
Perfusion Considerations for Infants Weighing Ten Kilograms or Less

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Abstract

Technical and philosophical perfusion considerations for infants weighing 10 kg. or less are addressed. Experience derived from 178 infants weighing from 1.7 to 10 Kg. is reviewed.

Specific topics include cannulation, priming, equipment selection, deep hypothermia vs. normothermia vs. moderate hypothermia, and special considerations in congenital cardiac surgery.

From January 1979 to December 1983, 178 consecutive infants weighing 10 Kg. or less have undergone complete surgical correction of congenital cardiac defects at the Donald Sharp—Children's Hospital Cardiac Center in San Diego. The smallest infant weighed 1700 Gms. The average weight was 7.1 Kg. Ages ranged from one day to four years (average age 13^{3/4} months). The overall operative mortality was 8% and was unrelated to age or weight, but was directly related to the complexity of the surgical repair. Of the eleven deaths, none were directly attributed to cardiopulmonary bypass (CPB).

General Considerations

The infant weighing 10 Kg. or less who is scheduled for complete repair of a congenital cardiac defect represents one of the most interesting challenges to a perfusionist. Factors such as diagnosis, previous palliative surgery, pathophysiology of the defect, weight, age, hematocrit, and the proposed surgery have a much greater significance than may be encountered in perfusing adults.

Cannulation

We have discovered that each case requires special considerations in the selection of cannulae. Some congenital defects are associated with a large ascending aorta, whereas, other defects have a small aorta. The ascending aorta is usually quite large in Tetralogy of Fallot (TOF). On the other hand, the aorta tends to be quite small in infants with Ventricular Septal Defects (VSD). Therefore, the perfusionist can expect a slightly higher arterial line resistance in the VSD infant compared to the TOF infant when utilizing the same size cannula. Also, a smaller size aortic cannula may be required for the infant with a VSD.

For infants under 10 Kg., the 3.8mm Sarns Aortic Cannula^a allows adequate flow at a low resistance. For infants weighting less than 3 Kg., this cannula may be too large and a 10 Fr. cannula is used^b.

When selecting the size and type of venous cannulae, the weight of the infant and the anticipated surgical repair are considered. If profound hypothermia and circulatory arrest are to be employed, then a single venous cannula is adequate. For infants under 5 Kg., a 4 mm venous cannula will provide adequate venous return. Infants 5-10 Kg. will require a 5 or 6 mm venous cannula.

If the superior and inferior vena cavae are to be cannulated as is necessary in all right heart procedures, we utilize the following as a basis for cannulae selection: 1 to 5 Kg.—Two 4 mm venous cannulae; 5 to 7 Kg.—One 4 mm and One 5 mm venous cannulae; 7 to 10 Kg.—Two 5 mm venous cannulae.

Recently, we have utilized the Pacifico Venous Cannulae^c for infants with small vena cavae and for com-

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plex intra-atrial corrections such as a Senning Procedure. These cannulae provide excellent venous return and therefore enable us to utilize continuous CPB for the complex intra-atrial repairs in place of profound hypothermia and circulatory arrest.

Due to the small size of the heart, the perfusionist should pay particular attention to any problems resulting from cannulation. During cannulation of the Inferior Vena Cava (IVC) and Superior Vena Cava (SVC), the cannulae may impede venous return to the heart due to their size. The perfusionist should anticipate the possibility of instituting CPB prematurely if the venous return to the heart is sufficiently reduced. In this situation, the perfusionist should also be aware that the venous cannulae may have to be withdrawn into the right atrium to discontinue CPB.

During the institution of CPB, the perfusionist should direct her attention to the central venous pressure (CVP) and to the level of blood in the oxygenator. If the venous return is decreased at this time, the IVC cannula may be in the hepatic vein and it should be withdrawn into the IVC. Once complete bypass has been instituted, if an increase in the CVP and a slight reduction in venous return occurs, the SVC cannula should be suspected of being advanced too far. The surgeon should be notified and the cannula withdrawn a small distance. The resulting venous hypertension from these situations can cause cerebral edema, systemic edema, and metabolic acidosis if undetected for any degree of time.

