Trifurcated graft replacement of the aortic arch: State of the art

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Objective: To review the contemporary practice in total arch replacement (TAR) by using the trifurcated graft technique.

Methods: The evolution of the trifurcated graft technique in total arch replacement is described. Axillary artery perfusion with antegrade cerebral perfusion (ACP) is routinely performed, with systemic deep hypothermia based on the anticipated interval of lower body ischemia. Cerebral oxygen saturation is monitored and bilateral ACP (BACP) is performed if the adequacy of collateral circulation is questioned. Potential advantages and disadvantages of unilateral ACP (UACP) vs BACP are discussed.

Results: The advantage of the trifurcated graft technique in TAR is that it facilitates the creation of an “elephant trunk” in the proximal arch, making the operation technically easier and avoiding the risk of recurrent laryngeal nerve injury. The technique is also versatile in a variety of aortic arch anatomies and pathologies, while enabling continuous ACP without hypothermic circulatory arrest for cerebral protection. UACP during TAR is acceptable for shorter intervals (<30-40 minutes) if combined with moderate hypothermia. BACP should be considered for prolonged ACP interval or if left cerebral oxygenation is inadequate during UACP.

Conclusions: The trifurcated graft technique is a versatile method in TAR that can be applied to a diverse range of aortic anatomies, pathologies and hybrid arch procedures, with concomitant or staged endovascular options. UACP or BACP and lower body ischemia can be performed without adding significant complexity to the procedure, while conferring maximal cerebral, spinal, and lower body protection. (*J Thorac Cardiovasc Surg* 2015;149:S55-8)

In September 1999, we initiated a series with a new approach to total aortic arch replacement (TAR) that uses a trifurcated graft to address some deficiencies of the standard Carrel patch technique. Among these deficiencies, a critical problem was that the Carrel patch and the origins of the brachiocephalic vessels were often severely involved with atherosclerotic disease, posing an important threat for cerebral embolization. We were quickly impressed by the simplicity and versatility of the trifurcated graft method and reported on our first series of 22 patients in 2002.¹ Initially, the brachiocephalic anastomoses were constructed during a single interval of deep hypothermic circulatory arrest (HCA), followed by antegrade selective cerebral perfusion (ACP) through the trifurcated graft.¹ With experience, the technique was modified, with various strategies of ACP through the trifurcated graft, permitting the entire

procedure to be performed without any HCA and with only a brief period of lower body ischemia (LBI), permitting more moderate cooling, earlier rewarming, and shorter cardiopulmonary bypass times. In addition, the risk of cerebral embolization was minimized with the trifurcated graft technique by avoiding the Carrel patch anastomosis altogether.

From 1999 through 2013, a total of 253 patients underwent TAR with the trifurcated graft method. The overall mortality was 7.1%, with a stroke rate (permanent neurologic deficit [PND]) of 4.3% and a temporary neurological dysfunction (TND) frequency of 5.1% (Unpublished data, 2014).

The method has become standardized. Unless contraindicated, axillary artery perfusion is used, and the degree of systemic cooling is based on the anticipated interval of LBI. Spinal cord and visceral injury are rare in arch surgery with HCA but must be safeguarded against if long periods of moderate hypothermic ACP are used.² When LBI time exceeded 60 minutes, Kamiya and colleagues³ found a significant increase in paraplegia (18%) at moderate hypothermia (25°C-28°C) relative to the 0% seen at lower temperatures (20°C-24°C). Experimental data suggest that significant spinal and multiorgan injury occur with LBI greater than 90 minutes and ACP at 28°C, with prolonged LBI being an independent predictor of short- and long-term mortality. Importantly, even experimental animals without overt paraplegia had significant histologically

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Abbreviations and Acronyms

ACP	= antegrade selective cerebral perfusion
BACP	= bilateral antegrade cerebral perfusion
HCA	= hypothermic circulatory arrest
LBI	= lower body ischemia
PND	= permanent neurologic deficit
TAR	= total aortic arch replacement
TND	= temporary neurological dysfunction
UACP	= unilateral antegrade cerebral perfusion

detectable spinal cord damage.² Safe ischemic intervals for the spinal cord at various temperatures were identified as follows: 20 minutes at normothermia (37°C), 50 minutes at mild hypothermia (32°C), 75 minutes at moderate hypothermia (28°C), and 120 minutes at deep hypothermia (20°C).⁴ Total body protection thus depends not only on cerebral protection but also on a sound strategy to protect the spinal cord and lower body. Prolonged LBI requires that TAR be performed either with moderate to deep hypothermia or with distal lower body perfusion to minimize spinal cord and visceral injury. Two methods for lower body perfusion can help avoid LBI: retrograde perfusion through the femoral artery or antegrade perfusion through a sidearm graft incorporated with the arch replacement graft.

