MOCK CIRCULATION TO TEST PUMPS DESIGNED FOR PERMANENT REPLACEMENT OF DAMAGED HEARTS

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IN the future it may become feasible to replace an irreparably damaged heart with a permanently indwelling mechanical pump to propel the blood through both the pulmonary and the systemic circulation. Setting aside for the moment the problems concerning clotting and injury to the blood cells or plasma, such a pump requires the mechanical definition as follows.

1. It should be a small double pump (right heart, left heart).
2. The pumping rate should be variable between 60 and 160 strokes per minute.
3. The output volume should be variable between 1.5 and no less than 5 liters per minute for each side of the pump.
4. The input pressure or 'atrial' pressure should be no more than 16 mm. of Hg, and no less than 0. In other words, suction should not be strong when available blood is not sufficient to fill the heart.
5. The output pressure of the right 'ventricle' should be 20 but capable of increasing to 80 mm. of Hg. The output pressure of the left 'ventricle' should be 120 but capable of increasing to 180 mm. of Hg.
6. The 24-hour output of the left side must equal that of the right side: the filling of each 'atrium' must determine the output of the corresponding 'ventricle.'
7. It is not absolutely necessary that the 'atria' contract, but the diastole should be sufficiently long to allow filling of the 'ventricles.' Wiggers [1] gives an example of diastole both in man and in dogs of 0.53 sec.; systole occurs in 0.27 sec.; and the time of maximal ejection to the ventricle takes only 0.09 sec. or 0.12 sec.
8. Possible source of energy: (a) a battery with a charger for direct-current motors or solenoids; or (b) an alternating power supply for motors operating on alternating current. The power supplies, (a) and (b), will be outside the body and will require wires into the chest; or (c), a small atomic power plant placed inside the chest.
9. Dissipation of the heat generated: the heat will be best transmitted to the blood so that the body and the lungs act as radiators.
10. The mechanical heart should be easy to insert, require no maintenance and should be easy to replace.

In order to reduce animal experimentation to a minimum, a simple system of mock circulation has been erected in which most of the tests can be performed *(Fig. 1).* In the diagram the left and right 'ventricles' are separated to make it easier to outline the path of circulation, whereas in reality they are adjacent. The blood leaves the left 'ventricle' (LV) through a corrugated 'aorta' (AO) to enter