Equipment Selection

Our current perfusion objectives in determining the type of equipment utilized are a low priming volume, minimal surface area, minimal destruction to blood elements, precision control of oxygenation and carbon dioxide removal, efficient heat exchange, short circuit transit time, minimal embolic release to the patient, and additional factors providing for the patient's safety. Unfortunately, we have been unsuccessful in achieving all of our objectives but continue to search for improved equipment manufactured specifically for infant and pediatric perfusion.

An oxygenator should be selected which has a low priming volume, a short transit time, an efficient heat exchanger, and precision control of oxygenation/carbon dioxide removal. The difficulties with the current pediatric bubble oxygenators in perfusing infants under 10 Kg. are related to the inability to independently regu-

late oxygenation/carbon dioxide removal. The gas to blood flow ratios many times are 0.1:1 with resulting pO₂s of 200-400 mmHg and pCO₂s of 40-45 mmHg. This is generally true in perfusing infants under 6 KG and during moderate to deep hypothermia.

The resulting high pO₂s may be hazardous to premature infants undergoing cardiac surgical repair. Retro-lental fibroplasia is caused by oxygen toxicity. The hyperoxia vasoconstricts the retinal arteries leading to abnormal vasoproliferation.¹ Permanent eye damage has occurred when arterial pO₂s are 110mmHg for longer than one to two hours.^{2-6,3} No absolute safe value of oxygen has been identified for the premature infant.

The new generation membrane oxygenators appear promising in the area of precision regulation of oxygenation/carbon dioxide removal and may alleviate some of our concerns for hyperoxia. They may also eliminate the concern of Antifoam A emboli and the unknown long term effects of this substance.³

In an effort to minimize our priming volume, we utilize 1/4 x 3/32 wall tubing for our arterial and venous lines for infants up to 8 Kg. and 3/8 x 3/32 wall tubing for infants weighing over 8 Kg. This provides adequate venous return and small pump stroke volumes for fine control in establishing, maintaining, and discontinuing CPB.

We consider filtration essential. Filters are placed in the arterial perfusion line, gas line, and an integral cardiotomy reservoir filter is used. All bank blood and cell saver blood are filtered with a transfusion filter.

Priming Considerations

In determining the composition of the prime, the perfusionist must consider the infant's diagnosis, proposed surgical procedure, weight, hematocrit, degree of hypothermia to be used, and the minimal amount of prime needed.

Complex congenital defects such as Tetralogy of Fallot, Transposition of the Great Arteries, Truncus Arteriosus and other combinations of defects in which a right to left shunt is evident may have varying degrees of polycythemia. The causative factor of the polycythemia is hypoxia due to the right to left shunts which result in arterial desaturation. The hemoglobin values may be as high as 25 GM/dl. Normal hemoglobin values are listed in Table 1.⁴

In order to reduce the increased viscosity associated with polycythemia, the prime composition should have

TABLE 1
Normal Hemoglobin Levels

AGE	HEMOGLOBIN VALUES
1 DAY	18-22 GM/DL
2 WEEKS	17 GM/DL
3 MONTHS	10-GM/DL
3-5 YEARS	12.5-13 GM/DL

an increased amount of diluent to decrease the hematocrit to acceptable levels during CPB. We feel a hematocrit of 22 to 25% is adequate during CPB. The diluent should consist of fresh frozen plasma or colloid which will maintain an adequate colloid oncotic pressure and thus reduce the possibility of edema. Priming with fresh frozen plasma may be beneficial since it is rich with clotting factors and plasma proteins.

The blood volume for an infant under 10 Kg is approximately 85cc/Kg. Therefore, a 10 Kg. infant has an approximate blood volume of 850 cc. The amount of prime necessary for our circuit is 800 cc. We are therefore diluting the infants blood volume by approximately 100%. In this instance, the composition and amount of the prime are extremely important. The formulas in Table 2 may be helpful in determining the desired volumes.⁵

Once the amount of blood and diluent is determined and placed in the circuit, the prime is buffered with Sodium Bicarbonate to an approximate pH of 7.40. In newborns and small infants, Sodium Bicarbonate must be given judiciously due to the increased amount of sodium as well as the increased serum osmolarity. Sudden increases in an infant's serum osmolarity can result in brain damage and even intracranial hemorrhage from changes in the Cerebral Spinal Fluid (CSF) pressure. (Administering 3 Meq/Kg of Sodium Bicarbonate = an increase of 7.5 mOsm/Kg in the serum osmolarity.)^{2, pg 61}

Other additives to the prime include 2,000 USP of heparin, 30 mg/Kg of Methylprednisolone, and 1.25

Gm of Mannitol. If profound hypothermia and circulatory arrest are to be employed, the Mannitol is not administered until rewarming occurs. This is due to our concern over the possibility of Mannitol crystallizing and precipitating during circulatory arrest at 20C.

