

# Limiting Circulatory Arrest Using Regional Low Flow Perfusion

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**Abstract:** Deep hypothermic circulatory arrest (DHCA) is commonly used for neonatal cardiac surgery. However, prolonged exposure to DHCA is associated with neurologic morbidity. The Norwood operation and aortic arch advancement are procedures that typically require DHCA during surgical correction. Regional low flow perfusion (RLFP) can be used to limit or exclude the use of circulatory arrest. This technique involves cannulation of the innominate or subclavian artery using a *Gore-Tex* graft, allowing isolated cerebral perfusion. Data was collected in 34 patients undergoing either neonatal aortic arch reconstruction or the Norwood procedure using RLFP. All patients had two arterial pressure monitors using either the umbilical or femoral artery catheters and radial or brachial catheters. Adequacy of perfusion was determined using cerebral saturation, blood flow velocity, mean arterial pressures, and arterial blood gas results. Cerebral saturation and blood flow velocity were monitored using the near-infrared spectroscopy (NIRS) (INVOS 5100, Somanetics Corp, Troy, MI) and a transcranial Doppler pulse-wave ultrasound (TCD) (EME Companion, Nicolet Biomedical,

Madison, WI), respectively throughout the entire bypass period. Blood gases were monitored using a point of care blood gas analyzer (Gem Premier, Mallinckrodt Sensor System, Inc., Ann Arbor, MI). Data collected revealed total bypass times for repair between 69-348 min, with a mean of 180 min. Regional low flow perfusion times lasted between 6-158 min, with an average of 50 min., and DHCA times ranged from 0-66 min, with a mean of 19 min. The perfusion techniques used allowed patient clinical data to remain consistent throughout the cardiopulmonary bypass period, regardless of lower flows (Figure 1) The 30-day postoperative mortality rate was 2.9 %, with no evidence of neurologic injury during follow up. In conclusion, regional low flow cerebral perfusion might benefit patients by limiting the use of circulatory arrest during cardiac surgery. Further study is necessary to evaluate patient outcomes, comparing regional cerebral perfusion and circulatory arrest techniques. **Keywords:** regional low flow perfusion, deep hypothermic circulatory arrest, cerebral monitoring, pH stat, arterial pressures. *JECT. 2004;36:133-138*

## INTRODUCTION

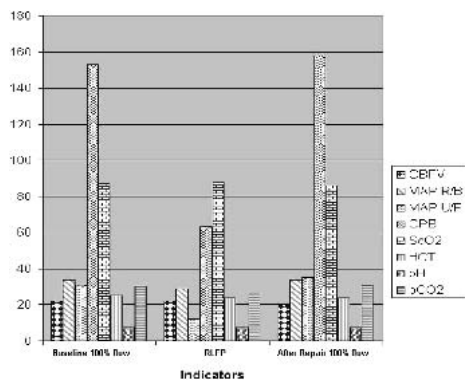
Prolonged periods of deep hypothermic circulatory arrest (DHCA) are associated with neurologic injury. In a 1997 study focusing on the complications of DHCA, 19% of patients undergoing DHCA developed transient neurologic dysfunction (TND)(1). Symptoms in the study included agitation, confusion, disorientation, delayed awakening from anesthesia, and Parkinson-like movements. A study by The John Hopkins Medical Institutions suggested that these neurologic complications using DHCA might be caused by the intracerebral accumulation of glutamate, aspartate, and glycine (2). Glutamate excitotoxicity produces nitric oxide resulting in neurologic injury.

Factors that contribute to neurologic injury include the duration of DHCA, the rate of cooling the patient, and

blood gas management (3). It is known that the length of time and degree of hypothermia correlates with the severity of complications. At decreased temperatures, the metabolic rate of the body decreases, as well as brain activity. This becomes particularly important for handling pediatric patients (3). Pediatric perfusion protocol must consider that the brain of an infant receives 34% of the cardiac output (4). Thus, neurologic monitoring has become an important tool used for optimal perfusion at DHCA. Many studies have proved the importance and validity of neurologic monitoring in neonates and adults using the TCD and NIRS systems (5-8) Thus, both are used routinely in all cardiopulmonary bypass (CPB) cases especially when DHCA or regional low flow is to be used.

