arteries and one femoral artery. The body temperature is monitored by two separate temperature probes, one for brain temperature which is placed at nasopharynx or tympanic membrane and the other is placed to monitor core body temperature which is either placed in the rectum or bladder. We use rectal and nasopharyngeal temperature monitoring.

The neurocognitive and cerebral metabolism monitoring methods can be done either by measuring cerebral substrate delivery by Jugular bulb oximetry, transcranial Doppler sonography and near-infrared spectroscopy. The other method is to measure cerebral function by quantitative electroencephalography or evoke potential monitoring. We use near-infrared spectroscopy (NIRS) at our center.

Near-infrared spectroscopy uses the principle of transcranial cerebral oximetry (TCCO) to detect cerebral hypoperfusion. Cerebral oximeters measure regional hemoglobin oxygen saturation (rSO2) in the frontal lobes by using a probe which is fixed on the forehead (Fig. 3). The probe used comprises of adhesive pads containing diodes (LED) or laser light sources which emit photons in the near-infrared (NIR) spectrum which are capable of penetrating through the cranial bone to the underlying cerebral tissue for few centimeter [5]. The emitted photons are either reflected, redirected, scattered, or absorbed. Thus, when they come in contact with hemoglobin molecules, there is a change of light spectrum depending on the oxygenation status of hemoglobin. A fraction of this resultant light is reflected towards the surface and is captured by detectors embedded to the adhesive pads. These photons take a banana-shaped course from the emitter to the detector. The monitor differentiates the two forms of oxygenated and deoxygenated hemoglobin using specific computational algorithms in order to determine the rSO2 (regional saturation) in the frontal lobes. Thus, the technique used is optical spectrophotometry which measures the difference in absorption spectra of HbO2 and Deoxy Hb.

Hence, NIRS provides the opportunity to optimize cerebral blood flow (CBF) by increasing $PaCO_2$, arterial pressure or perfusion pressure (during optimize CBF), FiO_2, and hematocrit. Furthermore, when unilateral selective antegrade perfusion is done, its sufficiency can be monitored at the left frontal cortex and, if the difference between the two lobes is more than 30%, the strategy is, changed to bilateral perfusion. The threshold of "sufficient CBF" varies in the literature between 55 and 75%; however, achievement of preoperative values and broadly stable saturation appears to be superior to the usage of the absolute saturation measures as there are many confounding factors which effect the oxygenation of hemoglobin (Fig. 4) [6]. Diagnostic value of NIRS monitoring becomes limited because the monitored area is restricted to the position of the sensors, and differentiation between causes of

Fig. 3 NIRS probe placed on the forehead during the surgery

Fig. 4 NIRS monitor showing rSO2 of the left and right sides

reduced rSO_2 like hypoperfusion/malperfusion, embolus, and air bubbles is not possible [6]. NIRS values are affected by the use of electrocautery and if the patient has hemoglobinopathies.

Cerebral protection

Replacement of aortic arch portion by definition requires exclusion of the brachiocephalic vessels which supply the brain. The brain is unique in a way that it constitutes 5% of the body weight but requires 15% of cardiac output. Thus, the vulnerability of the brain is attributed to high metabolic rate and lack of glucose store and therefore the brain requires high oxygen and glucose supply all the time. Under physiological condition, the brain has autoregulation which maintains a constant perfusion despite systemic blood pressure. So, to prevent cerebral damage during arch surgery, either the cerebral metabolic demand has to be suppressed or the supply of the oxygen and glucose is to be maintained. The cerebral protection strategies aim at either or both of these techniques.

Hypothermia

Deep hypothermic circulatory arrest (DHCA) There are two main pathways of ischemic neural injury:

(I) When there is a lack of oxygen, adenosine triphosphate (ATP) is synthesized through anaerobic glycolysis, which is not sufficient to maintain normal neuronal function. Concurrently, lactate accumulates in the neurons, lowering the intracellular pH. Such energy depletion and waste product accumulation within brain cells lead quickly to permanent damage and necrosis. (II) Calcium ion plays a central role in ischemic neuronal injury. Hypoxia leads to a release of excitatory neurotransmitters, such as glutamate, which in turn activates the *N*-methyl-D-aspartate (NMDA) channels. Once these channels are activated, calcium ions easily enter the cells and accumulate. Such an imbalance in the calcium level leads to the activation of intracellular proteases and mitochondrial dysfunction, which result in neuronal cell death. Hypothermia inhibits both of these injury-inducing pathways as it decreases the global cerebral metabolic rate for glucose and oxygen. So every 1 °C drop in the body temperature, cellular metabolism slows down by an average of 5–7%. The lower the rate of anaerobic metabolism, the less lactate is accumulated and the less pronounced is any cellular acidosis. Lowering the temperature has been proven to reduce to a larger extent ATP breakdown than its synthesis in the brain, which increases cerebral ATP supply for energy-consuming processes. Hypothermia also reduces temperature-dependent release and extracellular levels of excitatory neurotransmitters such as glutamate, an NMDA receptor agonist. Hence, this is a dual mechanism for decreasing the activity of the NMDA channels, which significantly reduces the amount of calcium that is drawn into the neuronal cells. This provides a very effective neuroprotective effect, preventing irreversible neuronal injury [7]. Patients should be cooled at a rate of 0.2 °C/min [8]. The safe time limits before transient or permanent neurological deficits are DHCA maximum 40 min [7], DHCA plus retrograde cerebral perfusion (RCP) 60 min, DHCA plus antegrade cerebral perfusion (ACP) 90 min [9].

Retrograde cerebral perfusion

It provides cerebral protection by maintaining a supply of oxygen and glucose but it is not as effective as the antegrade method. Standard bicaval cannulation with caval snaring is done to provide standard retrograde perfusion and arterial return is through the femoral artery. The superior vena cava (SVC) is isolated from the venous circuit and connected to the arterial line. Blood is transfused retrogradely via SVC. The driving pressure is monitored via an SVC central line, zero being adjusted to the level of the external auditory meatus with the patient in the Trendelenburg position. Optimal rate of flow is 300 ml/min and jugular venous pressure of around 25 mmHg. Our method of retrograde perfusion is different and was used in the distal arch and proximal descending aortic lesions where a patient might require a posterolateral thoracotomy. A 5-cm-long incision is made along the anterior border of the sternocleidomastoid muscle, and left internal jugular vein (LIJV) was dissected and looped. Once the LIJV was dissected and looped, cardiopulmonary bypass (CPB) was established with the arterial cannula in the femoral artery and venous return through two cannulas, one in the femoral vein and the other in the pulmonary artery as shown in Fig. 5. The arterial line had a bifurcation to supply the proximal aorta during distal reconstruction. To deliver RCP, a retrograde cardioplegia cannula is inserted into the LIJV and was connected to the cardioplegia delivery system. The sidearm of the cardioplegia cannula was connected to the pressure transducer. Retrograde cerebral perfusion was started with a flow of 500 to 600 ml/min with a pressure limit of 25 mmHg [8].

The advantage of our type of RCP is that it can be done in a lateral position so no change in position required if posterolateral thoracotomy is to be done. The use of retrograde cardioplegia cannula gives an advantage of an additional limb through which perfusion pressure can be measured.

Selective antegrade cerebral perfusion

In the current scenario, antegrade cerebral perfusion is the most effective way of cerebral perfusion when combined with hypothermia. Antegrade cerebral perfusion can be done either by direct cannulation of the left common carotid and right brachiocephalic or by the axillary artery. Earlier in the mid-1970s, direct cannulation of arch vessels for antegrade cerebral perfusion was abandoned as it was considered to increase the chances of stroke [10]. Thus, the selection of cannulation site is of paramount importance as the advent of antegrade cerebral perfusion has brought down stroke rate and mortality rate drastically [10]. The right axillary artery is usually free of atheroma so is the preferred site. Some centers prefer direct cannulation or selective perfusion of carotids in view of the fact that in a significant number of individuals, the circle of Willis is not well developed. But within 45 min of arrest time, the clear benefit of bilateral antegrade perfusion is not seen over the unilateral antegrade perfusion via the axillary artery [11]. We use right axillary cannulation with an anterograde flow rate of 7–10 ml/kg/min with perfusion pressure maintained at around 50 mmHg.

European guidelines from 2014 suggest that selective ACP be considered for brain protection, although they were class IIa recommendations with only Level B evidence for support. [12] Table 1 shows advantage and disadvantages of different cerebral perfusion strategies.

Options for exposure

Incision to be given for aortic arch dissection or aneurysm varies depending on the site and extent of dissection or aneurysm and surgeons preference. We prefer a midline sternotomy sometime with neck extension.

