THE PRACTICE OF TOTAL CARDIO-PULMONARY BY-PASS

A Short Review

By L. D. ABRAMS, M.B., F.R.C.S.

Department of Surgery, University of Birmingham

Total cardio-pulmonary by-pass allows deliberate open-cardiac surgery. Its use for the repair of congenital defects is well established. Progress is being made in the treatment of acquired heart disease, notably mitral regurgitation.

The first successful operation in man, suture of an atrial septal defect, was carried out in 1953 by Gibbon,¹ using his machine which has since been used in a modified form for many cases by Kirklin at the Mayo Clinic.² In the same year Andreason and Watson³ showed that dogs would survive if both venae cavae were clamped for 30 min., leaving the azygos vein as the only return to the heart. This reduces the cardiac output by nearly 90 per cent. and they took advantage of this to carry out 'cross circulation' experiments in which a second dog acted as the 'heart lung machine' with little strain on its heart. Lillehei and his associates⁴ at Minneapolis repeated this work and in 1954 successfully repaired ventricular septal defects in children, using cross circulation with a donor.⁵ Unfortunately this did not prove free from risk for the donor and the technique was abandoned.

Since 1955 various machines have been used successfully for large series of cases; they all share certain basic characteristics.

The venous flow to the heart is diverted through large cannulae introduced into the venae cavae through the right atrium. These cannulae are connected to a hose which drains either into an open 'well,' about 12 in. below the patient, or into a chamber to which constant gentle suction is applied; in either case it may be pumped to the oxygenator. If the oxygenator can be placed lower than the patient then blood can drain directly into it and the venous pump is not needed. Oxygenation and removal of carbon dioxide is carried out in the oxygenator and the blood is passed to the patient's aorta through a cannula in a femoral or subclavian artery by the 'arterial' pump. A filter is interposed in the arterial line. The volume of blood in the machine must be

controllable and provision is made for maintaining the blood temperature. All parts in contact with blood must be easy to sterilize.

The various machines differ in pump and oxygenator design and these may be considered separately.

Pumps

The pump must have an adequate output to perfuse any size of patient without damaging the blood—this is best measured by circulating a small volume of blood through the pump and measuring the increase in plasma haemoglobin with time. There is no evidence that the pump need reproduce the pulsatile flow from the heart (there is little pulsation in the lower part of the body in coarctation of the aorta). The two most widely used pumps are the de Bakey⁶ roller pump and the sigmamotor.⁵ In the former, a length of elastic tube is squeezed against the inside of a semicircular back plate by a spring-loaded roller on the end of a moving radius arm passing the blood along. As the roller comes off the tube at the end of the semicircle a second roller on the diametrically opposed radius squeezes the tube at the beginning; a practically continuous directional flow is produced without valves. The sigmamotor—first used by Lillehei—achieves much the same effect by means of a series of steel fingers which compress the tube one after the other against a spring-loaded back plate, the first finger squeezing again as the last lifts. The flow has low-amplitude pulsation.

In pulsatile flow pumps, the blood is drawn into a container through a one-way valve and ejected through another. The valves may be mechanically operated, as in Melrose's⁷ pump in which a length of elastic tube is compressed between two plates, the valve action being provided by metal bars which occlude the tube at each end in turn. This pump, with its large stroke volume and slow action, is remarkably gentle in its action.

The valves can also be operated by the blood

stream itself as in the Dale and Schuster⁸ pump, and its modification described by Dennis.⁹

Perfectly continuous flow can be provided by the 'Mono' pump,¹⁰ which is a very refined archimedean screw, very gentle in its action.

Comparisons of various pumps have been made by Hall *et al.*¹⁰ and Hodges *et al.*¹¹

Oxygenators

The patient's lungs would be the best oxygenator, but the technical difficulties of collecting the pulmonary venous return have not been overcome (Bailey¹² has recently reported the use of the patient's lungs in 13 cases of aortic stenosis, the longest by-pass with survival being 140 min., but he has an oxygenator connected in parallel). The closest imitation is provided by a membrane oxygenator, in which the blood is separated from the oxygen by exceedingly thin plastic sheeting through which the gases diffuse. Clowes¹³ has used such an oxygenator successfully in clinical practice but it is cumbersome and requires much further development.

Other oxygenators function either by bubbling oxygen directly into the blood or exposing blood films to an atmosphere of oxygen.

