TOTAL MECHANICAL REPLACEMENT OF THE HEART IN CALVES

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"Perhaps most dramatic of all, research efforts are now being directed towards the development of an artificial heart to replace a diseased heart. . . . This challenge —as exciting as any across the entire range of science—is enormously complex. . . . The goal is feasible; the problems are not insuperable."[1]

Artificial hearts inside the chests of animals, replacing the natural heart, have been developed at the Cleveland Clinic since 1957.[2] Currently, an artificial heart has been made that fits inside the pericardial sac of a calf. Thus, it does not encroach upon the space normally occupied by the lungs. Calves were selected because the size of the heart required is the same as in the adult human, and also because the problems with thrombosis are perhaps less difficult than in dogs.

It would be of great importance if more investigators would enter the field. Basic surgical experiments can be done and much useful experience can be obtained with the use of equipment developed earlier in our laboratory and now made available to other investigators through the National Heart Institute.** It is not implied that this equipment is perfect, or ready for clinical use. This paper, however, will show that it can be used in calves. We hope that other investigators will help to improve it.

Total replacement of the natural hearts of calves was accomplished with two different artificial hearts and three different driving systems. The following three combinations were used.

1. Composite heart, handmade, driven by the servomechanism developed for us by the National Aeronautics and Space Administration (NASA), Lewis Research Center.[3]

2. Composite heart, handmade, driven by an air-valve mechanism developed at the Cleveland Clinic and made by the Detroit Coil Corporation.††

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***The National Heart Institute has given contracts to industry so that Silastic hearts to be used inside the chest, and driving mechanisms to drive these hearts, could be produced. This is the first time that such an attempt has been made to get more investigators interested in these problems. Dr. Frank W. Hastings of the National Heart Institute, National Institutes of Health, Bethesda, Maryland, administrates the program. Investigators wanting to participate in the coordinated, experimental, surgical application of mechanical hearts inside the chest are advised to communicate with him.*
††Available through the National Heart Institute.

3. Injection-molded Silastic heart developed in collaboration with and made by The Holter Company* and driven by a reciprocating pump invented by Mr. S. Harry Norton and built by the Thompson Ramo Wooldridge Company (T.R.W.).[4]

The composite artificial heart is a further development of the sac type of artificial heart made by the layering technic with Dacron-reinforced Silastic developed and described by Akutsu and associates.[5] The shape of the ventricles was redesigned; the positions of the great vessels were changed; and teardrop valves instead of ball valves were used. When the right and left hearts are put together they look like the normal heart of a calf (*Fig. 1*). Their size is so compact that they can be accommodated inside the pericardium (*Fig. 2*). This heart has been described in detail by Akutsu and associates.[6]

The injection-molded hearts are made of Silastic and have ball valves built inside the one-piece heart.

Materials and Methods

Three young calves that each weighed between 140 and 160 pounds were used. The technics of anesthesia, surgery of replacement of the natural heart, and the extracorporeal circulatory support by disc oxygenator and roller pump during the period of occlusion of the big vessels were those as previously described.[7]

After the artificial heart in the chest was connected, it was set to pump with a low output, to obviate the pulmonary complications that marred the previous experiments with artificial hearts in calves.[8] A major part of the circulation was still supplied by the heart-lung machine. The output of the artificial heart was gradually increased when the samples from the left atrial return were found satisfactory in regard to oxygen saturation. As the output of the artificial heart was increased, the flow from the heart-lung machine was reduced proportionately. When the output reached a level considered enough for the calf, and the lung oxygenation was adequate, the heart-lung machine was stopped and the calf was entirely dependent upon the efficient function of the artificial-heart pump. Pulmonary complications in calves cannot always be avoided; they may occur despite the utmost care.

Results

In the first experiment a composite heart was assembled inside the chest of a calf. It pumped for 2 hours and 10 minutes and then it ruptured, but the artificial heart fitted into the pericardial sac and it appeared that it would not be difficult to assemble the three components of each side of the heart before insertion. In the second experiment this was done, and the heart was driven by the Detroit Coil driving mechanism (*Fig. 3*). It pumped for 3 hours and 22 minutes, and the heart-lung machine was stopped 1 hour and 48 minutes after the artificial heart started

