Cardiol Young 2004; 14 (Suppl. 1): 70–74
© Greenwich Medical Media Ltd.
ISSN 1047-9511

Antegrade regional cerebral perfusion

Christo I. Tchervenkov, Abdulaziz Al-Khaldi, Dominique Shum-Tim

The Division of Cardiovascular Surgery, Montreal Children's Hospital, McGill University Health Center, Montreal, Canada

A QUIET AND BLOODLESS FIELD PROVIDING optimal surgical conditions has been a crucial prerequisite for the performance of complex cardiac repairs in early life. The use of deep hypothermic circulatory arrest has fulfilled this role, and has been a catalyst for the development of neonatal and infant cardiac surgery. The recently increased awareness of possibly increased incidence of adverse neurological events and developmental outcome associated with this technique,[1–5] however, has led to a general trend away from its use. In its place, techniques have been developed to provide cerebral perfusion during reconstruction of the aortic arch and the Norwood operation. Some have described the techniques as regional low-flow perfusion. In our opinion, they are described more accurately as antegrade regional cerebral perfusion. In this review, we discuss the recently described techniques for such antegrade regional cerebral perfusion during surgery on the aortic arch, with emphasis both on the Norwood operation and the observed physiological changes in the cerebral and systemic circulations. The neurologic and developmental outcomes following the use of the technique are still unknown.

Techniques for antegrade regional cerebral perfusion

The various methods described to provide antegrade regional cerebral perfusion share the common characteristic of perfusion through the brachiocephalic artery, or rarely directly through the carotid arteries. They differ in terms of the techniques used for cannulation, whether there is concomitant perfusion of the myocardium and/or the systemic circulation via the descending aorta, and the rates of flow and temperature during the process of antegrade perfusion.

Polytetrafluoroethylene graft anastomosed to the brachiocephalic artery

This was the first technique for antegrade cerebral perfusion, and was described by Asou et al.[6] in 1996 for repair of patients with hypoplastic aortic arches. Initial systemic perfusion is achieved via an arterial cannula placed in the patent arterial duct with proximal snaring. A second arterial cannula, connected to the arterial line by a "Y" connector, is placed into the proximal end of a polytetrafluoroethylene graft that is anastomosed distally to the brachiocephalic artery (Fig. 1). After achieving deep hypothermia, the cannula is removed from the duct, the proximal brachiocephalic artery is snared, and antegrade regional perfusion to the brain is provided at low rates of flow during reconstruction of the aortic arch. To ensure a bloodless field, it is also necessary to snare the left common carotid and left subclavian arteries, along with the descending thoracic aorta. Once the repair of the aortic arch is completed, all snares and clamps are removed, and the arterial cannula is transferred to the neoaorta. During rewarming, the proximal end of the polytetrafluoroethylene graft is anastomosed to the right pulmonary artery. This serves as a modified Blalock-Taussig shunt if one is performing the Norwood operation. The technique includes a short period of deep hypothermic circulatory arrest for the transfer of the arterial cannula and the atrial septectomy. The potential risk of air embolism during initial cannulation of the open end of the polytetrafluoroethylene graft, and transfer of the cannula, is of concern, but can be avoided by careful deairing and compression of the right common carotid artery at the time of initiation of blood flow.

Direct cannulation of the cerebral vessels

Asou et al.[7] subsequently described a modification of their initial technique in which they achieved cerebral

Correspondence to: Christo Tchervenkov MD, Director, Cardiovascular Surgery, Room C-829, The Montreal Children's Hospital, McGill University Health Center, 2300 Tupper Street, Montréal, Québec, Canada H3H 1P3. Tel: 514 934 4400 ext. 2394; Fax: 514 934 4330; E-mail: christo.tchervenkov@muhc.mcgill.ca

https://doi.org/10.1017/S104795110400633X Published online by Cambridge University Press