The Lillehei de-Wall Helix Reservoir Bubble Oxygenator¹⁴ has been used at Minneapolis for the largest single series of cardiac by-pass operations (over 400); sigmamotor pumps are used. The blood is pumped from a venous well up a vertical 1½-in. diameter tube. A perforated plate surrounds the entry tube and through this oxygen is bubbled, so that the vertical tube is filled with a column of bubbles, in the wall of which gas exchange takes place. At the top of this tube the bubbles spill into a 2½-in. diameter tube placed at an angle of 30° below horizontal, the inside being very thinly coated with a silicone anti-foam which makes all the bubbles break. From this debubbler the blood runs into a long coiled tube (1 in. diameter) immersed in a water bath. This tube acts as a long incline up which any tiny remaining bubbles rise. Bubble-free oxygenated blood is taken from the bottom of this helix and passed to the patient by the arterial pump. At first this apparatus was used for low flows¹⁵ (35 cc./kg./min.) but gradually increasing flows have been used up to outputs of more than 3 l. per min. The metabolic effects of varying flow rates have been described by Varco¹⁶ and others.¹⁷ This oxygenator has the advantage of being made up of disposable polyvinyl-chloride tubing and stainless-steel connectors which are easily cleaned. The whole apparatus is sterilized by autoclaving. It is mechanically simple and cheap, but requires a rather large charge volume for high flows. At Guy's Hospital¹⁸ this oxygenator is used with a

'Mono' pump on the arterial side. By placing the oxygenator and helix on the floor, gravity flow from the venous well takes the place of the venous pump.

Of the film oxygenators the best known is the Stationary Vertical Screen Oxygenator, described by Gibbon and modified at the Mayo Clinic,² where it has been used in a very large number of cases by Kirklin. De Bakey pumps are used. The venous pump passes blood from a suction chamber to a reservoir with a number of long slits in its floor. In each slit is the top edge of a stainless-steel mesh screen down which the blood flows, forming a continuous film. The screens are enclosed in a lucite case through which 9.5 l. of oxygen and 0.3 l. of CO₂ are passed each minute. Blood is taken from the bottom of the container by the arterial pump.

Kirklin¹⁹ uses this machine to provide perfusions approximating to the basal cardiac output under light anaesthesia (2.2-2.5 l./sq.m./min.). It is provided with rather elaborate devices to keep the blood volume constant. Its chief disadvantages are the difficulties of cleaning and the need to use chemical sterilization—10 per cent. formaldehyde—and to wash this out before use.

Film oxygenation is also achieved by rotating disc oxygenators—first developed by Bjork²⁰ and then by Melrose⁷ in this country and by Kay and Cross²¹ in the United States.

In these machines the venous blood drains into a long cylinder, forming a shallow pool in the bottom. A series of thin, closely spaced, circular discs dip into this pool. In the Kay-Cross machine these are made of stainless steel on a rotating shaft, so that each disc picks up a film of blood as it rotates. In the Melrose machine perspex discs are fixed in relation to a perspex drum, which is itself rotated, producing the same effect. The arterial pump takes blood from the drum—only one pump is needed.

The Melrose machine has the distinction of having been subjected by Gerbode²² to direct comparison with a Vertical Screen Oxygenator of Gibbon pattern designed by Osborne,²³ using disposable plastic screens.

It was found that the Melrose oxygenator was as safe as the Gibbon type and had greater oxygenating capacity (more than 4 l./min.). The perspex parts are now being replaced by stainless steel so that the whole apparatus can be autoclaved. It also has the advantage of a relatively small charge volume. There can be little doubt that the Melrose machine in its latest form is extremely satisfactory.

Application

Whatever machine is used the basis technique

of setting up total cardio-pulmonary by-pass is the same.

Sufficient donor blood to charge the machine and provide an adequate reserve is collected not more than 24 hours before the operation. Heparin has to be used as the anti-coagulant, because the patient must be given the same anti-coagulant to prevent any clot formation during the period of cannulation.

Immediately before the operation the machine is set up and charged. The pumps are adjusted to provide an appropriate flow for the size of the patient.

Because the normal vital signs are absent during perfusion, monitoring apparatus is set up. It is customary to record the aortic pressure, vena caval pressure, electrocardiograph, and the electroencephalograph. The pressure recordings demonstrate that the arterial pressure is adequate and the venous pressure normal. The electroencephalogram demonstrates that the brain is being adequately perfused—there being a regular pattern of deterioration with increasing anoxia, as described by Hudson.²⁴

For the repair of congenital defects the chest is opened either with a bilateral anterior trans-sternal incision or a mid-line sternal split—the latter being preferable because of the great reduction of post-operative discomfort and improvement in breathing (Gerbode *et al.*²⁵). Both the aortic and mitral valves can be exposed using a long right thoracotomy, the former through the ascending aorta and the latter through an incision in the enlarged left atrium behind the venae cavae.

