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# Outcomes of Aortic Arch Replacement Performed Without Circulatory Arrest or Deep Hypothermia

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## Abstract

***Background:*** **Aortic arch replacement using standard techniques, including deep hypothermic circulatory arrest and selective antegrade cerebral perfusion, is still associated with significant mortality and cerebral morbidity. We have previously described the "branch-first" technique that avoids circulatory arrest or profound hypothermia with excellent outcomes. We now describe our clinical experience with a larger cohort of patients as well as follow-up of our earlier results. We also describe a further technical simplification to this technique.** ***Methods:*** **From 2005 to 2010, 43 patients underwent a "branch-first continuous perfusion" technique for aortic arch replacement. In this technique, arterial perfusion is peripheral, usually by femoral inflow. Disconnection of each arch branch and anastomosis to a perfused trifurcation graft proceeds sequentially from the innominate to the left subclavian artery, with uninterrupted perfusion of the heart and viscera by the peripheral cannula. In the first cohort perfusion to the trifurcation graft was by right axillary cannulation. Since 2009, a modification was introduced such that perfusion is supplied directly by a sidearm on the trifurcation graft. This was used in the last 18 patients of this series. After reconstruction of the debranched arch and ascending aorta, the common stem of the trifurcation graft is anastomosed to the arch graft. In this series, there were 27 males, and mean age was 63 ± 13 years. Fifteen cases (35%) were performed with urgent/emergent priority. Nineteen patients (44%) were operated for aortic dissection, and the remainder for aneurysms. Seven patients (16%) had previously undergone a cardiac surgical procedure.** ***Results:*** **There were two (4.7%) early mortalities while one patient (2.3%) experienced a permanent stroke. One patient (2%) required mechanical support while three (7%) required hemofiltration for renal support. Extubation was achieved within 24 hours in 21 patients (49%) while 19 (42%) were discharged from the Intensive Care Unit (ICU) within two days. Eight patients (19%) did not require any transfusion of red cells or platelets. Mean follow-up duration was 21 ± 19 months and was 100% complete. At three years, survival was 95 ± 3.2%. No patients required subsequent aortic reoperation during this early follow-up period.** ***Conclusions:*** **This modified branch-first continuous perfusion technique brings us closer to the goal of arch surgery without cerebral or visceral circulatory arrest and the morbidity of deep hypothermia. Our early experience is encouraging although greater numbers and longer follow-up will reveal the full potential of this approach.** 

## Key Words

**Aortic arch · Aortic surgery · Cerebral protection**

## Introduction

Deep hypothermic circulatory arrest with or without selective antegrade cerebral perfusion is currently

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widely utilized for cerebral protection during aortic arch surgery. Nonetheless this technique is still associated with significant risks. Even short periods of cerebral circulatory arrest have been shown to be deleterious for higher cognitive function [1]. While deep hypothermia is frequently used to compensate for the unpredictable duration of cerebral circulatory arrest, its associated morbidities such as prolonged bypass times for cooling/rewarming and coagulopathy are well documented. Selective antegrade cerebral perfusion while providing nutritive cerebral flow introduces the risk of atheromatous and/or air embolism from direct manipulation of the arch branches. It also relies on deep hypothermia alone to provide distal organ protection.

Since 2005, in an attempt to minimize the risks and morbidity associated with aortic arch replacement, our center has adopted a branch-first continuous perfusion technique, in which there are no periods of global cerebral circulatory arrest or deep hypothermia, with encouraging early results [2]. More recently, modifications of this technique have been made to enhance applicability and reduce technical complexity.

We hereby describe our technical modifications and report our early experience with this branch first continuous perfusion technique for replacement of the aortic arch in both elective and emergent settings.

## Methods

### *Patients and Methods*

Between, 2005 and 2010, 43 patients have undergone this technique, selectively in the first year and as a routine from 2006 onwards. Of these, 27 were male and 16 were female. The average age was 64 years (range 29 – 85 years). Preoperative demographic data are shown in Table 1. Of note, 15 were operated as urgent/emergent cases for aortic dissection.