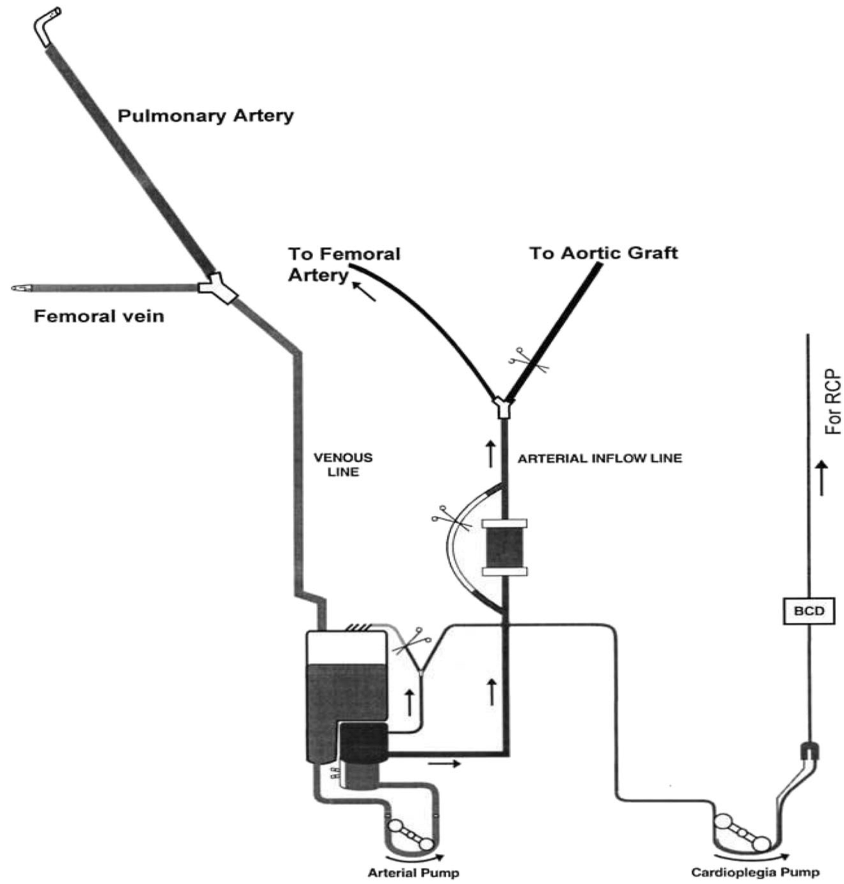


Fig. 5 The modified extracorporeal circuit to deliver retrograde cerebral perfusion

Cannulation strategies

Cannulation to initiate CPB can be achieved via different vessels and approaches, with each site providing specific benefits and risks. The different sites used are:

- Femoral
- Right axillary
- Innominate
- Direct aortic
- Carotid artery

Femoral artery cannulation route is the easiest to approach but is associated with the risk of retrograde cerebral embolization from debris and thrombi dislodged from the descending aortic lumen or initiating organ malperfusion in cases of a dissected aorta. It is also associated with retrograde dissection and lymphatic fistulae [6]. Some authors have described innominate artery cannulation to provide adequate systemic blood flow allowing for enhanced cerebral protection and selective antegrade cerebral perfusion (SACP) in cases of circulatory arrest. However, in cases of dissection, the innominate artery is frequently involved, rendering access of the true lumen hazardous. Furthermore, the innominate artery is often the site of significant atherosclerosis in the non-dissected aorta. We prefer an axillary artery direct cannulation. European guidelines also recommend preferential

Table 1 Advantage and disadvantage of different type of cerebral perfusion system

	Advantage	Disadvantage
SACP	-Prolongs safe length of DHCA more than RCP. -Less hypothermia required. -Helps maintain cerebral cooling. -More reliable global oxygenation than RCP.	-Risk of embolization. -Increases the complexity of surgery. -Risk of cannula displacing or kinking decreasing oxygen supply. -Needs intact circle of Willis, if unilateral perfusion used.
RCP	-Helps maintain cerebral cooling -Helps prolong safe length of DHCA to 60 min.	-Variable amount of oxygen delivery due to shunt. -Cerebral edema -Raised ICP (intracranial pressure)

Table 2 Comparison of arterial cannulation strategy

Site	Advantages	Disadvantages
Direct aortic	Single-incision so less time-consuming. Large cannula can be placed.	Proper exposure of arch not possible. False lumen can be cannulated which can increase the dissection.
Femoral	Easily accessible, away from the main surgical site. Venous cannulation through the same incision possible. Large cannula with adequate flow can be placed.	Retrograde embolization. Perfusion of false lumen with risk of rupture.
Subclavian/Axillary	Clear of atheroma/dissection. Allows single site of cannulation for whole repair.	Second incision needed. More time-consuming.
Innominate	Single incision. Away from the distal arch anastomosis site.	Possibility of air embolism. Iatrogenic dissection of the brachiocephalic vessel.
Carotid	Safe, efficient, and quick in its execution and, therefore, suitable in emergencies and in obese patients.	Fragile vessel Chance of embolization

use of axillary cannulation, but the evidence class is only "IIa, level C" [5]. Table 2 mentions the advantage and disadvantages of different arterial cannulation strategies.

Right axillary artery cannulation

At the time of surgery, bilateral radial arterial lines are placed for pressure monitoring. Cerebral oxygenation is routinely monitored with near-infrared spectroscopy (INVOS). Core body temperature is monitored by rectal and nasopharyngeal thermometers. The patient is placed in a standard supine position and draped, exposing the right deltopectoral groove. The axillary artery is exposed for cannulation through a horizontal 5–6-cm incision ~ 2 cm below and at the junction of the middle and outer thirds of the right clavicle, overlying the deltopectoral groove. The pectoralis major muscle is dissected and divided using the electrocautery, and the clavipectoral fascia is incised, exposing the pectoralis minor muscle. The pectoralis minor is retracted or divided. The axillary artery, which lies superior and posterior to the vein, is identified by palpation and then exposed using sharp dissection. The artery is then gently mobilized for ~ 2 cm and may be looped with an umbilical tape or a vessel loop. After the administration of heparin, the vessel is open through a 10–12-mm transverse arteriotomy incision and the cannula has been placed. Alternatively, 8-mm graft can be sewn and cannula been placed through it. We prefer direct cannulation of the axillary artery. Venous return is obtained through a single double-stage right atrial cannula or through direct cannulation of both the superior and inferior venae cavae. CPB is then established at 2.2–2.4 l/min/m^2 at normothermia. Adequacy of perfusion is confirmed by transoesophageal echocardiography, measurement of blood pressure in the left radial artery, and intraoperative regional cerebral oxygen saturation.

Post-initiation of cardiopulmonary bypass cardioplegia, preferentially custodial, is administrated via direct osteal route. Cooling of the patient is done with a maximum temperature gradient of 10 °C between the water and the arterial line [5].

How much arch is to be replaced is the next important question. In an acute dissection setting where the dissection flap originates in the ascending aorta or root, we prefer to do a hemi-arch replacement. Arch replacement is reserved for patients who have a separate tear in the arch, dilated aortic arch (burst arch), or significant cerebral malperfusion. With this approach, our 10-year intervention rate for distal aorta was 2.8%.

In the case of an aneurysm, the extent depends on the site and extent of aneurysm.

If the anterior arch is involved, hemi-arch is performed. In the hemi-arch replacement, the lesser curvature of the arch is been replaced leaving behind native greater curvature containing the brachiocephalic vessels intact. With the patient on antegrade cerebral perfusion, the posterior layer of distal anastomosis is done first and then the anterior layer is continued as shown in Fig. 6 [13].

If only the right brachiocephalic vessel is involved in the aneurysm, the aorta is transected between the innominate and left carotid and the innominate is re-implanted over the graft either directly or by means of a short vascular graft as seen in Fig. 7.

If the transverse arch is involved:

There are two issues to be kept in mind; firstly, the method of implantation of the brachiocephalic vessel and secondly, the approach and sequence of anastomosis [13].

1. Re-implantation of supra-aortic arch (brachiocephalic) vessels

Depending on the morphology and the location of the intimal tear, the re-implantation of the supra-aortic vessels can be done "en bloc" as an island of the aortic wall or by separate re-implantation of the arch branches using a trifurcated graft, like in patients with dissection extending into the arch vessels or young patients with connective tissue disorders.

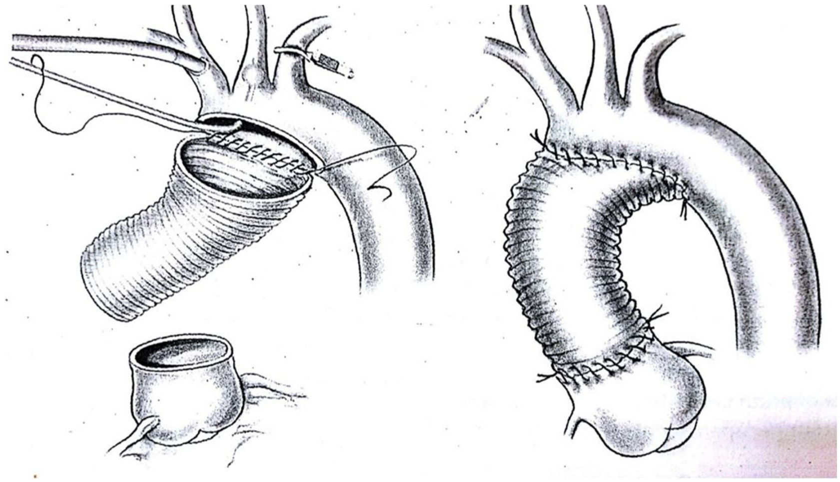


Fig. 6 Hemi-arch surgery without involvement of right brachiocephalic artery

En bloc re-implantation

In en bloc implantation, the supra-aortic arch (brachiocephalic) vessels are excised as a Carrel patch with a 1-cm rim of the aorta. The cuff containing the brachiocephalic vessel is secured on a corresponding orifice on the convexity of the prosthesis by means of running suture as shown in Fig. 8. The cardiopulmonary bypass is resumed as soon as the cuff is anastomosed; the prosthesis is then de-aired and clamped and is placed on the proximal end of the graft. Later, the proximal anastomosis is carried out.

