medium (60% medium 199, 20% whole egg ultrafiltrate, and 20% horse serum). Lowering the serum content in the new medium to 10% still permitted better growth than the standard reference medium. The yeast extract-proteose peptone solution could be sterilized by autoclaving without affecting its growth-stimulating properties.

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Evaluation of a Rotating Disc Type Reservoir-Oxygenator.* (22710)

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The historical development of various pump-oxygenators is well covered in the literature(1,2,3). Many of the early machines, utilized both experimentally and clinically, bypassed but one side of the heart, this being a simpler solution to the overall problem(4, 5,6). However, Gibbon(7) and Dennis(8) have continually stressed the necessity of total cardiac bypass as a requirement for an entirely satisfactory pump-oxygenator. Lillehei and associates(9,10,11,12) hastened the reality of direct vision intracardiac surgery through the use of controlled cross-circulation, oxygenated blood reservoirs, and biological oxygenators, as temporary expedients before the final utilization of a pump-oxygenator. They also have stressed the concept of the low flow principle which has been satisfactory in their hands for shorter periods of bypass, and which possibly has simplified certain problems inherent in the development of effective pump-oxygenators.

It was the purpose of the present study to evaluate a rotating disc type reservoir-oxygenator, which has been used successfully for open intracardiac surgery experimentally and clinically.

Description of apparatus. The essential components of the present pump-oxygenator are a model TS Sigmamotor pump and a rotating disc type reservoir-oxygenator. (Fig. 1 and 2). The basic mechanism of the oxygenator is a series of 59 plastic coated stain-

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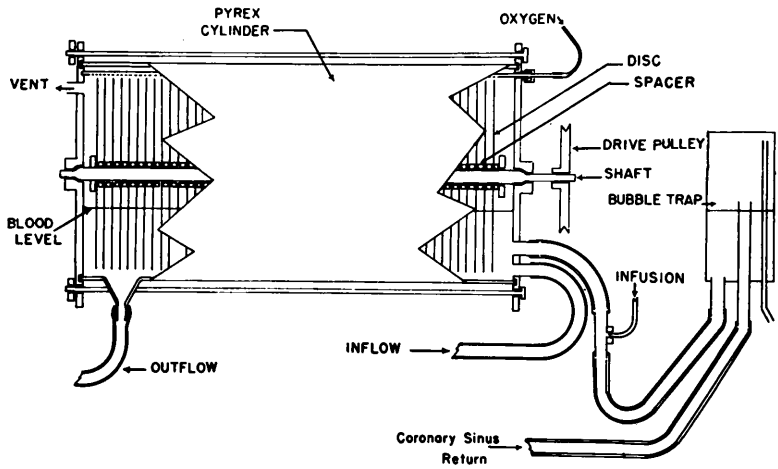

FIG. 1. Diagram of reservoir-oxygenator with attached defoaming chamber for coronary sinus return.

less steel discs 0.15 inch (0.4 mm) thick, and 4 13/16 inches (12.2 cm) in diameter, mounted 0.18 inch (0.5 mm) apart by means of stainless steel spacers on a central shaft. Previously the stainless steel discs were coated with silicone resin; at present they are coated with teflon. The disc assembly is supported horizontally within a silicone-coated pyrex cylinder 13 inches (33 cm) long, and 5¼ inches (13.3 cm) in diameter, by gasketed end plates of stainless steel, likewise treated with silicone resin. Blood is introduced at one end of the cylinder and is removed from the bottom of the opposite end. Rotation of the discs effectively prevents channeling of the blood along the bottom of

