MANAGEMENT OF CARDIAC SURGERY IN THE NEONATE

W. J. GLOVER

The incidence of major congenital defects is approximately 2.5% of total births. Congenital heart disease and neural tube defects each account for about one-third of all defects. From several studies in Europe and the United States it is estimated that the incidence of congenital heart disease is about seven cases per 1000 births (Lancet, 1975).

As more than one cardiac lesion is sometimes present, classification is usually based on the major lesion or combination of lesions, for example Fallot's tetralogy. On this basis, ventricular septal defect is by far the commonest defect with an incidence of 2.1/1000 births, followed by patent ductus arteriosus 0.7, pulmonary stenosis 0.5 and atrial septal defect 0.5/1000 births. Transposition of the great arteries, aortic stenosis, coarctation of the aorta and Fallot's tetralogy each have an incidence of about 0.3/1000 births. Total anomalous pulmonary venous drainage, although it has an incidence of only 0.1/1000 births, is of considerable importance in neonatal cardiac surgery, for reasons given later.

Some of these lesions produce no symptoms in the neonatal period or in infancy. However, about 50% of children born with congenital heart disease die in the first year of life unless effectively treated. One-third of these deaths occur in the first month of life (Mehrizi, Hirsch and Taussig, 1964). Lesions which often pose an early threat to life and present as neonatal emergencies are: total anomalous pulmonary venous drainage, transposition of the great arteries, aortic stenosis, coarctation of the aorta and Fallot's tetralogy each have an incidence of about 0.3/1000 births. Total anomalous pulmonary venous drainage, although it has an incidence of only 0.1/1000 births, is of considerable importance in neonatal cardiac surgery, for reasons given later.

Serious hypoxia occurs in those infants who have a severe obstructive lesion in the pulmonary circulation, for example, pulmonary stenosis or pulmonary atresia resulting in a large right-to-left shunt through an atrial or ventricular septal defect (ASD or VSD). Oxygenation then depends on blood reaching the pulmonary artery via the ductus arteriosus and when this closes urgent operative treatment is required. Severe hypoxia will also occur in transposition of the great arteries because the pulmonary and systemic circulations are separate unless there is an abnormal communication between them such as a patent ductus arteriosus, or an atrial or ventricular septal defect. If the ductus arteriosus is the sole communication, its spontaneous closure will precipitate an emergency.

Severe congestive failure occurs in infants with a large left-to-right shunt through a ventriculo-septal defect, but it will also occur where there is a severe obstructive lesion on the left side of the heart, such as aortic stenosis or coarctation of the aorta. Hypoxia of varying degree will, of course, be associated with congestive cardiac failure.

The combination of congestive cardiac failure and hypoxia is at its most serious in total anomalous pulmonary venous drainage (TAPVD). The pulmonary veins in this condition usually drain into a common posterior venous chamber which, in turn, drains into the systemic venous circulation, for example the venae cavae. Pulmonary venous obstruction is present in approximately half the patients and can occur in any variety of TAPVD (Gathman and Nadas, 1970). If the obstruction is severe, pulmonary blood flow is decreased and cyanosis may be intense. The presence of a patent ductus arteriosus acts as a vent for the congested pulmonary bed into the descending aorta. Congestive cardiac failure and early death are inevitable unless the lesion is corrected by surgery (Barratt-Boyes, 1973). Fortunately, this is usually technically possible by anastomosing the common posterior venous chamber to the posterior wall of the left atrium (Kirklin, 1973a).

It is evident, therefore, that many neonates can continue to survive so long as the ductus arteriosus or the foramen ovale remains patent. Their spontaneous closure in such infants causes an acute emergency. In this connection, the reported use of prostaglandin...
in two neonates with cyanotic heart disease is interesting, as it is known to dilate the ductus arteriosus of the newborn human in vitro. In both infants there was an improvement in arterial oxygen saturation following infusion of prostaglandin E1. This suggests that such an agent might be useful as a short-term palliation to enable the patient's hypoxic condition to be improved before surgery. Further trials are awaited (Elliott, Starling and Neutze, 1975).

ANAESTHESIA

Anaesthesia in the neonate is dealt with elsewhere in this journal and only special points will be mentioned here.

Many of these neonates, particularly those with TAPVD, are already seriously ill when admitted. Intensive care begins immediately on admission in such patients. Intra-arterial and central venous cannulae are inserted and the pressures monitored. The e. c. g. and body temperature are monitored and the blood-gases measured. If respiratory insufficiency is present, nasotracheal intubation and mechanical ventilation are commenced. This management is continued in the cardiac catheterization room.