Eighteen patients underwent reimplantation of all three arch branches. Twenty-three patients did not require reimplantation of the left subclavian. Two patients underwent reimplantation of only the innominate. Arch branch reconstruction ceased at the point where the aorta became free of disease.

Concomitant aortic root surgery was performed in 19 patients in whom six patients underwent root replacement via the David reimplantation technique, while other valve-sparing techniques (Yacoub remodeling or reconstruction of the non-coronary sinus and sino-tubular junction) were applied in four patients. Nine patients underwent a Bentall's procedure, with three and six patients receiving mechanical and tissue valves, respectively. Six patients underwent concomitant coronary artery bypass grafting.

**Table 1.** Preoperative Clinical and Operative Data

| Clinical | Patients (n = 43) |
|---|---|
| Age | 64 (55–74) |
| Male | 27 (63) |
| Nonelective cases | 15 (35) |
| Current smoker | 12 (28) |
| Hypertension | 30 (70) |
| Cerebrovascular disease | 3 (7) |
| Diabetes | 1 (2) |
| Coronary artery disease | 13 (30) |
| Previous cardiac surgery | 7 (16) |
| Previous Type A dissection | 3 (7) |
| AVR/ASD | 1 (2) |
| CABG | 1 (2) |
| Coarctation | 1 (2) |
| Bentall's | 1 (2) |
| Type A aortic dissection | 19 (44) |
| Acute dissection | 15 (35) |
| Chronic | 4 (9) |
| Operative | |
| Arch branches reimplanted | |
| Trifurcation | 18 (42) |
| Bifurcation | 23 (53) |
| Innominate only | 2 (5) |
| Side-arm inflow modification | 18 (42) |
| Coronary artery bypass grafting | 6 (14) |
| Bentall's | 9 (21) |
| Mechanical valve | 3 (7) |
| Bioprosthesis | 6 (14) |
| David reimplantation | 6 (14) |
| Other valve-sparing | 4 (9) |
| Elephant trunk | 6 (14) |
| Frozen | 4 (9) |
| Regular | 2 (5) |
| Miscellaneous | 1 (2) |
| Cardiopulmonary bypass time (min) | 285 (219–329) |
| Minimum temperature (degrees C) | 27 (22–31) |
| Cerebral exclusion time | 165 (133–222) |
| Cerebral perfusion flow rate (L/min) | 1.0 (0.8–1.4) |
| Distil circulatory arrest | 20 (47) |

Continuous variables expressed as median (interquartile range).
Categorical values expressed as absolute values (percentages). AVR/ASD indicates aortic valve replacement, atrial septal defect; CABG, coronary artery bypass grafting.

### *Operative Technique*

Preoperative investigations include axial computerized tomographic angiography (CTA) of the thoracic and abdominal aorta and transesophageal echocardiography (TEE). Intraoperative cerebral monitoring is performed by a combination of electroencephalogram bispectral index (BIS) monitoring, cerebral oximetry (INVOS 3100, Somanetics Corp, Troy, MI) and transcranial Doppler (TCD).