Separate brachiocephalic implantation

Separate implantation is carried out in hypothermic arrest with SACP. During a brief period of hypothermic circulatory arrest (HCA), the brachiocephalic arteries are dissected free. They are transected and sequentially anastomosed to a readymade graft, beginning with the left subclavian then the left carotid and then the innominate artery as shown in Fig. 9.

Even in patients with severe atherosclerotic disease, dissection or aneurysm of the Aortic arch, the arch vessels are usually spared just beyond their origins, making this location ideal for subsequent anastomosis [14]. This method was described by Kazui et al. We at our center use this method of implantation of brachiocephalic vessels.

2. Different approaches of anastomosis in arch surgery

- Distal first
- Arch first
- Proximal first
- Trifurcated graft

Distal-first anastomosis is the traditional and the most commonly used method. Below, Table 3 is a schematic representation of how we approach at our center. Later, other approaches are discussed in detail in the text.

Distal anastomosis in the arch further depends if the descending aorta is involved or not

If the descending aorta is not involved, the distal anastomosis is generally performed directly between the aorta and the

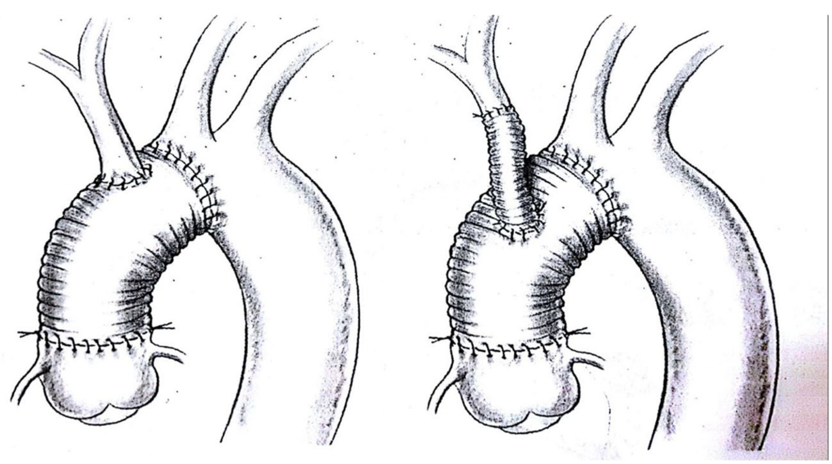


Fig. 7 Hemi-arch procedure if the right brachiocephalic vessel is to be implanted

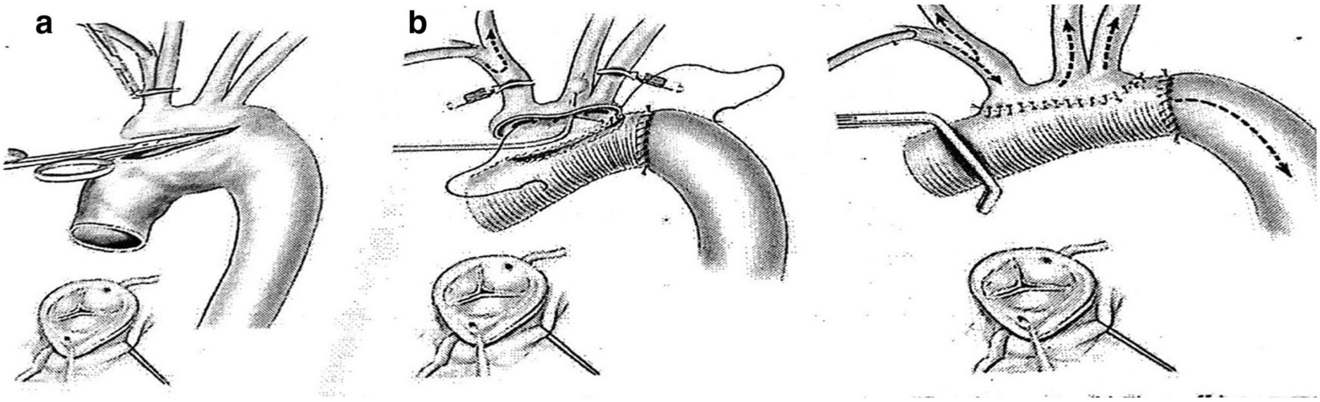


Fig. 8 En bloc implantation of supra-aortic arch vessels

prosthesis, edge to edge, in an end-to-end fashion using a 3/0 or 4/0 polypropylene continuous suture. When there is some degree of the discrepancy between the diameter of the distal aorta and the diameter of the prosthesis, the anastomosis is preformed using U-shaped pledgeted stitches as shown in Fig. 10. In this stitch, first, the aortic wall is pierced from outside in and then, the graft from inside out.

If the descending aorta is involved the distal anastomosis is preformed using the so-called elephant trunk technique described by Borst et al. [15]. There are three modes of inserting an elephant trunk extension of an aortic arch graft. Initially, the end of the arch graft was inserted distally, and the side of the fabric tube then was anastomosed to the origin of the descending aorta with a circular tangential suture. As this was cumbersome, the other technique of invaginating the future trunk was by anastomosing it to the aortic wall and the trunk extending it antegradely into the descending thoracic aorta immediately before completion of this anastomosis. A more elegant variant then was developed by Crawford and associates and Svensson, modifying an unfolding technique that originally had been used by Griepp and colleagues for end-to-end aortic arch replacement [16]. A heavy retracting suture first is attached to the end of the future proximal arch portion of the graft. Passing this suture through the graft and pulling on it allow for invaginating the length of the arch graft. The resulting outer coat of the doubled-up graft thus will become the trunk portion. It is cut back to the desired length. The whole graft is inserted into the descending aorta and the distal

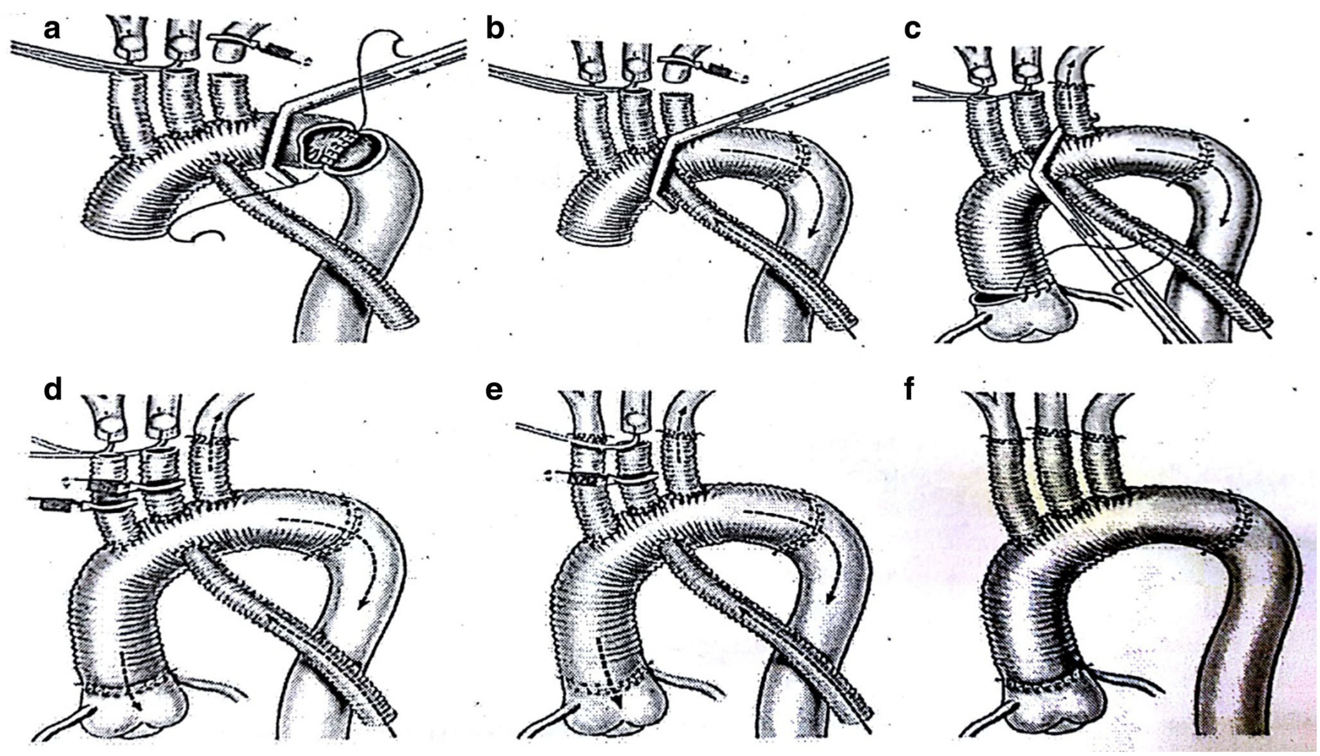


Fig. 9 Individual implantation of supra-aortic arch vessel

Table 3 Distal-first technique of arch surgery

Nasopharyngeal temperature: 25 degree Celsius

⇩

Circulatory arrest

⇩

Cross clamping of the origin of the innominate artery

⇩

Right axillary or innominate artery perfusion: 7-10 ml/kg/min

⇩

Opening of the aortic arch

⇩

Resection of the aortic arch

⇩

Division of the supra-aortic vessels (en bloc or separately)

