DEVELOPMENT OF ELECTRIC AND ELECTROHYDRAULIC HEARTS FOR FUTURE HUMAN APPLICATION


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INTRODUCTION
After 2 decades of research (1) for a total artificial heart (TAH), the pneumatically driven heart has achieved consistent surgical success with design, implantation and routinely reliable postoperative care (2,3). More recently, 2 calves lived for over 6 months. Two-month survival rate is now 65%, and the surgical mortality is less than 20%.

However, the electrically powered devices are the most promising for eventual human use (4), because of the best potential for miniaturization of their power source. In contrast the pneumatic power source cannot be miniaturized as well, and requires large, transcutaneous air drive lines. The Department of Energy (DOE) has successfully developed an effective and reliable blood pump which has been implanted in calves (5). Additionally, the integrated electrical energy convertor has successfully been developed. It is very small and can drive mechanically the DOE blood pump in the chest (Fig. 1). The electrohydraulically driven heart (Fig. 2), using a reversing axial flow pump energy converter, has also been developed.

Key Words: 1) artificial heart, 2) electric heart, 3) electrohydraulic heart.

MATERIALS AND METHODS

A. PROSTHETIC DEVICES

The DOE blood pump consists of a Silastic soft shell and diaphragm, and drives ventricles alternately. It has been used in both the in vitro and the in vivo studies. The Jarvik-5 (J5) blood pumps, which are made of polyurethane (with rigid housings), also have been used in both studies with the electrohydraulic energy convertor. The DOE blood pump, including the Scotch yoke system, without a long, flexible driving shaft, utilized for the integrated DOE heart, but the cooling system is eliminated. Three small wires connect the integrated heart and the implantable controller (5 x 5 x 2.5 cm) and the extracorporeal power source and monitoring systems.

The electrohydraulic pump is connected to the extracorporeal controller, power source and automatic feedback system with 3 small, electric transcutaneous wires. J5 ventricles also are utilized for the axial flow pump by using relatively large drive tubes at the bases (Fig. 3). Hydraulic fluid was primed in the bases under the diaphragms. Plain water was used as the hydraulic fluid.

B. EQUIPMENT TO DRIVE THE PUMPING DEVICE

The extracorporeal power control system, automatic feedback system, and heart beat monitoring and power requirement systems, have been made for both the new electric heart and...
the electrohydraulic heart, in this laboratory, by including the same kind of alarm systems and emergency supply systems as the pneumatic heart has.

Figure 3. Hemodynamic changes with the modified DOE blood pump in the mock circulation system. LA pressure stays below 40 mm Hg, and 15 mm Hg.

C. IN VITRO STUDIES

For in vitro evaluation of both hearts, the Donovan double-sided mock circulation system has been used to determine the standard function curve with various filling pressures, from -5 to +20 mm Hg. The Donovan mock circulation system simulated the calf's circulatory system, including the resistance of systemic and pulmonary arterial vessels, and the compliance of both venous and arterial systems, by using 4 air chambers in the closed circuit, and fluid flow orific control valves, which can control resistance of blood flow by manual selection and automatic adjustment of the system, beat by beat (6). The following standard driving conditions have been used: 110 mm Hg mean aortic pressure, and 25 to 30 mm Hg mean pulmonary artery pressure. Heart rate was 120 beats/min with the DOE blood pump and 90 beats/min with the Jarvik-5 blood pump. Four Bjork-Shiley valves were used in the inflow and the outflow positions.

D. IN VIVO STUDIES

The new DOE heart with an integrated brushless DC motor and control system has been implanted in 4 calves weighing 105 to 120 kg. The electrohydraulic heart has not been used in vivo yet. In anesthetized animals the natural heart was exposed through the right lateral thoracotomy, excising the fifth rib. The natural heart was excised, saving the natural outflow valves in situ, and replaced with the TAH using quick connect systems. Under total extracorporeal perfusion with mild hypothermia (32° C). The blood pump device was placed in the chest close to the diaphragm, and was fixed to the sternum with umbilical tape or stainless wires, to avoid the rotation of the blood pump. Those surgical procedures were necessary because of its large volume (1000 ml) and heavy weight (1200 gm filled with blood). Pumping of ventricles was started at the same time, immediately after replacing all the air bubbles in the ventricles with blood. The blood in the heart-lung machine was slowly returned to the body, increasing heart rates up to 110 beats/min. The extracorporeal perfusion was disconnected and removed. The chest was closed in the usual fashion. Postoperative care was started immediately after the animal was placed in the holding cage. The respirator was disconnected as soon as possible after the animal awoke from anesthesia, and extubated. Both mean pulmonary and systemic venous pressures were kept between 0 to 5 mm Hg. The animal was allowed free food and water, even immediately after extubation. Antibiotic therapy was started immediately after surgery with penicillin and streptomycin. Anticoagulant therapy on the postoperative second day (dipyridamole, aspirin and warfarin).

