TYPES OF HEART-LUNG MACHINES USED IN EXTRA-CORPOREAL CIRCULATION

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It is to extra-corporeal circulation that cardiac surgery owes its present momentum. Without this system of circulating blood outside the body through a variety of pumps and oxygenating devices, it is fair to say that no adequate access to the interior of the heart could have been obtained. Correction of congenital defects within the heart demands that the interior of its cavities be available without the obscuring presence of blood and, further, that the heart be temporarily rested from its burden of carrying on circulation during this time. Hypothermia alone has not offered more than a small increase in access to the interior of the heart and it is the development of the heart-lung machine that has most advanced intracardiac surgery. It is perhaps difficult to decide the beginning of this development, but it is generally accepted that the pioneer work of J. H. Gibbon Jr. in Philadelphia in 1937 (Gibbon, 1937) should be so regarded though S. S. Brukhonenko in Moscow has also claims to be considered the father of the heart-lung machine (Brukhonenko, 1929).

But it was not until 1953 that Gibbon reported the repair, under direct vision, of an inter-atrial septal defect. The patient, an adult woman, recovered completely. The normal circulation was excluded from the heart for 25 min., the heart's function and that of the lungs being imitated successfully by a heart-lung machine. This report confirmed the application to man of many years of speculation and experimentation, and ushered in a new era of surgery (Gibbon 1953). At the outset two streams of development were explored. On one side there were those who set out to imitate as closely as possible the normal function of the heart and the respiring ability of the lung. Another group of workers decided that it would be more profitable first to establish the minimum requirements of the body for circulation and respiration, and then to imitate these. In Minneapolis, C. W. Lillehei and his colleagues (Lillehei, Cohen, Warden, Read, De Wall, Aust and Varco, 1955), making use of a human donor

to supply oxygenated blood, perfused small children through a system of pumps and treated isolated ventricular septal defects. His success in more than 30 patients stirred the many groups who had tentatively begun clinical exploitation of heart-lung machines into renewed action and soon at the Mayo Clinic, Kirklin and his colleagues (Kirklin, Dushane, Patrick, Donald, Hetzel, Harshbarger and Wood, 1955) were operating within the heart as a routine, this time with their version of Gibbon's machine designed to imitate not part of the natural requirements but the whole. In Minneapolis the donor circulation gave way to a form of oxygenator whereby oxygen as gas was bubbled directly through blood and the low flow principle gradually was supplemented to provide a more normal environment for the body. Now the many groups carrying out clinical perfusions agree that if the circulation is to be imitated it should be done in as full a manner as possible. The only deviation from this which is accepted is perfusion carried out at reduced body temperature; then, inevitably, a different set of circumstances applies. The cardiac output necessary at any given temperature is provided and, with effective heat exchange systems, it is possible to set the temperature at an adequate level for carrying out the particular operation required.

The Pumping Circuit

Pumping system

Were there any conclusive evidence as to the role of the pulse in the circulation of the blood, our choice of a mechanical substitute for the heart would have to be made wholly on these grounds. However, no such evidence is available and though we must assume that the human body is adapted to a pulsatile flow, it is clear that wide variations in pulse pressure and contour are acceptable. The cardiovascular malformations of coarctation of the aorta and aortic valvular incompetence indicate that the extremes of minimum and maximum pulse amplitudes are

equally well tolerated. Thus without exacting physiological criteria to satisfy, the factors underlying the choice of pump are essentially practical.

The ideal pump

The ideal pump has certain well-defined features apart from the prerequisite of complete reliability. It should not damage blood while pumping it, nor should bacterial or chemical contamination be possible. Several factors influence the degree of trauma a pump will inflict on blood. Among these is the pressure difference between the input and the output sides of the pump. If a pump aspirates at a considerable vacuum and then suddenly ejects the blood at high pressure, and particularly, if this cycle is frequently repeated each minute, then such a pump will inevitably be very traumatic. Ideally, the pressure gradient in the pump must be minimal, that is, it should fill at a positive pressure without suction and then impose a steady rise in pressure to reach only that level which will overcome the resistance imposed by the tubing, the cannula and peripheral vessels. Minimizing changes in the bore of tubing reduces the possibility of additional pressure gradients. Absence of valves inside the blood stream contributes to the reduction in pressure changes by avoiding possible turbulence in these areas.

A smooth inert internal surface to all parts through which blood flows is essential and it is usual to make such surfaces 'non-wetting'. Though the vascular epithelium does not exhibit this characteristic, there are no means of reproducing the natural surface which actively inhibits coagulation, and a 'non-wetting' surface is the best alternative.