⇩

Distal anastomosis

⇩

Re-implantation of the supra-aortic vessels

⇩

De-airing

⇩

Re-warming

⇩

Proximal anastomosis or repair

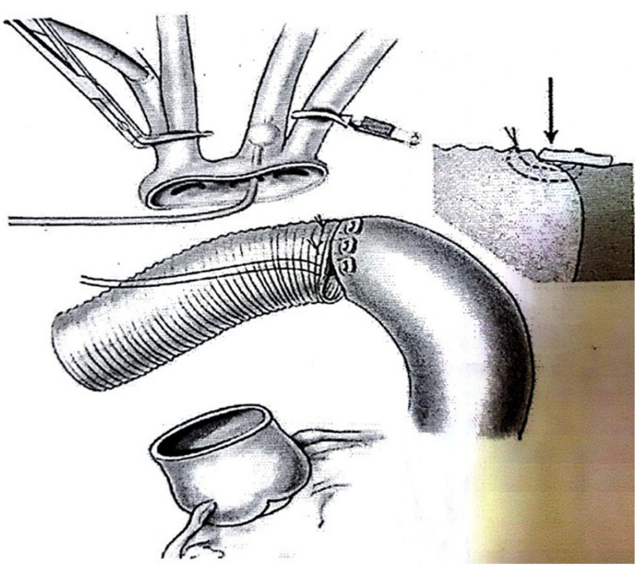


Fig. 10 Distal anastomosis using Ustitch

anastomosis is created between the fold in the prosthesis and the aortic wall. Upon completion, the stay suture is retrieved via the lumen of the graft, unfolding the total length of the invaginated portion. The length of the elephant trunk should be between 7 and 10 cm [17]. In chronic dissection, it is important to remove the remaining intimal flap for the length corresponding to the length of the elephant trunk in order to properly place the prosthesis and make sure that both the false and true lumen are perfused well as the visceral and intercostal arteries may arise from either of the lumens. Below, Fig. 11 shows a schematic diagram of an elephant trunk procedure.

The main advantages of the elephant trunk technique become obvious during the second operation and include (i) reduced dissection and surgical preparation of the distal segment of the arch where nerve, bronchial, gastrointestinal, and lymphatic structures may potentially be injured; (ii) a facilitated and shortened clamping time during open thoracoabdominal aneurysm; and (iii) no need to clamp proximally

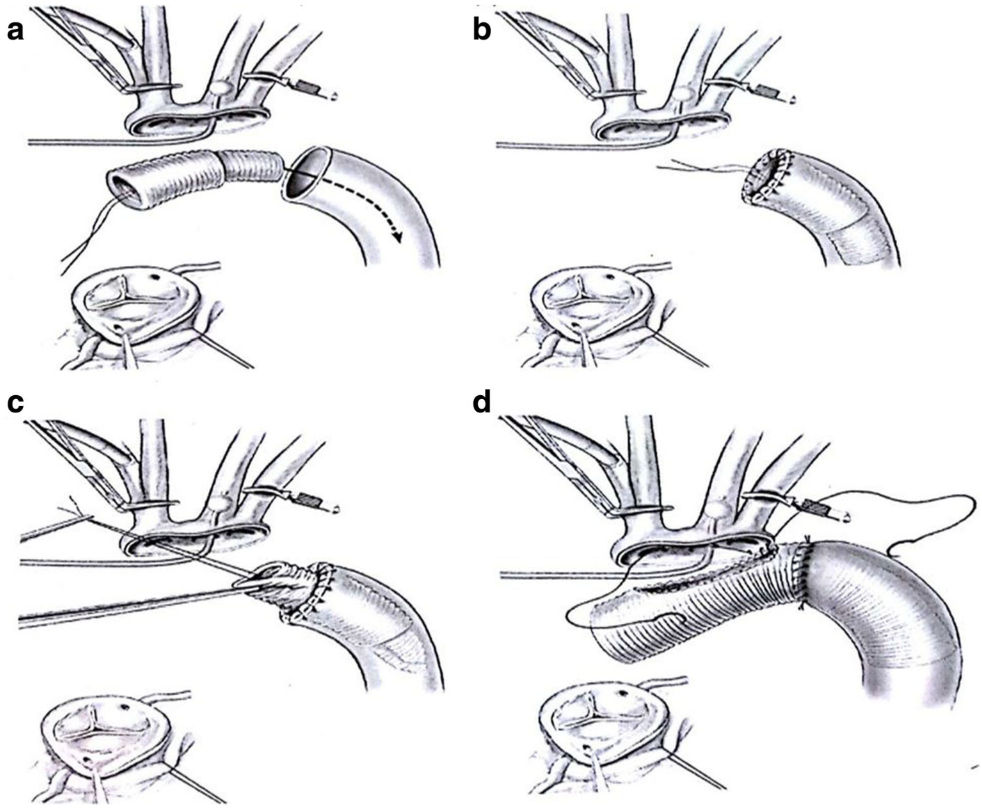


Fig. 11 Elephant trunk procedure

the left subclavian artery (reduced risk of stroke and paraplegia) [17].

The frozen elephant trunk technique

With the advent of hybrid technique and use of a preassembled or custom-made hybrid prosthesis, there was an introduction of frozen elephant trunk technique. In this technique, the graft used has a proximal portion which is non-stented and consists of a Dacron sleeve for conventional surgical handling and a distal part which consists of a stent graft. In frozen elephant trunk surgery, we first resect the aortic arch completely and prepare the distal aortic stump with obliteration of the false lumen using U stitches with pledgets inside and a Teflon felt outside. Once this is done, a guide wire is advanced retrogradely via femoral artery into the true lumen and the stented graft is deployed over it. The vascular collar is then sutured to the distal aorta before or after the origin of the left subclavian artery. Finally, the brachiocephalic arteries are re-implanted over the non-stented part and the proximal end of the graft is anastomosed to the ascending aorta. The final result is shown in Fig. 12 [18].

The main disadvantage of the elephant trunk techniques in both degenerative and chronic post-dissection aneurysms is the increased risk of Spinal cord injury (SCI). The reported incidence of permanent or transient ischemic SCI after an elephant trunk implantation ranges between 0.4 and 2.8%. A significantly higher rate is described after Frozen Elephant Trunk implantation, with studies reporting incidences greater than 10%. Possible explanations are the prolonged hypothermic circulatory arrest time required to implant the frozen elephant trunk device and/or the occlusion of intercostal arteries at the level of stent-graft deployment [17].

The arch-first technique

The arch-first technique was introduced by Rokkas and Douchoukos. In their method, they used bilateral anterior thoracotomy [9]. Later in the modified version, median sternotomy was preferred. The aortic arch was exposed through median sternotomy and cardiopulmonary bypass was initiated with arterial perfusion through the right axillary artery and single venous drainage using a two-staged cannula in the right atrium (Fig. 13a), then the patient was cooled to below 25 °C rectal temperature and 23 °C nasopharyngeal temperature. The perfusion was then stopped, and the aortic arch was opened (Fig. 13b). The arch vessels were transected and reconstructed using an arch graft with four branches during circulatory arrest (Fig. 13c). Then, with clamps on both ends of the graft, cerebral perfusion was restarted through the right axillary artery (Fig. 13d). Perfusion monitoring at that point is usually from the left radial artery pressure. Distal anastomosis is performed using a piece of the graft with a 4–0 polypropylene running suture and Polytetrafluoroethylene

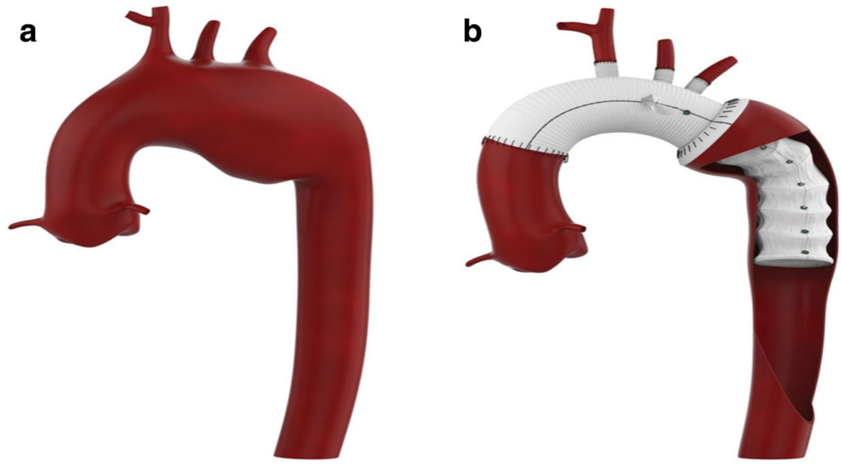


Fig. 12 Frozen elephant trunk technique

(PTFE) felt strip reinforcement on the adventitia. The two grafts were then anastomosed with 3/0 or 4/0 polyethylene running suture. After the two grafts were approximated, full re-warming is started by switching the arterial return to one of the branches of the graft, and proximal anastomosis was performed with a 4–0 polypropylene running suture using a PTFE felt strip reinforcement on the adventitia (Fig. 13 e, f).