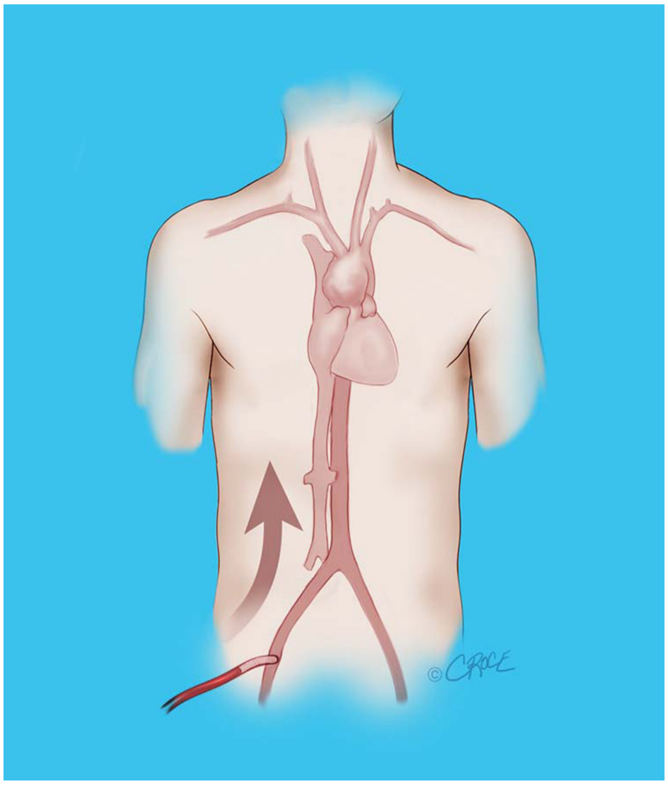

**Figure 1.** Arterial cannulation is femoral. In cases of severe aortoiliac atheroma, axillary or direct ascending aortic cannulation may be used.

The chest is opened via a median sternotomy. Cardiopulmonary bypass is instituted via femoral arterial inflow and central right atrial drainage (Fig. 1). Left axillary or direct ascending aortic [3,4] cannulation could be used in cases of severe aortoiliac occlusive or iliofemoral dissection or severe descending aortic atheroma, although this was only necessary in a couple of cases.

In the initial experience, left axillary cannulation was added to the femoral inflow to act as a source for antegrade perfusion to the arch branches reimplanted into the trifurcation graft [2]. In the last 18 patients, we totally replaced the need for axillary cannulation by the use of a modified trifurcation graft with an added perfusion side arm (Vascutek Ltd., Renfrewshire, Scotland, UK).

The arch branches are exposed for a length of 3–4 cm using a "no touch" technique. To facilitate this, the thymus is divided in the midline and the innominate vein is mobilized by dividing all its tributaries. This allows complete mobility of the latter structure without having to divide it and potentially impede left cerebral venous drainage.

The innominate artery is clamped just proximal to its bifurcation and about 1 cm distal to its origin from the arch (Fig. 2A). The innominate artery is then divided between the clamps and proximal stump ligated, allowing removal of the proximal clamp and excellent access to the distal innominate stump, which is anastomosed to the first limb of the three-branched graft (Fig. 2B). After the innominate artery anastomosis is completed and deairing maneuvers performed, the side arm of the trifurcation graft is used for antegrade flow. Median cerebral perfusion flow was 1.0 (0.8–1.4) liters per minute with an aim to achieve a right radial pressure of 50–70 mm Hg.

Completion of the innominate anastomosis removes tension on the convexity of the arch, increases its mobility, and enhances access to and exposure of the left carotid artery and in turn the left subclavian artery. A similar process is followed for the anastomosis and reperfusion of the second and third limbs of the branched Dacron graft to the left carotid and left subclavian arteries respectively (Fig. 2C and 2D).

Note that in roughly half the cases the nature of arch pathology allowed retention of the subclavian on the distal aorta, avoiding the need for this step. Where a large arch aneurysm interferes with access to the left subclavian artery, we utilize a number of maneuvers to facilitate its reconstruction. These include (1) a short (1–2 cm) extension of the neck incision along the anterior border of the left sternocleidomastoid muscle can greatly improve exposure; (2) temporarily decreasing the distal perfusion pressure, which reduces the turgidity of the arch and avails more space; and (3) delaying the left subclavian reconstruction until the descending aorta is clamped and the arch resected, thus leaving ample room for left subclavian anastomosis.

At this stage, the perfused trifurcation graft can be laid easily out of the field over the patient's neck. It is important to note that during this whole process the circulation was not interrupted to either the heart or the distal organs. Also of note is that all arch branch anastomoses are readily in view and complete hemostasis from these sites can be ensured with ease.

