Supplemental Perfusion Techniques for Aortic Arch Reconstruction, With Emphasis on Direct Cannulation of the Descending Aorta

James M. Hammel, MD

The established techniques of deep hypothermia with circulatory arrest and regional cerebral perfusion expose infants and children to additional physiologic stress and deleterious effects which may adversely affect the outcome of operations involving reconstruction of the aortic arch. Alternative techniques to supplement perfusion support are an area of innovation today. The most effective adjunct for somatic perfusion during arch reconstruction is direct cannulation of the innominate artery and the descending aorta, with full flow at mild hypothermia distributed throughout the entire body just as it is during routine, single cannulation surgery with an intact aorta. Detailed facilitating techniques for descending aortic cannulation are discussed.
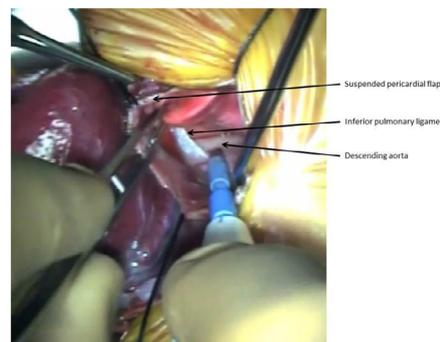
Surgeon's view of exposure of the descending aorta for direct cannulation.

Central Message

Alternatives to deep hypothermia with circulatory arrest or regional cerebral perfusion may improve outcome. Cannulation of the descending aortic allows continuous full-flow bypass during aortic arch reconstruction.

BACKGROUND

The recognition of deep hypothermia's effect in reducing the consumption of oxygen and metabolic substrates facilitated the earliest successful intracardiac repairs [1]. The combination of extracorporeal circulation and deep hypothermia with circulatory arrest brought more complicated lesions within the reach of the congenital heart surgeon [2,3] while reducing time and extent of the exposure of a patient's blood to biologically injurious surfaces. As surgeons' ambition to achieve earlier anatomic correction drove surgical correction into the neonatal age range, the relative unwieldiness of available devices for cannulation, combined with the perceived benefit of a still, bloodless field in achieving an expeditious yet accurate repair, favored the continued application of deep hypothermic circulatory arrest, until its neurologic impacts as it was then practiced were appreciated [4].

With the development of more biologically compatible apparatus for extracorporeal circulation, even prolonged intracardiac repairs lasting 3−6 hours or more could be performed under support of continuous cardiopulmonary bypass at moderate (25−28°C) or milder degrees of hypothermia [5]. In the current era, DHCA is very rarely employed for intracardiac repairs that do not involve the aortic arch [6]. For reconstruction of the aortic arch itself, however, the use of deep hypothermia (18−20°C), with variable periods of complete circulatory arrest (deep hypothermic circulatory arrest, DHCA) and reduced-flow perfusion to the cerebral circulation (RCP), remains in common use [7]. Operations for which DHCA and RCP are employed are among those with the highest morbidity and mortality for infants.

With the intention of reducing the physiologic impact of such operations, various techniques have been applied in order to improve the distribution of perfusion flow during aortic arch reconstruction, to reduce the need for deep hypothermia, or ideally both. The focus of this article is on techniques to allow additional direct perfusion of the lower body throughout aortic arch surgery. Special attention will be paid to the technique of direct cannulation the descending aorta above the diaphragm, with emphasis on details which allow that technique's safe implementation.

Cardiothoracic Surgery, Children's Hospital and Medical Center, Omaha, Nebraska

Address correspondence to: James M. Hammel, MD, Cardiothoracic Surgery, Children's Hospital and Medical Center, 8200 Dodge St, Omaha, NE 68104. E-mail: jhammel@chsomaha.org

IMPACT OF DEEP HYPOTHERMIA WITH CIRCULATORY ARREST OR REGIONAL PERFUSION

DHCA, as currently practiced, reliably allows at least a 30−40-minute period to work, unencumbered by clamps, snares, and cannulae, without causing overt neurologic injury. As mentioned above, DHCA was not developed specifically for arch surgery, but rather has remained in use for aortic surgery as its use for intracardiac operations fell away. As such, it is the standard of care only by default. With the intent to extend the safe duration of cerebral protection, many surgeons interposed 1 or more periods of RCP, even though there is scant evidence to substantiate this practice. The safety and biological impact of DHCA and RCP have been studied mostly in retrospect.