The approach through median sternotomy has several advantages to the approach through thoracotomy. Firstly, there is less chance for pulmonary complication because the pleural spaces remain untouched. Secondly, the bilateral internal thoracic arteries are saved. Thirdly, this is a standard approach for cardiac operation so myocardial protection and exposure for a concomitant cardiac procedure are easier. The drawback of median

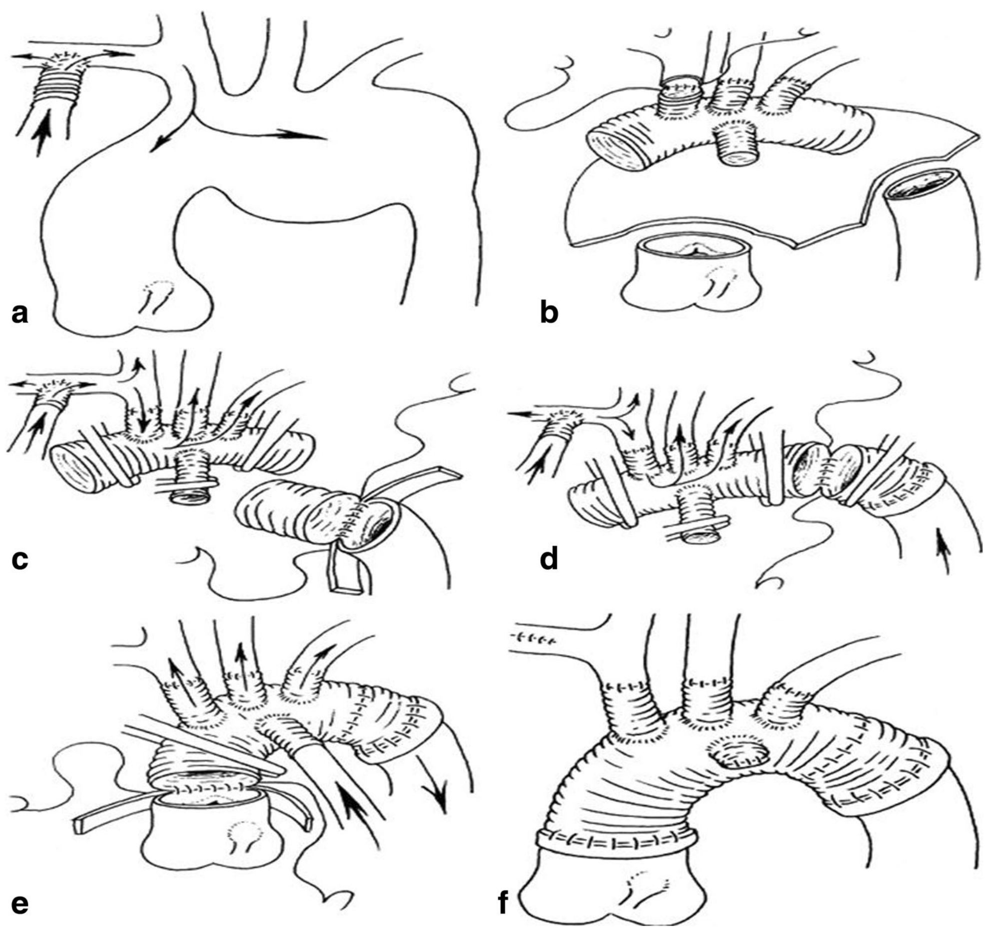


Fig. 13 Arch-first technique

sternotomy is that it does not always provide good exposure for extensive aortic arch aneurysm, especially when it extends to the mid-portion or distal descending thoracic aorta. This technique involves a short period of circulatory arrest (less than 30 min) and subsequent antegrade cerebral perfusion. It does not require cannulation of the carotid vessels, which can cause cerebral thrombo-embolism, and it enables antegrade cerebral perfusion to be resumed after a relatively short period of circulatory arrest. Thus, it is thought to be a useful technique to reduce cerebral complications in complicated arch reconstruction operation for patients with severe atherosclerotic carotid vessels [19].

Proximal-first technique

In this method of anastomosis, the proximal anastomosis with ascending aorta is done first. In this approach, patients are intubated with a double-lumen endotracheal tube as the distal anastomosis is performed under single-lung anesthesia. A patient is positioned in a left anterolateral position and a left fourth to sixth intercostal space (ICS) anterior thoracotomy is performed along with upper half median sternotomy as shown in Fig. 14. The left internal thoracic artery (LITA) is ligated and divided.

Cannulation is done in the bilateral axillary and femoral artery as seen in Fig. 15. Two venous cannulas were inserted directly into the superior vena cava and inferior vena cava. Left ventricular is vented through the left superior pulmonary vein. Systemic cooling is initiated and the ascending aorta, aortic arch, and descending thoracic aorta are exposed. The fat pad containing the vagus and phrenic nerves is isolated by a tape. The patient is then cooled and aortic cross-clamp is applied and antegrade cardioplegia administered.

The ascending aorta is then anastomosed to a sealed graft with four branches as seen in Fig. 16A. Once the proximal anastomosis is completed, the heart is reperfused through one branch of the graft [20]. After this patient is cooled to around 20 °C, RCP is started (Fig. 16 B). Retrograde cerebral perfusion is performed through the superior vena cava cannula, while maintaining the jugular vein pressure of 15 to

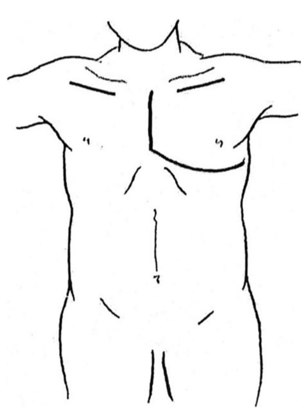


Fig. 14 Incision in proximal-first technique

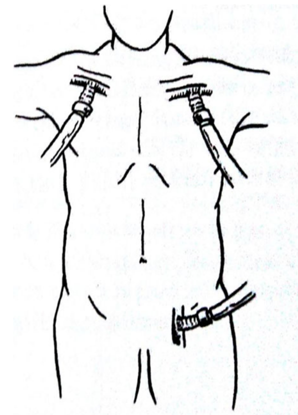


Fig. 15 Cannulation strategy in proximal-first technique

25 mmHg with a flow rate of 300 to 400 ml/min. Systemic perfusion of the lower body and viscera is maintained through the femoral artery after descending aorta is cross-clamped. Arch vessels are then reconstructed in sequential order, that is, the left subclavian artery first, then the left carotid artery, and finally the innominate artery. Once arch vessels reconstruction is complete, RCP is stopped and antegrade cerebral flow through the graft and arch vessels is restored (Fig. 16C). The left lung is then deflated to expose the descending thoracic aorta. The distal anastomosis is then performed using the elephant trunk technique (Fig. 16D); during this period, lower body perfusion is stopped. As the graft-to-graft anastomosis is performed, femoral arterial perfusion is re-established to remove air and debris. Upon completion of the distal anastomosis, the patient is rewarmed (Fig. 16 E) [21].

Merits of this approach are that it decreases the myocardial ischemic time and decreases the period of interrupted normal antegrade cerebral perfusion.

Trifurcated graft technique

Median sternotomy with the incision extended superiorly along the medial border of the left sternocleidomastoid muscle is performed. Cardiopulmonary bypass is then started using the right axillary artery and two-stage right atrium cannulation strategy. Cardioplegia is given and at the same time, a trifurcated graft is constructed after sizing the brachiocephalic vessels using Dacron graft between 8 and 14 mm in size. After this patient is placed in the Trendelenburg position, a circulatory arrest is started and the brachiocephalic vessels are transected just distal to its origin where they are free of disease. The trifurcated graft limbs are cut according to the length required for anastomosis and the graft is anastomosed in the sequence of left subclavian, left carotid, and then right brachiocephalic. Perfusion through the right axillary artery is started and the proximal portion of the trifurcated graft is clamped as seen in Fig. 17 [22].