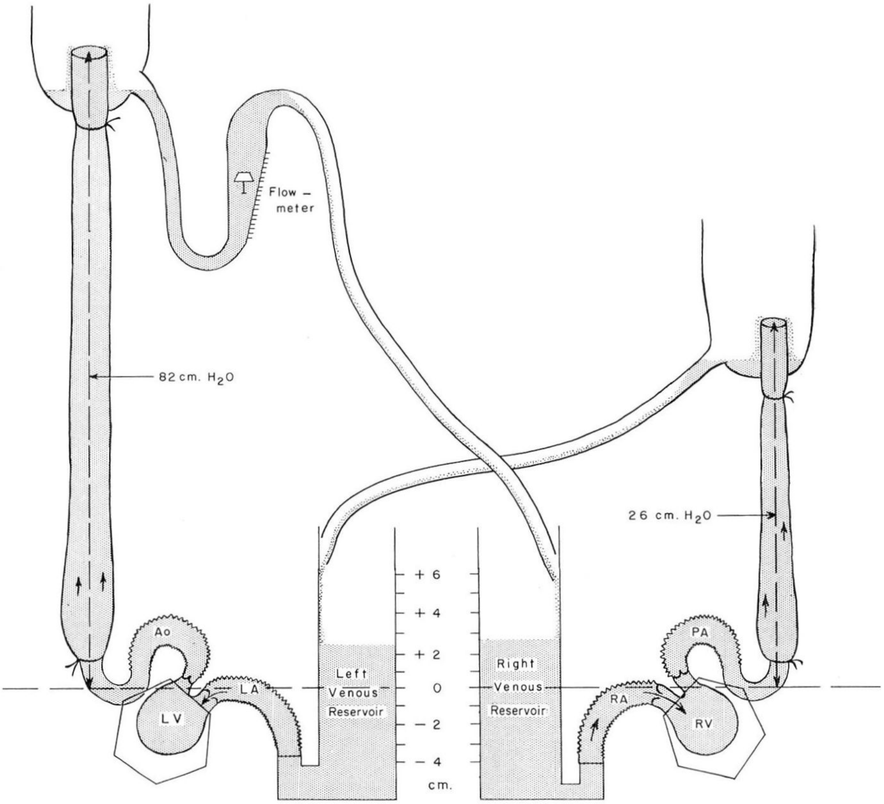

Fig. 1. Diagram of system for mock circulation. LV is the left 'ventricle'; RV is the right 'ventricle.' The 'ventricles' though actually adjacent are separated from each other in the diagram for clarity.

a distensible tube. The diastolic pressure in the base of the 'aorta' is determined by the height of the column of water of 82 cm., which corresponds to 60 mm. of Hg. One disadvantage of a fluid column is that inertia must be overcome to move a considerable amount of fluid in order to make room for the 'ventricular' output. This inertia is somewhat overcome by using distensible tubing or by surrounding its lowest part with an air chamber (not indicated in the diagram) under pressure.

The diastolic pressure can be varied by changing the height of the fluid column. Screw clamps or partial occlusions are not used to increase the resistance in a flow system, since their resistance increases with increased flow. The height of a fluid column does not change with a varying flow, and the resistance provided by it varies little. The overflow of the fluid column must be open to the air to avoid formation of a siphon. From the overflow the fluid drains through a simple flowmeter* into the right venous reservoir, the level of which indicates the pressure in the right 'atrium' (RA). Blood from the right 'atrium' goes to the right 'ventricle' (RV), to the 'pulmonary artery' (PA) and then through another distensible tube. The height of this tube is only 26 cm., corresponding to approximately 20 mm. of Hg. Fluid from the right overflow is routed back to the left venous reservoir; the fluid level in the left venous reservoir indicates the pressure in the left 'atrium.' From there the fluid goes to the left 'ventricle' and the circulation is completed.

If the descending tubes are crossed over from left to right as in the diagram, the output of left and right 'ventricles' can be compared. In properly designed mechanical artificial hearts, an equilibrium is produced which stabilizes the left and right venous pressures at certain levels. If equilibrium exists, the flow rates on the right and the left sides must necessarily be the same, and a single flowmeter will serve both sides.

With this simple system of mock circulation we have been able to evaluate roughly the properties of several models of artificial hearts.[2] The solenoid heart†[3] proved to have too much suction; this was remedied by removing certain springs. A pendulum type of artificial heart seemed to fulfill the criteria postulated at the beginning of this paper, and subsequently proved satisfactory in an animal experiment. A roller type of artificial heart was satisfactory; a fourth type of artificial heart‡ is currently being tested.

The same equipment, minus the flowmeter, can be used for in vitro tests for hemolysis[4] if certain precautionary measures are taken to prevent formation of foam and froth in the overflow or descending lines. If the crossing over is eliminated and each descending line is returned to its own venous reservoir, the degrees of hemolysis in the left and the right sides can be compared.

Summary

The mock circulation to test artificial hearts makes it possible for the left ventricle to pump against a diastolic pressure of 82 cm. of fluid and for the right ventricle to pump against a diastolic pressure of 27 cm. of fluid without constriction in the lines. Thus a stable system is obtained in which the pressures are to a large extent independent of variations in cardiac output. The fluid levels in the venous reservoirs indicate the venous pressures available to the right and left atria. The heights of the aorta and pulmonary artery can be varied, thereby altering the diastolic pressure to be overcome. Crossing over makes it possible to measure the flow rates on both sides with one flowmeter, once equilibrium is established.

**Manufactured by Fisher and Porter Co., Hatboro, Pennsylvania; Precision Bore Flowmeter Tube No. B-4-97-10/77.*

†Manufactured under the guidance of Mr. Harry Norton by Thompson Ramo Wooldridge Inc., 23555 Euclid Avenue, Cleveland 17, Ohio.

‡Manufactured by Curtis Industries, Inc., 1130 East 222d Street, Cleveland 17, Ohio.

References

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