HEART PUMP AND OXYGENATOR

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This paper is a general review of the development of the artificial heart-lung to facilitate open-heart surgery. At the close of World War II many centers began investigating the possibility of total cardiac bypass. Over the past decade, pump oxygenators of various types have become popular and recent clinical successes throughout the world have given further impetus to the study of problems posed by the artificial heart-lung apparatus.

The subject divides itself into three separate parts, the first two being concerned with the maintenance of life in an experimental animal during a total cardiac bypass. One must take all the blood from the animal and return it to the animal by means of a pump. Secondly, one must oxygenate the blood before returning it. The third part of the problem confronting the surgeon is the selection of cases and correction of defects in human subjects.

The pumping mechanism must duplicate as nearly as possible the action of the chambers of the heart. Pumping action must be smooth so as to prevent hemolysis and to avoid turbulence with thrombosis. It is not difficult to construct a pump with which hemolysis can be kept to relatively negligible amounts. Most of the pumps in use throughout the world give an hemolysis of less than 50 mg of hemoglobin per 100 ml of blood, which is perfectly safe. Turbulence with thrombosis can be overcome by removing valves inside the stream and placing valves outside of, rather than within the stream of blood. Furthermore, heparinization of the blood lessens the tendency to thrombosis. It was the experience of all the early investigators, including ourselves, that postoperative bleeding was a serious complication. It was not until the neutralizing effect of protamine on heparin was appreciated that many dogs survived a simple bypass for any length of time without bleeding to death. This postoperative bleeding, due both to heparinization and perhaps to the reduction of platelets from prolonged extracorporeal pumping, was overcome by administration of protamine and successes were achieved.

The problem of delivering the blood to the experimental animal is relatively simple. It can be delivered into a subclavian artery where it passes centrally, closes the aortic valves and is redistributed to the body. This is the common practice with most surgeons in both experimental and clinical application at the present time. The actual removal of the blood from the dog constituted a major problem in the early phases of study. It was not until catheters were inserted through the right auricular appendage into the superior and inferior vena cavae that the removal of the blood was adequate. Even this presents occasional hazards and some controversy exists as to whether one should remove this blood by a vacuum pump or by gravity. Certainly, if one increases the pressure slightly the cannulae are apt to become blocked, and it may be that suction through the vena cavae causes some deleterious effect on both liver and brain. Gravity methods of removal are not always certain although in use in some centers.

The oxygenation of the blood proved at first to be a most difficult stumbling block. It was felt that large quantities of blood would have to be oxygenated to approach the normal flow, that is, somewhere in the neighborhood of 4 to 6 l/min, and a tremendous surface must be created to oxygenate such a large quantity of blood. It

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was probably for this reason that most oxygenators were inadequate during the early years and the contribution by Andreason (as applied by the Minneapolis group) of the azygos flow principle lessened the need for oxygenators with such large surface and for such large quantities of blood to be oxygenated. Life can be maintained in the experimental animals for a few moments on the return flow through the azygos vein when the vena cavae are clamped. Periods up to ½ hour of the total venous occlusion are compatible with life if two and one-half times the azygos flow are used—about one-third of the normal venous return.

The use of low rates of flow reduced the necessity for very large oxygenators and as a result numerous types of oxygenators are now being used experimentally and clinically. These oxygenators can be divided into four groups: The first group films out a thin layer of blood to come in contact with oxygen. Examples are the Jongbloed oxygenator1 which was one of the first, the oxygenator of the Swedish group now being used in Stockholm, and that of Gibbon,2 now being used successfully in the Mayo Clinic.3 A second method of oxygenation of blood is the bubbling of oxygen through the blood. Removal of the bubbles by antifoam preparation and a specially designed helix such as in DeWahl's oxygenator is now being used successfully in Minneapolis. Other bubble oxygenators are those of Dodrill and Kaplan, where finer bubbles of oxygen are used with less foaming. Membrane dialysis would seem a physiologic approach to oxygenation of blood and such an oxygenator has been constructed by Kolff.4 The use of a biologic oxygenator as advocated by our center many years ago has the disadvantage of the possibility of introducing into the circulation organisms and proteins foreign to the patient.

In surveying in a broad way the biochemistry of the blood after cardiac bypass for 15 to 60 minutes, it appears that none of the constituents are seriously altered. A lowering of the pH appears to be the most significant change and this can be overcome by the administration of appropriate alkali at the termination of a cardiac bypass.

At this time it would be appropriate to give a brief description of the various types of artificial heart-lung machines which are in use clinically at the present time. Gibbon, in 1937, carried out experiments on animals5 designed to determine whether the circulation could be aided by artificial means in the presence of partial occlusion of the pulmonary artery. The means employed were the withdrawal of blood from a peripheral vein, the introduction of oxygen into the blood and the reinjection of the blood into a peripheral artery in a central direction. The present modified apparatus of the Gibbon type is being used successfully by Kirklin at the Mayo Clinic.3

The basic hemodynamic feature of the Gibbon type apparatus is automatic maintenance of a constant volume of blood in the extracorporeal circuit during the perfusion. This is accomplished by the combined action of three mechanisms: A level-sensing device which maintains a constant volume within the venous reservoir; a second level-sensing device which maintains a constant volume in the oxygenator reservoir; a constant rate of flow of blood across the screens of the oxygenator, thus insuring constant volume of blood within the oxygenator proper. The components of the machine are as follows: Flow circuit of tygon tubing; pumps of the nonocclusive DeBakey roller type; venous and coronary sinus reservoirs; occluder mechanisms; high pressure stops; the oxygenator composed of 14 wire mesh screens measuring 12 by 18 inches enclosed in a lucite case and arterial filter (Fig. 1).