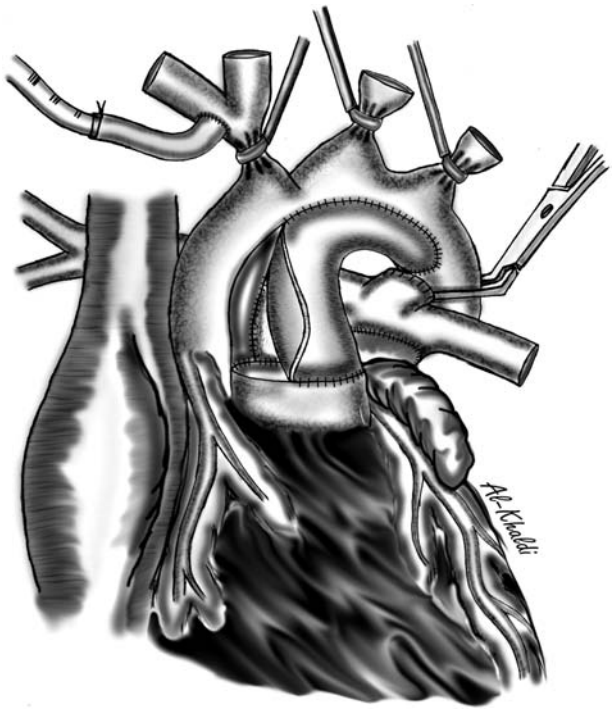


Figure 1.
This first technique for antegrade cerebral perfusion as described by Asou et al.[6] in 1996 for repair of patients with hypoplastic aortic arches.

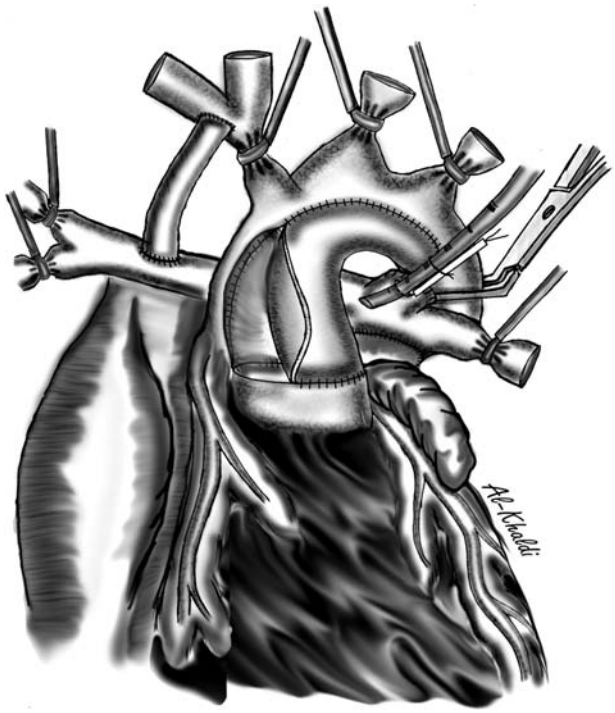


Figure 2.
The technique specifically designed to provide antegrade regional cerebral perfusion during the Norwood operation.

perfusion through a thin-walled and metal-tipped aortic cannula, with a high ratio of internal to external diameters, inserted directly into the brachiocephalic artery. This technique is used more frequently for repairing an interrupted or hypoplastic aortic arch, when construction of a modified Blalock-Taussig shunt will not be a part of the procedure. The external diameter of the cannula is sufficiently small to allow flow around its tip for systemic perfusion. Direct cannulation of the cerebral vessels, however, carries the risk producing stenosis of the carotid artery, or occlusion at the site of cannulation, and therefore has few advocates.

Cerebral perfusion using the completed shunt via the confluence of the pulmonary arteries

This technique, specifically designed to provide antegrade regional cerebral perfusion during the Norwood operation, was introduced by our group in 2000[8] (Fig. 2). Following systemic heparinization, and prior to cannulation for cardiopulmonary bypass, a modified Blalock-Taussig shunt is constructed between the brachiocephalic artery and the right pulmonary artery. Great care is used to avoid kinking of the diminutive ascending aorta by placing gentle traction sutures to its adventitia and pulling to the left. Clamping of the right pulmonary artery for the construction of the distal anastomosis usually increases the hemodynamic stability by decreasing the run-off into the pulmonary circulation. Once completed, the modified Blalock-Taussig shunt is clamped. Cannulation for arterial inflow for cardiopulmonary bypass is achieved using direct placement of a flexible 8 French arterial cannula (Bio-Medicus, Medtronic; Minneapolis, MN) into the proximal end of the patent arterial duct, and directing it distally toward the descending aorta. Venous drainage is obtained using either a single atrial cannula, or by means of bicaval cannulation. The patent arterial duct is snared proximal to the arterial cannula as cardiopulmonary bypass is begun. During the period of cooling needed to achieve systemic hypothermia at around 18°C, the pulmonary trunk is transected proximal to its bifurcation, and the distal end is closed with a homograft patch. Just before completing the suture line, the modified Blalock-Taussig shunt is unclamped briefly to deair the pulmonary arteries in a retrograde fashion. Once deep hypothermia has been achieved, the right and left pulmonary arteries are snared distally, and the clamp is removed from the modified Blalock-Taussig shunt. Without removing it, the arterial cannula is redirected into the confluence of the pulmonary arteries, and the patent duct is now snared distally. Low-flow antegrade regional cerebral perfusion can now be provided via the brachiocephalic artery, which is perfused through the confluence of the pulmonary

https://doi.org/10.1017/S104795110400633X Published online by Cambridge University Press