The purpose of this study was to prove that by incorporating the techniques of good surgical technique, pH stat blood gas management, and neurologic monitoring patients might be adequately perfused in a low flow state versus long periods of circulatory arrest, limiting the risk of neurologic injuries.

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**Figure 1.** Intraoperative perfusion data. CBFV = cerebral blood flow velocity; MAP R/B = mean arterial blood pressure radial/brachial; MAP U/F = mean arterial pressure umbilical/femoral; CPB = cardiopulmonary bypass flow; ScO<sub>2</sub> = cerebral saturation X-axis: 1) baseline 100 % flow, 2) RLFP, 3) after repair 100 % flow cardiopulmonary bypass flows decrease as do mean arterial pressures of umbilical/femoral arteries because of snaring of the thoracic aorta and decreased flows at RLFP. All other data remain consistent throughout the entire bypass period regardless of RLFP.

## MATERIALS AND METHODS

The patient population chosen for this study included those patients undergoing the Norwood or aortic arch advancement repairs due to their use of circulatory arrest and regional low flow. After approval of the Institutional Review Board, between January 2001 and February 2002 data was collected from 34 patients. Of these 34 patients, 13 underwent the Norwood operation, 13 aortic arch advancement repairs, and 8 interrupted aortic arch repairs. Data were collected intraoperatively from three different time intervals during CPB. The time intervals included: 1) during full flow whole body perfusion at 17–22°; 2) during RLFP at 17–22° after adjustment of flow to baseline of ScO<sub>2</sub> and CBFV values; 3) 5 min following resumption of full flow before rewarming.

## CANNULATION

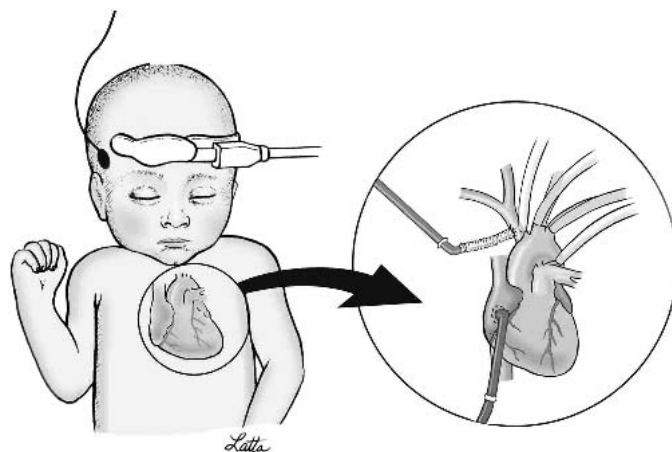
Before the initiation of CPB, 1 mg/kg of heparin is administered before occluding the innominate artery. After approximately 5 min, an activated clotting time (ACT) (ACT II, Medtronic Blood Management, Parker, CO) is run to ensure that the patient is anticoagulated (> 200 sec). Cannulation of the innominate or subclavian artery occurs using a *Gore-Tex* graft, usually 3.0 mm or 3.5 mm proportionate to the anatomy of the patient. Size of the graft also depends on the aortic cannula, usually 8 or 10 Fr. needed for optimal perfusion during the case. The *Gore-Tex* graft is anastomosed into the distal right innominate artery or proximal right subclavian artery. The patient is then given the full dose of heparin of 3–4mg/kg, and an ACT is run to ensure proper anticoagulation (> 480sec) before CPB. The aortic cannula is then placed inside of the *Gore-Tex* graft

and secured. Venous cannulation consists of a single atrial cannula placed in the right atrium or bicaval cannulation in the event of an intracardiac repair (Figure 2)

## PERFUSION TECHNIQUES

The CPB setup consists of a Stockert CAPS (computer-aided perfusion system) heart-lung machine (Stockert Instrumente GmbH, Munich, Germany) roller head pump and a Hemotherm Dual Reservoir Heater Cooler (Cincinnati Sub-Zero Products Inc., Cincinnati, OH). A Capiox SX 10 oxygenator (Terumo Cardiovascular Systems, Ann Arbor, MI) is used with 1/4-inch venous and 3/16-inch arterial line for patients < 4 kg. Patients weighing 4–6 kg. have the same CPB setup with a change in the arterial line from 3/16 to 1/4 inch. Silastic tubing is used for every case in the raceway of the arterial head because of its durability and flexibility at low temperatures. A pediatric arterial filter (Terumo Cardiovascular Systems, Ann Arbor, MI) is also used in the perfusion packet along with a Hemocor HPH 400 (Minnitech, Olson Medical Sales [subsidiary of Terumo Medical Co.], Ashland, MA) hemoconcentrator for continual ultrafiltration during the bypass run.