The proximal descending aorta is now readily mobilized. This can be assisted by temporary reduction in distal perfusion to increase its maneuverability. Also, division of the ligamentum arteriosum is key to allowing the recurrent laryngeal nerve to "drop away" from the aortic wall. Complete distal control with a clamp is readily achieved in over half of the cases. In the remainder where this is difficult because of adhesions or fragility, use of intraluminal balloon occlusion together with reduced distal flow (so as to not dislodge the balloon) allows distal perfusion to continue. Once the distal anastomosis is completed (20–30 minutes), a clamp is applied to the graft, allowing resumption of full distal flows. If an elephant trunk procedure is needed, then a brief period of distal arrest is used to allow insertion of the prosthesis into the descending aorta, then the composite descending and (soft graft component of) the elephant trunk is controlled as above to allow resumption of distal flows.

Distal anastomosis is performed between the distal arch/descending aorta and an appropriate size tube Dacron graft with a preattached single side arm graft (Ante-Flo Prosthesis, Vascutek Ltd., Renfrewshire, Scotland, UK) (Fig. 2E), or in elephant trunk cases the preexisting Dacron graft is anastomosed to the descending aorta. After completion of this anastomosis, distal body flow is changed from femoral to the sidearm graft (or directly into the graft in the case of frozen elephant trunk) and a clamp applied to the main arch graft immediately proximal to the perfusion port.

Aortic root reconstruction can now proceed if required, and anastomosis between the arch graft and root is com-

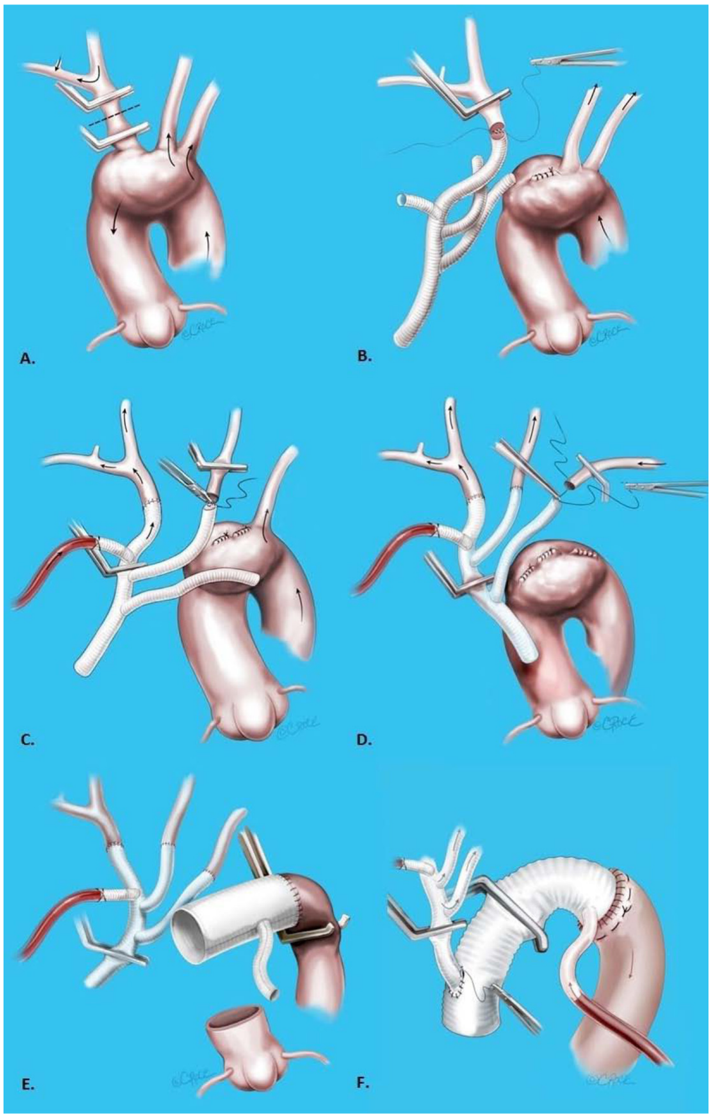


**Figure 2.** (A) The innominate artery is clamped proximal to its bifurcation and distal to its origin from the arch and divided between the clamps. (B) The innominate artery's proximal stump is ligated and the distal anastomosis to the first limb of the three-branched graft is performed. (C) The second limb of the branched graft is anastomosed to the left common carotid artery. (D) The third limb is anastomosed to the left subclavian artery. (E) Distal anastomosis of the arch graft to the distal arch. (F) The trunk of the trifurcation graft is passed under the innominate vein and anastomosed to the arch graft.

pleted. Finally, the trunk of the branched graft is passed deep to the innominate vein and anastomosed to the ascending graft, in end-to-side fashion, again without the need to interrupt cerebral perfusion (Fig. 2F).