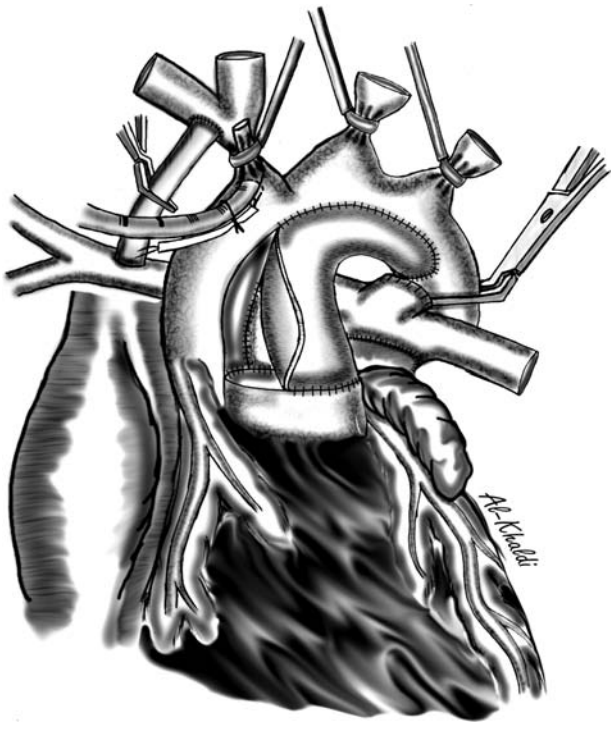


Figure 3.
Antegrade regional cerebral perfusion when the ascending aorta is large enough for arterial cannulation.

arteries and the previously constructed modified Blalock-Taussig shunt. Snares are placed on the proximal brachiocephalic, left common carotid, and left subclavian arteries, and a clamp is placed on the upper descending thoracic aorta to control backbleeding. The snared arterial duct is transected distally, all ductal tissue is excised, and the aortic arch and the opened ascending aorta are reconstructed with a pulmonary homograft patch. The reconstructed aorta is then anastomosed to the proximal end of the transected pulmonary trunk, thus completing the Norwood operation. After the completion of the repair, the neoaorta is deaired by removing the clamp on the descending aorta and the snares on the arch vessels, followed by tying down the suture line. The arterial cannula is then rapidly transferred to the ascending neo-aorta, the proximal end of the patent arterial duct is ligated, and the shunt is clamped. The patient is rewarmed on full cardiopulmonary bypass.

Indirect cannulation of the brachiocephalic artery via the ascending aorta

Our group[9,10] has also described a technique for providing antegrade regional cerebral perfusion when the ascending aorta is large enough for arterial cannulation (Fig. 3). The arterial cannulation is achieved by placing a flexible 8 French cannula on the right side of the ascending aorta, close to the base of the brachiocephalic artery. After systemic cooling to about 18°C, the cannula is advanced into the brachiocephalic artery without removing it, and a snare is applied around it. Snares are also placed on the left common carotid and left subclavian arteries, and a clamp is placed on the upper descending thoracic aorta to control backbleeding. The aortic arch is then reconstructed, usually with a pulmonary homograft patch, while maintaining continuous antegrade regional cerebral perfusion into the brachiocephalic artery. Following this, the descending aortic clamp is removed to deair the ascending aorta, followed by removal of the snares from the arch vessels, and the arterial cannula is pulled back into the ascending aorta, again without taking it out. Full cardiopulmonary bypass is reinstituted, and the patient is rewarmed. We have used this technique for antegrade regional cerebral perfusion when performing the Norwood operation for patients with hypoplastic left heart syndrome or associated lesions when the ascending aorta is equal to or greater than 5 mm in diameter.