CPB primes consist of whole blood if available or fresh pack cells less than 3 days old and fresh frozen plasma for patients < 8.5 kg. A crystalloid mixture of plasmalyte A and 0.45% sodium chloride is used to wet the bypass lines before blood priming. 0.45 % sodium chloride is used in place of 0.9% sodium chloride to maintain sodium levels



**Figure 2.** Neurologic monitoring and cannulation. The transcranial Doppler is placed on the patient's right temple, detecting the middle cerebral artery for measurement of cerebral blood flow velocity. The near-infrared spectroscopy sensor is placed on the right side of the forehead to measure cerebral saturation. Cannulation for regional low flow perfusion consists of an arterial cannula placed in a *Gore-Tex* graft anastomosed to the base of the distal right innominate or proximal right subclavian artery. Venous cannulation consists of a single atrial cannula in the right atrium. Snares are placed on the base of the right innominate, left common carotid, left subclavian arteries, and the descending thoracic aorta.

within normal physiologic ranges of 135–145 mmol/L. The addition of 8.4% sodium bicarbonate, calcium chloride, and sodium heparin are also necessary to create a pump prime compatible with the patient and properly anticoagulated for CPB.

Bypass is initiated after cannulation and full heparinization of the patient. To provide long-acting vasodilatation, most patients are given a dose of phenoxybenzamine 0.25–1.0 mg/kg on initiation. The patient is perfused at full flow (150 mL/kg/min, cardiac index 3.0–3.2) for those weighing  $\leq 10$  kg. The perfusionist cools the patient to a nasopharyngeal temperature of 18°C (temperatures ranged from 17–22°C) over a period of 30–45 minutes, using an 8° gradient between the patient's temperature and temperature of the blood flowing to the patient. Cold crystalloid cardioplegia is routinely used for myocardial arrest. For the Norwood procedure, cardioplegia is administered most often through a stopcock on the aortic cannula.

## BLOOD GAS MANAGEMENT

During hypothermia, pH-stat strategy is used to manage blood gases. Blood gases are analyzed every 10–20 min with temperature-corrected blood gas target ranges as follows: pH 7.35–7.45, pCO<sub>2</sub> 35–45 mmHg, and pO<sub>2</sub> 150–250 mmHg. To obtain these blood gas ranges the perfusionist must adjust the sweep gas and FIO<sub>2</sub> accordingly, and additional CO<sub>2</sub> is added if needed using a CO<sub>2</sub> tank routed to the blender. Arterial pO<sub>2</sub> values are kept on the high end of the target range to saturate the brain and replenishing the tissues with oxygen, thereby decreasing the potential of lactic acid production (9). The perfusionist also targets a hematocrit level around 25–28% to optimize oxygen-carrying capacity. During this cooling period, it is essential that the perfusionist maintain these goals in: blood gas management, cooling, flow and pressure, and cerebral monitoring to optimize the patient's condition before initiation of regional perfusion and circulatory arrest. As the nasopharyngeal temperature approaches 18°, ice is placed on the head for additional cerebral protection and uniform cooling.

## CEREBRAL MONITORS

The perfusionist must pay close attention to readings from the near-infrared spectroscopy (NIRS) and a transcranial Doppler (TCD), monitoring cerebral perfusion and oxygenation. The NIRS system uses a somatosensor strip that is nonsterile and disposable (10). This strip or transducer is placed on the patient's forehead either unilaterally or bilaterally, where it detects optical data from the patient and converts it to an electrical signal (Figure 2). The system measures cerebral saturation (ScO<sub>2</sub>) by sending a low-intensity near-infrared light at wavelengths

730 and 810 nm to the patient's forehead, penetrating the skull. The returned light can be measured to determine the total saturation and desaturation of the hemoglobin in the frontal cortex. The monitor displays a waveform and a percentage of saturation. Hematocrit affects calculated ScO<sub>2</sub> of the brain, as do such other factors as flow and CO<sub>2</sub> management.