Jongbloed's oxygenator1 was also a pioneer apparatus in the field. The artificial heart-lung consists of six parts, each part consisting of a rigid tube of some suitable plastic material bent into the shape of a spiral. The six spirals are mounted in a frame with their axes pointing slightly downward. They turn about this axis
FIG. 1. The Gibbon pump in use at the Mayo Clinic.

synchronously with the pumps. As the blood passes through the spiral tube it will adhere to the wall and form a thin layer. Streams of oxygen and carbon dioxide constantly pass through the tube and the exchange of gases takes place.

The artificial bubble-oxygenator of De-Wall has no moving parts. It is assembled entirely from commercially available plastic (pure polyvinyl) food hose, and is sterilized by autoclaving. The pump used extensively is the milking type of sigmamotor available commercially. Oxygenation of the venous blood occurs by the direct introduction of 100% oxygen in the form of large bubbles in a vertical plastic mixing tube. The blood and oxygen make contact at the surface of these bubbles as they rise in the column of venous blood circulating through the mixing tube. The bubbles present the large surface area necessary for efficient uptake of oxygen and elimination of carbon dioxide without the intervention of a foreign substance for filming. The bubbles are then largely dissipated by momentary contact with a patent nontoxic silicone antifoam substance sprayed on or painted on the distal portion of the walls of the mixing tube and the smaller plastic connecting tube. Any remaining bubbles rapidly rise to the surface and are eliminated, carrying off carbon dioxide as well, as the blood descends by flow of gravity in a plastic settling tube (helix). From the settling tube the now arterialized blood enters the central collecting reservoir from which it is
perfused through the patient after passing through standard blood filters (Fig. 2).

In the artificial lung of Kolff\textsuperscript{4} oxygenation occurs through a polyethylene membrane. The membrane consists of three layers of fiberglass window screen, two polyethylene tubes and three pairs of spacers (to allow space for the tubes to become distended with blood). The plastic coated fiberglass strips 7 m long are wound around a can and the completed coil is placed in a plastic bag. Oxygen is blown into the bottom of the artificial lungs at a rate of 30 l/min (for eight lungs).

Experimentally and clinically our group has used a pump designed by Cowan.\textsuperscript{5} The advantages listed for this pump are adequate output, easy regulation by hand control, easy sterilization, absence of internal valves and negligible hemolysis. The oxygenator is a biologic one. The advantages of a biologic oxygenator of this type are that it allows a massive surface area for oxygenation of blood, causes minimal trauma to constituents of the blood, is a filter, and probably carries out some detoxifying function.

In the remainder of the extracorporeal system there is included a bubble trap to safeguard against air embolism and a water bath to maintain perfusing fluid at body temperature. All tubing is of plastic material with plastic connections.

We must now return to the third part of the problem, namely, the selection of cases for direct intracardiac surgery and must also consider the complications of this type of surgery. It is without question that the daring and boldness of Lillehei\textsuperscript{6} provided the answer to the latter problem. His group in Minneapolis used a human donor as a perfect physiologic pump-oxygenator and were able to perform intracardiac surgery under direct vision. They opened the field for the actual surgical technique and the selection of cases for operation. After initial success with the human donor, the Minneapolis group returned to the bubble oxygenator and sigmamotor type of pump, and have continued with their successes.

The artificial heart-lung type of bypass
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is most useful in operations requiring interruption of cardiac flow for more than 8 or 10 minutes. For interruption of cardiac flow of shorter duration, protection could be afforded with hypothermia. The interventricular septal defect requires use of an extracorporeal circulation and successful surgery in such cases is being reported all over the world.

Coronary and cerebral air embolism has not proven hazardous in the presence of an extracorporeal circulation. The reverse flow from the pump appears effective in closing the aortic valves, and air in the left ventricle escapes through the defect during closure. Flow through bronchial arteries with return to the left side of the heart is sufficient to fill and expel air from the left ventricle. Indeed, this flow, particularly in cases of tetrad of Fallot, is considerable and must be returned to the extracorporeal system.

Experience is being gained in many centers with different methods of closure of interventricular septal defects either by direct suture or by the use of some form of plastic material. Further experience is being gained in the selection of cases and in the problem of the reversibility of pulmonary hypertension. It would appear that the younger the patient at the time of operation, the greater the possibility of alleviating pulmonary hypertension. It has been our experience and that of many others that the infant is a poor operative risk for extracorporeal circulation because of the frequency of postoperative complications. However, progress is being made and, as each center gains more experience with the correction of interventricular septal defects, the artificial heart-lung will be used for correction of tetralogy of Fallot and for certain cases of infundibular stenosis with normal outflow tract. It is still very hazardous to attempt correction of atrioventricularis communis.

During the time the pump-oxygenators were being developed in various centers, hypothermia, as introduced by Bigelow, was receiving wide recognition and used for short-term cardiac bypasses. It was felt by many investigators, including ourselves, that a combination of hypothermia and artificial heart-lung, might reduce the rate of flow to such an extent that oxygenation would not be necessary and that one could simply use preoxygenated blood. The idea is intriguing but from our experimental studies has not proved feasible. Irreversible ventricular fibrillation occurred frequently. There may be some promise in the future if this can be overcome. With the use of reduced rates of flow the added hazard of ventricular fibrillation due to hypothermia did not seem warranted.

In conclusion, it seems justifiable to state that after one decade of trial and tribulation the artificial heart-lung is here to stay as part of the armamentarium of the cardiac surgeon.

REFERENCES
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