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# Technique Article

# Sustained Total All-Region (STAR) Perfusion: An Optimized Perfusion Strategy for Norwood Reconstruction

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**Abstract:** Early iterations of the Norwood procedure used aortic cross-clamping, myocardial arrest, and, sometimes, deep hypothermic circulatory arrest. The resulting hypothermia and prolonged ischemia caused frequent cardiac, neurologic, renal, and other end-organ dysfunctions. Our group describes a novel technique, sustained total all-region (STAR) perfusion, which circumvents these issues by providing continuous perfusion to the head, heart, and coronaries at temperatures of 32–34°C. A single DLP® straight venous cannula (Medtronic, Minneapolis, MN) is placed in the right atrium, and a DLP® pediatric arterial cannula, with a high-flow stopcock attached, is placed in the ascending aorta or innominate artery to provide flow to the head. A cardioplegia needle with walrus tubing is connected to the stopcock to provide flow to the coronary arteries. For lower body perfusion, an olive tip cannula is placed into the descending aorta lumen and attached to the 1/8″ line from the cardioplegia system which provides warm arterial blood flow. STAR perfusion allows the Norwood procedure to be completed with mild hypothermia and continuous perfusion to all vascular beds with reduced cardiopulmonary bypass as well as total operative times. This technique is successfully achieved with minimal changes to circuitry, minor modifications to heart–lung machine servoregulation and few additional cannulation disposables. **Keywords:** cardiopulmonary bypass, three-region perfusion, hypoplastic left heart syndrome, ischemia, Norwood, all-region perfusion. *J Extra Corpor Technol. 2020;52:332–6*

The Norwood procedure was first described in 1983 as a palliative procedure for a diagnosis of hypoplastic left heart syndrome (1). Surgical techniques for the procedure have evolved, as well as the accompanied perfusion strategies. The first successful operations used deep hypothermic circulatory arrest (DHCA) during the aortic reconstruction phase, which is known to be associated with adverse neurological sequelae as well as kidney and other visceral ischemic injuries (2). This was the predominant technique until 1996 when selective antegrade cerebral perfusion, also referred to as regional low-flow perfusion (RLFP), was introduced for neonatal aortic operations (3). RLFP allowed the Norwood procedure to be performed with continuous perfusion to the brain and upper extremities, albeit at significant hypothermia. In this technique, cardiopulmonary bypass (CPB) flow rates to the head were generally maintained at 50 mL/kg/min with adjustment based on pressure measurements from the left temporal and right radial arteries. Since then, attempts to perfuse the heart and lower body during parts of the operation have been reported, but these techniques still require hypothermia to as low as 18°C as well as myocardial and visceral ischemia during the aortic reconstruction phase (4–6).

More recent strategies outline the use of RLFP with concomitant coronary perfusion during the Norwood procedure (7,8). One of these studies found decreased post-operative serum lactate levels compared with DHCA (8), which could represent decreased ischemic insult to the myocardium or

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increased lactate clearance secondary to normalized metabolic function (9). However, both of these techniques are still associated with lower body ischemia at moderate hypothermia.

To circumvent this issue, our group has developed a technique for the Norwood procedure in which the head, upper extremities, heart, and lower body are continuously perfused. This strategy, sustained total all-region (STAR) perfusion, allows for continuous perfusion of all vascular beds at mild hypothermia with minor CPB circuit modifications. Here, we aimed to outline the technical aspects of this strategy from a perfusionist's perspective. The surgical technique for Norwood reconstruction using STAR perfusion has been described by our surgical colleagues (10).

## DESCRIPTION

Before outlining the technical aspects of STAR perfusion, an illustration is shown which depicts the surgical field during the most complex phase of the operation (i.e., proximal aortic repair) where total body perfusion is provided via two pumps supplying a total of three cannulas (Figure 1). The arterial pump is connected to a cannula in the innominate artery A) via 3/16″ arterial line. Arterial flow is bifurcated to a branch supplying continuous coronary perfusion B), either an olive tip or standard cardioplegia catheter, placed in the aortic root. The second pump, which in this case is the cardioplegia blood pump, is reconfigured for lower body perfusion by using an olive tip cannula C) placed in the descending aorta lumen D).