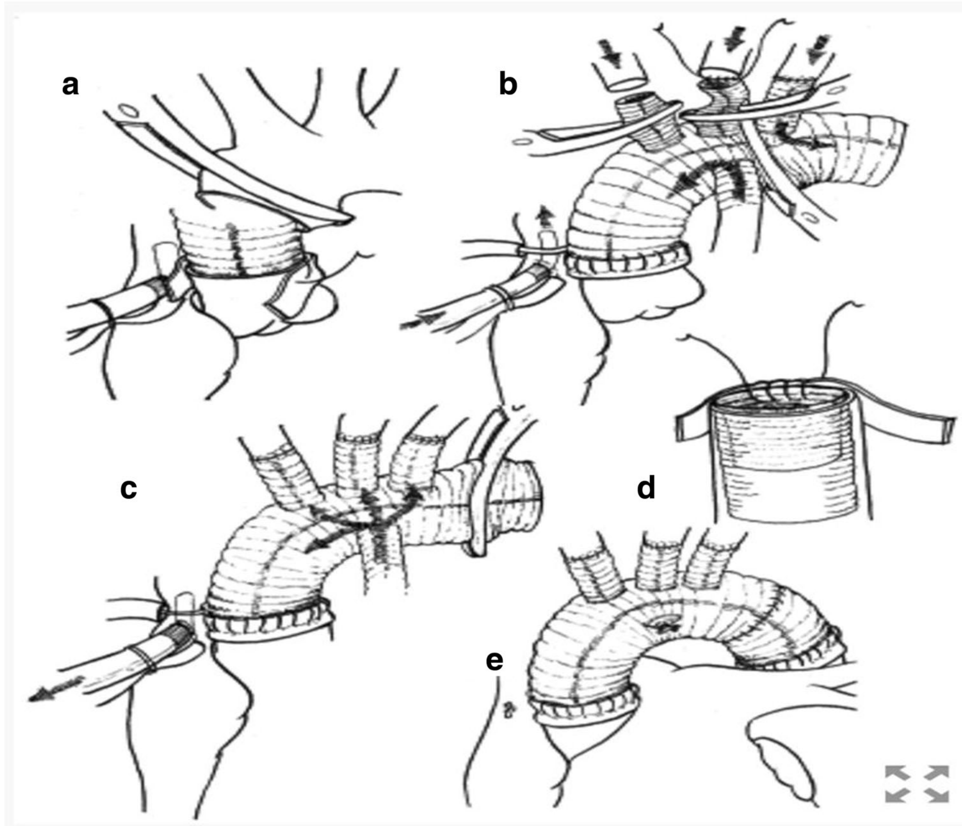


Fig. 16 Proximal-first technique

After this, the continuity between the ascending and descending aorta is established using an interposition graft. The interposition graft is distended with cardioplegia solution and the trifurcated graft is anastomosed at an ideal site as shown in Fig. 18.

There are two surgical approaches which use the combination of deep hypothermia and SCP: (i) integrated, four-branched arch graft technique of Kazui and (ii) trifurcated graft technique. The trifurcated graft technique offers a number of advantages over the four-branched arch graft technique, used by Kazui. In the Kazui technique, they employed direct cannulation of the brachiocephalic vessels with balloon tip catheters which increased the chance of embolism. Secondly, the branches

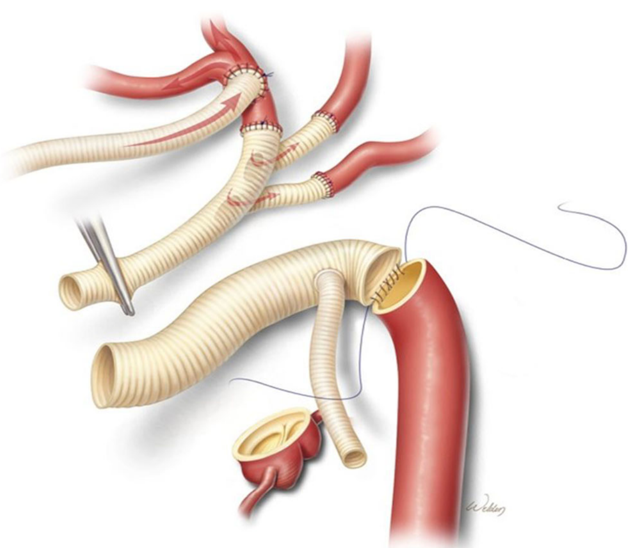


Fig. 17 Anastamosis of supra-aortic arch vessels to the trifurcated graft

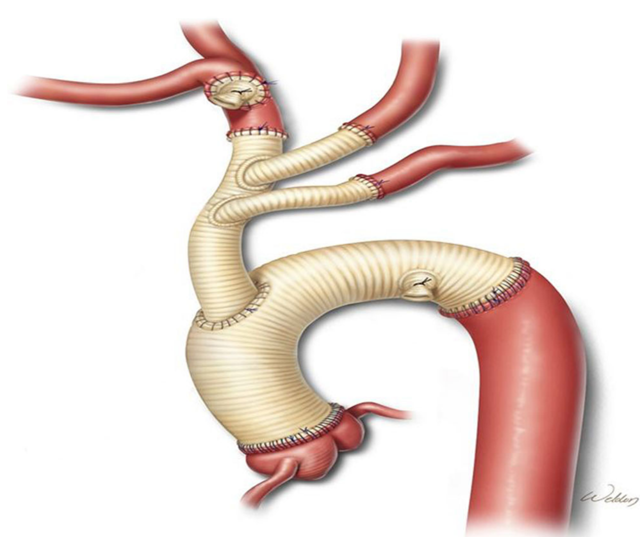


Fig. 18 Trifurcated graft technique

of the branched graft are fixed in position on the arch graft where it limits its use in arch anomalies and there is more chance of kinking of the supra-aortic vessel anastomosis A disadvantage of the trifurcated graft technique is that lower core temperatures and longer DHCA intervals are required [23].

Hybrid or endovascular technique

Criado and colleagues defined the proximal landing zone as: zone 0 (proximal to the innominate artery), zone 1 (between the innominate and left common carotid artery), zone 2 (between the left common carotid and subclavian arteries), and zone 3 (distal of the left subclavian artery) as shown in Fig. 19 [24].

Surgical procedure zone "0"

If the aortic arch lesion involves the origin of the innominate artery, the use of autologous brachiocephalic vessels alone is not very feasible because if it is done, sufficient length for a proximal landing zone will not be possible. Therefore, prosthetic material is necessary to re-establish perfusion of the cerebral circulation and upper extremities [25].

The median sternotomy is done and the incision is extended superiorly 5 cm along the anterior border of the right sternocleidomastoid muscle. The pericardium is then opened and the ascending aorta is exposed. The proximal right subclavian and common carotid arteries are isolated just distal to the brachiocephalic bifurcation. Then, the innominate trunk, the left subclavian artery, and both carotid arteries are circumferentially freed and encircled with elastic tapes. The brachiocephalic vessels are anastomosed in the sequence—first, being the left subclavian, then the left common carotid, and finally the right innominate as seen in Fig. 20B. After the brachiocephalic vessel

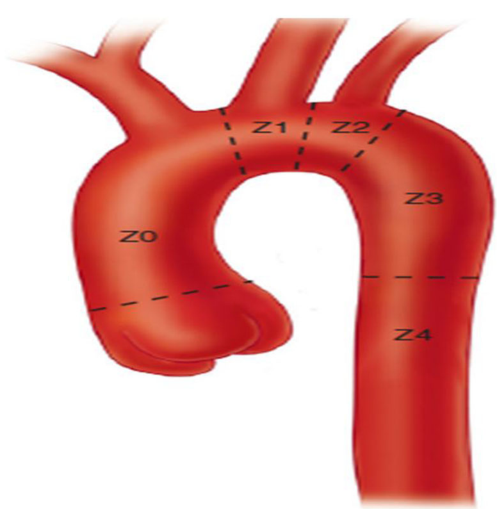


Fig. 19 Landing zones of endovascular stents

anastomosis is done, a partial clamp is placed on the proximal ascending aorta and the inverted Y trifurcated graft is anastomosed to it in an end-to-side manner Fig. 20A [26]. Later, a vascular graft is delivered either antegradely (Fig. 20D) or retrogradely (Fig. 20E) depending on the condition of the iliofemoral vessel and the surgeons' choice.

Surgical procedure zone "1"

If aortic arch lesion involves the origin of the left common carotid artery, an autologous procedure to maintain cerebral perfusion can be performed. Median sternotomy is done and the skin incision is extended parallel to the left clavicle to have a better access of the left subclavian artery to expose supra-aortic vessels. After systemic heparinization, clamping test is performed by placing a side-bite clamp on the distal portion of the innominate artery just below its bifurcation. The side-bite clamp is used to maintain flow in the carotid artery on the right side. Right radial artery pressure is also monitored to ensure there is adequate perfusion pressure and that the side-bite clamp is not occlusive in the innominate artery. The left carotid is then clamped high up into the neck. Blood pressure is optimized to ensure higher perfusion pressures during this time so that there are no changes in cerebral saturation or the EEG. The origin of the carotid is ligated at the level of the aortic arch; the divided part is then fully mobilized so that it reaches the innominate artery. The carotid has to be placed about 3 cm distal to the aortic origin of the innominate artery. This provides an appropriate landing zone for the side-branch graft that has to be placed into the innominate artery [25, 27].

A longitudinal incision is made on the medial leftward side of the innominate artery equivalent to the size of the left carotid artery. The left common carotid artery is then anastomosed in an end-to-side fashion to the innominate artery. Once the carotid has been mobilized, the subclavian artery can be found directly posterior. This is also mobilized from its origin off the aorta up to the vertebral branch. The subclavian is then divided and anastomosed to the underside of the left carotid artery. Finally, a branched graft covering the origin of the left subclavian and left carotid artery is placed through the femoral access (Fig. 21) [27].

