
Refinements in Infant/Pediatric Perfusion

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Abstract

Little has been written in recent years to update the pediatric perfusion literature. This paper is a review of the perfusion techniques we use with 200 children a year in Denver and we believe it is a reflection of the state-of-the-art. We will discuss equipment selection (including a method of streamlining inventory), circuit prime, anticoagulation, temperature control, blood flow, myocardial protection, blood conservation, patient safety, and cost containment.

Deep hypothermia and circulatory arrest are used with most children under 8 Kg. and acid-base status is managed to maintain respiratory alkalosis with the help of on-line monitoring. Pulsatile flow is used on all patients and hollow fiber membrane oxygenators and blood cardioplegia are used on most. The choice of oxygenator size, and subsequent priming volume, is influenced by the decrease in gas exchange efficiency (-20%) at this altitude and must be understood in that context. All other information is appropriate at any altitude and will be helpful to a team who does few pediatric cases or is starting up a program.

Introduction

Infant and pediatric open heart surgery is a small part of the total cardiopulmonary bypass caseload in this country. Not much is written in the current perfusion literature about the progress in pediatric perfusion techniques and equipment. In this paper we will discuss the perfusion techniques that we use with more than 200 patients a year in Denver at The Childrens and University of Colorado Hospitals. We will outline the components of what is a successful method of dealing with the unique considerations in the perfusion of small children.

Equipment/Disposable Selection and Inventory

We use Cobe^a or Cobe Stockert pumps, one with the Computerized Perfusion Controller™ and one without. The Cobe pumps allow us to pulse, flow at very low pump speeds—for cardioplegia, for instance—and allow for fine control of pump speed. Each pump is equipped with the standard equipment as well as an air-oxygen blender (with an oxygen analyzer for safety), and a Forane vaporizer (a gas-scavenging vacuum system for the oxygenator is employed if Forane is used).

We use the Cincinnati Sub Zero^b Hemotherm™ to drive the cooling-warming mattress and the oxygenator-heat exchanger. We use Hollow Fiber membrane oxygenators for two of the surgeons and bubblers for one. We use the Terumo^c 0.8 m² lung for children below 4.5 Kg. and the Terumo 1.6m² for children 4.5–9 Kg. The weight ranges are approximate. We calculate our maximum flow on the basis of 3.2 l/m²/min and if the child's maximum flow will approach or exceed 700 c.c./min we will not use the 0.8m² lung or if it approaches or exceeds 1.5 l/min. then we will not use the 1.6 Terumo. At 5300 ft. elevation we have found that we can rely upon adequate oxygenation for a liter of blood flow for every square meter of membrane surface area in a Terumo.

On all patients above 9 Kg. we use a Maxima^d oxygenator. Having only one oxygenator for all patients above 9 Kg. has saved us carrying a larger inventory of membrane oxygenators. It has also allowed us to use a generic tubing pack which is made for the Maxima. We have a box designed for each size range in our patient population (Table 1). The warehouse puts the tubing pack, the appropriate size A-V loop, oxy-

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b Cincinnati Sub Zero Products Inc., Cincinnati, OH 45241

c Terumo Corp., Piscataway, NJ 08854

d Johnson and Johnson Cardiovascular, King of Prussia, PA 19406

Table 1
Selection of equipment based
upon patient size

	EQUIPMENT SELECTION			
	< 4.5 Kg	4.5-9 Kg	9-40 Kg	> 40 Kg
Membrane	Terumo 0.8 m ²	Terumo 1.6 m ²	J & J Maxima	J & J Maxima
V.R. Bag	Terumo 100 cc or 400cc	Terumo 400 cc	Terumo 1000 cc	Shiley or BMR 1900
A-V loop	1/4" x 1/4"	1/4" x 3/8"	3/8" x 3/8"	3/8" x 1/2"

generator, reservoir, cardiotomy reservoir, paperwork, etc. in the box and we have everything we need for a case. When we re-order we don't have to order each of the components, just the box.