Clinical researchers studying the impact of cardiac surgery on the infant patient have focused some attention on the incidence and outcome of transient perioperative renal dysfunction. Overt renal failure, that is that requiring protracted dialysis, is as rare as choreoathetosis is today. But transient postoperative oliguria is a well-known phenomenon, and subtle changes in glomerular filtration, inferred with arguable reliability from small changes in the routinely measured and readily available serum creatinine, are easier to study than subtle neurologic injury. Many authors have reported on the strikingly high incidence of mild acute kidney injury (AKI) after cardiac surgery, and have correlated the occurrence of AKI to various measures of poor outcome. Gil-Ruiz Gil-Esparza et al reported that in a population of children undergoing a variety of repairs, the use of DHCA and the duration of cardiopulmonary bypass were risk factors for the development of AKI. Further, they found that even after correcting for the effect of DHCA itself, bypass time, and patient age, AKI was correlated with longer intensive care unit length of stay and longer duration of mechanical ventilation [8]. Similarly, Piggott et al found cardiopulmonary bypass (CPB) time, and the repair of the aortic arch using deep hypothermia and selective cerebral perfusion (SCP), among other factors, to predispose to AKI, as well as to fluid overload [9]. Fluid overload and AKI were both strong risk factors for longer duration of mechanical ventilation, longer length of stay, and mortality. Reports from multiple institutions confirm these findings [10,11]. Still, questions remain. Last preoperative creatinine may not reflect a true baseline glomerular filtration rate, and varying filtration and fluid management strategies intra- and postoperatively may affect spot creatinine values, also in ways which do not reflect actual changes in glomerular filtration rate (GFR). This is supported by the findings of Piggott et al that while fluid overload and AKI share the same risk factors and have the same impact on outcome, they found, counterintuitively, that AKI and fluid overload did not occur in the same patients [9].

The biochemical findings of AKI after DHCA or SCP may be better understood as a biomarker for more generalized bodily injury or stress. The most recent aggregated data from the Society of Thoracic Surgeons indicate that 58% of patients were treated with open sternum after repair of transposition, ventricular septal defect, and arch obstruction repair, as compared to only 37% of those with transposition and ventricular septal defect (VSD) without arch repair, the main difference presumably being the use of DHCA or SCP, and being reflected in greater truncal and abdominal edema (Society of Thoracic Surgeons Congenital Heart Surgery Database Report, June 2018).

SCP AT MILD OR MODERATE HYPOTHERMIA

In an effort to avoid the additional cardiopulmonary bypass time of cooling and rewarming, and the physiologic effects of deep hypothermia, some have advocated the application of SCP at moderate hypothermia. Gates et al report performing the Norwood operation at 30−32°C, with flow into the innominate artery not arbitrarily limited by volume but rather to maintain right arm arterial mean pressure of 50 mm Hg [12]. Kornilov et al retrospectively compared a similar technique to DHCA, however, with RCP flow limited to 30 mL/kg min. They found that patients undergoing arch repair during an average of 25 minutes DHCA at 20°C had more neurologic complications (31% vs 6% incidence) than those who had SCP for 20 minutes at 25°, but the SCP patients had higher rates of kidney injury, more positive intraoperative fluid balance, higher inotrope score, and more frequent use of peritoneal dialysis [13]. It appears that limited periods of lower body hypoperfusion are tolerated at greater than deep hypothermic temperatures, as is known from experience with noncardiopulmonary bypass thoracotomy coarctation repair, but that the time of such hypoperfusion must be limited. This may be prohibitive of certain more complicated aortic reconstructions for many surgeons.