Czerny et al. used branched Dacron graft instead of autologous vessel for the transposition between the carotid and brachiocephalic vessels.

Surgical procedure zone "2"

In zone 2, the left subclavian artery is involved and is to be revascularized so that the stent can be placed in descending

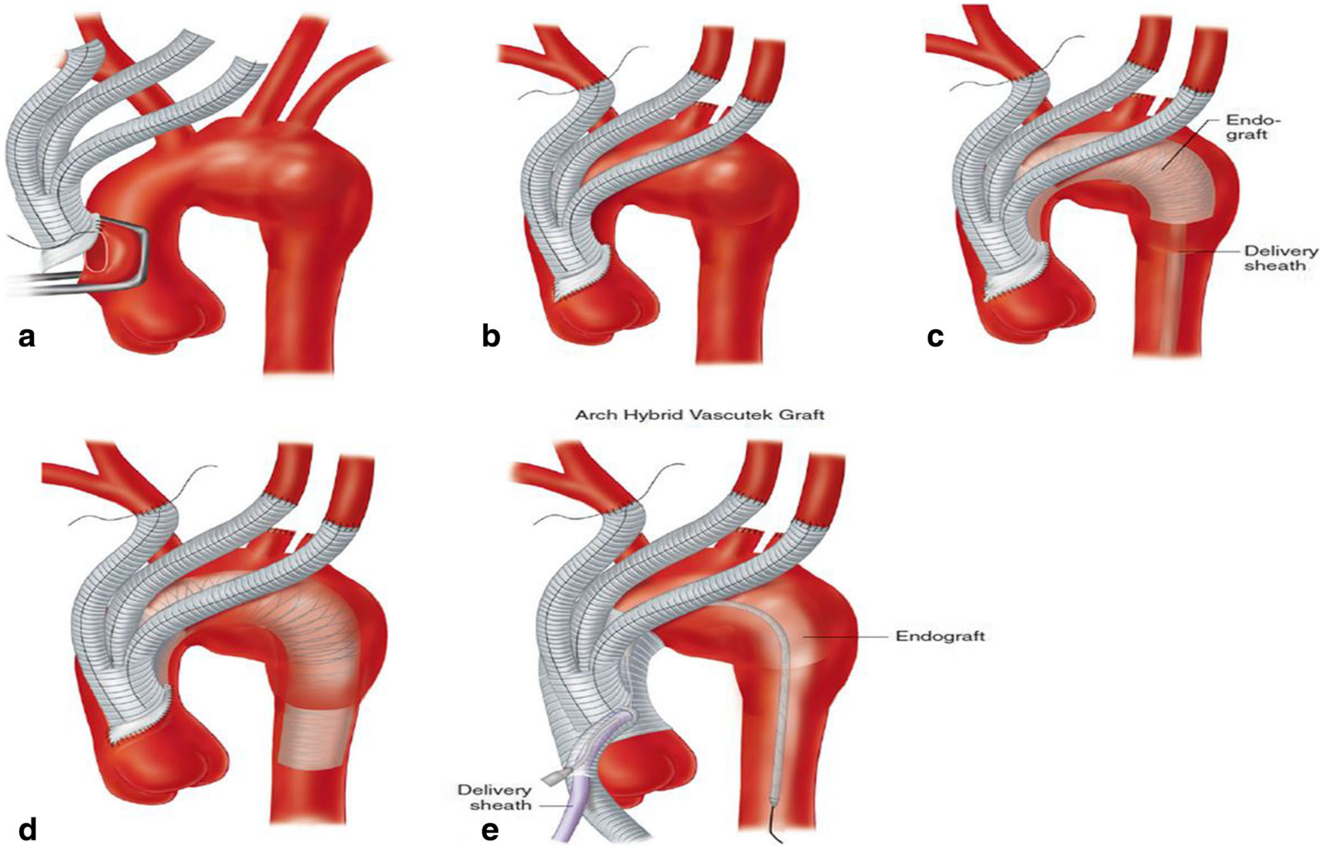


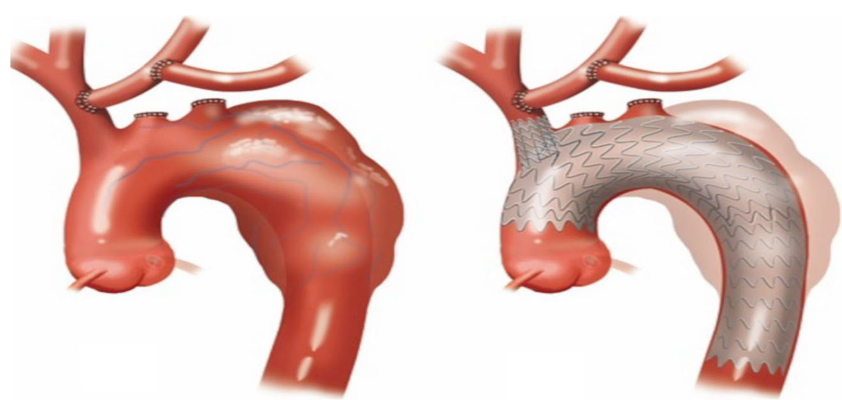
Fig. 20 De-branching procedure of supra-aortic arch vessel in zone 0

aorta until this zone. Therefore, for revascularization, the left subclavian-to-left carotid artery transposition is done through a supraclavicular incision. Both vessels are exposed between the medial and lateral clavicular insertion of the anterior scalene muscle. After transection of the proximal left subclavian artery, the stump is oversewn and an end-to-side anastomosis between the subclavian and the carotid artery is performed or an interposition graft can be used between the carotid and subclavian artery (Fig. 22). This medial surgical approach helps to avoid injuries to the recurrent laryngeal and phrenic nerves, as well as to the thoracic duct [27].

Results and discussion

The aortic arch operation is one of the most complex surgeries which required multiple aspects to be taken care of, most importantly the requirement of neuroprotective methods to achieve satisfactory outcomes, other aspects being the spinal cord, renal, bowel ischemia, and hemostasis. Hypothermia continues to be an effective protective technique since it was first introduced. Multiple studies have demonstrated the effect of hypothermia is achieved primarily by decreasing the rate of cellular metabolism [28]. Because more complex

Fig. 21 De-branching of subclavian and left common carotid artery



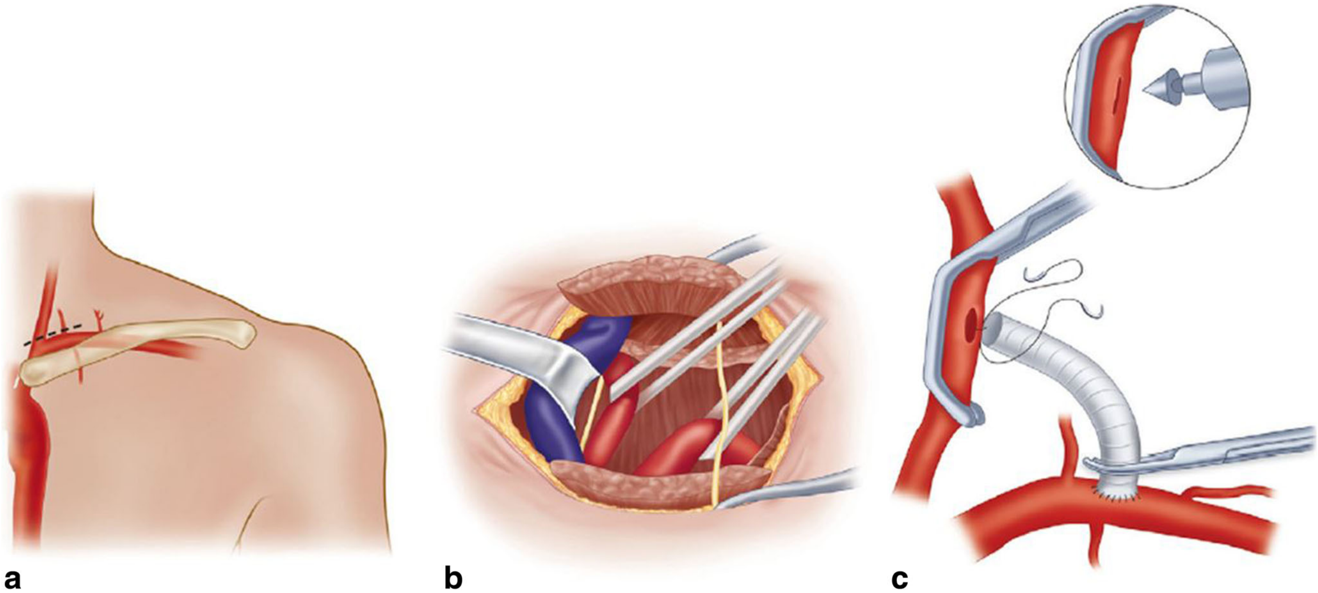


Fig. 22 When landing zone is zone 2, only the subclavian artery needs to be re-implanted

reconstructions required a longer operative period, additional techniques of cerebral perfusion were introduced. The advantage of SACP is in that it maintains an antegrade (physiologic) blood supply, whereas its disadvantage is in the requirement to manipulate inflow vessels with the risk of precipitating embolic events [29].