Deep hypothermia (18°C–22°C) is induced while the proximal reconstruction takes place. The need for a sinotubular repair, Bentall procedure, or valve-sparing root replacement determines the rate of cooling before lower body circulatory arrest. Epiaortic scanning is used to assess the degree of intraluminal atheromatous disease or thrombus before crossclamping of the aorta. Flow is reduced to 6 to 8 mL/kg, initiating unilateral antegrade cerebral perfusion (UACP), and the brachiocephalic arteries are occluded, beginning sequentially with the innominate artery. Direct arterial pressure monitoring ensures that

hyperperfusion of the right cerebral hemisphere does not occur. Cerebral saturation is monitored with near-infrared spectroscopy, with particular attention paid to the left side, where a significant drop (>20%) relative to the right might signify inadequate collateral circulation and the need for bilateral antegrade cerebral perfusion (BACP).⁵ The 3 brachiocephalic vessels can be anastomosed to the trifurcated graft in less than 30 minutes, at which time BACP (10–12 mL/kg; mean arterial pressure of 40–60 mm Hg) through the trifurcated graft can commence through the axillary artery, with the perfusate temperature allowed to drift upward.

The potential advantages and disadvantages of BACP relative to UACP in TAR are summarized in Table 1. A recent review by Luehr and colleagues⁴ detailed differences between the 2 strategies, but several large studies are worth discussion (Table 2). Krähenbühl and colleagues⁶ compared UACP with BACP among 280 patients and found no differences in mortality, TND, and PND, but the BACP group had better midterm quality of life scores. Zierer and colleagues⁷ compared UACP with BACP at 28°C to 30°C in 184 propensity-matched patients who underwent TAR with mild hypothermia (30°C). A trend toward higher PND (2.2% vs 9.7%; $P = .06$) was found in the BACP group, despite no differences in early mortality and TND. Angeloni and colleagues⁸ compared UACP and BACP in a meta-analysis of more than 5000 patients (28 studies) and found no difference in early mortality, TND, and PND; however, higher temperature and longer HCA time were associated with higher mortality and PND. In the German Registry for Acute Aortic Dissection type A study,⁹ there was no difference in mortality or PND between UACP and BACP; however, cerebral perfusion flows greater than 600 mL/min and pressures greater than 60 mm Hg were associated with reduced PND but not mortality, and cerebral perfusion greater than 60 minutes was associated with increased mortality regardless of strategy. Papantchev and

TABLE 1. Advantages and disadvantages of UACP versus bilateral antegrade cerebral perfusion in aortic arch surgery

Antegrade cerebral perfusion strategy		Advantages	Disadvantages
Unilateral	Simple cannulation		Insufficient left brain protection in subset of patients
	Axillary		Dependence on collaterals
	Innominate		Circle of Willis
	Carotid		Leptomeningeal
	Brachial		Extracranial
	Uninterrupted cerebral flow		Potential cerebral edema from hyperperfusion
	Clear operative field		
Bilateral	No instrumentation of cerebral vessels		
	Consistent, complete brain perfusion regardless of vascular anomalies		Instrumentation of cerebral vessels
	May be superior for prolonged antegrade selective cerebral perfusion (>40 min)		Obstructed operative field
			Migration of balloon tip catheters with possible malperfusion

TABLE 2. Select studies comparing unilateral antegrade cerebral perfusion with bilateral antegrade cerebral perfusion in aortic arch surgery