Miscellaneous techniques for antegrade regional cerebral perfusion

The approach promoted by Imoto and colleagues[11,12] for use during the Norwood operation combines the technique described by Asou et al.[6] with the additional direct cannulation of the descending aorta above the diaphragm to avoid deep hypothermic circulatory arrest. Through a median sternotomy, a polytetrafluoroethylene graft is sewn to the proximal brachiocephalic artery, an arterial cannula is placed into its open end, and connected to the arterial line via a "Y" connector. The descending aorta is identified through an incision in the posterior pericardium just superior to the diaphragm. An angled metal-tipped cannula is used to cannulate the descending aorta, and is connected to the arterial line. Flow from the pump is maintained at 150 to 180 ml/kg/min, and the systemic temperature at 29 to 31°C. Applying a clamp to proximal descending aorta and snaring the cerebral vessels allow isolation of the aortic arch for reconstruction while the brain and lower body are continuously perfused at moderate hypothermia. In our opinion, the main concern with this technique is the need for dissection and cannulation of the descending aorta behind the heart, which adds another potential site for postoperative bleeding that may be difficult to control, along with the potential to produce stenosis at the site of cannulation. Furthermore, in the face of uncertainty of the optimal rates of flow at different temperatures, it is questionable that moderate hypothermia should be used instead of deep hypothermia.

Another technique combining selective cerebral and myocardial perfusion was described by Ishino

https://doi.org/10.1017/S104795110400633X Published online by Cambridge University Press

et al.[13] that used direct cannulation of the brachiocephalic artery and the aortic root.

Rates of flow and monitoring of cerebral flow

The optimal rates of flow at different temperatures during antegrade regional cerebral perfusion remain to be defined. This is mainly due to the absence of clear end-points that define adequate cerebral perfusion at various conditions. Hypoperfusion or hyperperfusion of the brain may both be deleterious. Assessments of neurological outcome in the short term are currently crude, and the methods currently available to evaluate the adequacy of cerebral perfusion intra-operatively are inadequate. A method to determine the optimal flow during antegrade perfusion has been to target the flow of blood to the brain achieved during full cardiopulmonary bypass. The limitation of this assumption is that, due to disturbances of cerebral autoregulation and characteristics of flow, while the blood reaching the brain on full cardiopulmonary bypass may be physiologically appropriate, this may not necessarily be the case during deep hypothermia.

Near-infrared spectroscopy has been used to provide useful information about relative changes in cerebral saturations of oxygen, and the index of cerebral blood volume, at different rates of flow. Pigula et al.[14] used this technique to investigate the optimal rates necessary to restore these parameters during reconstruction of the aortic arch while using continuous antegrade perfusion delivered via a polytetrafluoroethylene graft sewn to the brachiocephalic artery. They incrementally increased the rates of flow during antegrade perfusion until they achieved the baseline values obtained on full flow hypothermic cardiopulmonary bypass. They have demonstrated that, at deep hypothermia, a rate of 20 ml/kg/min, equivalent to approximately 0.3 l/min/m^2, is adequate both to restore the cerebral blood volume and maintain the appropriate saturations of oxygen.

Andropoulos et al.[15] also used near-infrared spectroscopy to evaluate optimal antegrade perfusion while reconstructing the aortic arch in 34 neonates, monitoring the velocity of flow of blood to the brain by transcranial Doppler ultrasonography, and measuring cortical saturations of oxygen. Having established these values at baseline, that is during cardiopulmonary bypass at full flow at temperatures from 17 to 22°C, they adjusted the rates of flow during the period of antegrade perfusion so as to maintain a velocity of flow within 10% of baseline. The mean rate of flow needed to maintain such velocities was 63 ml/kg/min, representing almost half the full flow achieved during bypass. They attributed the need for higher flows during antegrade perfusion in their study compared with previous studies to their use of pH-stat strategy, which provides relatively more cerebral flow and volume due to the decreased cerebral vascular resistance, their use of α-receptors antagonists such as phenoxybenzamine or phentolamine which dilate the cerebral vessels, and because more than half of their patients underwent advancement of the arch without needing to snare the brachiocephalic vessels or open the proximal aortic arch. The left subclavian and left carotid arteries were perfused during their technique because the descending aorta was cross-clamped distally. They may, therefore, have potentially perfused additional vascular beds.

