



Recent Advances in Congenital Heart Surgery: Alternative Perfusion Strategies for Infant Aortic Arch Repair

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Abstract

Purpose of Review This paper will discuss current cannulation strategies for infant aortic arch repair and compare them to more traditionally used techniques.

Recent Findings Aortic arch reconstruction in infants has traditionally involved deep hypothermic circulatory arrest which results in total body ischemia. This has been associated with an increased risk of morbidity including bleeding, renal dysfunction, and neurologic injury. Advances in perfusion techniques have allowed for preserved perfusion to the brain during arch repair. Current techniques have further evolved that allow for continuous perfusion of the heart and even the lower body during arch reconstruction.

Summary With current techniques, aortic arch reconstruction in infants can be performed with continuous perfusion to the brain, heart, and lower body. Further technical refinements will be helpful, and study is necessary to evaluate the benefit of these strategies.

Keywords Aortic arch · Perfusion · Cardiopulmonary bypass · Infant · Congenital heart surgery

Introduction

Surgical reconstruction of the aortic arch in neonates and infants has been traditionally performed using deep hypothermic circulatory arrest (DHCA). DHCA involves cooling the body to a very low temperature (typically 18 °C) using the cardiopulmonary bypass (CPB) circuit with or without adjunctive methods such as topical cooling. Once the target temperature

is reached, the circulation is stopped and the patient's blood is drained into the CPB circuit reservoir which facilitates performing repair in a bloodless field unencumbered by the cardiopulmonary bypass cannulae, which can be removed if desired during the repair. Once the critical portion of the repair is done, the cannulae are replaced, extracorporeal circulation is recommenced, and the patient is warmed. There are a number of potential problems with DHCA including the possibility of end-organ dysfunction, increased bleeding after surgery, and perhaps most concerning, neurologic injury [1–3]. The latter issue led to the development of regional cerebral perfusion (RCP) which provides continuous brain perfusion during arch repair. Importantly, although RCP provides blood flow to the brain, the heart is typically rendered ischemic due to aortic cross-clamping and cardioplegic arrest—a technique in which potassium-rich solution is delivered via the coronary arteries to produce a diastolic arrest of the heart. In addition, the lower body, including the kidneys, is relatively ischemic and only receives flow from upper to lower body collaterals. Because of this, there is a risk for myocardial dysfunction and other end-organ dysfunction that can contribute to postoperative morbidity and mortality. Recently, experience with and refinement of alternative perfusion techniques that allow for ongoing blood flow to the heart and the lower body during arch reconstruction

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have developed. In this article, these perfusion strategies and their applications will be discussed.

Traditional Perfusion Techniques

DHCA was developed for a number of reasons. From a technical standpoint, DHCA is advantageous during aortic arch reconstruction because it allows for a relatively unencumbered and bloodless field during the critical part of the surgery. While the aortic arch is reconstructed, the aortic cannula can be removed and clamps in the field can be avoided. The beneficial effects of such actions include quicker and more efficient suturing, less distortion of the anatomy, and potentially a more accurate reconstruction. At the completion of the repair, air is carefully excluded from the aorta and its branches, the cannula is replaced, and perfusion is resumed. The benefits mentioned above, however, come at the expense of the need for deep hypothermia and a period of total body ischemia. Deep hypothermia induces a profound decrease in metabolism that serves to protect the body and its organs from the lack of blood flow for a period of time. Extensive research has been done to try to ascertain the “safe” period of circulatory arrest. However, it is likely that there is sufficient variability from patient to patient that what seems safe for one might not be safe for another. In addition, substantial research has demonstrated that there are likely significant consequences of DHCA, some of which may be permanent. The most concerning of these relate to late neurodevelopmental outcomes [4, 5]. Another significant field of study has investigated strategies to monitor and protect the body, and in particular the most sensitive organ—the brain, from the effects of DHCA. Numerous techniques in current clinical practice have come out of this research, including the use of topical cooling of the head, intermittent perfusion, neuro-monitoring strategies, and the use of specific medications to attempt to reduce or eliminate the injurious effect of DHCA [6–12]. As more literature has accumulated and techniques and equipment have continued to evolve, interest in and strategies for aortic arch reconstruction that avoid total circulatory arrest have developed as well.

