A GREAT variety of perfusion pumps and blood oxygenators have been described during the past 80 years. A review of the necessary qualifications for such devices is given in part by Bjork and by Dubbleman.

During the past six years the author has designed, constructed and tested several heart-lung machines. This report describes and discusses the one which as of 1952 showed the greatest possibilities of clinical utilization.

DESCRIPTION OF THE APPARATUS

For purposes of description, this mechanical heart-lung may be divided into a pumping mechanism, oxygenator, blood conduits, and the various auxiliary devices. Figure 1 is a diagram of this structure.

Pumping Mechanism.—The double pumping mechanism (figure 1, A) combines the advantages of a streamlined flow without moving valves within the blood stream with pulsatile flow, positive delivery, compactness and a high and readily variable output.

In each side of the pump, a resilient tube of 3.5 cm ID and 0.45 cm wall thickness, is flattened between the chassis of the pump and a brass plate 20 cm long and 7 cm wide to the extent that the lumen is reduced to 12 mm. These brass plates are mounted on either side of the drive shaft on which are two eccentrically mounted roller bearings. As the drive shaft turns, the roller bearings impinge on neoprene strips fastened to the backs of the brass plates, thereby smoothly forcing the brass plates laterally, compressing the pump tubing further and forcing the blood from it. In order to reduce the hemolysis the tube is not completely compressed.

The opposed arrangement of the tubes in relation to the drive shaft is such that elastic expansion of one tube helps to compress the other. The direction of blood flow in each tube is governed by external valves, one near either end of the brass compression plates. Each valve consists of a thin, dull blade which is driven laterally by a cam on the drive shaft so as to pinch off the pump tubing in the proper sequence. The cams are so arranged that either one or the other end of the tube is closed at all times, thereby preventing back-flow or any forward flow other than that arising from the action of the pump. The output of each side of the pump can be independently varied from 0 to 5000 cc. per minute by limiting the medial excursion of the brass compressing plate with an adjustable back stop which restricts the degree of filling of the tube. Although only 1/2 hp would be sufficient, the pump is driven at 80 rpm by a 1/4 hp induction motor, a "V" belt, and a Boston V18 reducer.

The Oxygenator.—Efficiency of oxygenation is achieved by gentle turbulence induced in the blood stream by causing the blood to tumble and ripple over the irregularities in the floor of a conduit, thereby exposing each erythrocyte to the blood-gas interface rather than relying on diffusion of gases through the blood.

In its present form, the oxygenator consists of a tygon tube 6.6 meters long, 2.5 cm. ID and a wall thickness of 0.3 cm. A plastic covered wire is tightly spiralled around the outside of the tube with the turns 2.7 cm. apart so as to cause a 2 mm indentation in the tube wall. The tube itself is wrapped in eight evenly spaced turns around a metal drum 23.6 cm. in diameter and 61 cm. long. Further distortion of the tube is achieved by 64 evenly spaced "U" shaped clamps that alternately constrict the lumen to an internal width of 1.5 cm. at angles of 90 degrees and 45 degrees to the axis of the helix. Each end of the tube is attached to a cylindrical chamber (C) mounted with their axes coincident with the axis of rotation of the drum and inside the hollow 10 cm. supporting bearings of the drum. The axis of the drum is inclined 10 degrees from the horizontal to facilitate filling and emptying of the cylindrical chambers. Blood is introduced into the upper cylindrical chamber at "D" from which it periodically empties into the first turn of the helix. The axis of the drum is inclined 10 degrees from the horizontal to facilitate filling and emptying of the cylindrical chambers. Blood is introduced into the upper cylindrical chamber at "D" from which it periodically empties into the first turn of the helix. As the helix rotates, the blood is carried along and, after eight revolutions, empties into the lower cylindrical chamber from whence it flows past another gland into a conduit (F) leading to a bubble-trap reservoir (F). With the drum rotating at the opti-
The maximum rate of 72 rotations per minute and a blood flow of one liter a minute, the blood transverses a helix of eight turns in 6.7 seconds; 110 cc. of blood in transit at one time while an additional 20 cc. clings to the walls.

The cylindrical chambers at each end of the helix are sufficiently large to permit the attachment of additional helices. Thus the machine can be adapted to carry the large blood volume necessary for use in human surgery without changing the blood-flow characteristics in the helices from that observed in the animal experiments. Five helices would be adequate to handle a flow of 4800 to 6000 cc. per minute and would contain a total of only 650 cc. of blood at any one time.