We currently employ an arterial Gas-STAT™ e probe on every case. We have used a Gas-STAT™ probe in the venous line but found it very unreliable, of limited practical value, and not cost effective. We are not perfectly happy with the Gas-STAT™ in the arterial position and look forward to a better solution to the critical need for on-line monitoring of acid-base status in infant perfusion.

We use metal tipped cannulae, DLP^f venous and Sarns^g arterial, for all but newborns where we use a custom-made 2.5 mm metal aortic tip.

Blood flow

Our flows are based upon body surface area and we flow at a maximum of 3.2 l /m²/min during cooling and warming in deep and profound hypothermia cases. When using hypothermia we will reduce our flows to the range of 1.5 l /m²/min or lower for short periods of time and occasionally use short periods of arrest if necessary to allow the surgeon to do the operation.

Circuit prime

Our current priming solution consists of Fresh Frozen Plasma (FFP) and packed red blood cells. The reasons for this choice are: 1) FFP has a desirable oncotic pressure, compared to crystalloid, and may decrease third spacing, and 2) FFP contains important plasma buffers (the imidazole moiety of histidine) which greatly enhances buffering during hypothermia.¹ With the FFP prime the amount of sodium bicarbonate administered has decreased. Sodium bicarbonate

increases the sodium level in infants, which can increase fluid retention, and it is not an effective buffer at low temperatures.¹ The cost of FFP at our hospitals is \$24/unit, which is \$72/three units, compared to 12.5 grams of albumin which has a patient cost, at one of our hospitals, of \$120. The concern of donor exposure with FFP has been addressed by getting the plasma from the same donor as the red cells that are used on the child. Because we use blood cardioplegia on many of our children and are concerned about the low ionized calcium levels in a prime containing citrated blood products we add heparin and calcium chloride, sufficient to bring the ionized calcium level in the prime to low normal. This is verified with an ionized calcium level on the priming solution every case.

Pulsatile Perfusion

The physiologic advantages of pulsatile flow are well supported in past and current literature.² It has been suggested that pulsatile flow will provide a more uniform and rapid reduction in body temperature for infants undergoing procedures with hypothermia and circulatory arrest.³ In their study Williams³ and associates documented a 30% reduction in cooling and rewarming times which reduced the total bypass time. They also observed a close correlation of the rectal and tympanic membrane temperatures during cooling and rewarming with pulsatile flow. This suggests a more uniform perfusion with pulsatile flow, which in turn provides a consistent temperature of body tissues at the time of circulatory arrest and a uniformity in the reduction of metabolic demands. In our practice we use pulsatile flow on all pediatric cases requiring cardiopulmonary bypass. After initiating bypass the Cobe roller pump is converted from non-pulsatile to pulsatile flow when the heart stops ejecting and pulsatile flow is used until the heart starts ejecting again during the latter stages of re-warming. Naso-pharyngeal and rectal temperatures are monitored closely for confirmation of even cooling and re-warming. Forane (half MAC-MAC) is used from the beginning of bypass until arrest to promote vasodilation and for whatever cerebral protective effects it may have. Regitine (1/2 mg. aliquots) is given to improve perfusion through its alpha blockade if N/P-Rectal temperature gradients exceed 5°C. Sodium Nitroprusside is titrated by anesthesia to maintain low SVR during rewarming. The arterial blood pressure is monitored, and a minimum 20 mmHg pulse pressure is maintained.

TOTAL CIRCULATORY ARREST

Deep hypothermia with total circulatory arrest (TCA) is used on most patients weighing less than 8 kgs. All patients undergoing TCA are pre-treated with Dilan-

e American Bentley, Irvine, CA 17502
 f DLP Inc., Grand Rapids, MI 49501-0409
 g Sarns Inc./3M, Ann Arbor, MI 48103

tin (7 mgs./kg) and Solu-Medrol (30 mgs./kg). The patient's head is packed in ice and surface cooling is used to lower the patient temperature to 31°C.