The TCD is also an important tool to use in conjunction with NIRS. A 2 mHz probe is placed over the right temporal area or over the anterior fontanelle to receive optimal blood flow velocity signals from the middle cerebral artery (11) (Figure 2). Positioning of this probe is very important to obtain an adequate signal. These blood flow velocity signals detected from the probe are displayed on the monitor as a waveform with a measured cerebral blood flow velocity. In combination, these monitors are used to determine brain blood flow and saturation.

## REGIONAL LOW FLOW PERFUSION

Once these baseline cerebral values are obtained from the monitoring devices at full flow, and hypothermia is reached with optimal blood gases, flow on CPB is decreased. Snare is placed on the base of the right innominate, left common carotid, left subclavian arteries, and around the descending thoracic aorta distal to the coarctation before RLFP (Figure 2). For aortic arch repairs during the dissection of thoracic aorta, all brachiocephalic vessels receive flow after the ligation of the aortic isthmus. CPB flows are slowly increased until the NIRS and TCD values are within 10% of baseline values obtained during full flow bypass to the entire body. Baseline values are typically obtained by flowing 30–40% or 24–94 mL/kg/min. Mean arterial pressures are used for trend monitoring along with the NIRS and TCD. A right radial or brachial artery catheter is placed to monitor pressure for aortic arch repairs and a left radial or brachial catheter for Norwood procedures. Another analyte the perfusionist measures on CPB is lactate. A lactate level is run with each gas to ensure proper perfusion and oxygen supply to the tissues. Target ranges for lactate levels are <2.0 mmol/L or a downward trend, depending on the patient's status before bypass. Any upward trends of lactate levels on bypass indicate an accumulation of lactic acid and poor tissue perfusion. Although at low flows, lactate levels are monitored, but flows remain unchanged, based on these results independently, as increased flows may lead to hyperperfusion of the brain. Flow rates may be increased at full flow to correct for this lactic acid production.

The surgeon proceeds with the arch repair or construction of the new aorta as in the Norwood procedure. In the aortic arch repair when the arch has been completely repaired, the vessels are unclamped, full flow is initiated, and the patient is warmed slowly using an 8° gradient, as

stated previously. The cross clamp is removed, and warming is concluded. The entire repair of most aortic arches can be accomplished with no circulatory arrest, depending on the difficulty of the anatomy of the patient. Following termination of bypass, the shunt is removed, and the innominate or subclavian artery is repaired.

The Norwood procedure is accomplished with limited circulatory arrest time. Perfusion procedures are similar between the two surgical procedures. The same *Gore-Tex* graft is used, as previously stated, and the cannulation remains the same. A brief period of circulatory arrest is necessary while performing an atrial septectomy, lasting < 10 min. This is usually done immediately following administration of cardioplegia. Another difference in technique is the relocation of the aortic cannula. After the new aorta is constructed for the Norwood procedure, snares are removed, and the pump is turned off for 1–2 min. The aortic cannula is then removed from the *Gore-Tex* graft and placed into the root of the new aorta. Bypass is resumed at full flow. The distal anastomosis of the Blalock–Taussig shunt is then completed while rewarming.

## STATISTICAL ANALYSIS

Data was analyzed using analysis of variance (ANOVA) (SPSS Inc., Chicago, IL) to compare values between three time periods. The Bonferroni test was used for post hoc pairwise comparisons of the changes in parameters during the three times with  $p < .05$ . Last, the  $t$ -test was used to compare RLFP times and flow rates between the Norwood and aortic arch patients.

## RESULTS

Patient demographics and CPB times are presented in Table 1. Total bypass times for the repair lasted between 69–348 min, with a mean of 180 min. Times varied among the degree of difficulty presented with each defect. RLFP times for all of these patients lasted between 6–158 min, with an average of 50 min. There was no statistical difference in RLFP times between the Norwood operation and the aortic arch repairs; Norwood patients were  $62 \pm 14$  min, while aortic arch procedures averaged a time of  $43 \pm$

36 min. ( $p = .078$ ). DHCA time ranged from 0–66 min, with a mean of 19 min. The average regional low flow rate was 42% of the full flow rates calculating a range of 24–94 mL/kg/min, with a mean of 63 mL/kg/min to obtain baseline values and acceptable pressures. These regional low flow rates between the Norwood and aortic arch procedures were similar ( $59 \pm 18$  vs.  $66 \pm 19$  mL/kg/min, respectively,  $p = .329$ ).