Warmed, moistened oxygen is introduced into the lower end of the helix at (P) escaping along with the released CO2 through a channel in the double lumen conduit (D).

The Blood Conduits and Auxiliary Devices.—Blood was withdrawn from the animal through polyethylene tubing (6 mm OD and 4.5 mm ID) (G) passed via the right external jugular vein, into the inferior vena cava. Blood was drawn by gravity and by the negative pressure developed by the right pump into a small elastic chamber (H) consisting of a cellulose acetate-butyrate tube of 2.9 cm. ID and 10 cm. in length which had been bisected diagonally, creating a broad end which was capped with a lax thin rubber membrane and a hollowed lucite plate. The right pump propels the blood into a reservoir (I) 2.9 cm. ID and 15 cm. high, from which it flows, via a short length of soft tubing and the double lumen conduit (D), into the intake manifold (C) of the oxygenator. A screw clamp constricts the short length of rubber tubing to an adjustable degree so that the height of the blood in the reservoir, which is a function of the rate of blood flow and its viscosity, serves as a means for estimating the rate of flow. An accurate rate of flow was obtained by stopping the outflow of the reservoir and determining the volume pumped into the reservoir by a predetermined number of strokes of the pump. From the outlet of the oxygenator, the blood flows down conduit (E) at the bottom of which a loose vinylite membrane separates the blood from a 3% aqueous solution of sodium chloride in a chamber connected to a small vertical tube. The height of the blood in the conduit is reflected, with some damping, in the height of the salt solution in the small tube which in turn controls the level of the blood in the conduit (E) and bubble trap (F) in the manner shown in figure 2: Within the tube is one fixed platinum electrode with two adjustable platinum-tipped electrodes above it. When the level of the blood in chambers E and F and therefore the level of the saline solution in the tube drops below the level of the lower adjustable electrode, a 5 ma. 10 v alternating current is interrupted causing release of the armature of a sensitive relay which results in the actuation of the 110 v. solenoid (O) which clamps off the blood conduit between the reservoir and the left pump. The solenoid remains energized until the level of the blood in the reservoir rises so that the saline solution touches the upper adjustable electrode, a half-centimeter higher, fully energizing the sensitive relay and breaking the circuit to the power relay. Contact of the saline solution with the lower adjustable electrode does not cause the sensitive relay to close because of attenuation of the current by a series resistance. The current being only strong enough to hold the relay closed once it is actuated by the unattenuated current from the upper electrode. This arrangement prevents chattering or unnecessary frequent operation of the system.

From the bubble trap-reservoir (F) the blood is pumped by the left pump into a buffer chamber (K) similar in design to (H). The air filled space between a polyethylene diaphragm and the lucite cover plate of the bubble trap serves both to cushion and
broaden the ejection stroke of the pump and to permit attachment of a pressure gauge. After leaving the bubble trap, the blood passes through a conical filter made of 80 mesh monel screening, 36 cm. long with a base of 1.4 cm. that fits snugly inside the 1.3 ID tygon tubing which is used for most of the blood conduits. The arterial injection cannula (M) is made of 8 mm polyethylene tubing drawn out to a tip of 3 mm OD. Conduits leading to a 1200 cc storage reservoir (N) from T-tubes on the intake line and from the output just beyond the filter permit blood to be withdrawn from, added to, or circulated through the reservoir at will.

The entire heart-lung apparatus is encased in fiberboard insulation and celluloid and mounted on casters. Temperature of the enclosed air and apparatus is controlled by a 1000 watt coil heater and fan combination, and a Fenwal thermostat. The gas passing through the helix is heated and moistened by passing first through a humidifier as shown in figure 3. The drum is powered by a 1/6 hp electric motor and the rate of rotation may be varied from 0 to 120 rotations per minute by means of a variable auto-transformer. The majority of controls and indicating devices are arranged on a small panel at the head end of the machine along with the quick release master switch.