Regional Cerebral Perfusion

In response to the growing body of literature raising concerns about neurologic outcomes after the use of DHCA, interest grew in developing techniques to avoid its use. Low-flow cardiopulmonary bypass was an early strategy, but this is not practical in reconstruction of the aortic arch where the arch is open during the critical part of the

operation. In the early 2000s, the technique of RCP was developed and refined. This technique employs isolated perfusion of the brain (and a portion of the upper body), usually by directing flow into one of the brachiocephalic vessels—most commonly the innominate artery [13]. There are a variety of ways to accomplish this. In adults, it is achieved most commonly by cannulation of the right axillary artery via a side graft that is sewn onto the artery. A cannula is then placed in the graft, and when desired, perfusion can be isolated from the rest of the body by temporarily occluding the origin of the innominate artery with a clamp. In infants, the axillary artery is too small to make this technique practical, and other methods have been developed. Perhaps, the simplest way to accomplish this is to use the existing ascending aortic cannula and reposition it by advancing it into the innominate artery when RCP is desired. Placing a snare around the innominate artery and tightening it around the cannula within the artery will direct flow to the cerebral circulation. At the conclusion of RCP, the cannula can be withdrawn into the aorta to provide full systemic flow. This technique is not applicable in all situations. It is primarily useful when the ascending aorta is relatively large. It has the disadvantage of potentially distorting the ascending aorta and proximal arch during the reconstruction due to traction on the cannula that is translated to the arch. Care must be used to account for this to avoid kinks or folds when the traction is removed.

The most common way to provide RCP in infants is to sew a PTFE side graft onto the innominate artery, similar to the axillary artery cannulation described above (Fig. 1a and c). The arterial cannula is then placed into the graft. The advantages of this method include that the graft can be used for full body perfusion without having to reposition a cannula, does not compromise the innominate artery, can be used in any size infant, and avoids distortion of the arch and branch vessels during the reconstruction. It does, however, introduce another potential source of bleeding and adds time to the operation.

Another technique that is used less frequently is direct cannulation of the innominate artery itself [14–16] (Fig. 1c). This avoids the use of a graft and having to reposition the aortic cannula, and can potentially provide adequate perfusion to the entire body when desired during the case. It must be done very carefully, however, and is not favored by many because of the size of the cannula is approximately the size of the innominate artery itself leading to concern of obstruction of the artery during and after the operation, and inability to achieve adequate flow if a smaller cannula is used.

The proponents of RCP state that it provides better cerebral protection compared to DHCA, and that it allows more time for a careful arch reconstruction without the