When the neonate is not so seriously ill, and especially when congestive failure is not present, either mild sedation or anaesthesia is required for cardiac catheterization. We routinely employ sedation using an injection, 1 ml of which contains pethidine 25 mg, chlorpromazine 6.25 mg and promethazine 6.25 mg. The dose is 0.05 ml/kg body weight given i.m. 30 min before the investigation. This is half the dose given to older infants. Should any further sedation be necessary, as may occur in long investigations, diazepam 0.1 mg/kg may be given via the catheter.

If anaesthesia is preferred by the investigator, then the conduct of anaesthesia both in the investigation room and the operating theatre may be as described elsewhere in this issue.

OPERATIVE SUPPORT TECHNIQUES

Definitive open intracardiac operations in infants are now performed much more frequently than a few years ago. Consequently palliative "closed" cardiac operations have declined in number and importance.

The risk of intracardiac operations in infants remained high for longer than such operations in older patients. However, in recent years, as a result of several factors, the risk has declined considerably and this has led to the increase in open intracardiac operations.

Factors enhancing the safety of these operations are: more precise diagnosis and better understanding of the effects of congenital cardiac defects, considerably improved techniques of operating inside the infant heart, improved support techniques during cardiac surgery and improved care after surgery (Kirklin, 1973b).

It is widely accepted that the "priming volume", that is the volume of blood and diluents in the pump-oxygenator, should be as small as possible. In the past this volume was many times that of the blood volume of the infant, whereas it is now only about twice that of the blood volume of a neonate.

Considerable advances have been made in reducing platelet-fibrin aggregates which can form emboli and damage the patient (Osborn et al., 1970; Ashmore et al., 1972). This has been achieved mainly by the use of improved filters in the oxygenators and in the lines through which blood is added to the pump-oxygenator.

Haemodilution improves the flow characteristics of the perfusate at low temperatures and improves post-perfusion urine flow (Beall et al., 1964; Mielke et al., 1966). However, after perfusion it causes an increase in interstitial fluid and total body water (Cohn, Angell and Shumway, 1971). As the neonate has difficulty in excreting a large fluid load, haemodilution is not used to produce a haematocrit of less than 30%.

Even with perfusion maintained within normal limits, it is difficult to maintain homeostasis (Kirklin, 1973b). Blood lactate concentrations increase, suggesting that anaerobic metabolism is occurring in some areas. Therefore it follows that the shorter the perfusion the less damage will occur to the patient. Fresh heparinized blood (diluted to a haematocrit of 30%) is usually used for the perfusate in small infants. This minimizes coagulation disorders and avoids the severe metabolic alkalosis which may occur in the postoperative period following the use of citrated blood.

Hypothermia

Initially, intracardiac surgery was performed in children and adults using a pump-oxygenator to perfuse the patient at normal body temperature or at slightly decreased body temperature, about 32 °C. Moderate hypothermia such as this allowed some reduction in flow and some protection from hypoxia in the less well-perfused areas of the body. Subsequently, as more complex anomalies were corrected, the enormous advantage to the surgeon of very low
flows or total circulatory arrest became apparent. The pump-oxygenator was used, therefore, to cool the patient to much lower temperatures to enable circulatory arrest to be carried out with safety. It is generally accepted that when the nasopharyngeal temperature is 28 °C, 20 min of total circulatory arrest is safe for all patients; at 26 °C, 30 min is safe; and at 22 °C, 45 min is safe (Kirklin, 1973b).

The use of both surface hypothermia and bypass cooling for intracardiac surgery in infants was then introduced (Hikasa et al., 1967). In most centres this technique is now employed for intracardiac surgery in neonates and young infants (Subramanian et al., 1971; de Leval and Stark, 1974).

The advantages claimed for this method are as follows:
(a) Cooling of all the organs and tissues of the body is more even than with "core"-cooling and this is of considerable importance with respect to the brain and liver.
(b) The period of perfusion by artificial means is considerably shortened and this is an advantage to the patient.
(c) The period leading up to cannulation and the establishment of bypass in very ill infants is always hazardous at normal temperatures because of the possibility of a severe decrease in cardiac output. The protection afforded to the brain by surface cooling to about 28 °C before thoracotomy and the slow cardiac rate associated with this temperature make cannulation less hazardous. For example, if ventricular fibrillation or asystole should occur at this stage, cannulation can continue without haste and perfusion can be established well within the period of protection available to the brain. To the author, this advantage alone is an important justification for its use in very ill infants.

**MANAGEMENT**

**Before bypass**

After being anaesthetized, the neonate is placed on a water blanket through which ice-cold water is circulated. Plastic bags filled with ice are placed over the major vessels, the head and abdomen. Care is taken not to place an ice-bag directly over the precordium, to avoid selective cooling of the heart and a consequent decrease in cardiac output while the body temperature is still near normal. The bags are moved from time to time and the skin gently massaged to avoid any direct tissue damage from the ice.