Blood transfusion equipment is tending to be made of expendable plastic material and this should become a prerequisite of pump design. The great difficulties arising in cleaning blood and protein residues from metal or plastic surfaces even when they are smooth and simple in shape, should indicate that no pump chamber should be re-used.

The design of a pump must include a method for controlling the flow from it; this must be continuously variable from zero to about 5 litres/minute. Either the stroke volume, stroke rate, or both, may be utilized, and as both are used in the body, we may again accept a wide variation.

An accurate measure of the pump output from minute to minute is as important, perhaps, as the ability to control its rate of flow. Either a flow-meter must be incorporated in the circuit, or the effects of varying diastolic filling or systolic ejection pressures must be known and allowed for in calibration. For this particular reason the

ideal pump should be able to eject the same volume of blood against varying resistances. Some pumps are deliberately arranged to allow a certain degree of reversed flow in an effort to reduce trauma; this is neither desirable nor necessary.

Pulsatile flow pumps

Unlike the continuous flow pump, those of pulsatile type require some sort of valve to give direction to flow and produce a discontinuous output. The pulse can be of almost infinite variety and may even be of such low amplitude as to appear nonexistent. For convenience, these pumps can be regarded as falling into two categories, those of high amplitude pulsation and those of low amplitude pulsation.

In the first category are those pumps in which blood is drawn into a container through a one-way valve and then during the pumping stroke it is ejected through another one-way valve. The design of Dale and Schuster (1928) is perhaps the best known and serves as a pattern. Recent modifications employed on several machines allow a simple straight elastic tube to be used as a pump chamber, pumping being carried out by external compression of the tube (Melrose, 1955). Direction to the flow is given by occluding the tube at either end for appropriate periods. This phased occlusion takes the place of external valves and eliminates them as a source of turbulence. Adjustment of both stroke volume and rate are possible. Such a pump can be remarkably atraumatic and is capable of accurate imitation of the natural pulse. A disadvantage is that it must be mechanically rather elaborate to function well though the pump chamber itself is simple and disposable.

An alternative to this type of pump is known as the roller pump. Jouvelet (1934) and DeBaakey (1934) have given their names to two versions in which rollers are used to occlude an elastic tube in such a manner that, when these rollers are moved along the tube, their action is to squeeze out blood contained in the tube. No valves are used, progression of the rollers along the tube acting both to provide the pumping stroke and to give direction to the flow. When one roller finishes its stroke, another has already begun and hence reversed flow is prevented. The changeover from one roller to another is accompanied by a momentary fall in forward flow and pressure, and hence the output is pulsatile. The pressure curve shows a sustained mean pressure interrupted at the changeover point by a dip.

A good deal of debate has centred around the degree of occlusion required to make these pumps effective. While forward flow can be produced

without complete closure of the tube by a roller, it is unwise to attempt to use pumps when adjusted in this manner. Any rise in resistance will increase the reversed flow past the roller and at a certain resistance all forward flow will cease. At this point the pump will still be apparently functioning perfectly. To be effective, complete occlusion of the tube is required, which should be brought about by the use of compression springs adjusted to maintain occlusion of the tube to the desired pressure gradient. Further, the manner in which the roller occludes the tube is important. A single parallel arrangement between roller and backplate is inefficient. More satisfactory is a backplate grooved to accept the tube along which runs a roller the shape of which is such that it invaginates one wall of the tube into the other. If the radii of roller and groove are arranged to match one another, an efficient occlusion is produced with a minimum of trauma (Fig. 1).

No adjustment of the stroke volume is possible with the roller pump — an alteration of the pulse rate is the only way of altering the output. However, this may easily be done by means of a variable speed gearbox and, as the output is only minimally pulsatile, no attempt need be made at reproducing the normal pulse rate. There are many advantages to these pumps, which perhaps most nearly fill the criteria of an ideal pump. The blood comes only in contact with a disposable tube; no valves intrude in the lumen; the pulse-wave is subdued and causes minimal difficulties in passage through a restriction such as the arterial cannula; mechanically, it is relatively simple and can be very robust.

A variation of the roller pumps—perhaps occupying a position between them and the more intermittent types—is known as the Sigmamotor pump (Lillehei, De Wall, Read, Warden and Varco, 1956). Here progressive occlusion along a tube is carried out by a series of compressing fingers whose action resembles a sine wave. This pump has commanded a very large use and has undoubtedly been important in the development of the heart-lung machine. However, it is unnecessarily traumatic in its present form due largely to the very small stroke volume used, and to the shock wave induced by the rapid oscillations of the compressing fingers. It is best used at flow rates below 2 litres/minute, when this characteristic is not so pronounced.