PARTIAL LOWER BODY PERFUSION TECHNIQUES

Recognizing that the protection afforded by deep hypothermia during ischemia is incomplete, some groups have recognized the potential benefit of restoring at least partial perfusion of the lower body during SCP. Rajagopal et al report insertion of a 3 fr 3 cm femoral arterial line, or a 3.5 fr 10 cm umbilical artery catheter, and connecting this, presumably through a Leur connection, to the arterial cannula [14]. They found a reduced incidence of AKI despite the use of higher temperatures in some patients; however, despite less cooling and warming, the technique did not result in a difference in cardiopulmonary bypass or cross-clamp time, and despite less AKI, the patients treated with this additional flow did not experience a shorter intensive care unit length of stay. Duebener et al reported a similar technique, but placed a 4 fr sheath in the femoral artery [15]. Through this larger device, in which the lumen diameter is equal to the outer diameter of a 4 fr catheter, they were able to flow 40−70 mL/kg min; however, they still cooled their patients to 18°C. They report a lower serum lactate at end of procedure, however the same change in creatinine postoperatively, and no significant difference in clinical outcomes.

These techniques have in common that the perfusion to the lower body is supplied by means of a percutaneously inserted catheter, such that the catheter limits flow. An alternative technique has been described, in which a second arterial cannula, similar to the primary arterial cannula, is connected to a branch

in the arterial line [16]. This cannula is inserted into the lumen of the opened descending aorta after the distal part of the arch reconstruction has been started. While the cannula is in place, full flow is delivered to the lower body. Raees et al compared retrospectively patients operated with this technique and cooled only to 30°, to patients receiving ordinary DHCA at 18°. Patients receiving descending aortic flow during part of the reconstruction had a higher postoperative calculated glomerular filtration rate, but there was otherwise no difference in clinical outcomes. This may have been because the total of time before and after insertion of the descending cannula amounted to an average of 22 minutes (range, 17—29 minutes) of lower body ischemic time, protected only by a lesser degree of hypothermia.

FULL-FLOW WHOLE BODY PERFUSION TECHNIQUES

In surgery with cardiopulmonary bypass, besides that which involves the aortic arch, a single cannula placed in the aorta or a major branch provides inflow, and the distribution of flow throughout the body depends on the vascular resistance of the various perfusion beds. The most physiologic means of support possible during reconstruction of the aortic arch is to provide inflow to the descending aorta beyond the area opened for the reconstruction, such that the pressure in the descending aorta is maintained nearly equal to that in the upper body, for example, the brachiocephalic artery. Such a technique should in theory provide blood flow for the kidney and the other tissues perfused by the descending aorta which is not different from what they would receive during ordinary cardiopulmonary bypass without aortic clamping. The concept of delivering full-flow perfusion to the descending aorta during arch reconstruction was first reported by Yasui et al in 1993, in their effort to improve the outcome of interrupted arch repair [17]. Their technique began with left thoracotomy for connection of an ePTFE tube graft to the descending aorta. This same approach has been reported in the current era. Fernandez-Doblas et al compared a small group of patients receiving flow through a tube placed by left thoracotomy in addition to RCP, to a historical group operated with RCP alone. In both groups, the procedure was performed at 26—28°. They found that the additional descending perfusion resulted in better urine output but the same trend in serum creatinine, better hepatic function, and faster resolution of lactate elevation [17].

In 2001, the same group from Fukuoka reports a refinement of their technique, accessing the descending aorta above the diaphragm and directly inserting a second arterial cannula [18]. Despite the perceived additional difficulty of this cannulation, it has become the standard approach at some institutions. Kreuzer et al reported the results of 407 patients operated with direct cannulation of the descending aorta between 2003 and 2015. They report excellent outcomes and no complications, but they had no group against which to offer direct comparisons [19]. A few years after adopting the descending cannulation technique at Children's Hospital in Omaha, we compared patients undergoing arch reconstruction with direct descending aortic cannulation to a recent historical cohort operated on prior to adopting the technique [20]. We found reduced incidence of AKI, better early postoperative urine output, and less positive postoperative fluid balance. Operative times, cardiopulmonary bypass time, and cross-clamp time were all shorter. Because only direct cannulation of the descending aorta has the potential to achieve perfusion that is physiologically equivalent to that delivered during nonaortic surgery, this technique is the subject of the remainder of this report.