The ascending aorta is cannulated, and a single venous cannula is placed in the right atrium. Pulsatile flow is used to cool the patient to a temperature of 17°C rectal. When 17°C is reached the aorta is clamped and the arterial pump is stopped. The blood is drained into the venous reservoir bag and the venous line is clamped. The surgeon is informed every 5 minutes of TCA time. TCA time in the 45 to 60 mins. range (at 17°C) appears to be well tolerated. During arrest the perfusate is rewarmed to 28°C. This is accomplished with a recirculation line built into our circuit.

Prior to our reinstating CPB, the patient is transfused from the pump and when adequate volume has been transferred to the patient the venous line is opened. Pulsatile CPB is started and a temperature gradient of 10°–12°C between perfusate and nasopharyngeal temperatures is maintained for traditional reasons. After rewarming the patient is weaned from CPB by carefully restoring adequate filling pressures while decreasing pump flow. TCA allows the surgeon to remove the venous cannula from the small operative site and operate in a bloodless field. In our experience TCA allows relatively safe surgery in infants and offers little additional risk.

ACID-BASE MANAGEMENT

Acid-base status is managed to maintain some degree of respiratory alkalosis (pH >7.4, pCO₂ <40mmHg @ 37°C). Because of the short cooling phase of the pump run, the successful use of this technique depends on a normal pre-pump acid-base status. This requires correction of any metabolic or respiratory acidosis which may exist before or after induction of anesthesia. The pump prime is buffered with bicarbonate, and the dissolved CO₂ used to flush the system is blown off. Upon cooling, the sweep gas is increased and CO₂ aggressively removed. The pO₂ is maintained at around 150 mmHg by continually decreasing the FiO₂ as the patient cools. When circulatory arrest is employed, a more profound alkalosis (pH ~7.6, pCO₂ ~20mmHg @ 37°C) is used prior to the arrest period. This satisfies the theoretical consideration that with a higher starting point (pH ~7.6) the ensuing metabolic acidosis associated with the arrest period will be better tolerated. The use of on-line pH, pCO₂, and pO₂ monitoring allows for precise manipulation of these values not only during the cooling and warming phase, but also during recirculation in the arrest period. Once the arrest has begun, the blood volume in the pump is recirculated through a shunt, the acid-base status is monitored and corrected if necessary. The pH, pCO₂, and pO₂ are adjusted such that the values at reinsti-

tution of bypass are "ideal" for prevention of reperfusion injury.⁴ These values generally are: pH >7.7, pCO₂ <20mmHg, and pO₂ ~150 mmHg. The pO₂ levels are kept low to avoid the increased damage associated with high pO₂s during reperfusion.^{5,6} Upon rewarming, the acid-based status is gradually brought back to alpha-stat values (pH 7.4, pCO₂ 40mmHg @ 37°C). At termination of bypass, the acid-base status is normal.

Myocardial Protection

We currently use blood cardioplegia on all children over about 15 Kg. We have not used blood in the smaller children for a number of reasons. The infants tolerate ischemia better than mature individuals,⁷ we had bad experiences with a commercially prepared crystalloid cardioplegic solution, which our laboratory experience confirmed, and we have just recently developed with Electromedics^h an inexpensive low prime blood cardioplegia delivery system that we can use in infants.

The additive for the cardioplegia (ratio 1 part additive to four parts blood) is: 500 c.c. 5% Dextrose in 0.2 NaCl, 40 mEq. KCl, 50 mEq. NaHCO₃, 1 bag CPDA-1. (This represents a decrease in the potassium that we would give an adult for an initial dose.) When the cross clamp is about to be removed we give about 1 Gram/Kg. body weight of Mannitol slowly into the venous reservoir bag. This is for the protective value mannitol has as an osmotic agent⁸ and a scavenger of the hydroxyl radical.^{9,10,11}

ANTICOAGULATION

All patients are systemically heparinized with 300i.u./kg of beef lung heparin. Subsequent heparin is given by using a dose response curve.¹² Activated Clotting Times (ACT) are done prior to heparin, 5 mins. post heparin, approximately every 20 minutes on CPB, and after protamine reversal. By using the dose response curve we have minimized our heparin and protamine amounts.¹³ We have seen different individual responses to heparin in infant and pediatric cardiac surgery and the dose response curve takes this individual response into account. Heparin metabolism is influenced by continuing changes in flow and temperature. Anticoagulation management in pediatrics is not routine and individual response to heparin and protamine demand special attention to coagulation parameters which are further complicated by the large volumes (relative to patient blood volume) of citrated blood products used.