To prepare for STAR perfusion, the CPB circuit is built and primed in a normal sterile fashion. At our institution, a Terumo FX05 oxygenator with integrated hard shell reservoir (Terumo Medical, Somerset, NJ) is used with a custom tubing pack (LivaNova, London, United Kingdom) including a 3/16″ × ¼″ atrioventricular loop and ¼″ arterial boot. A Sorin S5 heart–lung machine (HLM) (LivaNova) with an arterial roller head is used, and the cardioplegia delivery system consists of twin roller heads and a Sorin Vanguard CSC 14 heat exchanger (LivaNova) delivered to the field via a 1/8″ line. The arterial roller pump is the main source of blood flow at the beginning and end of the bypass period and is the source of blood flow for the head and heart during STAR perfusion. The cardioplegia circuit is used to provide blood flow to the lower body. The cardioplegia blood pump is linked to the arterial pump to provide servoregulation in the case of an arterial pump stop. Just after initiation of CPB, blood is flushed through the cardioplegia system to ensure it is warm and the priming solution has been expelled. In addition, we use the CDI500 (Terumo Medical) for blood gas trending and an M4 monitor (Spectrum Medical, Gloucester, United Kingdom) to monitor main arterial and venous line flow, arterial and venous saturation, and hemoglobin levels.

A more extensive patient monitoring strategy during these cases is of vital importance. We continuously monitor two arterial blood pressure lines, one in the right radial artery to monitor upper body pressure and the other in the umbilical or dorsalis pedis artery to monitor lower body pressure. Near-infrared spectroscopy (NIRS) readouts from the head and somatic viscera are monitored as well. Taken together, these monitoring systems allow us to more accurately provide appropriate perfusion flow rates to all regions of the body. This is especially true when controlling flow to separate regions of the body using two independent arterial pumps.

Regarding initial cannulation, a single DLP® straight venous cannula (Medtronic) is placed in the right atrium. A DLP® pediatric arterial cannula (Medtronic) is placed either in the ascending aorta for patients with an ascending aorta diameter greater than 5 mm, or innominate artery if the ascending aorta is less than 5 mm (10). Before arterial cannulation, a high-flow stopcock is added to the luer port of the arterial cannula. This will be used to supply blood flow to the coronary arteries during STAR perfusion. There are no other circuit modifications made from our standard pediatric CPB setup.

After initiation of CPB with appropriate systemic heparinization, the patient is cooled to mild hypothermia (typically 32–34°C). To initiate isolation of the aortic arch, the surgeon first advances the arterial cannula from the aorta into the innominate artery, if not already cannulated directly. During this step, flow is reduced to 50–75 mL/kg/min to perfuse the head and heart while adjusting for a target upper body blood pressure of 40–50 mmHg and adequate head NIRS measurements. Arterial flow is measured directly on the 3/16″ arterial line, after any shunts, using a separate flow probe incorporated with our M4 monitor (Spectrum Medical). At this time, clamps are placed such that flow from the arterial cannula supplies the innominate artery and aortic root, thus supplying both the head and coronary arteries.

Next, lower body perfusion is rapidly initiated to minimize lower body ischemic time. This is performed by placing a 4-mm (outside diameter [OD]) olive tip cannula (DLP Arteriotomy Cannula, Medtronic) directly into the open lumen of the descending aorta. A snare is placed around the descending aorta and cinched around the cannula to prevent back-bleeding. This cannula is attached to the 1/8″ line coming from the cardioplegia system. Flow to the descending aorta is started using the cardioplegia blood pump at a flow rate of approximately 50 mL/kg/min and adjusted appropriately based on lower body blood pressure and somatic NIRS measurements. Our target lower body blood pressure is typically 35–50 mmHg. After this step, flow to the arterial pump is increased to compensate for the "steal" by the cardioplegia blood pump.

To complete the proximal arch reconstruction and construction of the neo-aorta via a Damus–Kaye–Stansel