TECHNIQUES

A technique of dual arterial cannulation has been recently described and thoroughly illustrated, in the context of a Norwood operation [21]. In brief, the technique begins with direct cannulation of the innominate artery. The heart is then elevated gently and an incision is made through the pericardium into the left pleural space. A flap of the posterior pericardium is developed and used to suspend the heart without other retraction. Division of the inferior pulmonary ligament up to the left lower pulmonary vein readily exposes the descending aorta, which is then also directly cannulated, using an arterial cannula identical to the first. Both cannulae are connected to a branched arterial line (Figs. 1 and 2).

In order to derive the full benefit of a technique which provides full-flow perfusion to the lower body as well as the upper, several modifications to the ordinary sequence of operation should be considered. First, because there will be no time of cooling on cardiopulmonary bypass prior to starting the arch repair, all the dissection of the arch and its branches should be performed prior to initiating bypass. Finishing all the dissection necessary for the repair prior to heparinization and achieving hemostasis before cannulation may help in achieving hemostasis at the end and will reduce the duration of cardiopulmonary bypass. To further reduce bypass time, we have found that cannulation of the descending aorta has been possible in all cases without bypass support, even in hypoplastic left heart syndrome and in hearts with compromised function due to arch obstruction without ductal patency. It is helpful in this regard to not place the caval cannulae before elevating the heart, as this risks greater obstruction of caval venous return.

The objective of descending aortic cannulation is to achieve full-flow perfusion to the lower body; therefore, it is necessary to monitor the pressure in both the right upper extremity and somewhere in the lower body. An umbilical artery catheter is ideal; however, if one is not present, we routinely insert a tibial arterial line in lieu of femoral. This second line is removed at the end of the operation. In patients beyond the newborn period, we also occasionally monitor lower body pressure by inserting an 18 g aortic root needle directly adjacent to the descending aortic cannula, through the pleural incision, thus also avoiding instrumenting the femoral artery. After initiation of bypass, with division of the aortic arch, the differing total resistance in the arterial beds perfused by the 2 cannulas may
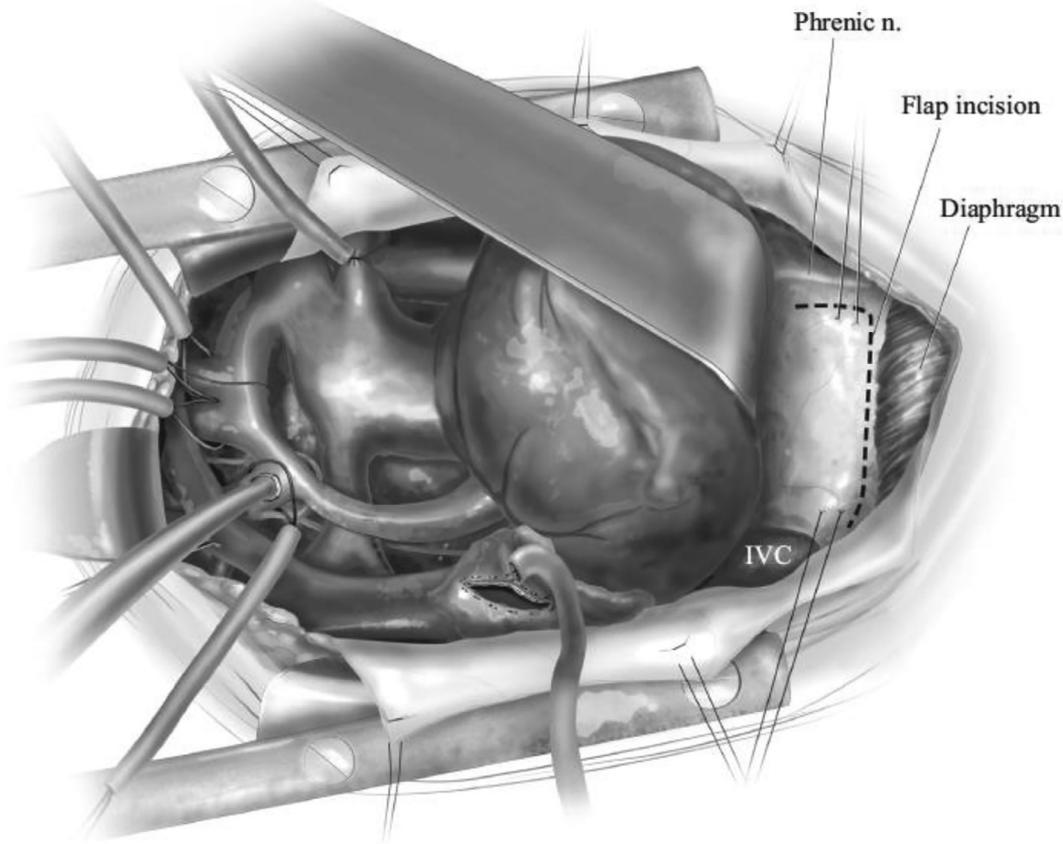
Figure 1 Direct access to the supradiaphragmatic descending aorta. The cardiac apex is elevated out of the chest. The phrenic nerve is visualized through the pericardium, then a transverse incision with vertical extension is made through the pericardium into the left pleural space. Reproduced with permission from ref [21].