For short circulatory arrest times, RCP maintains cerebral cooling and prevents air and debris embolization but does not provide adequate substrate to the brain [30]. The mortality rate for a total arch replacement has declined from 34.6% with profound hypothermia and circulatory arrest to 21.1% with retrograde cerebral perfusion and to 6.0% with selective antegrade cerebral perfusion. The corresponding stroke rates were 19.2% with profound hypothermia and circulatory arrest, 5.3% with retrograde cerebral perfusion, and 6.0% with selective antegrade cerebral perfusion [31].

With the advent of the hybrid technique, it was thought to have an advantage over the conventional open technique in view of the following:

- Can be used in high-risk patients
- Less invasive
- Technically easy and free of complications
- Immediate results

Though most of the studies mention that hybrid procedures are used in a high-risk patient in whom the open surgery is not amenable, but hardly any of the studies define the risk in terms of STS or EuroSCORE. No randomized control trial has been performed yet comparing those methods with the conventional open surgical techniques of total aortic arch replacement. Therefore, the comparison can rely only on the results of reported experiences of single centers, or on meta-analyses. In fact, a study by Iafrancesco et al. which reviewed high-risk patient undergoing hybrid or open aortic arch surgery between 2000 and 2013 found that open surgery had lower mortality and morbidity even in high-risk patients; thus, it is a gold standard even in the high-risk patients [32]. The meta-analyses by Koullias et al. in 2010 who reviewed 15 studies with a total of 463 patients who underwent hybrid arch surgery concluded to have an overall 30-day mortality rate of 8.3%, stroke rate of 4.4%, paraplegia of 3.9%, and endoleak rate of 9.2% [33] Similarly, Cao et al. published a series of 1886 patients in 50 studies undergoing hybrid aortic arch procedures in a period of 10 years from 2002 to 2011. Targets of their study included peri-procedural mortality, stroke, and spinal cord ischemia. On conclusion of their study, they found the peri-operative mortality rate of 10.8%, pooled stroke rate of

Table 4 Comparison of meta-analysis of complications in hybrid procedure

Author	Year	Patient	Mortality (%)	Stroke (%)	SCI (%)	Endoleak (%)
Koullias	2010	463	8.3	4.4	3.9	9.1
Cao	2012	1886	10.8	6.9	6.8	–

Table 5 Comparison of rate of complication in hybrid procedure in different study

Author	Year	Patient	Mortality (%)	Stroke (%)	SCI (%)	Endoleak (%)
Czerny	2004	5	0	0	0	–
Czerny	2012	66	9	5	3	9.1
De Rango	2013	104	5.7	3.8	2.9	–
Andersen	2013	87	20.3	4.2	0	13

6.9%, and spinal cord ischemia rate of 6.8% as mentioned in Table 4 [34].

In terms of reduction in invasiveness, in a meta-analysis, Koullias et al. suggested that for zone 0 and zone 1, de-branching procedure was required, so chest opening had to be done similar to the conventional open method. Apart from the chest incision, the hybrid procedure required a supraclavicular or a neck incision for exposure and anastomosis of supra-aortic vessels or a groin incision for deploying a vascular graft. So once sternotomy was required, the hybrid procedure no longer remained minimally invasive [33, 35].

Thirdly, neither the hybrid procedure is technically simpler as it requires dissection of supra-aortic vessels and their re-implantation nor it is complication free. In fact, the hybrid procedures are responsible for few severe and immediate or delayed complications that are almost completely not seen with the conventional open methods, namely, retrograde acute dissection, spinal cord injury, and endoleaks [36]. Table 5 shows the results of a few studies in terms of complication of the hybrid procedure [35–39].

Among these, *De Rango* in 2013 had the largest study of 104 patients who underwent de-branching surgery with thoracic endovascular graft deployment. They showed to have a mortality rate of 5.7%, neurological deficit of 3.8%, and spinal cord ischemia of 2.9%. The rate of retrograde dissection was 3.8% and the rate of endoleak was not defined [37]. In another paper by De Rango et al., they compared endovascular and open conventional surgery and found that the stroke rate was 5.6% in the endovascular and 3.4% in the open group. Spinal ischemia, retrograde dissection, and endoleak were not present in the open group but in the endovascular group, the percentages were 2.8, 4.2, and 4.2 respectively. They concluded to have no mortality benefit of endovascular over the open. In fact, the stroke rate and spinal cord ischemia rate are more in the endovascular group [40].

Bachet et al. in their review paper gave a comprehensive overview of all the studies comparing the hybrid and conventional open surgery for arch dissection or aneurysm. They concluded that there was no obvious evidence that supported the superiority of the hybrid technique relative to open arch replacement. Contrary to their expectation, the hybrid repair of the aortic arch was associated with higher rates of late complications [35]. Table 6 shows the comparison.

Moulakakis and co-workers have identified 196 articles published up to December 2012 that described hybrid aortic arch repair with intra-thoracic supra-aortic branch revascularization and subsequent stent-graft deployment and compared this group with the patients who underwent conventional arch replacement with an elephant trunk technique. They conducted a separate meta-analyses to assess technical success, stroke, spinal cord ischemia (SCI), renal failure requiring dialysis, and cardiac and pulmonary complications rates, as well as 30-day/in-hospital mortality. In this meta-analysis, they found the 30-day mortality rate for the "de-branching" (hybrid) procedures was 11.9%, stroke rate was 7.6%, and the spinal cord ischemia rate was 3.6%, while pulmonary complications were observed in 12.6% of patients. Cardiac complications, such as myocardial infarction and cardiac arrhythmias, were present in 6.0% and renal insufficiency requiring permanent hemodialysis occurred in 5.7%. The spinal cord ischemia incidence was low in their study which they believed to be because of the fact that there was no need for total aortic cross-clamping, which eliminates the ischemia time of the spinal cord. The technical success of this method was 92.8%. Other complications included a considerable rate of endoleaks (16.6%) and postoperative retrograde type A dissection (4.5%). Whereas in

Table 6 Comparison between conventional open and hybrid technique

Author	Year	Technique	Patients	Mortality (%)	Stroke (%)	SCI (%)	Re-intervention (%)
Moukalakis	2013	Open repair	1316	9.5	6.2	3.6	–
		Hybrid	956	11.9	7.6	5	–
Iba	2013	Open repair	143	3	3	–	0.60
		Hybrid	50	2	6	–	10
Tokuda	2016	Open repair	124	0	12	1.7	1
		Hybrid	58	3.4	17	0.8	21

the conventional surgery, the pooled 30-day mortality rate was approximately 9.5% and the stroke rate around 6.2%. Both of which were less as compared to the hybrid procedure. The pulmonary complications were more which lead to a prolonged stay in the ICU but the pooled rate estimated for Spinal cord ischemia symptoms and renal impairments requiring dialysis were 5% and 3.8%, respectively. The study concluded that the hybrid repair did not significantly improve operative mortality and was associated with a slight but non-significant increase in permanent neurologic deficits. Late mortality was slightly more in the hybrid group but was statistically not significant [41].

Iba and colleagues in 2014, published a comparative study of 143 patients who had undergone a conventional arch replacement with 50 patients who had undergone a hybrid procedure, between 2008 and 2013. Their study demonstrated that no statistically significant difference was seen in the early or late mortality rate of both the groups. Early morbidity in both the groups was similar but ICU stay was prolonged in the open group. The re-intervention rate was higher in the hybrid group because of the endoleak. [42]

In 2016, Tokuda and co-workers published a comparative study of 364 patients out of which 58 underwent isolated hybrid de-branching and 124 underwent conventional open aortic arch replacement. They found that the 30-day mortality rate was 3.4% in the hybrid group as compared to nil in the open group. Even in the midterm outcome, the survival rate was 88% in the hybrid group as compared to 96% in the open group at 1 year and 80% and 93% at 2 years. The rate of freedom from re-intervention was significantly higher in the open group. Thus, the study emphasized the fact that the hybrid procedure did not significantly decrease mortality, stroke, and spinal cord injury. So, it did not provide any benefits in this regards; in fact, the re-intervention rates were higher in the hybrid procedure. They concluded that based on midterm results, open surgery provided superior results as compared to hybrid ones, and the rate of complications like the proximal leak and aortic dissection is noteworthy in hybrid procedures [43].

Chakos et al. reviewed 9 studies including 1182 open repair plus 841 hybrid repair to publish a meta-analysis comparing the long-term survival and outcomes of the two groups. They did not find any conclusive difference in survival between the two groups but their study showed to have a statistically significant rise in spinal cord injury rate in the hybrid group. The rate of re-exploration due to bleeding was more in the open group [44].

So to conclude, conventional arch replacement can be carried out in a great majority of patients. Hybrid procedures are often as invasive and technically difficult as conventional ones. Moreover, their immediate results are, in many reported experiences, not better, and their long-term results are less favorable than the ones observed with conventional methods.

Thus the conventional open surgery remains the gold standard for arch aneurysm and dissection.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Human and animal rights and informed consent This article does not contain any studies with human participants or animals performed by any of the authors.

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