While cooling is taking place the e.g., nasopharyngeal and oesophageal temperatures are monitored and the arterial and central venous lines are inserted. Sometimes the radial artery can be cannulated percutaneously; otherwise the brachial artery is cannulated under direct vision.

The objective is to produce even cooling throughout the body and this is facilitated by vasodilatation. For this reason most anaesthetists add halothane, 0.25-0.5%, to the nitrous oxide in oxygen mixture. Muscular relaxation is produced by pancuronium bromide 0.06 mg/kg.

As the temperature decreases the metabolic rate is reduced and $P_{aCO_2}$ will decrease. In order to encourage cerebral vasodilatation and more rapid cooling of the brain, 5% carbon dioxide is added to the inspired mixture when the nasopharyngeal temperature reaches 32 °C (Kirklin, 1973b). $P_{aCO_2}$ is maintained at more than 45 mm Hg (6 kPa). It is important to note that allowance must be made for the low temperature of the blood sample, otherwise a false high $P_{aCO_2}$ result will be obtained. In the author's experience, in spite of these attempts to promote vasodilatation, the oesophageal temperature tends to be 1 °C lower than that in the nasopharynx.

The nasopharyngeal temperature at which surface cooling is discontinued varies from centre to centre: 24 °C (Barratt-Boyes, 1973; Subramanian, 1973), 28-29 °C (de Leval and Stark, 1974), 30 °C (Kirklin, 1973b). The ice-bags are removed, the baby is dried off and the operation begun. By the time cannulation is done, the infant's temperature will probably have decreased a further 2 °C.

Hypokalaemia has been reported in some infants during surface cooling (Johnston et al., 1974). Therefore it is advisable to measure the serum potassium concentration during this period.

**Bypass**

If a period of circulatory arrest is required to facilitate repair of the lesion, further cooling is done using the pump-oxygenator. The infant is perfused at a full flow rate of 2.5 litre/min.m$^2$ and 10% carbon dioxide is added to the oxygen in the oxygenator until the nasopharyngeal temperature reaches 22 °C.

The aorta is then cross-clamped proximal to the aortic cannula, the pump to the patient is turned off and the venous and arterial lines are clamped.

Repair of the lesion then takes place.

After the repair, the patient is rewarmed, using the pump-oxygenator, to a nasopharyngeal temperature
of 36°C, and water is circulated through the water-blanket to maintain this temperature.

If circulatory arrest is not required for repair of the lesion, the patient is usually cooled to about 25°C and it is then safe to perfuse the patient at a low flow for example 0.5 litre/min.m² for 30 min or higher rates for longer periods.

The advantages to the surgeon of a period of total circulatory arrest are considerable, especially when performing a difficult intracardiac repair in a small heart. There is no blood from the coronary or aortopulmonary collateral circulations to obscure the field, and the cannulae can be removed from the heart if they make the exposure more difficult.

Today, in most centres, cardiopulmonary bypass is used as a flexible tool in infants—that is it is combined with hypothermia to reduce the systemic blood flow during difficult parts of the operation or, if necessary, it may be turned off completely with safety within the time limits stated under "Hypothermia" above.

After bypass

Provided the lesion has been corrected to give a good haemodynamic result and provided any metabolic acidosis has been corrected, an effective circulation is usually restored quite easily in the neonate.

As perfusion is gradually reduced the heart fills and the left atrial, right atrial and systemic pressures are observed. When the left atrial pressure is about 10 mm Hg, a good output is usually achieved and perfusion is discontinued. At this point 0.25 mmol of calcium, as calcium chloride, is often given.

If the cardiac output remains poor, then a slow infusion of isoprenaline 1 mg in 100 ml of dextrose 5% is given. If the urine output is less than 1 ml/kg.h then frusemide 1 mg/kg may be given i.v. Potassium supplements are seldom required at this stage, but the serum electrolytes should be measured, nevertheless. Epidocardial pacemaker wires are inserted in every infant to enable the heart to be paced if necessary. Heparin is reversed with protamine sulphate as in older patients.

POSTOPERATIVE CARE

A variable degree of respiratory insufficiency occurs in the neonate after open heart surgery. This is because of an upset in the ventilation/perfusion ratio, the presence of chest drains (often bilateral), residual pulmonary venous congestion in some types of lesion and depression of respiration caused by analgesic drugs. Consequently, some form of respiratory support is required in a high proportion of infants and in most centres all neonates are intubated and ventilated for about 24–48 h after open heart surgery.