Deep Hypothermia vs. Normothermia vs. Moderate Hypothermia _____

When an infant requires corrective surgery, the decision regarding the perfusion temperature and approach will depend upon the diagnosis. For example, critical aortic stenosis in a newborn infant may be treated by an operation utilizing inflow occlusion, normothermic CPB, or deep hypothermia and circulatory arrest. In this condition, the operative procedure requires little time and the presence or absence of venous cannulae does not interfere with the conduct of the procedure. On the other hand, repair of Total Anomalous Pulmonary Venous Return (TAPVR) or the performance of a Mustard operation in a small infant requires extensive intra-atrial surgery. In such cases, the presence of indwelling atrial catheters may obscure the operative field. In such cases profound hypothermia and circulatory arrest has resulted in safe surgical therapy in the small and young patients by creating a bloodless field. Tetralogy of Fallot does not usually require intra-atrial surgery. Therefore, operative repair in TOF infants can be performed utilizing continuous CPB.

Hypothermia and Circulatory Arrest _____

Mohri first reported the use of hypothermia and circulatory arrest without CPB. Infants were anesthetized with ether and packed in ice. Surface cooling to a rectal temperature of 20C was followed by intracardiac repair. The infants were then rewarmed by surface techniques.⁶ Barret-Boyes introduced the concept of

TABLE 2

Helpful Formulas for Volume Determinations

$\frac{(\text{Patient Blood Volume} \times \text{Hematocrit})}{(\text{Patient Blood Volume} + \text{Priming Volume})}$	= The Resulting Hematocrit
$(\text{Patient Blood Volume} + \text{Priming Volume}) \times (\text{Desired HCT})$	= Red Blood Cell Volume
$(\text{Patient Blood Volume}) \times (\text{Patient HCT})$	= Patient's Contribution to Red Blood Cell Volume
$(\text{Red Blood Cell Volume}) - (\text{Patient's Red Cell Volume})$	= Amount of Red Blood Cells Needed
$\frac{(\text{Amount of Red Blood Cells Needed})}{(\text{Hematocrit of PRCs})}$	= cc's of PRCs needed

surface cooling followed by transient core cooling to a rectal temperature of 20C. After completion of the cardiac repair, the patients were rewarmed using CPB.⁷ This technique was expanded upon by others and for a number of years was considered the procedure of choice. Recent data has suggested that surface cooling is not necessary.

At the Sharp—Children's Hospital Cardiac Center in San Diego, we do not utilize surface cooling. When the infant is brought to the operating room, no measures are taken to maintain a normal temperature for the infant while the arterial and central venous monitoring lines are inserted. During this time the infant's rectal temperature may drift to 33C. CPB is utilized to further cool the infant. Ice bags are placed around the infant's head and neck to provide additional cooling to the brain and are not removed until the period of circulatory arrest is completed.

A nasopharyngeal temperature probe is used to monitor brain temperature, a rectal probe to monitor core temperature, and the blood temperature is monitored in the oxygenator. During cooling and warming, meticulous attention is directed toward maintaining a maximum temperature gradient between the blood and the nasopharyngeal temperatures no greater than 10C. A wider gradient may produce capillary shutdown and uneven body cooling.⁸ Also, due to the high efficiency of the heat exchanger, the water temperature is not lowered below 16C nor allowed to exceed 40C.

Once CPB has been instituted and the nasopharyngeal and rectal temperatures are approaching 20C, Thiopental 30 mg/KG is administered into the oxygenator for its potential cerebral protective effects. Although the beneficial cerebral effects are controversial, the possible mechanisms for protection by barbiturates include reduced metabolism, decreased edema formation, membrane stabilization, and suppression of the deleterious effects following reperfusion of ischemic areas.⁹ The cerebral protective effects of hypothermia have been documented. Hypothermia is reported to decrease oxygen consumption and cerebral metabolic rate linearly with the temperature falling about 5-6%/1°C.¹⁰ Therefore, 20C should provide adequate cerebral and systemic protection during the period of circulatory arrest.