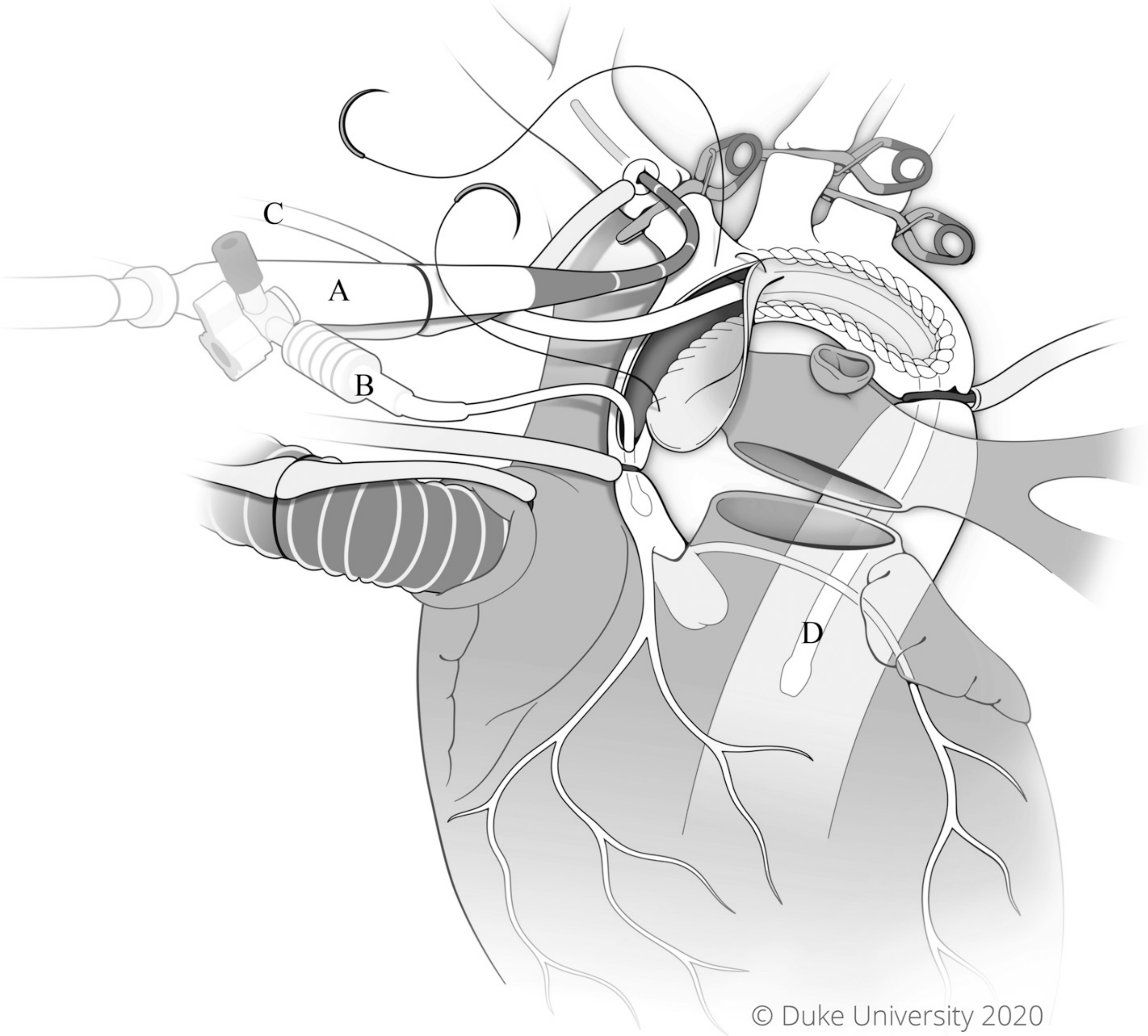

**Figure 1.** Surgical field during STAR perfusion where total body perfusion is provided via two CPB pumps supplying a total of three cannulas. (A) Cannula from the primary arterial pump supplying the upper body and heart. (B) Coronary perfusion cannula branched off the main arterial cannula. (C) Cannula from the cardioplegia blood pump supplying warm oxygenated blood to the lower body. (D) Olive tip in the descending aorta providing lower body perfusion.

anastomosis without arresting the heart, a standard cardioplegia needle (Medtronic is placed in the aortic root to allow for continuous coronary perfusion. This catheter is connected to the high-flow stopcock that was placed on the arterial cannula using a 24″ large bore pressure infusion extension set, "walrus tubing," (ICU Medical, San Clemente, CA). In cases where the ascending aorta is less than 4 mm in size, a 2-mm (OD) olive tip cannula (DLP® Arteriotomy Cannula, Medtronic) is used instead. We have been successful in fitting this 2-mm olive tip into ascending aortas as small as 1.5 mm by virtue of vessel compliance. Once the cannula is in place and attached to the main arterial cannula, the surgeon will turn the stopcock on to supply coronary blood flow. Then the aorta is clamped just distal to the coronary perfusion cannula. At this point, we closely monitor the electrocardiogram (ECG) for signs of coronary hypoperfusion such as ST segment changes, bradycardia, or arrhythmias. These changes are communicated to the surgical team immediately so they can be appropriately addressed. At this point, STAR perfusion is completely established and the surgeon is able to perform the entire arch reconstruction with sustained flow to the head, heart, and lower body with little to no ischemia.