E. HEMODYNAMIC AND BLOOD STUDIES

Regular blood chemistry and hematology studies were performed 3 times a week for 2 weeks. A multichannel autoanalyzer was used to quantitate levels of 15 different blood or serum components. Numerous hematologic factors were examined: platelet count, percent adhesiveness, fibrin degradation products, circulating platelet aggregates, plasma hemoglobin, fibrinogen, prothrombin time, and partial thromboplastin time. Femoral artery and venous catheters were usually removed in 24 hours. Indwelling pressure and sampling taps were built into the atrial cuffs and right ventricular outflow tracts. The left coronary artery afforded an excellent portal to the aorta for an aortic pressure line. The recording of hemodynamic parameters was obtained both at rest and during exercise on the treadmill.

F. AUTOPSY STUDIES

Complete autopsies were performed at the termination of the experiment in the suspended position.

RESULTS

A. IN VITRO STUDIES

1. The New DOE Heart: Efficiency of the DOE-type ventricle has been measured at approximately 75%. The efficiency of the brushless DC motor which was designed for the integrated electrical energy converter is 45%, including electronics efficiency. The efficiency of the Scotch yolk and crank shaft energy converter system is over 90%. So the total efficiency of the new DOE heart is approximately 25 to 30%. The mean power requirement to drive the new DOE heart was about 18 watts (with 4 Björk-Shiley valves), and 14 watts (using the 2 natural outflow valves). To provide a standard performance criteria for evaluating the DOE-type ventricle, an ideal performance standard or desiderata for the blood pump performance has been established. When the right and left
soft Silastic ventricles had the same stroke volume, pulmonary artery and venous pressures increased sharply, with increased right atrial pressure. Also, cardiac output at low right atrial pressure is higher than necessary. After careful analysis, a primary cause of this imbalance in performance with the same stroke volumes in both ventricles was attributed to the observation that under general conditions the right ventricle outpumped the left ventricle, resulting in the elevated pulmonary pressures. The mock circulation tests demonstrated the left-right imbalance to be about 10%. Sources of imbalance were traced to valve regurgitation and distension of the soft-shell ventricular components. For redesign of the DOE blood pump, the pusher cup displacement was reduced 8.5% in the right ventricle and the soft shell snout of the left ventricle was made rigid using glass epoxy reinforcement to reduce distension. With the modified DOE blood pump, pulmonary arterial and venous pressures were reduced approximately 50% at both low and high right atrial pressures in the range of -5 to +20 mmHg, and were maintained below 40 mm Hg (PA) and 15 mm Hg (PV) in the mock circulation system, using the new integrated DOE heart (Fig. 4).

Figure 4. The operating cycle of the reversing axial flow pump. The Phase B indicates left ventricular systole and Phase E indicates right ventricular systole.

2. The Electrohydraulic Heart: The predicted behavior of the axial flow pump was very close to the measured performance of the pump. The specified design point for the pump was 36 l/min of flow at 175 mm Hg, outflow pressure at 7.5 rpm. This was the point selected to achieve maximum efficiency, as measured in the actual tests. The peak efficiency of 40% was the overall machine efficiency of the axial flow pump, including losses associated with running the brushless DC motor with the back EMF (electric motion force) feedback system immersed in fluid.

Figure 5 illustrates the operating cycle of the reversing, electrohydraulic energy converter. During Phase A the pump is accelerated to full-speed, clock-wise rotation. The pump output is seen to slightly lag behind the impellor, speed during Phase B. Hydraulic fluid is pumped from the right to the left, corresponding to the left ventricular systole and right ventricular diastole. During Phase C the pump impellor is decelerated and during Phase D is accelerated in the opposite direction. This reverses the direction of the flow of the hydraulic fluid which, during Phase E, is pumped from left to right. During Phase F the motor is again decelerated and one full cycle has been completed. The mock circulation tests have demonstrated that the duration of Phase A and Phase D is less than 50 msec with the small atrial flow pump energy converter, and the system can pump up to eleven 1/min at 120 beat/min using the DOE-type blood ventricles. Heart rates could be increased up to 150 beats/min with full-stroke pumping.