It is fair to state that the problems of pumping blood during the relatively short period required by present surgical techniques have been satisfactorily solved by the examples already quoted. The search for better solutions will continue, for as surgical experience increases, so the demand for lengthy perfusions will impose new burdens.

FIG. 1.—Complete occlusion of the tube is achieved by shaping the roller and backplate so that they match one another, one wall of the tube being invaginated into the other.

Oxygenators

It is perhaps trite to underline the intimate relationship between the heart and lungs, but it is particularly a reality in open heart surgery. Many attempts to substitute for the heart alone have been tried and abandoned and it is usual to attempt to imitate the function of both as a corporate unit.

The use of the natural lung as an oxygenator has a long history in physiological experimentation, but has not found favour in clinical perfusions.

The homologous or heterologous animal lung is a very effective mechanism for the oxygenation of blood and has been used clinically both where cross-circulation between human donor and patient is employed (Lillehei and others, 1955), and where an isolated animal lung is provided for gas exchange (Mustard and Chute, 1951). In the first technique serious ethical and practical problems are raised by the use of a human donor and this solution has been abandoned. The second alternative has also failed to find favour on account of practical difficulties. A proper sterile technique is not easily preserved in the preparation and setting up on such an oxygenator, and there is always the danger of pulmonary oedema and cessation of function.

Semipermeable membranes

Of the artificial systems the most attractive is that by which an imitation of the natural pulmonary anatomy, a membrane, separates blood from gas. Such a membrane must have very special properties (Melrose, Bramson, Osborn and Gerbode, 1958), allowing diffusion of oxygen and carbon dioxide through it at a rate of about 20 ml. per sq. m. per minute without itself being so porous that blood leaks through. It must have sufficient mechanical strength to withstand pressure, be capable of sterilization by heat, and be inert in respect of blood—at first sight an almost impossible ideal. However, chemical engineers have found that silicone elastomers can be produced which virtually meet the specification. At this time the problem has advanced from the search for a perfect membrane to the problem of its best utilization. The mechanical device employing such a membrane will only be really practical when it has been mass-produced in a disposable form, but there is little doubt that this will eventually be accomplished.

The provision of a wholly suitable semipermeable membrane does not in itself answer the many problems of design encountered in an oxygenator of this type. The membrane must necessarily be supported in a manner which provides sufficient rigidity and protection, and which allows the maximum of surface area to be utilized. Unsupported membrane layers do not provide for an even distribution of blood on their surfaces, and the formation of rivulets and streams result in only partial use of the available surface. The most practical solution is to sandwich a pair of membranes between two plates whose surface is corrugated. If the grooves in one plate are set at an angle to those in the other, then a quilted effect is produced on the membranes between them and excellent distribution of blood results. By trial and error a matching of characteristics can be achieved whereby such a quilt will allow free blood flow at minimal pressure gradient without trapping a large quantity of blood between the films.

Having thus achieved an effective spreading of thin films of blood between adjacent membranes, another factor comes into play. There is on the surface of the membrane a layer of fluid known as the boundary layer: if this is not disturbed and broken up it acts as a barrier to the full efficiency of gas diffusion. The natural solution is the rhythmic pulsing of respiration in the lung which must in part disturb this layer. An imitation of this effect could be achieved in the membrane-oxygenator.

If a pulsing effect be given to the lung then it is logical to attempt to use the lung itself as a

circulating pump. If two sections of a membrane-oxygenator were set up so that they could be expanded and contracted alternately, and if the inlet and outlet to each section were equipped with valves, then a combined oxygenator and pump would be created. With the addition of accurate heat control a heart-lung machine very close to the ideal would be available. Even now much of this specification can be met and it would not be unreasonable to predict that such a machine will be available in the future.

Direct exposure of blood to gas

In the absence of an effective membrane-oxygenator it is necessary to expose blood directly to oxygen. The two methods most commonly in use involve either filming of blood on bubbles of oxygen or on some inert surface.

Bubble oxygenator

A large variety of designs to accomplish the former type of oxygenation have been described one of which, the oxygenator ascribed to De Wall Warden, Read, Gott, Ziegler, Varco and Lillehei (1956), is used extensively in clinical practice. In it large bubbles are formed as oxygen is dispersed in blood and these pass up a vertical tube of polyvinyl chloride. At the top of this tube is a debubbling chamber containing a silicone anti-foam compound, from which the defoamed blood is allowed to descend in a spiral of wide-bore tubing. This helix acts as a settling chamber and also a reservoir from which the oxygenated blood can be pumped. The tubing is disposable and the unit is newly constructed for each perfusion.