In some cases, an atrial septectomy is required. This step would typically be performed with myocardial arrest; however, we elect to keep the heart beating during the entirety of the operation. To accomplish this, the surgeon first makes a limited horizontal right atriotomy. At that point, we clamp the venous line, temporarily reduce flow on both the arterial pump and cardioplegia pump, and allow the heart to be evacuated of blood. This allows the surgeon to achieve good visualization of the atrial septum. We adjust the flows of the two pumps to continue to deliver blood to the head and heart as well as the lower body, giving preference to the head and heart. Two drop-style pump suckers are used by the surgical assistant, one placed in the superior vena cava and the other placed in the inferior vena cava, to achieve venous return. It is advantageous during this step to have a continuous video feed from cameras on surgeon headlamps or overhead lighting. This allows us to determine whether too much blood is returning to the heart and not being captured by the pump suckers, thus impeding visualization. Once the atriotomy incision is closed, we remove the clamp from the venous line and continue normal STAR perfusion.

Once the aortic reconstruction is nearly complete, the olive tip cannulas are removed from the descending aorta lumen and neo-aortic root just before the suture line is tied. Concurrently, we terminate flow to the lower body, and the surgeon removes clamps from the head vessels to restore the standard CPB circuit configuration. The surgeon also closes the stopcock associated with the coronary perfusion catheter at that time, and systemic flow is directed into the aorta at approximately 150 mL/kg/min.

## DISCUSSION

Although further investigation of short- and long-term outcomes associated with STAR perfusion compared with RLFP is warranted, we have observed increased perioperative urine output and decreased post-operative serum lactate levels associated with the STAR technique. In addition, the use of STAR perfusion does not significantly protract CPB or total operative times, which on average are 168 and 307 minutes, respectively (10). Despite the complexity of our perfusion strategy, the relatively short operative durations are related to the fact that we only use mild hypothermia instead of moderate or deep hypothermia, which is the standard when completing these operations with RLFP or DHCA. This also provides the additional benefit of attenuating the platelet dysfunction and endothelial injury caused by hypothermic CPB (11), as well as the loss of platelets and increased levels of circulating thrombin–antithrombin complexes associated with longer CPB duration (12).

One challenge we have had to occasionally overcome is the absence of regional arterial pressure monitoring. This is problematic when the team is unable to secure both the upper body (i.e., radial artery) and lower body (i.e., umbilical or dorsalis pedis artery) arterial line. Also, some neonates have an aberrant right subclavian artery precluding accurate measurement of upper body pressure during STAR perfusion. In these cases, it is imperative to use NIRS monitoring because this will primarily guide decisions as to the adequacy of upper body perfusion. In cases where we do not have the ability to measure an arterial pressure in the right radial artery, our experience has indicated that a target flow of 75 mL/kg/min, with close monitoring of the ECG, NIRS, and blood gases, provides appropriate flow to these regions. If on the other hand we do not have lower body arterial pressure monitoring, we target an initial flow of 50 mL/kg/min flow and closely monitor the somatic NIRS to determine our flow rate.

One of the keys to successful deployment of STAR perfusion is effective communication among all team members in the operating room. This starts early in the operative case during setup, ensuring the nursing staff has the correct connectors, stopcocks, and other disposables needed. Early communication with the anesthesia team is also vital so the perfusion team knows the location of blood pressure monitoring lines and NIRS monitoring locations. During the operation, constant communication with the surgeons regarding clamp placement on the head vessels is essential so the perfusionist can provide appropriate flow to the given region, as well as monitor for any issues. Communication between the surgeon and perfusionist is especially important during the period of continuous coronary perfusion so the two teams may alert each other of signs indicating inadequate coronary perfusion such as ST elevations or low cardiac motility. Last, communication between the perfusionist and anesthesiologist regarding arterial blood pressure management helps ensure adequate perfusion.

We use two pediatric perfusionists per case for all of our CPB procedures and believe it to be vital for the safety and success of STAR perfusion cases. The second perfusionist helps closely monitor vital signs and watch the video feed from the surgeon for any potential issues, and provides support to the primary perfusionist managing the conduct of perfusion.

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