### *Data Collection and Analysis*

Clinical, investigative, operative, perfusion, and early postoperative data were prospectively collected in a departmental database, with additional data extracted from operation reports, perfusion reports, and intraoperative computerized records. Follow-up data obtained from patients' records was collected up to August 1, 2011. Kaplan Meier survival analysis was performed using Predictive Analytics SoftWare Statistics Package 17.0 (SPSS Inc., Chicago). Continuous variables are expressed as median (first to third quartile) to account for their skewed distribution.

## Results

### *Intraoperative*

Intraoperative data are summarized in Table 1. Median cardiopulmonary bypass time was 285 (219 to 339) minutes. The median minimum temperature was 27 (22–

**Table 2.** Early Postoperative Outcomes

| | Patients (n = 43) |
|---|---|
| In-hospital mortality | 2 (5) |
| Neurological dysfunction | 3 (7) |
| Stroke | 1 (2) |
| Visual loss | 1 (2) |
| Hemiparesis | 1 (2) |
| Residual deficit | 1 (2) |
| Return for bleeding | 5 (12) |
| Tracheostomy | 3 (7) |
| Mechanical support | 1 (2) |
| Renal support | 3 (7) |
| Ischemic gut | 0 (0) |
| Ischemic limb | 1 (2) |
| Transfusion | |
| Red cells (units) | 2 (1–5) |
| Platelets (units) | 2 (0–4) |
| No transfusion (of both) | 8 (19) |
| No transfusion (either) | 20 (47) |
| Ventilation time <24 h | 21 (49) |
| ICU time <48 h | 20 (47) |
| Hospital stay <7 d | 14 (33) |

Continuous variables expressed as median (inter-quartile range).
Categorical values expressed as absolute values (percentages).

31) degrees Celsius. The lower range temperatures represent extra caution exercised early in our experience. Median cerebral perfusion flow was 1.0 (0.8–1.4) liters per minute with an aim to achieve a right radial pressure of 50–70 mm Hg. Cerebral perfusion was maintained on a separate antegrade circuit for a median duration of 165 (133–222) minutes. In 20 patients with adhesions or difficult access where distal clamping proved difficult, distal low flow combined with antegrade perfusion via a balloon occlusion catheter was used with moderate hypothermia (26–28 degrees Celsius).

*Early Postoperative Outcomes*

Postoperative outcomes are detailed in Table 2. There were two mortalities in the early post operative period. The first was due to right ventricular failure in an 85-year-old female patient. She had undergone emergency arch and root replacement in combination with coronary artery bypass grafting (CABG) for a delayed presentation of an acute Type A dissection with a preoperative right ventricular infarct and dysfunction. The second early mortality was in a 61-year-old male patient with acute Type A dissection associated with preoperative malperfusion of the lower limbs and gut. He underwent emergency ascending, arch, and frozen elephant trunk replacement. The procedure was completed uneventfully, however, he continued to suffer the consequences of preexisting gut malperfusion and died of multiorgan failure.

Three patients (7%) experienced neurological dysfunction. The first patient experienced amaurosis fugax, while the second patient experienced left hemiparesis. Both of these conditions resolved completely. These almost certainly occurred secondary to embolic events rather than hypoperfusion. Both early and delayed computed tomography of the brain in both patients did not show any infarction or hemorrhage. The third patient experienced short-term memory loss and expressive dysphasia that did not completely resolve. This occurred on the background of preexisting cerebrovascular disease and an acute Type A dissection with cerebral malperfusion (Table 2). There were no cases of global dysfunction or watershed infarcts to suggest inadequacy of collateral circulation during arch branch clamping. There was one case of transitory left hand hypoperfusion after ligation of an atheromatous left subclavian artery, which recovered spontaneously and did not require a carotid-subclavian bypass.