Once 20C nasopharyngeal and rectal are attained, the aorta is crossclamped and blood cardioplegia administered. Immediately prior to instituting circulatory arrest, the arterial and central venous monitoring lines are turned off at the patient to reduce the possibility of pulling air into the infant during exsanguination. The

pump is then turned off, the arterial line clamped, and the infant exsanguinated via the venous line into the oxygenator. The venous line is then clamped and timing of the circulatory arrest begun.

Once the surgical repair is completed, the venous cannula is reinserted and CPB is slowly reinstated. Slight metabolic acidosis may be seen during the re-warming period and will usually correct itself. As stated previously, a 10C gradient between the blood and the nasopharyngeal temperatures is maintained during re-warming since it is theoretically possible for oxygen bubbles to form in the plasma if the temperature gradient is too high.^{8, pg 487} It usually requires 45 to 60 minutes to rewarm these infants to a rectal temperature of 35C. Calcium chloride (100mg/Kg) is administered for its inotropic effects and to return the calcium levels to normal prior to the termination of CPB.

From April 1980 to December 1983, 34 infants have undergone intracardiac repair utilizing profound hypothermia and circulatory arrest. The weights ranged from 1700 Gms to 10 Kg., m=5.45 Kg. CPB time to cool the infants to 20C averaged 19 minutes with a range of 11 to 39 minutes. The period of circulatory arrest ranged from 7 minutes to 81 minutes, mean=41 minutes. Neurological deficits attributable to the length of circulatory arrest time have not been encountered.

Special Considerations in Congenital Cardiac Surgery

1. PREVIOUS PALLIATIVE SURGERY: A systemic-to-pulmonary shunt must be controlled before the institution of CPB. Otherwise, flooding of the lungs will occur when CPB is instituted. If this occurs, the perfusionist will see arterial hypotension, a decrease in venous return, and excessive arterial return through a Pulmonary Artery vent if one is utilized.

The surgical approach to a previously constructed systemic-to-pulmonary artery shunt may be straightforward in the case of a right Blalock Taussig shunt (Subclavian artery to pulmonary artery). On the other hand, takedown of a Pott's shunt (left pulmonary artery to descending aorta) may require institution of CPB with finger control of the shunt until moderate levels of hypothermia are obtained. Then, the pump must be turned off while the shunt orifice is quickly obliterated.

Excessive pulmonary venous return present in a patient with cyanotic congenital heart disease may represent incomplete obliteration of a previous shunt or an unrecognized patent ductus arteriosus or the presence of large bronchial collaterals. In these cases, the sur-

geon should promptly determine the cause of excessive pulmonary artery blood flow and act to control the source. In most cases, appropriate preoperative catheterization will determine the presence of a patent ductus arteriosus or the presence of large bronchial collateral arteries requiring special consideration. In cases where torrential pulmonary blood flow obscures the operative field, and surgically correctable causes of increased pulmonary blood flow have been excluded, the surgeon may decide to lower the perfusate temperature and then decrease blood flow rates. Such a maneuver will usually result in a marked reduction of pulmonary venous blood flow.

2. PERSISTENT LEFT SUPERIOR VENA CAVA (LSVC): Adequate preoperative evaluation will normally determine the presence or absence of a LSVC. A LSVC, which is unrecognized, will result in excessive return of venous blood to the right atrium via the coronary sinus. If intraoperative inspection does not reveal the presence of a LSVC, the surgeon should consider the possibility when he opens the right atrium and encounters excessive blood flow from an enlarged coronary sinus. Often the LSVC can be controlled by a simple tourniquet occlusion. If an innominate vein is not present and occlusion of the LSVC results in venous hypertension, a cannula can be inserted through the coronary sinus and a separate tube utilized to return this portion of the systemic venous drainage to the pump.