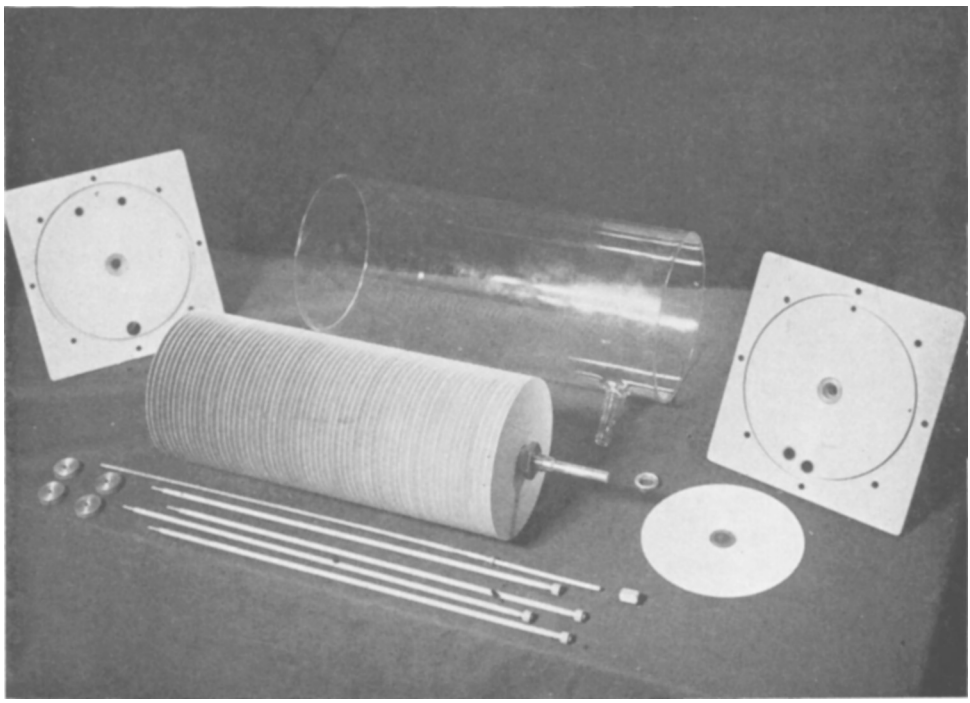

FIG. 2. Reservoir-oxygenator dissembled to show component parts.

the cylinder. The oxygenator is primed with 1400 cc of whole blood to immerse the discs to 1⅝ inches (4.1 cm), a level calculated to provide maximum exposure of blood to oxygen. When the discs rotate the blood films on the peripheral 1⅝ inches of each disc for exposure to oxygen. With the oxygenator primed with 1400 cc the static exposed area (that above the blood level) of the 59 discs is 9 square feet or 0.84 square meter. At a disc rate of 120 revolutions per minute, the rate generally employed, 1080 square feet or 110 square meters of filmed blood is exposed to oxygen per minute. To turn the discs, a pulley mounted on one end of the shaft is driven through a V-belt by a 1 80 horsepower motor controlled by a variac power rheostat. Oxygen is supplied at a rate of 5 liters per minute through a perforated stainless steel tube mounted within the cylinder above the discs. The oxygen is warmed by passing through tubing immersed in a sand-bath, heated by an electric mantle. The oxygenator itself is warmed by a wrapping of silicon rubber-covered resistance wire, the temperature of which is controlled by a variac. All electrical connections are mounted above the oxygenator, over 5 feet above the floor, to eliminate explosion hazards. Heat may be supplied selectively by increasing the current through the resistance wire and condensation within the oxygenator has been effectively prevented. Provision is made at the inlet face of the oxygenator for filling prior to use, the addition of blood to the cylinder during a run, and for sampling the venous return to the oxygenator from the patient. The output face is provided with openings to vent off the circulating oxygen, for collection of samples of oxygenated blood, and to receive a thermocouple for continuous monitoring of blood temperature. Recently a sump type suction tip has been used to collect coronary sinus return from the right atrium, utilizing a second Sigmamotor pump. Coronary sinus blood is pumped first to a defoaming chamber, from which it is returned to the input end of the oxygenating cylinder. Venous cannulations have been made with expendable nasal oxygen catheters, or with specially constructed adaptors of polyethylene, and all external tubing is tygon, 5/16 inch internal diameter, except the short sections of silicone coated rubber tubes in the pump head. To reduce turbulence and fibrin formation, all the adaptors are of high tensile, polished polyethylene, of the same internal diameter as the tubing they receive. A bubble trap has not been necessary on the outflow line since there is no bubbling present in the oxygenator, and filters in the external circuit are not used. Pump speeds are regulated through a previously calibrated speed changer. The oxygenator can easily be dissembled into its component parts for cleaning. It is sterilized in the autoclave after reassembly including the oxygen flow tube and the heating wire. The inside is then dried by flushing with oxygen or air while it is still hot, or by standing in the hot autoclave. Connecting tubes are sterilized in Zepharin for twenty-four hours and then rinsed and mounted in the pump circuit. The tubing is then rinsed in two liters of saline solution before being connected to the patient.

