Anesthesia for complex congenital anomalies

Profound hypothermia

David J. Steward, M.D.

Toronto, Ontario

Hypothermia as a means to perform direct intracardiac surgery was introduced in the early 1950s.[1, 2] The application of this technique to the treatment of infants with complex congenital lesions was soon envisioned but not widely accepted, as serious problems were foreseen if patients were to be cooled to the levels predicted necessary to allow time for the surgical repair.[3] The introduction of the oxygenator and its subsequent refinement resulted in decreased interest in pure hypothermic techniques, though induced hypothermia continued to be widely used as an adjunct to cardiopulmonary bypass. Cardiopulmonary bypass, however, was associated with a high incidence of complications, often fatal, when applied to small infants.

The technique of profound hypothermia (15 C) with circulatory and respiratory arrest was described by Drew and Anderson[4] in 1959. In 1963 Horiuchi et al[5] reported the use of simple (without cardiopulmonary bypass) deep hypothermia (25 C) for the correction of ventricular septal defect in infancy. During the past 17 years the use of hypothermia with circulatory arrest for the correction of congenital heart defects during infancy has been reported.[6-9] Reported results of cardiac surgery in infants indicated that for many lesions the mortality following early definitive operation was less than

the combined mortality following a palliative procedure and subsequent total correction. In addition early corrective surgery was recognized as offering other possible advantages: avoidance of the complications of the uncorrected cardiac disease, acceleration of retarded physical and intellectual functions, and lessening of stress on the parents. For all these reasons many have accepted corrective surgery of the heart lesion in infancy as the desirable practice.

Profound hypothermia with circulatory arrest offers the surgeon several advantages: the heart is still and exsanguinated, no cannulas are in the operative field, and cardiopulmonary bypass is of limited duration (or unnecessary if surface cooling and rewarming are used).[7] Many different techniques have been used to induce cooling and subsequent rewarming. Some teams have used only surface methods[7]; others have relied on bloodstream cooling and rewarming, with the use of a heat exchanger while using cardiopulmonary bypass[10]; still others use a combination of those methods.[8] There are no clear advantages of one method over the other in terms of ultimate outcome; however, the successful induction of profound hypothermia by surface cooling demands special care to avoid serious arrhythmias. In some units this has been achieved by the use of deep ether anesthesia,[5, 11] which appears to decrease myocardial irritability without marked myocardial depression.[12]

Management of profound hypothermia

At The Hospital for Sick Children in Toronto we have used a combination of surface and bypass cooling with subsequent rewarming to normal temperature on cardiopulmonary bypass[9, 13]; surface cooling is omitted for patients who are in a critical condition. Our present procedure is as follows:

Premedication with pentobarbital, 2 mg/kg by rectal suppository, is given 1 1/2 hours preoperatively, except for small infants younger than 6 months. All patients receive atropine, 0.02 mg/kg, intramuscularly, one half hour preoperatively.

After positioning basic monitors (precordial stethoscope, blood pressure cuff, and electrocardioscope) anesthesia is induced, usually with a small dose of thiopental. Orotracheal intubation is facilitated by succinylcholine, 1 mg/kg, intravenously. Esophageal and rectal temperature probes are positioned, and a radial arterial line is inserted. A central venous catheter is passed via the medial cubital vein. The electroencephalogram is monitored by a pair of occipital electrodes.

Anesthesia is maintained with nitrous oxide, 50% in oxygen with 0.5% halothane added. Patients who become severely hypotensive with halothane are managed with narcotic analgesics. Halothane is preferred when tolerated because the vasodilation it causes facilitates even cooling. In addition, halothane reduces cardiac work and may enhance myocardial perfusion. Muscle relaxation is obtained with *d*-tubocurarine, 0.5 mg/kg, intravenously, with incremental doses as required. Ventilation is carefully controlled to produce an arterial carbon dioxide tension of 35 to 38 mm Hg; 5% CO_2 is added to inspired gases when the esophageal temperature falls below 34 C. Surface cooling is produced by a cooling blanket and ice bags, the objective being to achieve an esophageal temperature of 30 to 31 C at the start of cardiopulmonary bypass. While the heart is being exposed and cannulated, a dose-response curve for heparin is plotted by determining activated clot-

ting times after sequential administration of each of three doses of 1 mg/kg of heparin. Before cardiopulmonary bypass is instituted, another dose of *d*-tubocurarine and sodium methylprednisolone, 5 to 10 mg/kg, is given. The curare is given to ensure that the patient will remain totally paralyzed during cooling and circulatory arrest. Diaphragmatic activity has been observed during circulatory arrest at 15 C. Steroid hormones may afford some protection during the arrest period.

Cardiopulmonary bypass is begun with a prime of cardiopulmonary bypass blood and Plasmalyte in volumes calculated to produce a hematocrit of 25% to 30% when mixed with the patient's blood. Mannitol, 0.5 g/kg, is added when perfusion is established, 10% carbon dioxide is added to the oxygenator below 25 C, and 15% CO_2 is added below 20 C to maintain optimal perfusion and oxygen transport at low body temperature.[14] During cooling, the temperature of the pump blood is maintained within 10 C of the patient's esophageal temperature. Phentolamine, 0.5 mg/kg, is administered during cooling to promote rapid, even cooling. Halothane is discontinued before bypass cooling as blood levels may rise significantly during hypothermia[15] and residual halothane might result in impaired cardiac action when rewarming bypass is discontinued. Cooling bypass is discontinued when the esophageal temperature reaches 15 C and the rectal temperature is less than 18 C. All the blood that can be is drained from the patient into the oxygenator. A cold cardioplegic solution is infused into the myocardium, and this process is repeated if necessary during circulatory arrest, if the period of arrest is prolonged or if the myocardial temperature rises.