Thirty-two patients (74%) did not experience any complications. In eight patients (19%), neither red blood cells nor any other blood product was required. Twenty-one patients were extubated within 24 hours and 20 were discharged from the ICU within 48 hours. Three patients (7%) required a tracheostomy while five patients (12%) returned to theater for bleeding.

*Follow-up*

Median follow-up duration was 21 ± 19 months and 100% complete. There was one late death, occurring in a patient with nonsmall cell lung cancer 58 months after arch replacement. At three years, survival was 95 ± 3.2%.

No patients required reoperation for residual or recurrent aortic pathology. There were no cases of aortic rupture or acute dissection. At last follow-up 31 (72%) patients were in New York Heart Association (NYHA) class 1. The Kaplan Meier survival curve is displayed in Table 3.

## Discussion

The combination of deep hypothermia and antegrade cerebral perfusion remains the mainstay of organ protection during circulatory arrest for arch surgery [5,6], yet the reported outcomes are still less

**Table 3.** Follow-up

| Follow-up 100% | Patients (n = 43) |
|---|---|
| At last follow-up (months) | 21±19 |
| New York Heart Association (NYHA) level | |
| I | 31 |
| II | 8 |
| III/IV | 1 |

favorable compared to procedures on the more proximal aorta especially in terms of cerebral events. In addition, deep hypothermia carries its own spectrum of complications [1,6], which may include coagulopathy. Periods of global circulatory arrest of as short as 20 minutes have been shown to be deleterious to higher mental function and fine motor skills [1].

The advantages of the branch-first continuous perfusion technique used in our center have been discussed in detail previously [2]. The essential advantage is that there are no periods of global circulatory arrest, thus possibly minimizing cerebral morbidity. Cardiac perfusion is maintained throughout the whole of the arch branch reconstruction phase, significantly reducing the period of time of reliance on cardioplegia and the risk of myocardial dysfunction. Maintenance of distal organ and especially liver and kidney perfusion during arch reconstruction reduces the risk of postoperative vital organ dysfunction and postoperative bleeding and may shorten ICU stays.

The two early postoperative mortalities represent a 4.7% in-hospital mortality rate. Both of these occurred in patients presenting with acute Type A dissection with malperfusion syndromes, which is known to have a high in-hospital mortality rate [7]. Nonetheless our results are in line with contemporary studies reporting 30-day in-hospital mortalities ranging between 3.4% to 13% [8–12]. We also continued to observe a low incidence of renal, gastrointestinal, hepatic, and ventilatory impairment.

Reported rates of permanent stroke in contemporary aortic surgery range from 2.0% to 4.8% [1,5,13–15]. The two transient and one permanent neurological deficit sustained in our series gives an incidence in line with these. Importantly, these deficits most likely occurred secondary to embolic events and not hypoperfusion infarcts, thus supporting the safety of individual arch branch clamping.

Early survival at 3 years in this series was 95%. Although longer follow up is required, these results are comparable to larger studies that have reported 3- to 5-year survival between 71% and 87% [8,10–12]. Importantly, no patient has required a reoperation for aortic pathology. If this persists into the long-term follow-up, it may be a testimony to the benefit that the maintenance of cerebral, cardiac, and distal body perfusion in this technique allows even the most complex reconstructions to be completed meticulously in an unhurried fashion, thus providing complete correction of pathology and eliminating imperfections that may have otherwise been tolerated in view of time pressures. This may also be a reflection of the excellent hemostasis achieved, as all anastomoses' suture lines remain visible and accessible at each stage of the procedure.