	Krähenbühl ⁶	Krüger ⁹	Zierer ⁷	Zierer ⁷	Angeloni ⁸
Centers	Bern, Switzerland	44 centers, Germany	Frankfurt, Bad Neustadt, Germany	Frankfurt, Bad Neustadt, Germany	28 studies, >30 centers worldwide
Period	2004-2007	2006-2009	2010-2012	2010-2012	1986-2009
Analysis	Retrospective	Retrospective	Retrospective, propensity matching	Retrospective, propensity matching	Meta-analysis
Aortic surgery	Hemiarch, total arch; 38% dissection	Hemiarch, total arch; 100% dissection	Hemiarch, total arch	Total arch	Hemiarch, total arch (~25%); ~25% dissection
Exclusion			Dissection	Dissection	
UACP (N)	118	628	246	91	1505
Systemic temperature	<24°C bladder	NA	30°C ± 2°C rectal	30°C ± 2°C rectal	NA
ACP temperature	18-20°C	<15°C, 14%; 15°C-20°C, 21%; 21°C-25°C, 23%; 26°C-30°C, 17%; >30°C, 25%	28°C-30°C	28°C-30°C	23.7°C
ACP flow	0.8-1 L/min	820 ± 436 mL/min	0.9 (LCC), 1.1, 1.5 L/min	0.9 (LCC), 1.1, 1.5 L/min	NA
ACP pressure (mm Hg)	50-60	66 ± 32	75-80	75-80	NA
ACP duration (min)	28 ± 12	32 ± 18	41 ± 19	65 ± 13	31 ± 12
In-hospital/30-d mortality	4.2%	13.9%	3.7%	6.6%	8.6%
TND	7.6%	NA	4.9%	6.6%	7.1%
PND	7.6%	10.0%	2.0%	2.2%	6.5%
BACP (N)	133 (innominate, LCC); 29 (RA, LCC)	453	246	93	3595
Systemic temperature	<24°C bladder	NA	30°C ± 2°C	30°C ± 2°C	NA
ACP temperature	18°C-20°C	<15°C, 7%; 15°C-20°C, 52%; 21°C-25°C, 27%; 26°C-30°C, 12%; >30°C, 2%	28°C-30°C	28°C-30°C	23.1°C
ACP flow	250-300 mL/min; 650 mL/min	758 ± 358 mL/min	1.4 L/min	1.4 L/min	NA
ACP pressure (mm Hg)	50-60	65 ± 26	75-80	75-80	NA
ACP duration (min)	16 ± 7; 43 ± 17	38 ± 24	43 ± 21	67 ± 18	31 ± 19
In-hospital/30-d mortality	3.0%; 6.8%	15.9%	4.5%	8.6%	9.2%
TND	8.2%; 13.7%	NA	4.1%	5.4%	8.8%
PND	6.0%; 13.7%*	11.0%	5.7%†	9.7%†	6.1%

UACP, Unilateral antegrade cerebral perfusion; NA, not available; ACP, antegrade cerebral perfusion; LCC, left common carotid artery; TND, transient neurologic deficit; PND, persistent neurologic deficit; BACP, bilateral antegrade cerebral perfusion; RA, right axillary artery. **P* = .057 versus other antegrade cerebral perfusion groups. †*P* = .06 versus unilateral antegrade cerebral perfusion.

colleagues,¹⁰ examining 500 circles of Willis postmortem with computed tomographic angiography and found that 58.6% had anatomic variations that could cause cerebral hypoperfusion during UACP, with 35.6% missing a left posterior communicating artery. They cautioned that prolonged UACP, in the presence of circle of Willis variations, may lead to subtle but significant neurocognitive deficits, such as delirium and psychocognitive changes.

Clinical and anatomic findings thus suggest that a more patient-specific ACP strategy might optimize neurologic outcomes. UACP is acceptable for shorter intervals (<30-40 minutes) if combined with moderate hypothermia. For prolonged ACP intervals, or if left cerebral oxygenation

becomes significantly reduced during UACP, BACP should be considered.

An advantage of the trifurcated graft technique is that it facilitates creation of an elephant trunk in the proximal arch, where it is technically easier and avoids injury to the recurrent laryngeal nerve (Figure 1). In addition, the trifurcated graft technique has proved versatile in dealing with various arch anatomies and anomalies. For a laterally displaced left subclavian artery, a preoperative left carotid to subclavian bypass simplifies the ensuing TAR, requiring only a bifurcated graft to complete the repair. Alternatively, a separate 8- or 10-mm Dacron polyester fabric graft can be sewn to the left axillary artery, brought through the left

FIGURE 1. An example of trifurcated graft total arch reconstruction with elephant trunk anastomosis and side-arm graft for lower body perfusion.

thorax, and attached to a limb of the trifurcated graft during rewarming. For a left vertebral artery arising directly from the aortic arch, the size and patency of the right vertebral artery determine whether the arch reconstruction strategy should permit early reperfusion of the anomalous left vertebral artery along with the brachiocephalic vessels or whether it can be anastomosed at a later point in the procedure. A number of configurations are possible for the anomalous vertebral, including direct anastomosis to the left common carotid artery or anastomosing the left subclavian and anomalous left vertebral artery with a “button” of arch tissue to the larger limb of the trifurcated graft.

DISCUSSION

The trifurcated graft technique for TAR is a versatile method that easily accommodates variable arch anatomies

while permitting continuous ACP without HCA. The technique can be applied to acute aortic pathologies and hybrid arch procedures, with concomitant or staged endovascular options. In cases of prolonged ACP and LBI, BACP and lower body perfusion can be performed without adding significant complexity to the procedure while conferring maximal cerebral, spinal, and lower body protection.

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