**Procedure**

Dogs weighing from 8 to 10 Kg were anesthetized with 240 mgm of pentobarbital and given 30 mgm of heparin. The right femoral artery was connected to a mercury manometer and the right femoral vein to a bottle containing 250 cc. of 36 N sodium lactate and 1 mgm nor-adrenaline. A vertical side tube from the connecting tube served as a means of measuring venous pressure. A 28 F catheter was passed into the trachea and its circumferential balloon inflated. The left femoral vein and a carotid artery were exposed and cannulated. The thoracic cavity was entered through either the fourth or fifth right intercostal space and the venae cavae loosely encircled with elastic ligatures at their junction with the right atrium. The cannula, as described above, was passed through the right jugular vein until only the unperforated portion of its wall lay between the two ligatures. The animal was then connected to the apparatus which had been previously filled with 1000 to 1200 cc of heparinized (20 mg/L) blood, and circulation begun by withdrawing blood from the jugular cannula passing it through the machine, and returning it via a femoral vein. After approximately five minutes, when the blood in the machine had been filtered through the animal's lungs and a steady physiologic state reached, the output side of the machine was connected to the carotid artery, the elastic ligatures drawn tight around the jugular cannula and the tracheal catheter clamped off. In this manner the major portion of the animal's circu-
E.C.G. was recorded on a portable direct writing machine, the electrodes being fastened to shaved areas of the limbs. Cleansing the machine by leaving it filled with double strength Detergex and rinsing with 1:1000 zepharin or 3 per cent formaldehyde, then water and isotonic saline for as long as 12 hours was apparently not successful. The use of Coagustil in one experiment was followed by a survival. Investigation of the efficacy of active pepsin or of sodium hypochlorite solutions was forestalled by termination of the research program due to the demands of the armed services.

RESULTS*

Venous oxygen saturations varied from 42 to 76.1 per cent and arterial saturations varied from 89 to 100 per cent, representing an oxygen uptake of from 27.4 to 60.9 cc./minute. Flow rates were varied from 500 to 1250 cc./minute, drum rate from 60 to 80 rpm, gas composition from 7 to 0 per cent CO₂ in oxygen and the gas flow from 2.5 to 1 L/minute. Optimal values were found to be a flow rate of 900 to 1250 cc./minute, drum rate of 72 rpm and gas flow of 1 L/minute of pure oxygen. Raising the blood flow from 800 to 1100 cc./minute did not decrease the degree of saturation of the outgoing blood even when it was not fully saturated as a result of severe venous desaturation. This indicated an improved efficiency of oxygenation with increasing rate of blood flow within these limits and is attributed to the more efficient mixing of the blood in the oxygenator afforded by the increased quantity of blood in each turn of the helix.

The pH values of the arterial blood ranged from 7.36 to 7.48 indicating that adequate quantities of carbon dioxide were removed by perfusing the oxygenator with pure oxygen at a flow rate of 1 L/minute. Adding CO₂ to the oxygen flowing at 1 L/minute lowered the pH of the blood to 7.01 when the partial pressure of the CO₂ was 40 mm Hg. Increasing the flow rate of this mixture to 2.5 L/minute raised the blood pH to 7.4. Increasing the flow of pure oxygen to 3.5 L/minute raised the arterial pH to 7.56.

In 19 cases in which complete hematological data was available, the hematocrit readings decreased by 1 per cent to 20 per cent (average 6 per cent); they remained unchanged in 3, and increased from 5 to 11 per cent in 4 cases. These variations depended on the type and quantity of fluids administered during the procedure. There were no significant changes in either the leucocytes or thrombocytes. Plasma hemoglobin increased at a rate of from 0.50 mg per 100 cc. per minute to 2.9 mg/100 cc. per minute, averaging 1.6.

The adequacy of the apparatus was evidenced by the fact that during the unopened chest experiments, respiratory efforts ceased, and during the open chest trials the heart grew soft and small while the lungs blanched. Once the experiment was under way, blood pressure could be maintained between 100 and 150 mm Hg without difficulty. No evidence of significant heart action on the systemic circulation during perfusion could be discerned. However, when the machine was stopped and the cavae untied, respiration resumed spontaneously and the heart began beating strongly, maintaining the blood pressure above 100 mm Hg. Inasmuch as the tracheal catheter had been either clamped off or attached to a nitrogen filled bag, it can be assumed that the apparatus had supplied all or nearly all the oxygen used by the animal during the perfusion in spite of some circulation of blood through the lungs.

Thirty-eight experiments were performed in which the animal's oxygen requirements were totally satisfied by the apparatus. However further perfections of technic are required because all but three animals died within 4 to 24 hours after termination of the perfusion due to hemorrhage, atelectasis or an irreversible fall in blood pressure. One animal died in a strikingly similar manner after receiving only an intravenous transfusion of washings from the apparatus. This indicates improper cleaning rather than improper operative procedure.

DISCUSSION

Evaluation of a mechanical heart-lung entails a comparison and integration of numerous factors. Some of the more important of these are: Oxygen uptake, CO₂ clearance, pH control, filling volume, prevention of emboli, fate of
cellular elements, coagulation, reliability of operation, simplicity of structure and principle, and general applicability.