Data were collected intraoperatively from three different time intervals during CPB (Table 2). Data were obtained from all 34 patients for each indicator with the exception of lactate levels. Instrumentation was not available in the operative setting on the first 15 patients; therefore, lactate values were only recorded for the later 19 patients. This is noted in Table 2. The time intervals included: 1) during full flow whole body perfusion at 17–22°; 2) during RLFP at 17–22° after adjustment of flow to baseline of ScO<sub>2</sub> and CBFV values; 3) 5 min following resumption of full flow before rewarming. It was noted that the mean arterial pressure in the umbilical/femoral artery while at regional low flow was 4–21 mmHg likely attributable to collateral flow. The mean arterial pressure in the radial/brachial artery at RLFP was 29 mmHg. Each patient was treated individually based on the data obtained from each monitoring device. Flow rates, arterial gas changes, hematocrit levels, etc. were changed as the patient data dictated the need. Of the 34 patients the 30-day postoperative mortality rate was 2.9%; one of the 34 patients died on postoperative day one. No neurologic morbidity was noted in any of the 34 patients in postoperative follow-up.

## DISCUSSION

RLFP allows patients to undergo major congenital heart surgeries, including the Norwood and aortic arch repair procedures with little or no circulatory arrest time. Limiting circulatory arrest time reduces the potential for neurologic insults from brain ischemia and acidosis. However, when using the techniques of RLFP a sufficient flow rate to the brain must be maintained and excess flow avoided. Watanabe, et al. (12) found that brain ischemia and acidosis occur at deep hypothermia with flow rates of <5 mL/kg/min and perfusion pressures of <10 mmHg. Inadequate flow rates can be detrimental because they do not meet the metabolic demand of the patient. During RLFP mean umbilical/femoral pressures are diminished because of the snaring of the thoracic aorta, and the pressure produced is likely caused by collateral flow from the vertebral artery off the circle of Willis. Because of this dampening, mean radial/brachial pressures are monitored to detect acceptable pressures. In our study, during RLFP the mean radial/brachial was 29 mmHg, reading lower than full flow pressures because of lower flow rate sup-

**Table 1.** Patient demographics and cardiopulmonary bypass data.

Weight (kg)	3.2 ± 0.7	2.0–5.8
Age (days)	13 ± 23	2–128
Total cardiopulmonary bypass time (min)	180 ± 68	69–348
Aortic crossclamp time (min)	94 ± 44	0–239
Deep hypothermic circulatory arrest time (min)	19 ± 16	0–66
Regional low flow cerebral perfusion time (min)	50 ± 31	6–158

$N = 34$ , results in second column expressed as mean ± SD, third column range of data obtained from study.

Modified from an article in press in *The Journal of Thoracic and Cardiovascular Surgery*.

**Table 2.** Intraoperative perfusion/monitoring data.

Indicator	Baseline Full CPB Flow 17–22°C	During RLFP 17–22°C	After Repair Full-Flow 17–22°C
MAP			
Radial/brachial artery (mm Hg)	34 ± 4	29 ± 8*	34 ± 5
MAP			
umbilical/femoral artery (mm Hg)	31 ± 6	12 ± 4*	35 ± 5†
CPB flow (cc/kg/min)	153 ± 8	63 ± 19*	158 ± 17
CBFV			
(mean, cm/sec)	22 ± 10	22 ± 9	20 ± 8
ScO <sub>2</sub> (% cerebral saturation)	87 ± 9	88 ± 8	86 ± 9
Calculated base excess (BE)	+1.0 ± 3.0	+0.1 ± 2.2*	1.5 ± 2.8†
Lactate (mmol/L)			
N = 19	3.0 ± 1.9	3.4 ± 1.8*	4.3 ± 1.6†
Hematocrit (%)	25 ± 3	24 ± 3	24 ± 3

Results expressed as mean ± SD.

\**p* < .05 versus baseline and post-repair values.

†*p* < .05 versus baseline.

‡*p* < .05 versus postrepair, one-way analysis of variance (ANOVA).

Temperature in all three categories measured at 17–22°C.

MAP = mean arterial pressure.

CPB = cardiopulmonary bypass.