Following the successful use of continuous positive airway pressure (CPAP) in intubated spontaneously breathing infants with respiratory distress syndrome (Gregory et al., 1971) some cardiac centres have applied this technique after open heart surgery in infants (Stewart et al., 1973). This system requires the infant to make adequate respiratory efforts and that may not always be possible. In a study at this hospital, comparing intermittent positive pressure ventilation and CPAP on infants after open heart surgery, it was shown that there was some improvement in $P_{A\text{O}_2}$ when pulmonary compliance was less than normal. If pulmonary compliance was normal, $P_{A\text{O}_2}$ was unaltered when the patient was removed from the ventilator and attached to a CPAP circuit (Hatch et al., 1973). Consequently, as mechanical ventilation has been extremely safe and satisfactory, it is used routinely in this hospital. The neonate is ventilated at a rate of 30–40/min with an oxygen-enriched mixture to produce a $P_{A\text{O}_2}$ of 70–100 mm Hg (9.3–13.3 kPa) and a $P_{A\text{CO}_2}$ of about 35 mm Hg (4.7 kPa). Should there be a tendency to atelectasis, positive end-expiratory pressure (PEEP) of about 8 cm H₂O may be applied (Pick, Hatch and Kerr, 1976).

After 24–48 h, if the chest x-ray is satisfactory, the cardiovascular system stable, the blood-gases and the urine output satisfactory, mechanical ventilation is discontinued and the neonate is attached to a CPAP circuit with a positive pressure of about 8 cm H₂O. The infant is then weaned off by decreasing the positive pressure over a period of a few hours and then extubated.

Mechanical ventilation is carried out via a plastic tracheal tube which may be placed orally or nasally. In this unit nasotracheal intubation is preferred for ventilatory care because it is easier to secure the tube and in older children it is much better tolerated than an oral tube. Great care is taken to avoid a tube which is too large, otherwise pressure at the level of the cricoid cartilage will lead to ischaemia, oedema and possibly subglottic stenosis. This is more likely if the tube is in place more than a few days. The best clinical guide is to use a tube which allows a slight audible leak of gas around it during inflation of the lungs. In practice this will be 0.5 mm i.d. less than that which gives an airtight fit. If this precaution is taken at the outset, then the tube may be left in
place for long periods of time (Battersby, Hatch and Towey, 1977).

While ventilation is obviously the main concern of the anaesthetists, there should be close collaboration with the cardiac surgeon on the monitoring and support for the cardiovascular system. Continuous monitoring of left and right atrial pressures, systemic arterial pressure, heart rate and rectal temperature is done. Blood loss and replacement are noted at frequent intervals and blood-gas analysis is performed as often as necessary. Blood and urinary electrolytes are measured, as are urinary output and osmolality. A chest x-ray is taken immediately on return to the ward. The circulating volume is kept at its optimum value by transfusion of blood or plasma depending on left and right atrial pressures. The haematocrit is kept at 38–40%.

If cardiac output decreases in spite of adequate blood volume it can be improved by catecholamines, as already described, or by digoxin.

As it is necessary to have easy access to these infants, incubators are not satisfactory. It is more convenient to nurse them under an infra-red radiator.

“CLOSED” HEART SURGERY

As already stated, the number of these operations has declined considerably, as a result of corrective surgery being undertaken earlier in life.

There remain some lesions, however, which do not require open heart surgery for their correction; for example, patent ductus arteriosus and coarctation of the aorta.

Coarctation of the aorta is a fairly common abnormality and, when it presents in infancy, it is usually the pre-ductal type. This means that the patent ductus provides much of the blood supply to the lower part of the body. These neonates are usually in severe congestive failure with a variable degree of hypoxia and resection of the coarctation is essential in such cases. Induction and maintenance of anaesthesia must be done with great care to avoid any reduction in cardiac output. Should this occur, ventricular fibrillation, which is usually irreversible, is likely to follow. For this reason halothane should be avoided in this condition and a 50% nitrous oxide in oxygen mixture plus relaxant used. It is advisable to insert an intra-arterial line for three reasons.

First, it enables any decrease in systemic pressure to be noted immediately and suitable steps to be taken to correct it before an irreversible situation occurs. Second, the acid–base state of the patient can be ascertained and the metabolic acidosis, which is usually present, corrected before surgery commences. Third, it facilitates postoperative care. Since these neonates with coarctation are in congestive cardiac failure, it is advisable to ventilate most of them for about 24 h after operation.

CONCLUSION

It will be apparent that accurate diagnosis and effective treatment of neonates requiring emergency cardiac surgery place considerable demands on the centre accepting them. A 24-h service for diagnosis, for intracardiac and for “closed” cardiac surgery is essential. Paediatric cardiologists, cardiac surgeons, anaesthetists, technicians and nurses experienced in the care of this age group must be available at all times.

REFERENCES