The heart is exposed, tourniquets placed round the cavae, the patient is heparinized and the cannulations carried out. Harshbarger *et al.*²⁶ have described in detail the techniques used at the Mayo Clinic. Although they always used the subclavian artery, many surgeons prefer the femoral artery. The arterial and venous hoses to the machine are connected, the machine started and the caval tourniquets closed on to the cannulae. Total cardiac by-pass is then established and the operation on the heart can be carried out. For many operations elective cardiac arrest is used. In 1955 Melrose²⁷ described the use of potassium citrate which Effler²⁸ used clinically in 1956. When by-pass is established the ascending aorta is cross clamped and 2.5 per cent. potassium citrate in oxygenated blood is injected into the base of the aorta, quickly stopping the heart in diastole. When the aortic clamp is removed the coronary circulation from the pump washes out the drug and the heart starts beating. This method is used by the great majority of surgeons. The same procedure, using acetyl choline, 10 mg./kg. body weight, in 20 cc. of physiological saline, was described by

Lam²⁹ in 1956 and he has used it for more than 100 operations.

In both methods the cardiectomy incision is not closed until vigorous heart action has resumed, otherwise the coronary return distends and weakens the heart, preventing contraction.

During the cardiectomy, any blood entering the heart—the coronary return or, if the heart is arrested, from bronchial anastomoses to the pulmonary circulation—is aspirated by gentle suction and returned to the oxygenator. When the operation on the heart is complete and the cardiectomy closed the caval tourniquets are opened and the machine stopped. The cannulae are removed and the heparin neutralized by intravenous protamine sulphate, the clotting time being checked against its pre-perfusion value.

Throughout the whole operation great attention is paid to the patient's blood volume. The patient is weighed at the beginning. All blood is measured by swab weighing and replaced. The amounts of other fluids used are kept to a minimum and also carefully charted (Patrick *et al.*²⁹). If, during the perfusion, the mean arterial pressure and venous pressure are kept at their pre-perfusion level and the volume of blood in the machine kept constant the patient's blood volume remains constant. After the operation the patient is again weighed.

Effects of Perfusion

Apart from the obvious risk of air or particulate emboli and of septicaemia, the effects of perfusion may be divided into metabolic upsets and specific effects on the blood.

The metabolic effects are probably produced by the use of inadequate flow rate, and appear to be similar to the effects of low cardiac output. This results in inadequate perfusion of some parts of the body with resultant metabolic acidosis, which may be masked in part by respiratory alkalosis caused by excessive washout of carbon dioxide in the machine.

The most constant effect on the blood is some degree of haemolysis caused by trauma in the machine. The platelet count is usually diminished but rapidly recovers. Fibrinogen may be removed and circulating fibrinolysins have been found after perfusion.³¹ There is also a tendency for some anaemia to develop after perfusion, probably because of the combined effects of trauma and 'replacement transfusion.'

Uses of Total Cardiac By-pass

These are best exemplified by the series reported by Lillehei^{32, 33} and Kirklin.¹⁹ Repair of ventricular septal defect is by far the commonest operation. The results in patients whose pulmonary arterioles are not seriously damaged

by hypertension are very good. Lillehei,^{31, 32} Kirklin¹⁹ and Cooley³⁴ have reported long series in the United States and in this country, Cleland³⁵ lost only one of 15 ventricular septal defects which were not associated with other congenital anomalies.

Experience in the correction of Fallot's Tetralogy is by no means so happy—in most hands the mortality has been high, but Lillehei,^{32, 33} and Kirklin³⁶ appear to have achieved reasonable success.

Repair of common atrio-ventricular canal has been carried out fairly frequently but with considerable mortality.

In these three conditions repair of the ventricular septal defect may damage the bundle of His, causing heart block, which may recover but is more usually permanent. Its treatment by artificial cardiac pacemaker and isuprel has been described by Lillehei.³²

More attention is now being focussed on acquired heart disease, the most promising results being obtained in mitral regurgitation.^{37, 38} Aortic stenosis and regurgitation³⁹ have also been corrected successfully.

Conclusion

There is no doubt that total cardio-pulmonary by-pass can now be safely achieved. Lillehei has done 40 consecutive operations with one death, and Kirklin 39 consecutive operations with three deaths, two being due to anatomically inoperable conditions and the other occurring 23 days after operation, due to heart block. The scope of cardiac surgery is greatly increased by its use and is growing. At present the techniques are elaborate and require skilled team-work for success. The setting up of such a team requires considerable laboratory work (Myerley *et al.*⁴⁰; Drew *et al.*⁴¹; Abrams *et al.*⁴²). However, we can now look forward to a period of rapid development and eventual simplification of the host of problems which this work involves.

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