A TECHNIQUE FOR THE COMBINATION OF PROFOUND HYPOTHERMIA AND EXTRACORPOREAL CIRCULATION WITH COMPLETE CIRCULATORY ARREST

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Varying degrees of hypothermia with extracorporeal circulation are being used with increasing frequency in the surgery of congenital and acquired heart disease. The use of an oxygenator combined with profound hypothermia (9°–15° C.) to achieve complete circulatory arrest during intracardiac surgery is not as yet widely practised. This technique has been in use in the Nuffield Department of Surgery since August, 1959.

APPARATUS

The Mayo-Gibbon vertical-screen oxygenator (a gift from the Wellcome Trust) is the type of heart-lung machine used. Incorporated in the pump-oxygenator circuit is a standard Brown-Harrison heat exchanger. This is fitted just beyond the blood filter in the arterial line (Fig. 1).

TECHNIQUE

The patient is weighed on a bed weighing machine, anaesthetized and draped using a standard technique (Hodgson and Parkhouse, 1961). A femoral artery and saphenous vein are first exposed at the groin. The vein is cannulated with suitably sized nylon tubing for recording central venous pressure. Both femoral arteries are exposed in children below the age of 4 years. In transposition of the great vessels the systemic artery is cannulated through the right ventricle; this allows a good-sized cannula of 3 to 4 mm. internal diameter to be used (Fig. 2). The heart is exposed through a mid-sternotomy incision; the pericardium is opened in the midline and its free edges sutured to the periosteum on the divided sternum. Great care, particularly in children, is taken not to open either pleural cavity. Through a small stab incision below the mid-sternotomy incision a plastic tube fitted with a small, short, multi-perforated suction tip at one end is threaded into the oblique sinus of the pericardium. The other end is attached by a Y piece to the general suction. The suction tubing is then led to a graduated cylinder of variable capacity which in turn is connected to a large graduated bottle. By means of a tap the graduated cylinder can be emptied into the lower bottle (Fig. 3). Blood lost from all areas is therefore collected in graduated bottles, one of which is at eye level next to the anaesthetist, who records blood loss. The swabs are weighed. Heparin, 3 mg. per kilogram of body weight, is administered and allowed to circulate for two minutes before the femoral artery is cannulated with the largest stainless steel cannula it will take. The cannula is connected to the arterial machine line from the pump and cleared of air.

The right auricle is explored through an incision in the appendage. If the heart rate is irregular or in any way giving rise to anxiety exploration of the auricle is dispensed with and the largest possible metal cannula, already attached to the venous machine line, is inserted and held in place with a purse string ligature (Fig. 4).

The perfusion is now started. The patient is perfused with blood at 37° C. until the predetermined flow rate of 2.0 to 2.8 litres per square metre of body surface is obtained. If this flow rate is easily obtained with the cannulation used an attempt is made to get a higher flow rate. Once the highest possible flow rate is obtained cooling is started and proceeds slowly. The water circulating through the heat exchanger is gradually cooled to 4° C. with ice. The difference in temperature between the blood leaving the heat exchanger and that of the nasopharynx, oesophagus, and mediastinum should be as close as possible, usually less than 5° C. As cooling proceeds the heart can be more fully examined, because it is now much smaller and can be manipulated easily and safely, e.g., a persistent left superior vena cava can be defined. The venae cavae are isolated and snared with ease; alternatively to avoid oozing raw surfaces the venae cavae need not be isolated but occluded with Glover's clamps when circulatory arrest is instituted. During this period the left atrial appendage can be cannulated; this procedure in the normothermic, enlarged, beating, and irritable heart can be a technically difficult problem. The drainage from here is led to the venous return line via a connexion on the right atrial cannula. Between 29° C. and 25° C. the heart slows and eventually fibrillates or stops. At 20° C. it has stopped, the heart being small, well-oxygenated, and firm.
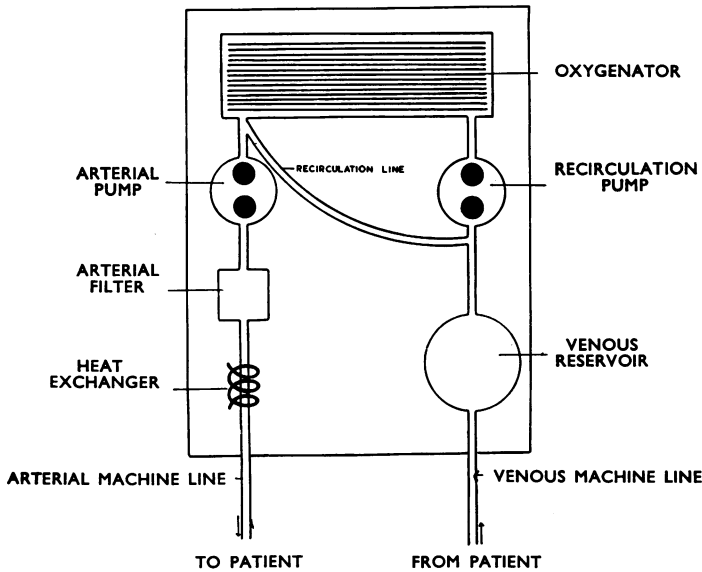
FIG. 1.—Plan of heart-lung machine.