The bubble-oxygenator has made it possible to perform several hundred intra-cardiac operations, though it has not solved the many problems of cardiac surgery, and it cannot be denied that the system has certain limitations. It is best used in circumstances in which perfusion rates are low and operation times are short. Improvements may fully overcome the present disadvantages and give to this relatively simple device a great range of use, though it seems a better principle still to exclude gas bubbles by not creating them.

Filming of blood

The alternative method of oxygenation involves the direct exposure of blood to gas, but does not require the bubbling of gas through blood. This principle whereby blood is spread in very thin films and exposed directly has been known for a long time. To enumerate the many methods described to ensure the provision of large surface areas would require a lengthy historical review. Three examples will make clear the principles. Von Frey and Gruber (1885) in their artificial

lung allowed blood to spread in a thin film over the inner surface of a cylinder exposed to oxygen. The surface area was approximately half a square metre. Variants of this were tried in succeeding years but proved ineffective.

Rotating disc principle.—Bjork (1948) in Stockholm described a machine using rotating discs to expose films of blood to oxygen. In this machine 40 or 50 discs dip into a trough of blood. When rotated they pick up on their surfaces thin films of blood and in this way create a large gas—liquid interface, the surface area being exposed and continually renewed as the discs rotate. The device was a great deal more efficient than any previously described and did much to renew interest in this type of oxygenator.

A practical model on this principle was perfected at the Postgraduate Medical School in 1952 (Melrose, 1952) and was first used clinically in 1954 (Aird, Melrose, Cleland and Lynn, 1954) (Fig. 2.) Today the most widely used oxygenator is that employing rotating discs and that of Kay and Cross the most popular model. They have improved the performance of their device by using convoluted discs in place of the smooth ones previously specified (Kay, Galadaj, Lux and Cross 1958). However, it is a disc oxygenator of quite new form that is the second of the new types. Osborn, Bramson and Gerbode (1960) have described their modification which has considerable advantages over the conventional type. With greatly increased efficiency of oxygenation they have combined a useful heat exchanger to make a very elegant improvement.

Vertical screen principle.—Miller, Gibbon and Gibbon (1951) described an oxygenator in which the blood was streamed over a number of wire gauze screens. These screens are stationary, and as the blood descends over them the turbulence of their passage exposes a great number of cells to oxygen. In order to make more efficient such a system, which has no moving parts, the blood is recirculated within its own 'pulmonary circuit'.

There are two disadvantages to the application of the vertical screen principle. One is the difficulty involved in creating a uniform film of blood over the screens, for there is a tendency for rivulets to form, which immediately limit the area of blood exposed. The screens themselves cannot be allowed to dry while filming is in progress and hence the film once established cannot be broken without danger of failure to reconstitute it. Thus the oxygenator once charged must be kept running throughout what may be a long waiting period. The second difficulty occurs because the faster the flow over the screens the greater the quantity of blood which is held on them. Therefore the blood volume of the artificial lung tends to increase

FIG. 2.—Pump oxygenator using the rotating disc principle perfected at the Postgraduate Medical School and first applied clinically in 1954.

with the flow rate; in order to control it a flow rate through the pulmonary circuit in excess of any expected during perfusion must be established and maintained. These practical disadvantages should be eradicated in the future and new materials may help to eliminate them.

Conclusions

These are but representative examples of the many continuing attempts to provide a perfect artificial lung and they are in routine clinical use. Each provides a satisfactory solution to most of the problems encountered and allows surgeons to advance to the much more complex problems involved in the treatment of cardiac abnormalities.

Mechanics of Perfusion

Though different in detail, all machines are similar in respect of the connexion they must make to the vascular system of the patient. It is essential to drain into them all the venous blood taken from a point just prior to its entry into the

heart and pump it back into the arterial tree at a rate similar to the cardiac output.

It is usual to extract the venous blood directly from the venae cavae by means of plastic tubes inserted into them through the right atrial appendage. The wall of the atrium is muscular and safely accepts such intubation. To prevent any leak around these plastic tubes, it is necessary to fix them within the veins by loops of tape or, preferably, of soft rubber material. These loops are only secured when the extra-corporeal circulation has begun and is effectively carrying out the work of the heart and lungs.

The return of oxygenated blood into the arterial tree is less easily solved. The subclavian and common femoral arteries have each been popular routes for this return, the flow in the latter case being retrograde up the aorta. However, neither is entirely satisfactory.