B. IN VIVO STUDIES

The new DOE heart fits well in the chest, although both inflow and outflow tracts were displaced a little anteriorly without obstruction or kinking. All of the 4 Holstein calves recovered from the surgery quickly and could stand up in 5 to 7 hours postoperative. There was no serious trouble with displacement of the ventricles as previously seen with the motor and long drive shaft. Blood chemistry and hematology studies demonstrated the regular values of postoperative courses of healthy calves having a TAH. All of them died of mechanical failures within 2 weeks postoperative. Two had trouble with the speed control pump, one had a broken wire, and another had artificial valve failure. The speed control failure was caused by electric component failure. After the 5th and 7th postoperative day, automatic heart rate became unstable at a range of 90 to 150 beats/min. It was a failure that had not shown up on mock circulation testing. The breaking of an electrical lead was caused by fluid infiltration into the percutaneous lead via a small cut. The artificial valve failure was caused by valve ring transformation on which a disc stuck.

At autopsy, the soft shell ventricle was not collapsed and the remnant inflow and outflow tracts, although the pump device had been placed close to the right chest wall, the diaphragm and the inferior vena cava. In the case with valve failure, several fresh blood clots were found in the Silastic ventricle inflow tract.

DISCUSSION

Little work has been done with electrically powered total artificial hearts. The greatest experience with these electrically powered devices, however, is in this laboratory using the DOE heart. The DOE device was developed to mate with an atomically powered system (7) and has been implanted in 33 calves since 1972, using a large, abdominally placed electric motor to simulate the atomically powered thermal converter. The longest survival with this system has been 37 days. The major problems were the large, heavy, abdominal
were not excellent. All of the 4 calves died has been markedly improved by the incorpor-

motor increased the incidence of infections but uncompressible drive shaft, resulting in

problems which chronic experiments of the relative to TAH's, including many of the

animals experiments with the new DOE heart done were not excellent. All of the 4 calves died of mechanical failure within 2 weeks postoperative. The surgical and postoperative manage-
ment was very simple and sufficient, almost the same as or better than the air-driven heart requires. A few small drive wires increased mobility of a calf and reduced pain and infection around an implanted blood pump device than with the old DOE heart or the air-driven heart. Displacement of the pump device has not occurred in these animal experi-
ments. Alternate right-left pumping with the electric heart has been acceptable. This has been proved also in the several animal experi-
ments with an air-driven heart. The calves with alternate pumping of the J5 ventricles that survived for nearly 3 months demonstrated normal data of blood chemistry and hematology, and normal exercise. The electrically power-
ed TAH's could provide adequate cardiac output to permit moderate exercise. One of the 4 calves walked well on the treadmill before dying. If mechanical failures could be solved, the outcome of the surgery would be improved greatly.

Mock circulation studies are now impro-
ving the durability of the new DOE heart and function of the electrohydraulic heart. Hopefully in the next 5 years we will use those devices routinely to study all areas relative to TAH's, including many of the problems which chronic experiments of the pneumatic heart have brought up to date, and have to be solved or answered before and/or after human application of TAH's. Also, battery-powered electric hearts will be studied in this laboratory, including automatic switchover to back-up batteries, and recharging studies with percutaneous leads and cable connectors. For future human applicat-

we expect that the entire circulation of the patient should be carried to allow good mobility and exercise of the recipient, so that he can look forward to a reasonably enjoyable and comfortable life with the TAH (8). Electrically powered TAH’s can meet long-term physiological requirements. When the artificial heart is able to be produced with some confidence in its quality, the ultimate decision will have to be made by the future recipient after having provided him and his family (and his personal physician) with the best informed consent that is known.

CONCLUSIONS

Recently, after two decades of research, consistent experimental success with the im-

plantation of the TAH has been achieved, using the pneumatically driven heart, and has sug-
gested that human application is getting closer to a reality, with a reasonably en-
joyable and comfortable life. However, in-
fection and septic thromboembolism in the pneumatic TAH are related to the use of large percutaneous air drive lines, and the power sources of air driven hearts cannot be mini-
turized to be portable or implantable. In contrast, the electrically powered devices are the most promising for eventual human use. We are studying 2 of the most successful electric hearts: the new ERDA heart and the electro-
hydraulic heart using an axial flow pump. The electric hearts have provided excellent re-

results in both in vitro and in vivo studies. We believe that the future recipients will have a more enjoyable and comfortable life with electric hearts.

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