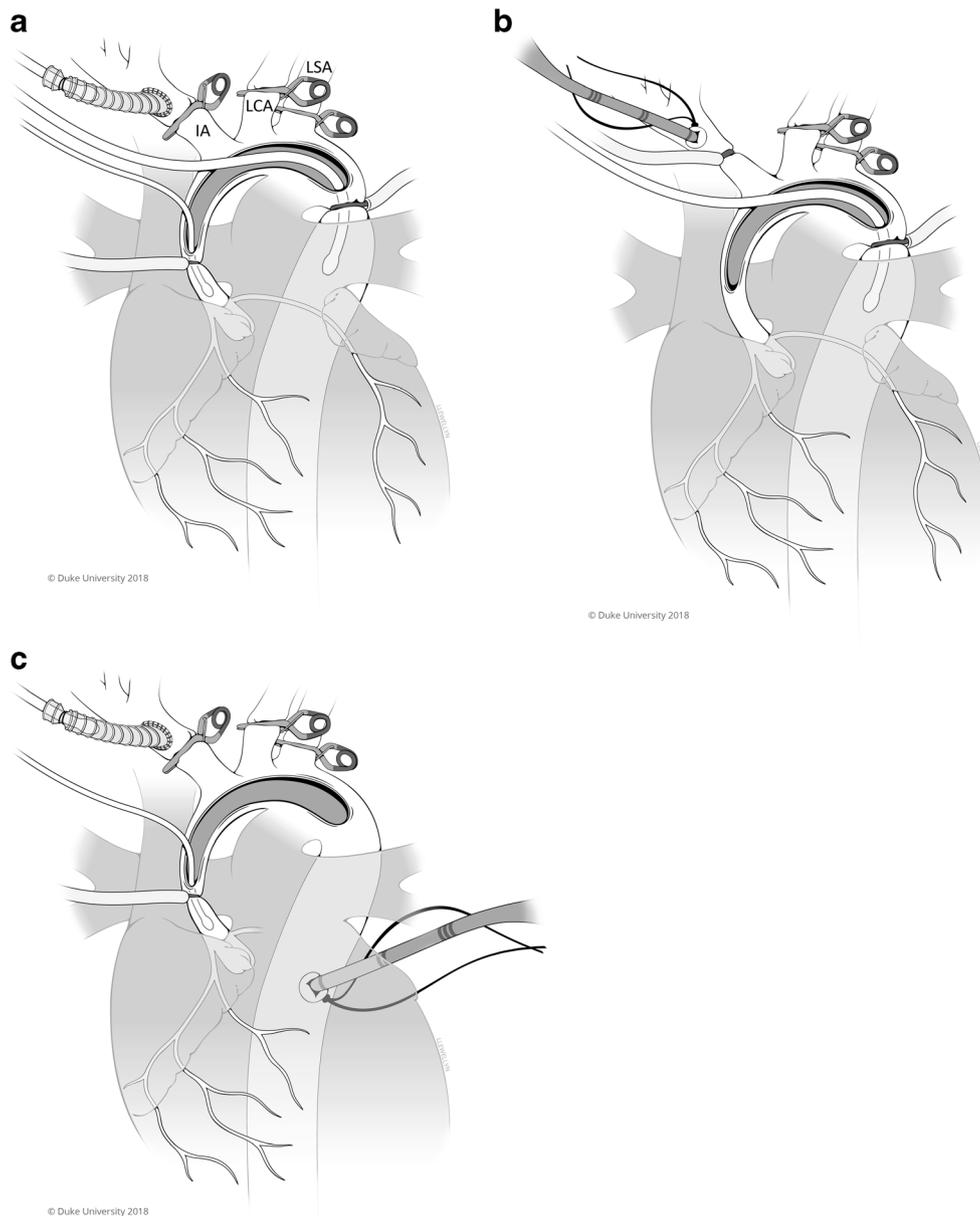


Fig. 1 Illustration of multi-region perfusion strategy used during infant aortic arch reconstruction as might be done during an operation for hypoplastic left heart syndrome with hypoplasia of the ascending aorta and entire aortic arch. In these illustrations, the aorta and branch vessels are emphasized and the other cardiac structures are shown in gray for orientation purposes. **a** Continuous cerebral perfusion is provided by a 3.5- or 4-mm PTFE graft sewn onto the innominate artery (IA). This graft can also be used for full CPB flow. Selective occlusion of the descending aorta, left subclavian artery (LSA), left common carotid artery (LCA), and proximal ascending aorta enables isolation of the aortic arch for augmentation. Continuous coronary perfusion is maintained through an olive tip catheter placed in the ascending aorta proximal to the augmentation. A vessel loop tourniquet can be used to secure the

cannula. A cardioplegia catheter can be used for larger diameter aortas with a clamp placed just distal to the catheter (not shown). Continuous perfusion of the descending aorta can be provided with the use of an additional larger olive tip catheter with a tourniquet snared around it to prevent back-bleeding. **b** In this case, the innominate artery has been directly cannulated with a cardiopulmonary bypass cannula in place of the PTFE side graft. For the purposes of the clarity, the illustration depicts it in more distal position than would be typical during surgery. The coronary perfusion catheter is not shown. **c** In this case, the descending aorta is perfused by direct cannulation with a cardiopulmonary bypass cannula rather than the olive tip catheter via the open lumen. Not pictured is a vascular clamp that would be placed between the aortic incision and the descending aortic cannula

time pressure of DHCA. Despite the theoretical advantages of RCP, there continues to be debate about whether it results in better neurological outcomes than DHCA [17–20, 21•, 22].

Current Practice

Both DHCA and RCP have typically been combined with cross-clamping of the ascending aorta and administration of

cardioplegia to arrest the heart during arch reconstruction. However, in the absence of concomitant intracardiac lesions that require repair, there is not really a good rationale for rendering the heart ischemic, as the arch reconstruction itself does not require it. We and others have begun to use a technique for isolated arch reconstruction, or even arch reconstruction combined with repair of other congenital heart defects, that provides continuous coronary perfusion during the arch repair [23, 24, 25]. To achieve this, we use a standard cardioplegia catheter that is placed low in the ascending aorta. An aortic cross-clamp is placed in the reverse orientation (compared to that commonly used for cardioplegic arrest), and the cardioplegia circuit is used to deliver continuous blood perfusion at the desired temperature during the repair. A left ventricular vent is generally used to avoid having the left ventricle eject a variable amount of venous return into the clamped aorta. The electrocardiogram is monitored for signs of ischemia and the flow or position of the catheter can be modified if these appear. Typically, a flow rate of 10 ml/kg is used and can be adjusted as needed. When used with RCP, the entire arch reconstruction can be performed without ischemia to the heart or brain, including instances where the reconstruction extends onto or involves the ascending aorta. An example of this is the reconstruction of the aortic arch and construction of the neo-aorta during the Norwood procedure. In cases with a very diminutive ascending aorta, a 2-mm olive tip catheter can be substituted for the cardioplegia catheter and is placed directly after the ascending aorta is opened (Fig. 1a). If needed to complete the reconstruction, a brief period of cardioplegic arrest can be used.