The absence of abnormalities in cerebral monitoring during the reconstruction of the left common carotid artery in cases leading up to 2009 encouraged us to apply the same principle "in reverse" to innominate artery clamping. Again this was supported by no abnormalities being detected on cerebral monitoring during the relatively short periods of innominate clamping required. This eliminated the need for axillary artery cannulation and its low but definite risks of axillary artery injury, dissection, or brachial plexus injury [16,17] as well as increased operative time. The latter is especially undesirable during emergency cases. This is particularly the case in obese patients and those with fragile or small-caliber axillary arteries. This technique has evolved to include an added side-arm to the trifurcation graft to provide direct cerebral perfusion. This modified technique has simplified the procedure, lessened technical demand, and has the potential to bring aortic arch replacement into the armamentarium of the nonaortic subspecialized cardiac surgeon.

There may be a number of potential disadvantages of this technique, which have also been previously discussed [2]. Specifically, a drawback of the modified technique described here is that direct right common carotid inflow is interrupted for the anastomosis of the first limb of the branched graft to the innominate artery. This is, however, analogous to interruption of direct left common carotid inflow during anastomosis of the second limb of the branched graft in the previous technique. We have not encountered any abnormality in intraoperative cerebral monitoring during this phase of the procedure thus far. This is most likely due to the extremely rich collateral network in the head, neck, and body wall connecting the three arch branches' distribution in addition to the typically short artery clamp times (typically 10–12 minutes). This collateral system significantly supplements the capacity of the Circle of Willis. Despite this theoretical disadvantage, our early experience has supported the ongoing use of this modification.

We acknowledge that cardiopulmonary bypass times are not significantly reduced by our technique and some might argue that the use of deep hypothermic circulatory arrest (DHCA) (along with the associated periods of cooling and rewarming) would result in similar operative and cardiopulmonary bypass times to those that we report. While we agree that DHCA is a well-established technique for arch reconstruction and that it provides the surgeon with a bloodless and uncluttered operative field we feel that its use is associated with a number of clinically significant disadvantages that are not solely associated with the periods required for cooling and rewarming. It is well established that even short periods of DHCA are associated with subtle higher cerebral dysfunction [1,18,19], cerebral reperfusion injury [20], impairment of normal cerebrovascular regulatory mechanisms [21–23], and the generation of excessive cerebral temperature gradients [24,25]. Although cerebral injury can be reduced by the use of ancillary methods of cerebral protection such as antegrade or retrograde cerebral perfusion [26–28], many of those techniques impose various periods of total circulatory arrest. Furthermore, while much of the emphasis during periods of circulatory arrest is focused on avoidance of cerebral injury, preservation of other organs such as the liver, kidneys, and spinal cord is often not specifically addressed, their protection relying on deep hypothermia alone. It is this global hypoperfusion of other organs that occurs during prolonged periods of DHCA with or without cerebral perfusion that we feel leads to much of the morbidity associated with arch surgery. Although the clinical impact of this organ ischemia may be clinically significant as acute specific organ failure, more often it masquerades as more subtle end organ dysfunction culminating in sepsis, gastrointestinal bleeding, and multiorgan failure. Thus, while our cardiopulmonary bypass times are not shorter than DHCA techniques, it is our opinion that the avoidance of deep hypothermia and, more particularly, global circulatory arrest results in lower morbidity and mortality [29].

We acknowledge the limitations of this series, primarily its small size, institutional bias, and evolution of technique over time. As expected, we have noticed shorter bypass and ischemic times with increasing experience that may translate to improved outcomes toward the latter stages of the learning curve. Care is still required to handle the aorta with a no touch technique so as to avoid the risks of embolic events caused by atheromatous disease.

## Conclusion

This branch-first continuous perfusion technique brings us closer to the goal of arch surgery without cerebral or visceral circulatory arrest and the morbidity of deep hypothermia. This technique presents another alternative to established techniques in aortic arch surgery. The modification described here technically partially simplifies a demanding procedure while our early experience remains encouraging. Greater numbers and follow-up are anticipated.

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## Conflict of interest

None

**Comment on this Article or Ask a Question**

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## EDITOR'S COMMENTS AND QUESTIONS

Matalanis shows us his technique for an ingenious sequential "branch first" approach to aortic arch replacement. His technique is able to avoid deep hypothermic arrest, albeit at the "expense" of short durations of deprivation of blood flow to individual arch branches. He has accumulated a considerable–and very favorable–experience with this alternative technique.