result in different pressures. This should be managed by applying a partial occlusion clamp to either the upper or lower arterial perfusion tubing, until the monitored pressures are nearly equal, for example, within 10 mm Hg. It is not necessary to monitor flow, any more than it is necessary to monitor the flow distributed to the descending aorta during perfusion by a single cannula.

In most cases, cannulation and purse-string closure of the descending aorta above the diaphragm has been uneventful; however, differences from the ascending aorta warrant mention. The tissue of the descending aortic wall is generally more friable than the ascending, and the fibers are oriented slightly differently. I have found it better to remove loose adventitia so that the depth of the purse string is more precisely seen, and to place this suture slightly more deeply in the wall (still without entering the lumen) than in the ascending aorta. It is critical that the proper placement of the descending cannula be checked as is done for the ascending, by clamping the line to the innominate cannula, measuring the mean pressure in the descending, and then giving a test infusion of blood and observing for signs of dissection or improper placement. In 1 unpublished case of which I am aware, an unrecognized

dissection at the descending cannulation site resulted in intestinal necrosis due to ischemia, despite repair of the site at the end of the case when recognized. Due to the nature of the tissue, I also favor use of a solid, beveled tip cannula such as the Edwards RMI, or for very small patients, that supplied by Livanova, as pictured in Fig. 3. The tip of the latter is quite long, and so a suture should be applied as a guide to depth of insertion. This cannula has been successfully used for direct cannulation of the innominate artery in a patient as small as 1.5 kg. Because both cannulae will be present throughout the period of cardiopulmonary bypass, a cannula size can be used which accommodates only just more than half the predicted full flow. Using the identical cannula for both the innominate and the descending cannulation makes it easier to achieve a balance of pressures between upper and lower.