Method of study. Effective pump-oxygenators must maintain circulation as well as oxygenation in total cardiac bypass with a low morbidity and mortality rate. To evaluate the present pump-oxygenator, both acute and survival experiments were carried out with dogs, as well as studies utilizing cow blood. Observations carried out during the cardiac bypass were continuous mean blood pressure recordings, blood oxygen and carbon dioxide content, blood pH, plasma hemoglobin, hematocrit, and platelet and red and white blood cell counts. It was difficult to evaluate the oxygenating capacity of the oxygenator by dog experiments alone because of limitations imposed by the size of the available dogs. For this reason, experiments were done using cow blood. In these experiments, warmed desaturated cow blood was run through the oxygenator at the different flow rates to be studied. In each experiment, after 4 liters of blood had passed through the oxygenator and equilibrium had been established, samples of venous and oxygenated blood were taken and analyzed for their oxygen content. Blood samples for oxygen determination were packed in ice and the oxygen content was de-

termined in duplicate within 24 hours by the method of Roughton and Scholander.

Results. Mortality and morbidity were necessarily high in the developmental stage of the pump-oxygenator. However, after the basic design and technics were standardized a survival series of 20 dogs was carried out in which there were 2 deaths. In 11 of the dogs, simple cardiac bypass without cardiotomy was done, with one death due to undetermined causes; and in the remaining 9 dogs a ventricular cardiotomy was done with one death due to postoperative ventricular fibrillation following the institution of a citrated blood transfusion.

Perfusion pressures measured as mean arterial blood pressures with a mercury manometer, at flow rates from 40 to 80 cc/kg/min., averaged from 50 to 80 mm Hg. To maintain such pressures it was necessary in most experiments to add varying amounts of blood to the total circulating blood volume even though there was no demonstrable extrinsic loss. This could be partly compensated for by adding small amounts of neosynephrine to the oxygenator. Although the blood pressure could be affected in some measure by increased perfusion rates, this was not constant, and initial small rises were not maintained.

A specific value as to the oxygenating capacity and efficiency of the oxygenator cannot be given at present. With such factors as oxygen flow rate, disc rate, and blood temperature held constant, the efficiency of the oxygenator varied not only with the blood flow rate but also with the degree of desaturation of the venous blood returning to the oxygenator. With low oxygen saturations in the venous blood the oxygenator was more efficient in that more cubic centimeters of oxygen were added to the blood per minute; but lower arterial oxygen saturations were obtained. The reverse was true with higher levels of venous oxygen saturation. This is well illustrated in experiments 8 and 9, 16 and 17, 24 and 25, in Table I. In these experiments the efficiency of the oxygenator ranged from 67 cc/min. of oxygen added to the circulating blood, to 207 cc of oxygen added per minute. The arteriovenous oxygen difference ranged from 3.7 to 13 vol. %, depending on the oxygen content of the venous blood and the blood flow rate employed. Pertinent oxygenation data from a typical dog perfusion experiment are found in Table II. There was adequate oxygenation at a flow rate of 2000 cc of blood per minute (59 cc/kg body weight per minute) with an arteriovenous oxygen difference of 6.8 vol. % and an oxygen uptake of 136 cc per minute.

TABLE I. 25 Oxygenation Experiments Using Cow Blood.