The subclavian artery is difficult of access and the cannulation demands a precise surgical technique; further, the median sternotomy incision cannot be used in such circumstances. Another possible contra-indication is that the returning blood enters very close to the cerebral circulation and any foreign material, clots, or entrained gas bubbles must have a maximum effect. A longer course up the aorta is perhaps a useful screen in the absence of the filtering effect of the natural lung.

The common femoral artery, while as remote as possible from vital centres and normally quite adequate in size, does not in every patient admit the optimum flow. Its size in infants, particularly those that have a relatively underdeveloped aorta, may be so small as to rule out this route; very rarely at other ages a similar condition may apply. In such cases an alternative may be the external iliac artery which can be reached without entering the peritoneal cavity; in very exceptional circumstances a direct entry into the thoracic aorta may be necessary by way of an end-to-side graft. This latter method provides a particularly natural route at the cost of considerable additional surgery. In practice a common femoral artery will usually be adequate and is certainly the route of choice.

The Dynamics of Perfusion

It is perhaps axiomatic that an adequate perfusion must provide all the body's needs. Oxygenated blood of normal chemical and cellular content must pervade every tissue at an accustomed rate of flow and head of pressure.

At normal body temperature adequate perfusion requires that at least 2.4 litres/minute of blood for each square metre of surface area be circulated. Surface area is usually derived from the Dubois

nomogram and is perhaps open to criticism in this regard, but nevertheless no better standard exists. Further, it can be argued that as no detailed study of regional flows has been conducted during clinical perfusions, no real evidence is available to support the figure of 2.4 litres/minute/square metre. Experience over a large number of perfusions is our best guide; it supports the adequacy of this flow rate.

There are special circumstances which modify the rule. Should the body temperature be reduced, then a reduction in flow rate could be effective because of the reduction in metabolic demands. Such controlled hypothermia is a feature of the system used by Sealey and Brown (1958) who operate with reduced perfusion rates after lowering the body temperature by means of a heat exchanger.

Where a large shunt exists between the arterial and pulmonary systems—and this shunt cannot be excluded at operation—then again the modification of the rule applies. The greatly increased collateral vasculature of the lung fields in severe cases of tetralogy of Fallot may allow a considerable proportion of the arterial perfusion to go to waste, because it spills into the open heart from the pulmonary veins without ever reaching the body tissues.

In such circumstances, what appears to be an effective perfusion rate may in fact be wholly inadequate, and an increase in arterial flow rate equivalent to the shunt is required. This may demand more of the heart-lung machine than can be safely supplied and a combination of hypothermia and extracorporeal circulation is particularly appropriate here.

A modification of the technique of Sealy and his colleagues which does not involve an oxygenator, is that of Drew, Keen and Benazon, (1959) and Drew and Anderson (1959) who have made use of the natural lung *in situ*. Two pumps carry the circulation from the right and left heart through a heat exchanger until the body temperature is reduced to below 15°C., at which time the circulations are discontinued. Surgery proceeds in cadaveric conditions with little need for intracardiac suction or even the presence of the cannulating tubes which occupy the right and left atria, the pulmonary artery, and femoral artery. When complete, the extracorporeal circulations are resumed and the cooling process reversed. In practice, good results are obtained by this method in spite of cessation of all circulation for protracted periods, sometimes for as long as an hour. Inherently simple in equipment and sparing of blood, it is a most interesting field and one which may alter our present concepts.

Maintenance of the blood volume

Maintenance of an adequate perfusion rate demands that the venous return into the great veins continues at a rate identical to that of the arterial inflow. This is essential, for no amount of suction force on these veins will create a venous return to the heart-lung machine in excess of the available blood flow from the peripheral tissues. Excessive suction would lead to collapse of the veins.

The guiding principle should be to maintain the pressure in the veins as nearly normal as is possible, for by doing so the blood volume of the patient will be maintained and no untoward peripheral mechanisms brought into action. In the ideal condition, a heart-lung machine can be brought into use without a detectable change in

the patient's condition and, as smoothly, be disconnected from the circulation. Attention to the details of cannula size, blood pressure and oxygenation should result in the elected flow being achieved and maintained without adjustment of the machine over periods in excess of an hour.

Conclusions

There are available several heart-lung machines of different design, each of which is capable of maintaining the circulation and respiration in man for sufficient time to allow a variety of intra-cardiac defects to be repaired. The development of these machines proceeds as does the exploration of new principles of design. It is clear that a mastery of this complex field will not be long delayed.

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