After surgical repair is completed, cardiopulmonary bypass is reinstituted and the patient rewarmed to 37 C, again maintaining a gradient of less than 10 C between the patient's esophageal temperature and the pump blood; 5% CO_2 is added to the oxygenator during rewarming. A degree of metabolic acidosis may be observed on blood samples analyzed at this time. This should not be corrected as it will improve spontaneously following bypass, and attempts at early correction of metabolic acidosis are usually followed by metabolic alkalosis in the postoperative period.[16] After bypass is discontinued packed red cells resuspended in recently thawed fresh frozen plasma are given to the patient to maintain an adequate preload. Platelet concentrates (1 unit/kg body weight) are administered. Residual heparin is reversed with protamine after determination of the dose required as evidenced by a recent activated clotting time and the initial dose-response curve for heparin in this patient.

Postoperatively, the patient is maintained on controlled ventilation or continuous positive airway pressure. After cardiac surgery the cardiovascular state of infants is managed along traditional lines. If inotropic agents are required, dopamine, 3 to 8 μg/kg/min, is preferred, and if afterload reduction is indicated, nitroglycerin or sodium nitroprusside is the drug of choice. Fluid replacement is continued at a rate determined by urinary output, together with predicted fluid requirements. Once a good urine output is established potassium supplements, 2 to 4 mEq/kg/24 hr, and magnesium, 1 mEq/kg/24 hr, are added to the intravenous fluid regimen. Serious renal impairment has been uncommon in our patients.

Metabolic effects of profound hypothermia

The effects of profound hypothermia are circulatory arrest on oxygen con-

sumption (VO_2) have been studied.[16, 17] These studies have shown that at a body temperature of 20 C, VO_2 is reduced to 24% of normal and at 15 C to 11% of normal. These are similar to values determined by Bigelow et al[1,3] in early experiments, and close to the results of our own studies.[14] After the period of circulatory arrest the VO_2 is initially high and then falls. Abbott[18] has suggested that this is due to replenishment of the body's store of dissolved oxygen, which has been depleted during the period of arrest. The rise in blood lactate levels, which has been reported following the arrest period, indicates that anaerobic metabolism also contributes to cell survival at low temperature.[17, 18]

It has been suggested that during profound hypothermia essential tissues are protected by three mechanisms: (1) the metabolic rate of the tissue is reduced, (2) oxygen dissolved in tissues is increased at low temperature and is available to help meet the reduced metabolic requirement, and (3) anaerobic metabolism contributes following depletion of oxygen supplies.

Results following profound hypothermia

A question of great current interest is whether children who have been subjected to profound hypothermia and circulatory arrest will experience any permanent central nervous system damage.[19] The results of follow-up studies are somewhat contradictory, but may reflect the different techniques of profound hypothermia used in different centers. Some authors report that children have a postoperative intellectual performance in the normal range.[20–22] Others have suggested that neurologic deficit may follow,[23] and that conventional cardiopulmonary bypass may be preferable to circulatory arrest under profound hypothermia for surgery in infants.[24, 25]

In our follow-up studies, we have reviewed the cases of 262 children who have undergone surgery with circulatory arrest during profound hypothermia. These children now range in age from 2 to 16 years; 248 have no symptoms of gross neurologic disease, but 14 have some impairment of central nervous system function. Reviewing the case histories of the latter 14 patients, an obvious cause for the central nervous system deficit could be found in all but one. This cause varied from congenital central nervous system defects, which antedated surgery and were unchanged since, to embolic episodes and postoperative cardiac arrest. One patient apparently had an uneventful operative period, but has some degree of neurologic deficit. He had a complex repair of a transposition with ventricular septal defect and had a period of circulatory arrest that was longer than usual (78 minutes at 15 C). The results of more detailed studies of some of our patients indicated that the development quotient of these children is similar to that of other children with congenital heart disease, but slightly lower than that of their normal siblings.[26] It was also noted that children who had undergone surgery for cyanotic congenital heart disease had a lower postoperative development quotient than those with acyanotic lesions, a finding that is described in unoperated children with congenital heart disease.[27] This is disappointing as one hopes that early surgery would permit the child to catch up with normal children.

Several follow-up studies have sought a relationship between postoperative impairment of intellectual performance and the duration of circulatory arrest, but have failed to demonstrate a convincing correlation within the limits of

what is usually accepted as a "safe" period of arrest. This is surprising if significant central nervous system impairment does occur after circulatory arrest with profound hypothermia.

Undoubtedly the application of techniques of profound hypothermia has done much to promote the concept of performing definitive surgery for congenital heart lesions during infancy. However, in recent years much experience has been gained in maintaining small infants on cardiopulmonary bypass, and this can now be achieved without a high incidence of complications. Whether circulatory arrest with profound hypothermia will stand the test of time will depend upon the results of further detailed studies of survivors, which are surely required. In addition, careful comparison is needed between overall results with hypothermic circulatory arrest techniques versus methods employing continued perfusion.

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