measured, and if this is within normal limits and the heart's action good the left atrial cannula is removed. During the early phase of rewarming while the repaired heart is quiescent the left atrial cannula acts as a vent for the lesser circulation.

Once the left atrial cannula has been removed and the auricle sutured the perfusion is stopped and all blood loss estimated and corrected before the remaining cannulae are removed. This restoration of blood volume can be very difficult and trying. Weighed swabs, suction drainage, towel staining, etc., can be very deceptive, particularly in small children. The open pleural cavity containing a pint or two of blood

Cooling is continued until the nasopharyngeal temperature is 8° C. to 10° C. At this temperature the arterial flow is stopped, the venae cavae clamped, and the heart emptied of blood through the right and left atrial cannulae. Definitive intracardiac surgery is then carried out on a heart that is dry and still. The coronary sinus suction is rarely if ever used. The little blood remaining in the heart is removed by the general suction. In this series the period of complete circulatory arrest has varied from 20 minutes to 70 minutes.

When intracardiac surgery is completed, the chamber opened is filled with blood from a syringe, the lungs are inflated by the anaesthetist, who floods the left heart with blood in an effort to remove as much air as possible from the heart, and the chamber is then closed by suture. The venae cavae clamps are removed and the arterial flow restarted. As there is a vacuum in the venous reservoir, any air remaining is removed via the right and left atrial cannulae. Gently squeezing the heart will also help to accomplish this. The patient is perfused with blood at about 15° C. before gradually rewarming. Rewarming usually takes longer than cooling because the temperature of the warming water (40°–42° C.) is nearer that of the body. Between 28° C. and 35° C. the heart may either start spontaneously or fibrillate. Fibrillation is usually reversed by a single shock which varies between 150 and 200 volts depending on the size of the heart. Once the temperature reaches 35° C. in adults or 37° C. in babies and small children the flow is gradually reduced and the patient allowed to " take over." As the flow is reduced and a carotid pulse becomes easily palpable the left atrial pressure is
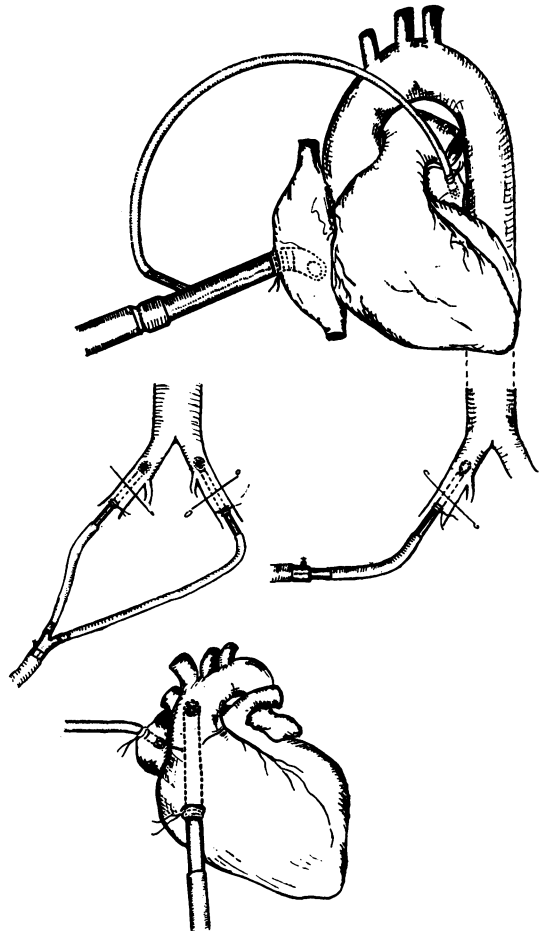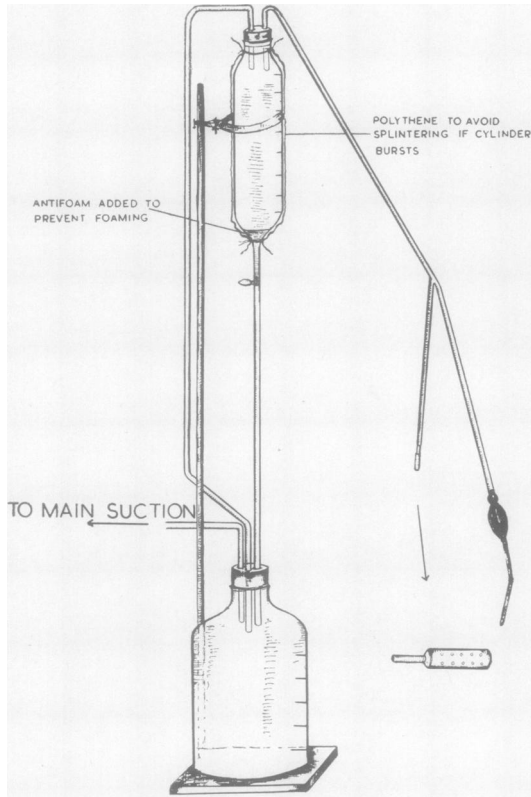

