APOLLO DOUBLE DIAPHRAGM PUMP FOR USE IN
ARTIFICIAL HEART-LUNG SYSTEMS

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The pump used to circulate fluid for thermal control in the astronauts' space suits for the moon landing program is being investigated for adaptation to extracorporeal heart-lung systems as well as in implantable artificial heart-lung systems. The results from our study are reported herein.

Several adverse physiologic effects occur in prolonged pumping of blood with a mechanical pump. These problems include hemolysis, "ghosts" (envelopes left over after red blood cells disrupt), anemia (decreased number of viable red blood cells), increased viscosity, protein denaturation (particularly albumin destruction), increased plasma turbidity, lipemia, and platelet abnormalities (especially thromboembolism and shortened survival of platelets) (1, 2, 3).

Pumps that have been tested for use in heart-lung systems include the roller pump (4), the single diaphragm pump (5), the ventricle pump (6), the impeller pump (7), the tube compression pump (8) and the cam-driven finger pump (9). The amount of hemolysis is the criterion most often applied to evaluate such pumps. In keeping with the studies of investigators of other pumps, we have limited the assessment of the pump used in our study to the degree of resultant hemolysis rather than to the other factors described in the preceding paragraph.

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PUMP DESIGN

The pump designed for the Apollo program incorporates properties that are desirable for a heart-lung system (10). These qualities include low weight, small size, high efficiency, high reliability, and direct current operability. This pump, the Apollo double diaphragm pump (ADDP) (Fig. 1) is a double-acting, positive displacement, diaphragm type with a constant flow rate of 2850 ml per minute. As shown in Figure 2, two Dacron diaphragms, coated with butyl rubber, are attached at the end of an oscillating beam mounted on a torsion bar. Each diaphragm covers a chamber equipped with inlet and outlet check valves.

While one diaphragm is pressurizing its chamber, thereby opening its outlet valve, the other diaphragm is providing suction to the alternate chamber opening its inlet valve. When the oscillating beam moves in the opposite direction, each chamber reverses its function. The resulting two pulsatile streams are combined to produce a nearly constant flow.

The pump "motor" is unconventional. Part of the oscillating beam is the armature for a two-position solenoid. The solenoid is actuated by an integrated electronic circuit at the natural frequency of the oscillating beam resulting in high efficiency. The "motor" and electronic components are in a separate compartment providing the advantages of being isolated from the blood being pumped.

TEST PROCEDURE

Hemolytic Index

Hemolytic index (HI), suggested by Allen (11) in 1958, is defined as the amount of hemoglobin in milligrams released into the plasma in pumping 100 ml of blood (12), and is given by

\[ HI = \frac{(100-Hct) \times C}{100} \times \frac{V}{Q \times t} \]
\[ C = \text{increase in plasma hemoglobin concentration in milligrams per 100 ml plasma during a test time } t \text{ (in minutes)} \]

\[ V = \text{volume in milliliters of total circulating blood} \]

\[ Q = \text{quantity of blood pumped in milliliters per minute} \]

\[ \text{Hct} = \text{hematocrit} \]

**Test System**

A standard procedure used to evaluate pumps in terms of HI was used (4). Tygon tubing (3/8 inch inner diameter and 1/2 inch outer diameter), 12 feet long, was connected between the output and input of the pump in a closed loop. The major portion of the tubing was wrapped as a helix with the top of the helix 60 cm above the base of the pump (Fig. 3).

**Technique**

All tests were done at room temperature. Fresh canine blood with a hematocrit of more than 35 percent was introduced into the test system until no air remained in the pump chambers or tubing. Plasma hemoglobin was determined in the standard manner using a hemophotometer (Fisher model 55). After three minutes of pumping in the test system, a control sample for plasma hemoglobin and hematocrit determination was drawn with the pump running. The time at which the first sample was taken is designated as "zero time." Additional samples were drawn at 1, 3, 5, 35, 60, 90, and 120 minutes after "zero time."

The change in plasma hemoglobin, C, for each sample was measured with respect to the "zero time." The pump system was thoroughly washed with water at the end of each experiment.
RESULTS

The results of five tests are shown in Figure 4. The average HI at the end of 35 minutes (time required to pump 100 liters) was .0032, at 60 min. = .0030, at 2 hours = .0027. Variation in five tests after 15 minutes remained within .0005. Microscopic examination of the blood samples qualitatively confirmed that relatively few red blood cells had been disrupted.

Following the five tests shown in Figure 4, four additional tests run at an average flow of 3150 ml/min. had an average HI at 60 minutes equal .0015 shown in Figure 5.

DISCUSSION

In a review by Hasting in 1966 (5), pump performance is reported in terms of HI and flow rate. The HI ranged from 0.09 to 5.31, with flow rates up to 3.5 liters per minute. Other results from the literature for HI in pump experiments are shown in Table 1. The average hemolytic index of .0032 for the Apollo double diaphragm pump was over ten times better than the best value for the other pumps, which was 0.04.

Recently, Bernstein et al (12) reported that the HI for their centrifugal pump was improved to 0.004 by utilizing special design features including increased flow rate and coating the pump housing and catheters with blood compatible surface material.

Because it was desired to obtain a baseline evaluation of the ADDP, the pump was not modified in any way nor was it preconditioned with anticoagulant or antihemolysis agents or coatings. The low HI achieved in these experiments suggests that the ADDP can be adapted for use in existing heart-lung machines.
The ADDP was selected by the National Aeronautic & Space Administration for the Apollo program because of its high overall efficiency. Inherent in such high efficiency are the qualities of low power consumption and low heat generation. Although temperatures of the blood and pump were not recorded, the pump (as determined by touch) remained essentially at room temperature throughout the tests.

The pump is designed to work from a 16 volt power source. This permits portability and emergency operation from batteries in case of a primary power failure. The electromagnetic device which actuates the mechanical part of the pump lends itself to design improvements in size and efficiency.

Current research is directed toward in vivo testing and variations of the pump frequency, displacement, and pulsatile signature. Changes in pump materials are being investigated to improve blood compatibility.

CONCLUSION

The Apollo double diaphragm pump has been evaluated for use in heart-lung systems. Hemolysis as measured by hemolytic index is less than that reported for any other pump. It is anticipated that modifications of the pump will provide further improvement in performance.

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**TABLE 1**

**HEMOLYTIC INDEX FOR OTHER PUMPS**

<table>
<thead>
<tr>
<th>Pump</th>
<th>HI</th>
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<tbody>
<tr>
<td>Imico roller</td>
<td>0.16</td>
</tr>
<tr>
<td>Olson roller</td>
<td>0.08</td>
</tr>
<tr>
<td>Med-Science roller</td>
<td>0.04</td>
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<tr>
<td>Sarns roller</td>
<td>0.04</td>
</tr>
<tr>
<td>Sigmamotor TM-2 finger</td>
<td>0.60</td>
</tr>
<tr>
<td>Bluemle triple ventricle</td>
<td>0.09</td>
</tr>
<tr>
<td>Dorman silastic ventricle</td>
<td>0.13</td>
</tr>
<tr>
<td>Cam-driven plungers (ventricle)</td>
<td>0.85</td>
</tr>
<tr>
<td>Ormonde-mono rotor</td>
<td>1.91</td>
</tr>
</tbody>
</table>
REFERENCES


LEGENDS

Fig. 1 Apollo double diaphragm pump.

Fig. 2 ADDP isometric projection. (Courtesy of M. Carson, reproduced with permission of NASA.)

Fig. 3 Test system.

Fig. 4 ADDP hemolytic index results.

Fig. 5 ADDP hemolytic index results.
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