The descending cannula is removed during weaning from bypass, so that if there should be any need for a second suture, this is placed without any hurry. Perhaps due to the nature of the tissue, or due in part to the tension on the aorta from its upward mobilization for most arch repairs, or due to the difficulty of tying gently through a smaller exposure, a bleeding cannulation site can be difficult to repair. In 1 case in our
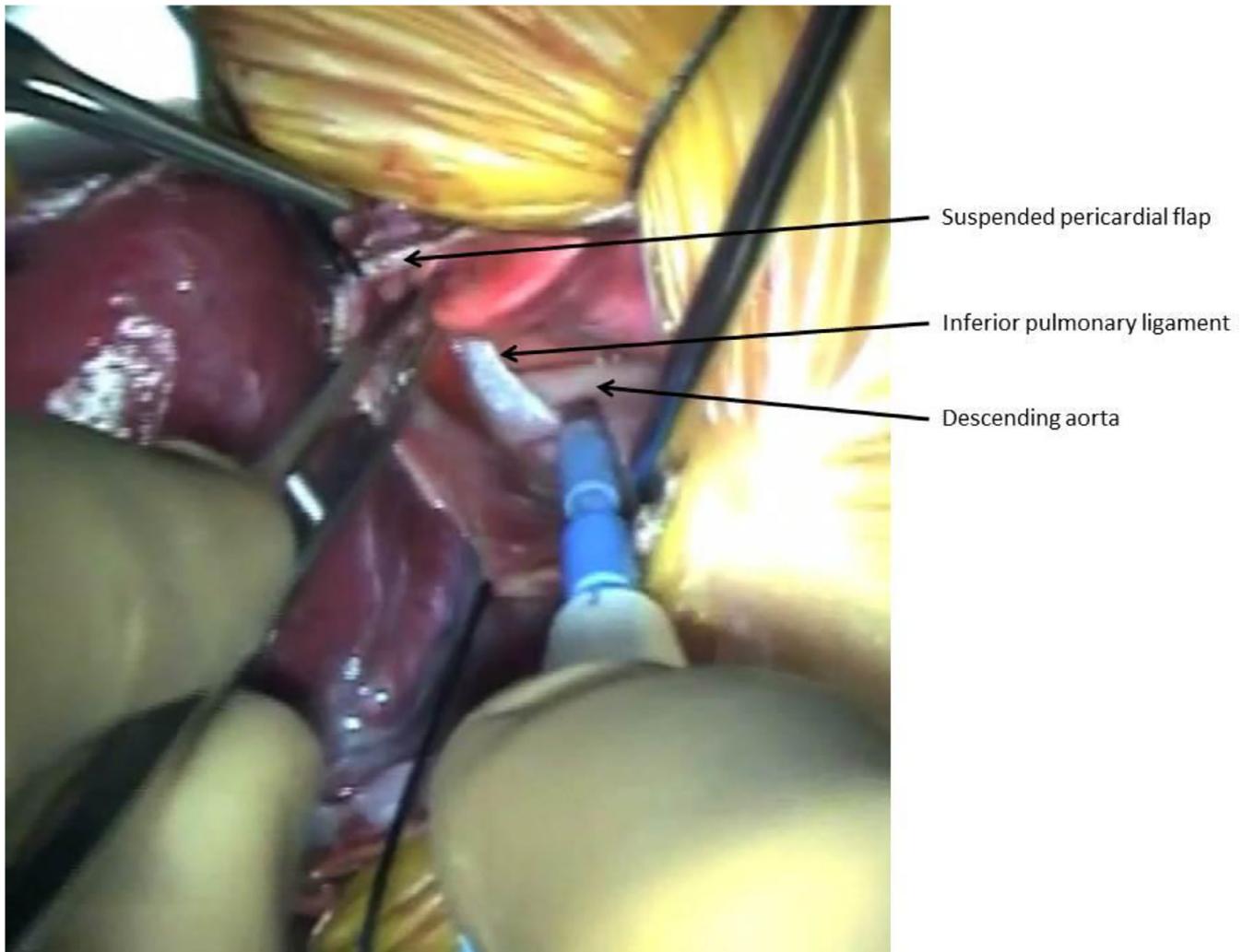
Figure 2 Surgeon's view: sutures placed in the right and left corners of the pericardial flap allow gentle suspension of the beating heart without hemodynamic compromise. The inferior pulmonary ligament is divided, readily exposing the descending aorta within the left chest.

experience, and 1 unpublished case of which I am aware, it has been necessary after several suture closure attempts, to apply a side-occluding clamp and suture in place a small circular patch to repair the cannulation site with hemostasis.

Concern has been expressed about adjacent structures at risk during the descending aorta exposure. Lymphatics of this region are generally located posterior and to the right of the aorta. We have not observed lymphatic leak at greater frequency than in other operations. Early in our experience with the descending aortic cannulation, we encircled the aorta with a silk suture to aid in control in case of hemorrhage; however, this potentially does risk greater lymphatic disruption, and in any case no longer seems necessary.