CBFV = cerebral blood flow velocity.

RLFP = regional low flow perfusion.

Modified from an article in press in *The Journal of Thoracic and Cardiovascular Surgery*.

plying sufficient blood flow only to the brain without hyperperfusion.

Excessive blood flow to the brain may lead to cerebral edema and/or cerebral hemorrhage and, thus, should be avoided. The use of the TCD and NIRS are essential to help maintain optimal blood flow to the brain throughout the entire bypass period. The mean radial/brachial pressure reading alone did not correlate well with the flow rate in this study; instead, it is used in conjunction with the TCD and NIRS systems. If TCD and NIRS values are within 10% of the baseline values, flows remain at that rate so that excess perfusion to the brain does not occur.

It was noted while using the NIRS that the highest reading from the monitor is 95%, making it impossible if used independently to determine if there is excess perfusion to the brain during RLFP. Because of this, the TCD is also used in conjunction to ensure proper perfusion because of its ability to monitor blood flow velocity to the brain in real time. Pigula and colleagues advocate the use of the NIRS and cerebral blood volume index to monitor blood flow to the brain during RLFP (13). We substituted the use of the cerebral blood volume index with the TCD device because of its accuracy and real-time results (14). Another issue that appeared during the study was the difficulty to maintain good skin contact when using the TCD and NIRS sensors on neonates. We found that applying the somatosensor unilaterally, preferably on the left side versus bilaterally was sufficient in detecting a good trace for the NIRS and more practical because of the size of the patient's forehead (14).

The use of a technique such as DHCA and RLFP add complexity to CPB. Communication between the surgeon,

anesthesiologist, and perfusionist is essential because of the complexity of manipulation of flows and cannulation. Our philosophy for optimal perfusion in children is to produce high flows with a vasodilated state. Because of this, we flow 150 mL/kg/min for our full flow for those patients weighing <10 kg. These flows are often increased because of the patient's needs assessed by cerebral monitors, blood gas results, lactate levels, and arterial pressures. We have incorporated into our perfusion protocol the use of pH stat blood gas management being aware of its role in the outcomes of patients undergoing DHCA. A debate over the pH-stat versus alpha-stat management of patients continues. Studies have been published defending either position including a study by Kurth, et al. at the Children's Hospital of Philadelphia. These authors measured the cortical oxygen saturation, cortical blood flow, and cortical physiologic recovery after exposure to DHCA using both pH-stat and alpha-stat (15). It was concluded that pH-stat blood gas management is superior to alpha stat for decreasing the rate of cortical oxygen consumption and increasing oxygen supply and recovery following DHCA. Another study from this group demonstrated that pH-stat management improved cerebral recovery, lowered postoperative acidosis and hypertension, and decreased postoperative morbidity (16). To achieve pH blood gas management throughout the bypass run, the addition of CO<sub>2</sub> is used as needed during cooling. By applying pH stat blood gas management, we can see an improvement in our perfusion of the brain based on values displayed by our cerebral monitors. As one can see from Figure 2, the blood gases, cerebral saturation, and cerebral blood flow velocity remained consistent throughout the

entire bypass period, regardless of RLFP. RLFP is one of several factors that have improved patient outcomes at our institution. Between July 1995–December 2002, 112 patients underwent the Stage 1 Norwood operation with an overall operative survival rate of 74%, including the use of both DHCA and RLFP. Of these 112 patients, the 30-day operative survival with DHCA was 67% versus the use of RLFP of 82% ( $p = .06$ ). During 2002, Stage 1 Norwood patients had a 30-day survival rate of 87% (21/24 patients) with the use of RLFP for all patients. Although we believe using RLFP is a main contributor to this success, there are other aspects in our practice that have changed including the use of new cerebral monitors and perfusion techniques. New techniques used include the use of the TCD and NIRS neurologic monitors, continuous CO<sub>2</sub>, implementation of higher hematocrit levels (17), measurement of lactic acid, and overall improvement of arterial blood gas management.

## CONCLUSION

Modifications of surgical and perfusion techniques have limited or eliminated the use of DHCA. Proper perfusion during RLFP can be accomplished using the NIRS and TCD in conjunction with monitoring blood gases, hematocrit, lactic acid, and arterial pressures. These advancements in surgical techniques and monitoring may produce improved outcomes for complex procedures.

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