It is of interest that, during antegrade regional cerebral perfusion, there is significant back bleeding from the descending aorta, suggestive of real perfusion to the lower body through collateral circulation. This possibility was first studied by Pigula et al.[16] They studied 15 consecutive neonates undergoing surgery on the aortic arch with antegrade regional cerebral perfusion, either during biventricular repairs or the Norwood operation. They found that antegrade perfusion through the brachiocephalic artery was associated with an abdominal aortic blood pressure at a mean of 12 mmHg, although this was lower than the simultaneously measured pressure in the left radial artery, which had a mean of 22 mmHg. Near-infrared spectroscopy was used to measure the index of blood volume, and the saturations of oxygen, for the quadriceps muscle. There was a significant increase in both these values during antegrade regional cerebral perfusion as compared with values obtained during brief periods of deep hypothermic circulatory arrest. In order to evaluate the degree of splanchnic perfusion, they also measured gastric tonometry and arterial tensions of carbon dioxide in 9 neonates undergoing antegrade regional cerebral perfusion, and compared them to 3 infants undergoing closure of ventricular septal defects during deep hypothermic circulatory arrest. Accumulation of carbon dioxide in the gastric mucosa was thought to result from inadequate flows of blood, and/or anaerobic conditions. They observed a significant difference in the gap during rewarming between the gastric mucosa and the arterial tensions of carbon dioxide. These findings suggest that the infradiaphragmatic systemic perfusion during antegrade regional cerebral perfusion is physiologically significant, and is likely to confer a protective effect to the other organs beside the brain. The magnitude and clinical significance of such beneficial effect remains to be determined.

De Campli and associates[17] studied the effects in neonatal piglets of antegrade regional cerebral perfusion at rates of 20 and 40 ml/kg/min on the brain, muscle, liver, and small bowel, and compared it with deep hypothermic circulatory arrest. They measured tensions of distribution of oxygen through the principle of oxygen-dependent quenching of phosphorescence.

https://doi.org/10.1017/S104795110400633X Published online by Cambridge University Press

They showed that tensions of oxygen in the cerebral cortex were significantly higher in the brain of animals receiving antegrade regional cerebral perfusion as compared with those undergoing deep hypothermic circulatory arrest. During the rewarming phase, cortical tensions of oxygen remained lower than the values measured prior to cardiopulmonary bypass in the animals having deep hypothermic circulatory arrest, whereas the values were not significantly different in animals receiving antegrade cerebral perfusion irrespective of the rates of flow. Even after 2 to 4 h recovery after cardiopulmonary bypass, values were still depressed below baseline in those subjected to deep hypothermic circulatory arrest, whereas the values were still comparable to baseline in the animals perfused at a rate of 20 ml/kg/min. Animals perfused at the higher rate of flow, in contrast, showed a significant deterioration in levels of cortical oxygen during recovery, and showed associated hemodynamic instability. These data suggests that higher flow during antegrade regional cerebral perfusion may not necessarily be protective for the brain. The cerebral effects of hypothermic cardiopulmonary bypass may also extend to the post-operative period, when neuroprotective measures need to be continued.

At Montreal Children's Hospital, during reconstruction of the aortic arch with antegrade regional cerebral perfusion, we continuously monitor mixed venous saturations of oxygen in the venous cannula, aiming to maintain an average mixed venous oxygen saturation of 80%. This usually requires mean rates of flow of 0.6 l/min/m^2 at 18°C, which is in keeping with the mean flow of 44 ml/kg/min reported by Pigula and his colleagues.[14] Other investigators have reported using similar flows.[6,11] The optimal rate of flow for antegrade regional cerebral perfusion at various temperatures, nonetheless, still remains undefined.

Conclusion

Several techniques have been devised to provide antegrade regional cerebral perfusion during reconstruction of the aortic arch and the Norwood operation. Although there is increasing information accumulating with respect to optimal rates of flow, as yet there is no long-term data concerning neurobehavioral outcomes. Whether the favorable biochemical and physiological changes observed during and after such cerebral perfusion compared to deep hypothermic circulatory arrest will translate into a clinically significant benefit with respect to protection of the brain and the other organs still remains to be proven. The development of antegrade regional perfusion during these operative procedures, nonetheless, represents a promising addition in the area of cerebral protection during pediatric cardiac surgery.