The phrenic nerve courses along the pericardium to its reflection on the diaphragm. This should be visualized through the pericardium prior to making the transverse incision more medially. In 1 case, I have observed a phrenic nerve located

significantly farther medially than usual, where it might have been injured if not recognized through the pericardium. The esophagus has not been a problem in any case, as it is adherent but generally rightward of the aorta. Few pediatric surgeons leave the transesophageal echo probe in the esophagus throughout the operation, but in this situation that practice would be problematic.

An advantage of the direct supradiaphragmatic aortic cannulation and innominate artery cannulation technique is that a single cannulation sequence prepares the patient for any type of aortic repair, without variation for anatomy. One exception is when the right subclavian artery takes an anomalous distal origin. Prior to inserting the innominate artery cannula, we occlude the innominate with forceps to observe the dampening of the peripheral right upper extremity arterial line waveform. In several cases in our experience, when the subclavian was known or found to have an anomalous distal origin, the right
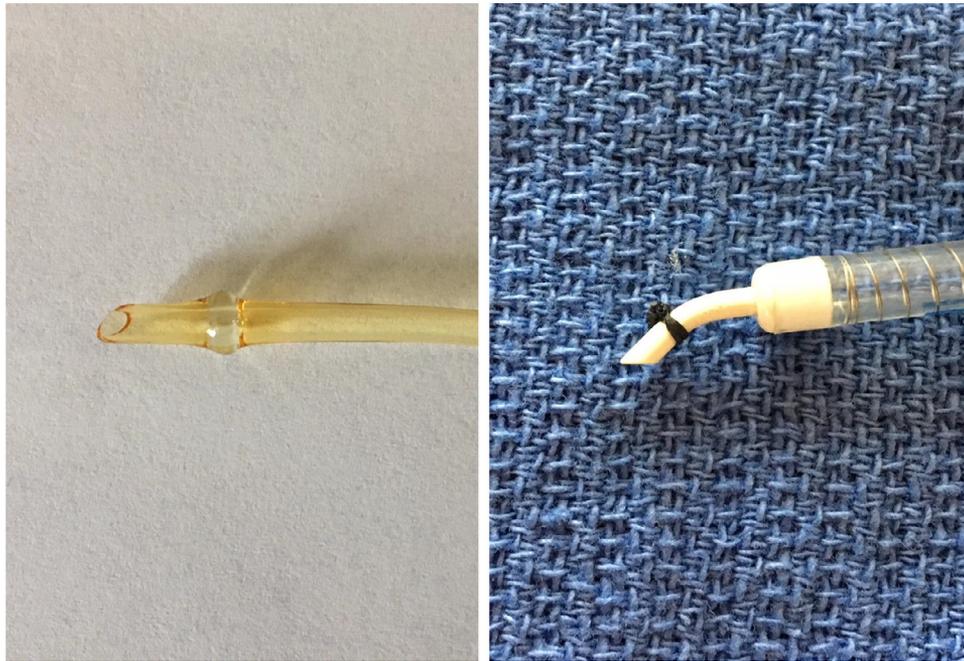
Figure 3 Solid-tip arterial cannulae. The absence of an obturator protruding from the tip allows smooth insertion with reduced likelihood of dissection of the arterial wall. Left, Edwards RMI; Right, Livanova (with depth marking suture).

carotid artery was directly cannulated, and a short 24 g pressure monitoring line was inserted just distal to the cannulation site through a separate purse string suture.

SUMMARY

The techniques described above, for dual arterial cannulation incorporating direct cannulation of the innominate artery and of the supradiaphragmatic descending aorta, with maintenance of full flow and equal blood pressure supplying all visceral vascular beds, and with obviation of hypothermia for tissue preservation in the face of relative hypoperfusion or ischemia, should alter the physiologic impact of aortic arch repair to be equal to that of other procedures utilizing cardiopulmonary bypass without aortic arch reconstruction. Once the barriers to comprehensive arch reconstruction are lowered, the questions surrounding indications for limited, thoracotomy coarctation repair vs potentially more extensive, sternotomy repair with cardiopulmonary bypass become only more difficult [22,23].

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