FIG. 2.—Method of cannulation.
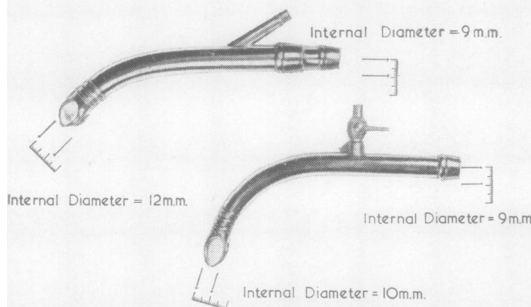
FIG. 3.—Suction apparatus.

FIG. 4.—Right atrial cannulae showing side-arms for attachment to left atrial line.

may easily be forgotten. Some indication can be obtained from the machine by ensuring that the blood levels in the venous reservoir and the lung are at pre-perfusion level. At the present moment our best criteria for adequate restoration of blood volume

before removing the cannulae are judged by the heart's action and appearance, the venous pressure and the arterial pressure. Of these we feel that the venous pressure is the most valuable single aid. The right atrial cannula is removed, and the arterial cannula is removed last in case any acute blood loss occurs with the removal of the atrial cannulae. The artery is repaired with 7-0 silk. The circulating heparin is neutralized with polybrene. The chest is closed in the routine way, draining the pericardial sac by a drain down to the oblique sinus. The anterior mediastinum is also drained. These drains are connected to a Roberts's empyema suction through a graduated polythene cylinder which will measure blood loss from this time and in the post-operative period. Before leaving the operating table the patient is catheterized and the urinary output noted. A bronchoscopy is also done. In very small children, particularly those who have been in cardiac failure, a tracheostomy may be done. The patient is reweighed on being returned to bed. This is a further check on the restoration of blood volume.

FLOW RATE

A flow of 2.0 to 2.8 litres per minute per square metre of body surface is used as a basic minimum flow rate, but if possible flow rates in excess of this are aimed at once the perfusion has started. It has been our experience that at about 30° C. an intense vasoconstriction sets in and the perfusion pressure rises alarmingly and the flow rate may drop. The vasoconstriction has been noticed at a higher body temperature if cooling is rapid and the body is perfused with blood at a low temperature from the outset. This leads, we believe, to areas with large temperature gradients, and causes a poor perfusion of many parts of the body. The flow rate in fact may drop only slightly. This may be due to the closure of capillaries and arterioles and the opening of arteriovenous anastomoses. The oxygen saturation of the venous blood is therefore increased, which might suggest a good perfusion, whereas in fact certain tissues, e.g., the gut with its rapid cell turnover, muscle, and skin, may be anoxic during the period of early cooling. If and when vasoparalysis occurs with redistribution of blood volume it occurs at a temperature at or below 20° C. and at a temperature at which the cell enzymes may well be inactive because of cold; they may therefore not be able to utilize the oxygen presented to them and remain anoxic. The concept that low flows are permissible during varying degrees of hypothermia may not be valid.

It was our experience during the early cases of this series that in spite of the rigid use of an accepted preset flow we were encountering metabolic acidosis during and after the operation. We felt therefore that if we were to take patients down to 10° C. or less then we should ensure adequate capillary perfusion throughout the cooling phase. In this respect we are trying to emulate nature, because one of the most important observations in the hibernating animal is

that, in spite of an environmental temperature of about 5° C. and a reduction in blood circulation, blood flow in the capillaries seems to be preserved, as evidenced by a bright pink paw. Furthermore, one of the prime functions of the cardiovascular system in the intact healthy animal is to ensure total and equal capillary perfusions.