^h Electromedics, Inc., Englewood, CO 80112

SAFETY DEVICES

Safety devices are designed to prevent the perfusionist from inflicting harm upon the patient. These devices may take the form of some mechanism to reduce the possibility of air embolism. While it is clear that the utilization of these devices in adult patients is often considered "standard of practice" it is not clear when it comes to infant and pediatric cases. Arterial filters are an example. Although we believe they should, theoretically, be used on all patients, the additional 15–20% increase in priming volume in an infant case probably offsets the safety advantage. Another example is the centrifugal pump. The considerations of priming volume and cost are opposed to whatever safety advantage there is to be gained with the use of a centrifugal pump. As with arterial filters, there is no clear answer.

We are currently using the Cobe Perfusion Controller at the University Hospital. This device comes with a blood level sensor and an air emboli detector. We are requesting an upgrade of our pump at The Childrens Hospital to include these devices.

We also use two perfusionists on every case for safety reasons. We have written protocols for each hospital which standardize the perfusion technique and allow the surgeons and anesthesiologists to know what we are doing and why.

One of the most important safety devices we use is an extensive two-part check list¹ filled out by both perfusionists prior to going on bypass. The check list has a "double check" built in. This is a function of the first section (comprehensive check-list) being filled out early followed by an abbreviated version to be completed immediately before going on bypass. Safety is a primary consideration for the perfusionist. Our desire to be as safe as possible is sometimes hampered in the infant case because of volume considerations, i.e., no arterial filter, sometimes running low levels, etc. Where the pump does not have level sensing and bubble detecting capability it is more critical if a filter is not used and should be provided for at the earliest possible time.

Blood Conservation

Conserving blood and limiting the amount of blood given to infant and pediatric patients undergoing cardiopulmonary bypass (CPB) is often difficult. The priming volume of the circuit can exceed the infants blood volume (approx. 90c.c./Kg.) by 2–4 times. Unless the patient has a high hematocrit (Hct), part of the CPB circuit priming solution must consist of blood if the Hct. is to be maintained above 15%.

In our practice, most infant and pediatric patients undergoing CPB are subjected to deep (28°–18°C) or profound (<18°C) hypothermia. It is believed that as the temperature of the patient is decreased, resistance to blood flow, and viscosity increase.^{14,15} It is for this reason that only the minimum amount of red cells required to maintain an Hct. in the 20–24% range are added to the pump when priming. This minimal amount is determined by the patient's size and pre-bypass Hct. If additional volume is required as the patient is rewarmed a minimal amount of red blood cells are added since further hemodilution is not desirable.

Careful attention should be given to the total volume in the CPB circuit towards the end of the pump run because all volume remaining in the circuit after bypass must be transfused, salvaged or discarded. When volume is required immediately after CPB the circuit volume is transfused to the patient. Packing and saving the unprocessed blood for later transfusion is not readily accepted because the heparin content of the prime can cause significant bleeding.¹⁶ Much controversy surrounds the issue of washing or using a cell saver to concentrate the remaining prime. Researchers¹⁶ using a cell saver have reported a 14% residual heparin content in the processed blood. In addition to this problem, routine use of a cell saver is probably not cost-effective,^{16,17} particularly in the infant or pediatric case.

There are considerable risks and costs associated with the use of banked blood. A goal of any surgery must be to use no blood products if possible. It is currently impossible in most infant and pediatric open-heart cases without significant compromise. It may be that the aggressive use of hemo-concentration, salvage of chest tube drainage, design of circuits requiring smaller priming volumes or a new blood substitute will make this an attainable goal in the future.

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