References

1. Swain JA, McDonald TJ Jr, Griffith PK, Balaban RS, Clark RE, Ceckler T. Low-flow hypothermic cardiopulmonary bypass protects the brain. J Thorac Cardiovasc Surg 1991; 102: 76–84.
2. Newburger JW, Jonas RA, Wernovsky G, Wypij D, Hickey PR, Kuban KC, Farrell DM, Holmes GL, Helmers SL, Constantinou J, Carrazana E, Barlow JK, Walsh AZ, Lucius KC, Share JC, Wessel DL, Hanley FL, Mayer JE Jr, Castaneda AR, Ware JH. A comparison of the perioperative neurologic effects of hypothermic circulatory arrest versus low-flow cardiopulmonary bypass in infant heart surgery. NEJM 1993; 329: 1057–1064.
3. Bellinger DC, Jonas RA, Rappaport LA, Wypij D, Wernovsky G, Kuban KC, Barnes PD, Holmes GL, Hickey PR, Strand RD, Walsh AZ, Helmers SL, Constantinou JE, Carrazana EJ, Mayer JE, Hanley FL, Castaneda AR, Ware JH, Newburger JW. Developmental and neurologic status of children after heart surgery with hypothermic circulatory arrest or low-flow cardiopulmonary bypass. NEJM 1995; 332: 549–555.
4. Sakurada T, Kazui T, Tanaka H, Komatsu S. Comparative experimental study of cerebral protection during aortic arch reconstruction. Ann Thorac Surg 1996; 61: 1348–1354.
5. Hickey PR. Neurologic sequelae associated with deep hypothermia circulatory arrest. Ann Thorac Surg 1998; 65: S65–S70, S74–S76.
6. Asou T, Kado H, Imoto Y, Shiokawa Y, Tominaga R, Kawachi Y, Yasui H. Selective cerebral perfusion technique during aortic arch repair in neonates. Ann Thorac Surg 1996; 61: 1546–1548.
7. Asou T, Yasui H, Kado H, Imoto Y, Shiokawa KF, Tominaga R, Kawachi Y. The use of a newly developed pediatric arterial perfusion cannula for neonates. Cardiol Young 1997; 7: 71–73.
8. Tchervenkov CI, Chu VF, Shum-Tim D, Laliberte E, Reyes TU. Norwood operation without circulatory arrest: a new surgical technique. Ann Thorac Surg 2000; 70: 1730–1733.
9. Tchervenkov CI, Korkola SJ, Shum-Tim D. Surgical technique to avoid circulatory arrest and direct arch vessel cannulation during neonatal aortic arch reconstruction. Eur J Cardiothorac Surg 2001; 19: 708–710.
10. Tchervenkov CI, Korkola SJ, Shum-Tim D, Calaritis C, Laliberte E, Reyes TU, Lavoie J. Neonatal aortic arch reconstruction avoiding circulatory arrest and direct arch vessel cannulation. Ann Thorac Surg 2001; 72: 1615–1620.
11. Imoto Y, Kado H, Shiokawa Y, Fukae K, Yasui H. Norwood procedure without circulatory arrest. Ann Thorac Surg 1999; 68: 559–561.
12. Imoto Y, Kado H, Shiokawa Y, Minami K, Yasui H. Experience with the Norwood procedure without circulatory arrest. J Thorac Cardiovasc Surg 2001; 122: 879–882.
13. Ishino K, Kawada M, Irie H, Kino K, Sano S. Single-stage repair of aortic coarctation with ventricular septal defect using isolated cerebral and myocardial perfusion. Eur J Cardiothorac Surg 2000; 7: 538–542.
14. Pigula FA, Nemoto EM, Griffith BP, Sieweers RD. Regional low-flow perfusion provides cerebral circulatory support during neonatal aortic arch reconstruction. J Thorac Cardiovasc Surg 2000; 119: 331–339.
15. Andropoulos DB, Stayer SA, McKenzie ED, Fraser CD Jr. Novel cerebral physiologic monitoring to guide low-flow cerebral perfusion during neonatal aortic arch reconstruction. J Thorac Cardiovasc Surg 2003; 125: 491–499.
16. Pigula FA, Gandhi SK, Siewers RD, Davis PJ, Webber SA, Nemoto EM. Regional low-flow perfusion provides somatic circulatory support during neonatal aortic arch surgery. Ann Thorac Surg 2001; 72: 401–407.
17. DeCampli WM, Schears G, Myung R, Schultz S, Creed J, Pastuszko A, Wilson DF. Tissue oxygen tension during regional low-flow perfusion in neonates. J Thorac Cardiovasc Surg 2003; 125: 472–480.

https://doi.org/10.1017/S104795110400633X Published online by Cambridge University Press