Exp. No.	Blood flow, cc/min.	Oxygen saturation vol, % Arterial	Venous	A-V diff.	cc O_2/min. added to blood
1	660	20.3	7.4	12.9	85
2	940	18.9	11.8	7.1	67
3	1060	17.6	5.0	12.5	128
4	1125	17.6	5.3	12.3	138
5	1200	14.4	1.4	13.0	156
6	1224	15.9	4.8	11.1	136
7	1240	19.1	7.4	11.7	145
8	1330	15.0	4.8	10.2	149
9	1350	17.5	11.7	5.8	78
10	1475	15.4	7.4	8.0	118
11	1500	12.3	1.9	10.4	156
12	1580	15.5	5.3	10.2	138
13	1670	15.6	5.0	10.6	177
14	1710	14.9	5.1	9.8	168
15	1920	14.7	7.6	7.1	136
16	2060	13.8	5.5	8.3	171
17	2120	15.1	11.4	3.7	98
18	2250	13.7	4.8	8.9	203
19	2500	13.2	5.1	8.1	203
20	2537	10.5	5.5	5.0	127
21	2600	10.4	3.3	7.1	182
22	2640	12.6	7.6	5.0	132
23	2860	15.8	11.8	4.0	114
24	3080	11.8	5.1	6.7	207
25	3080	16.1	11.8	4.3	132

Hemolysis was not excessive (Table III). The increase in serum hemoglobin over a 30 minute pumping period ranged from 10 mg% to 160 mg%. Variations in serum hemoglobin could not be related to such factors as disc speeds below 120 revolutions per minute, or pump speeds, but the degree of

TABLE II. Typical Dog Cardiac Bypass Experiment.

Wt, kg	Blood flow, cc/min.	Disc rate, r.p.m.	O_2 saturation vol, % Arterial	Venous	cc O_2/min. added to blood
34	1000	120	18.3	10.3	80
	1600	120	18.9	10.1	141
	2000*	120	18.6	11.8	136

* 59 cc/kg/min.

TABLE III. Average Increase in Serum Hemoglobin.

	Interval of bypass			
	10 min.	20 min.	30 min.	40 min.
No. of exp.	17	18	14	4
Serum hemoglobin (mg/100 cc)	29	36.4	67.7	88.5

hemolysis did increase with pumping time. At disc rates in excess of 120 revolutions per minute hemolysis was increased by the added churning, and in addition foaming occurred in the oxygenator. There was moderate destruction of platelets. In 13 experiments in which they were counted, the platelets dropped from an average of 184,770 to 96,000, or roughly to one-half of their preperfusion value over a period of 30 minutes. When protamine sulphate was given in amounts equal to one-half the calculated dose of heparin, and fresh citrated blood given postoperatively, the clotting time was restored to normal. Postoperative bleeding was not a serious complication. Leukocyte counts showed no consistent change following periods of cardiac bypass. Blood carbon dioxide content and pH studies are better controlled in the clinical cases done to date and will be discussed later.

Discussion. The oxygenator described is simple in design, easy to operate, and can be constructed to oxygenate over a wide range of blood flow rates without requiring excessive blood for priming purposes. Although it resembles the Bjork(13) apparatus in general principles, it differs in certain specific aspects of its design. More plates have been used and they are teflon coated which appears to reduce the degree of hemolysis and eliminates the tendency for fibrin formation on the disc surfaces. By increasing the number of discs and filling the cylinder to a higher level, the minute surface area of exposure to oxygen is 110 square meters compared to 44 square meters for the small oxygenator and the somewhat higher value for the large oxygenator of Bjork. The pump-oxygenator here described is considered to be the basic experimental model and it has been undergoing continual modifications which retain the basic principles of construction described. The oxygenating reservoirs are now being constructed from plexiglass and the discs are being made from teflon rather than from the stainless steel coated with teflon. In addition, a large cylinder is now available to increase the oxygenating capacity of the unit for use in adults; and a smaller cylinder is being constructed for use with infants in order to reduce the necessary priming volume. The present unit has been used in 30 clinical cases to date with no deaths specifically attributable to the pump-oxygenator. Details of this experience will be published later.

Summary. 1. A rotating disc type reservoir-oxygenator is described. 2. Its effectiveness in maintaining circulation and oxygenation is discussed. 3. It has proven satisfactory in both its laboratory and clinical application.

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