Using this system, the heart and brain are spared an ischemic insult, but the lower body receives relatively low flow during reconstruction of the aortic arch. Given this fact, moderate hypothermia (25 °C) is generally used to protect the abdominal organs from ischemia [26]. There is evidence that lower temperature perfusion and the relative ischemia to the abdominal organs during infant aortic arch reconstruction may lead to complications such as renal dysfunction. To avoid this, three-region perfusion can be used. In this system, continuous perfusion is provided to the brain via RCP, the heart as described above, and the lower body via cannulation of the descending aorta [27]. Some have provided flow to the lower body via femoral or umbilical arterial catheters connected to the CPB circuit [28]. This method raised the concern that inadequate and possibly unpredictable flow rates would be achieved. To avoid this, cannulation of the descending aorta can be accomplished in different ways. Perhaps, the most direct way to accomplish this is to place a cannula directly into the open lumen of the descending aorta after the aortotomy is made or the aorta is transected distal to the ductus arteriosus [29]. We have most recently used a large olive tip cannula that is inserted directly into the open lumen of the aorta (Fig. 1a and b). A snare is placed around the descending aorta and cinched around the

cannula to prevent back-bleeding and ensure flow is delivered distally. In the instances where olive tip or other cannulae are used in this manner, they are removed just before the suture line for the aortic reconstruction is completed and tied.

Another way to provide distal aortic perfusion is to directly cannulate the descending aorta by accessing it through the back of the pericardium or through the parietal pleura as described by Hammel and colleagues [30]. This technique, while more technically challenging, results in the distal perfusion cannula being removed from the operative field, which may make arch reconstruction less cumbersome (Fig. 1c). It also allows for the use of a larger cannula, which may result in more balanced flows. A disadvantage is that it creates a risk of postoperative bleeding at a site that will not be particularly easy to access once CPB has been discontinued. Both methods of distal perfusion provide improved flow to the lower body. In Hammel's retrospective series, this technique decreased the rate of renal dysfunction when compared to patients who had a combination of RCP and DHCA. When distal aortic cannulation is performed, it is recommended that the lower body arterial pressure be monitored to confirm adequate perfusion.

Using three-region perfusion, therefore, allows infant aortic arch reconstruction to be performed with continuous blood flow to all regions of the body, avoiding ischemia to the heart, brain, and lower body organs. Although this may allow for enhanced and more rapid recovery, and a lower complication rate, further study will be needed to confirm these findings.

Future Directions

As practiced currently, three-region perfusion can be somewhat cumbersome. Existing equipment (such as cannulae and clamps) is used to accomplish this newer CPB strategy. This results in the need to work around objects that sometimes encroach upon the operative field. Our current most frequently used descending perfusion cannula is a large, long olive tip catheter the lumen of which is smaller than a standard arterial CPB cannula. It offers the advantages of being flexible and easier to work around, being easier to remove through the completed but loose suture line, and possessing a bulbous tip that prevents it from becoming dislodged once the snare is placed around it. The disadvantage is that its smaller lumen diameter may result in less flow to the lower body that would be ideal. Placement of the descending aortic snare can also be a challenge and is ideally performed with the aid of a second assistant to ensure that the snare is distal enough to allow for adequate distal extension of the arch reconstruction. Innovations that would eliminate these challenges would be a cannula specifically designed for descending aortic perfusion without direct cannulation such as a thin-walled flexible cannula, possible with a balloon incorporated to avoid the need for a snare or clamp. Alternatively, or in addition, a

Javid-like clamp specifically designed for use on an infant's descending aorta would avoid the need for a snare, allow for very distal placement and would remain out of the operative field. We are currently designing such a clamp to be custom made.

Conclusion

With current available instruments, perfusion equipment, and technology, there is no longer a need to use DHCA for repair of the aortic arch in neonates and infants. The brain, heart, and even the lower body can be continuously perfused. In theory, these techniques should enhance recovery and reduce the risk of complications such as low cardiac output syndrome, brain injury, and renal dysfunction. Further studies will be required to demonstrate the existence and magnitude of these advantages.

Compliance with Ethical Standards

Conflict of Interest Andrew J. Lodge, Nicholas D. Andersen, and Joseph W. Turek declare that they have no conflict of interest.

Human and Animal Rights and Informed Consent All cited studies performed by the authors have been approved by the appropriate institutional and/or national research ethics committee and have been performed in accordance with the ethical standards as laid down in the 1964 Declaration of Helsinki and its later amendments or comparable ethical standards.

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