3. PERFUSION FLOW RATES: Perfusion flow rates are calculated in two manners. The first method calculates Body Surface Area X 2.4L/min. The Body Surface Area is generally under 0.5 sq.m. in infants under 10 Kg. The second method utilizes cc/Kg/Min equation. Infants under one month of age require 120cc/kg/min. Infants from one month to three months of age are calculated at 110cc/kg/min. 100 cc/kg/min is calculated for children age three months to four years.

These blood flow rate calculations are utilized initially when instituting CPB. However, the blood flow rates are then determined by the continuous measurements of the venous saturations. This is accomplished by the Bentley Oxysat Meter.^d Venous saturations are maintained between 75 to 80% by adjusting blood flow rates. If the venous saturations remain low in the presence of high blood flow rates, additional muscle relaxants and anesthetic agents are administered. During moderate to deep hypothermia, venous saturations are maintained above 80%. This technique has resulted in maintaining a normal acid-base status.

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4. PHARMACOLOGICAL CONSIDERATIONS: The perfusionist must adjust the doses of pharmacological agents appropriately for the size of the patient.

Heparin management is determined by the Activated Clotting Time. The infant is initially heparinized via intracardiac injection with 300 USP units/Kg and 2,000 USP units of heparin are added to the prime. ACT's are maintained at 600 seconds. Heparin requirements appear to be decreased in cyanotic infants, during moderate and profound hypothermia, and when large ratios of prime are utilized. ACTs rapidly decrease during re-warming.

The amount of Protamine utilized to reverse the heparin is determined by an ACT taken at the end of CPB. The amount of Protamine administered is usually less than 1 mg of Protamine/each 1,000 USP of Heparin administered.

The electrolytes are monitored during bypass and replaced as needed. Potassium Chloride is administered carefully. 2 meq increments of Potassium Chloride are given to maintain a potassium level of 4.5meq/l. (Bank blood may contain a significant amount of potassium. If bank blood is administered, the potassium should be carefully monitored before additional potassium is given. Also, hemolyzed blood will release additional potassium.)

Calcium levels may be reduced due to the amount of CPD blood administered. Newborn infants have poorly developed mechanisms for regulating calcium and glucose levels of the blood. This may be due to inadequate calcium stores, stress leading to exogenous steroid production, or the administration of Sodium Bicarbonate.^{3, pg 59} Calcium chloride is administered at the end of bypass in 100 mg increments.

Diuretic administration may be necessary during CPB. The glomerular filtration rate is depressed in infants and only reaches adult "normal" values at 1 1/2 to 2 years. Urine output of less than 0.5 cc/kg/hr suggests pathological oliguria and requires attention¹¹. If the urine output decreases below 1 cc/kg/hr, we will administer either Mannitol 1.25 Gm increments up to 1 Gm/Kg or Furosemide 1 mg/kg. In the rare instance when hemoglobinuria occurs, we are aggressive in diuresing these infants. It is most important to maintain an adequate urine output since the serum potassium will rise quite rapidly if oliguric or anuric.

5. BLOOD CONSERVATION: Over the past four years, an effort has been made to conserve the amount of bank blood utilized. Our average number of units of packed red blood cells utilized intraoperatively was 0.75 units/case until the advent of blood cardioplegia.

Currently our usage is 2 units/case. With this one exception, several techniques have been developed to reduce the utilization of bank blood.

Once the pump is primed, a 50 cc syringe of prime is given to the anesthesiologist for volume replacement. The aorta is cannulated first so the infant can be transfused from the pump. Once the infant is off bypass, a 50 cc syringe of pump blood is given to the anesthesiologist for volume replacement. When the infant is determined to be stable, the remaining blood in the pump is spun down utilizing a Cell Saver^c and returned to the patient post-operatively. These techniques have reduced the amount of bank blood administered and probably their attendant complications.

Summary

The modern era of congenital heart surgery requires dynamic interaction between surgeon, anesthesiologist, and perfusionist. The selection of the operation and the perfusion technique will depend upon the age, size, and diagnosis of the patient. The surgeon, anesthesiologist, and the perfusionist must be prepared for the unexpected. Willingness to adjust the operative and perfusion plan is mandatory and preconceived notions must

not be adhered to rigidly. With a flexible game plan and open communication between surgeon, anesthesiologist, and perfusionist a successful outcome will almost always result.

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