Almost any oxygenator can provide the O$_2$ uptake sufficient to support a man if the oxygenation units are large enough or if enough of them are arranged in parallel. The limiting factor, however, is the quantity of blood necessary to fill the machine. The larger the amount of blood required, the greater is the number of units of bank blood required, each additional unit increasing the probability of incompatibility. Furthermore, as shown by Bjork (1), the use of a very fresh blood is preferable; a large filling volume would, in the absence of an organized donor service providing freshly-drawn blood, force the inclusion of less desirable bank blood. The machine employed in the present study would require only about 1 unit of blood (650 cc.) to fill an oxygenator of 5 helices sufficient to sustain a 70 kg. adult and no more than 1 additional unit for the conduits and pump. Five helices in parallel could oxygenate 5000 to 6000 cc. of blood per minute, providing an oxygen uptake as high as 300 cc. a minute. The use of a counter current of oxygen affords greater stability of the pH of the emerging blood with a relatively slow rate of gas flow.

Absolute freedom from gaseous or solid emboli is the sine qua non of successful operation of a mechanical heart-lung. The use of the 80-mesh monel screen reduces the probability of solid emboli, without significantly increasing the resistance to blood flow or increasing the blood volume. In order to prevent the injection of small bubbles, an efficient bubble trap must be used. One important feature in the design of such a trap is that the minimum time of transit of any one portion of the stream of blood through the trap exceeds the maximum time required for even the smallest bubble to rise from the deepest portion of the stream and reach the surface. In one of the bubble traps (F) in the mechanism described above this is achieved by having the blood enter through the diagonally-cut top of an inlet-tube thrust through the bottom and near the edge of a vertical cylinder 7.5 cm in diameter so that the blood flows in a long circular course around the bottom of the cylinder to an outlet located near the inlet. The use of antifoam coated reticulum or beads, as used by Clark, would also be very efficient, particularly when minute bubbles are involved.

One of the factors limiting the length of time the apparatus may be utilized is the lysis of erythrocytes. Levels of plasma hemoglobin in excess of several hundred milligrams per 100 cc. of plasma could be dangerous. The fact that values as low as 0.50 mg/100cc./minute could be achieved and that the higher values occurred with no change in the apparatus or procedure, as well as the fact that these values were in excess of those obtained from in vitro experiments, indicates that this rate of hemolysis might have resulted from the use of incompatible bloods. Matching bloods was not feasible because of the acute shortage of experimental and donor dogs at the time these experiments were being carried out. More careful adjustment and more thorough cleaning might effect a further reduction of the rate of hemolysis. Leucocytes are not removed by the apparatus in significant quantities. Thrombocytopenia leading to intractable bleeding post-operatively, can be countered only partially by transfusions of fresh blood at the end of the experiment and is more serious. Furthermore, deposition of the immobilized thrombocytes in the machine stimulates fibrin formation and clotting which can only be counteracted by using excessive quantities of heparin. The smaller the amount of heparin used, the easier it is to neutralize or to be removed by the body and the smaller the danger of hemorrhage. Since the machine incorporates plastic materials, wherever possible, avoids moving parts in the bloodstream, and has a stream-lined design devoid of pockets, it is believed that heparin requirements are reduced to near to the theoretical minimum.

The apparatus described above meets the requirements for reliability of operation and simplicity of structure in that (1) extensive training of personnel would not be necessary (2) it is constructed and maintained by commercially available materials, and (3) intricate moving parts auxiliary devices and electronic
components are reduced to a minimum. The use of an over size pump motor and gears, integral cams, external valve mechanism, relay actuated level control, and an oxygenator that need only be turned at 60 to 90 rotations per minute and supplied with some oxygen to operate and which may be stopped and started without special precautions help in meeting this requirement.

The apparatus described meets the requirements for general applicability in that it requires a minimum amount of blood, needs the attention of only one operator, can operate continuously for several hours, has sufficient flexibility of control and a reserve capacity to handle a wide variation in physiological states, is capable of being quickly connected to the patient and has ability to operate when used with a single right jugular cannula. An efficient method of cleaning the apparatus has yet to be developed.

**Summary**

A mechanical heart-lung apparatus is described which employs a smooth bore positive delivery pump and a gentle turbulence producing oxygenator. The machine incorporates several new features believed to be advantageous.

A series of experiments are described, which indicate that the oxygen requirements of dogs are satisfied; but further technical improvements will be necessary to insure better survival of animals.

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**References**