In an attempt to fulfil this criterion of adequate perfusion during the course of cooling to 8° or 10° C. we (1) cool slowly, starting with the blood in the pump warmed to 37°; this means that a sudden large infusion of very cold blood is avoided; (2) use the highest flow rates possible with the cannulation throughout the perfusion; (3) give a vasodilating drug, Arfonad (25–50 mg.), if vasoconstriction appears imminent or has occurred. Administration of the drug has been followed by a drop in perfusion pressure and a return to the original or more often a further increase in flow rate. Moreover, this increased flow rate would occur with a loss of 200 to 300 ml. of blood from the machine. The patient remains remarkably pink even at 10° C. If the drug is to be used it must be given before 29° C.; after this temperature it ceases to act effectively.

While it is agreed that the ultimate criterion of a successful perfusion is a living patient, and we agree that this may result from high and low flow perfusions, we feel that survival with physiological integrity has much to commend it.

MONITORING

The central venous pressure, arterial pressure, E.C.G., and E.E.G. are monitored on an eight-channel oscilloscope screen in a control room outside the theatre but visible to the surgeon and anaesthetist. Temperatures are recorded in the nasopharynx, oesophagus, mediastinum, and arterial line. Arterial and venous oxygen saturations are estimated at regular intervals. The venous oxygen saturation approaches arterial oxygen saturation between 15° and 20° C. The first venous sample taken on restarting perfusion after 50 to 60 minutes' circulatory arrest shows an oxygen saturation between 60 and 70%. The *p*H is measured throughout the operation at suitable intervals. These data, together with other details of events during the operation, are recorded on a large chart.

RESULTS

Thirty-two cases have been operated upon using the above technique. The cases are divided for the sake of convenience into seven groups according to the diagnosis as follows:

GROUP A: VENTRICULAR SEPTAL DEFECT.—The ages of the nine patients varied from 14 months to 12 years, seven being under 5 years of age. One of the nine patients was operated upon twice because of reopening of the defect. Circulatory arrest varied from a maximum of 58 minutes to a minimum of 22 minutes, five being over 40 minutes. All these patients are alive.

GROUP B: AURICULAR SEPTAL DEFECT.—The ages of these four patients varied from 5 to 20 years. Circulatory arrest was from 63 minutes maximum to 25 minutes minimum. There was one death in this group due to faulty surgical technique.

GROUP C: TETRALOGY OF FALLOT.—The ages of eight patients varied from 10 months to 23 years. Circulatory arrest varied from a maximum of 70 minutes to a minimum of 47 minutes. In four cases the period of arrest was more than one hour. There were two deaths in this group.

GROUP D: INFUNDIBULAR PULMONARY STENOSIS.—The patient was aged 13 years and the circulatory arrest 27 minutes. The patient is alive.

GROUP E: OSTIUM PRIMUM.—Both cases were associated with severe irreversible pulmonary hypertension in children aged 2 years and 7 months. Both died. Circulatory arrest was 60 minutes and 47 minutes.

GROUP F: COMPLEX COMBINED DEFECTS.—The ages of the four patients varied from 15 months to 21 years. Circulatory arrest varied from 70 minutes to 40 minutes. Of the four patients only one is alive.

GROUP G: TRANSPOSITION OF THE GREAT VESSELS.—All these four patients had intact ventricular septi and patent foramina ovalia, and their ages varied from 10 days to 4 months. Circulatory arrest varied from 23 minutes to 70 minutes. All died; one survived 18 hours and one one hour. The repair was that of atrial transposition described by Senning (1959).

Neither the perfusion technique nor the profound hypothermia was responsible for the deaths mentioned above. Complications have not been serious, and this aspect, together with the necropsy findings in the brains of patients dying under profound hypothermia, are the subjects of another report.

SUMMARY

A detailed account of the technique for the combination of profound hypothermia and extracorporeal circulation with complete circulatory arrest is given.

It is stressed that (*a*) cooling should be gradual and done with the highest possible flow rates to ensure total adequate capillary perfusion ; (*b*) a vasodilating drug in cases associated with vaso-constriction will help achieve (*a*).

The results of the cases operated on to date are given.

REFERENCES

Hodgson, D. C., and Parkhouse, J. (1961). *Brit. J. Anaesth.*, 33, 303.
Senning, A. (1959). *Surgery*, 45, 966.