**Available through the National Heart Institute.*

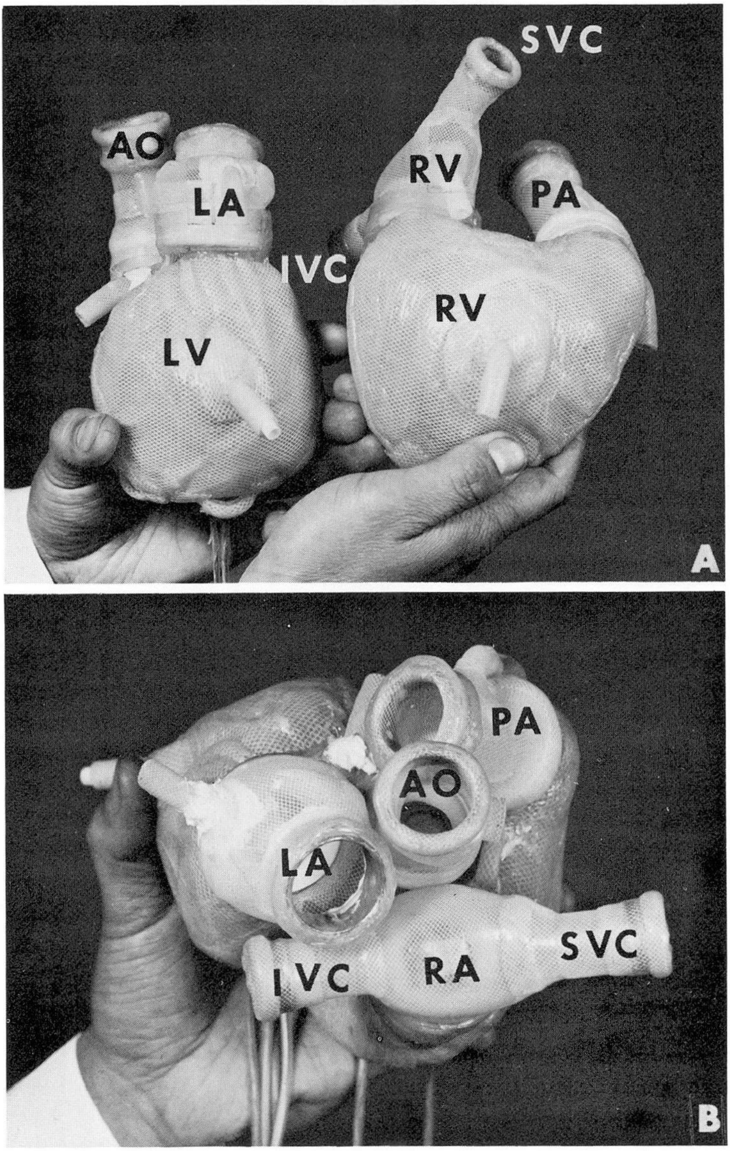

Fig. 1. A, Composite heart designed and made by Akutsu: (LV) left ventricle, (LA) left atrium, (AO) aorta, (IVC) inferior vena cava, (RV) right ventricle, (RA) right atrium, (PA) pulmonary artery, (SVC) superior vena cava; B, Composite heart designed and made by Akutsu. (LV) left ventricle, (LA) left atrium, (AO) aorta, (IVC) inferior vena cava, (RV) right ventricle, (RA) right atrium, (PA) pulmonary artery, (SVC) superior vena cava. (Courtesy of SenGupta, A., and Kolff, W. J.: Synthetic substitutes for artificial organs. Discovery 26: 38-43, 1965, and T. Loftas, editor, London, England.)

Fig. 2. Composite heart inserted into the chest of the calf. Pericardium is closed. Tubes for pressure measurements in different chambers of the heart emerge from the chest. (AL) air tube connecting the air chamber of the left heart to the driving mechanism. (AR) air tube connecting the air chamber of the right heart to the driving mechanism.

pumping. Oxygenation was satisfactory and the chest was closed. The calf was about to be turned on its feet when the float of the pulmonary valve became dislodged from its housing and the experiment was terminated. In the third experiment a Holter heart was used (*Fig. 4*). It pumped for 3 hours and 30 minutes after insertion, and for 2 hours and 30 minutes after the heart-lung machine was stopped. This heart was driven by the T.R.W. reciprocating pump[4] (*Fig. 5*). The pressure curves obtained from the three systems are shown in *Figure 6*.

Conclusion

From the experiments performed we have drawn the following conclusions.

1. The composite heart is ideal in shape, size, and positions of the inlets and outlets for insertion into the calf's chest. For proper functioning of the position transducer, the left and right hearts should be made into a single composite one so that there is no relative displacement between the coils of the two hearts. (The composite heart is undergoing further modification.)

2. Minor modifications have to be made of the existing Holter heart, in regard to the position of the big vessels. More experience with experiments on artificial

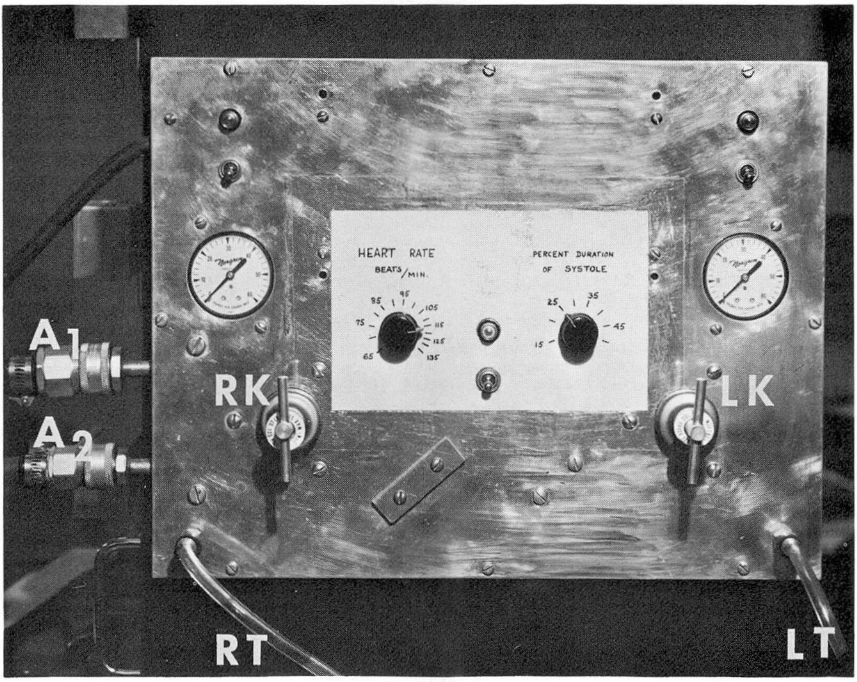

Fig. 3. Detroit Coil driving mechanism for artificial heart: Pulsations are created by solenoids; heart rate and percentage duration of systole of each cycle are electronically controlled; (RT) tube connecting the air chamber of the right heart, (LT) tube connecting the air chamber of the left heart, (RK) controlling knob for adjusting the compression force of each stroke of the right ventricle, (LK) controlling knob for adjusting the compression force of each stroke of the left ventricle, (A_1) hose delivering compressed air, and (A_2) hose connecting a suction pump.

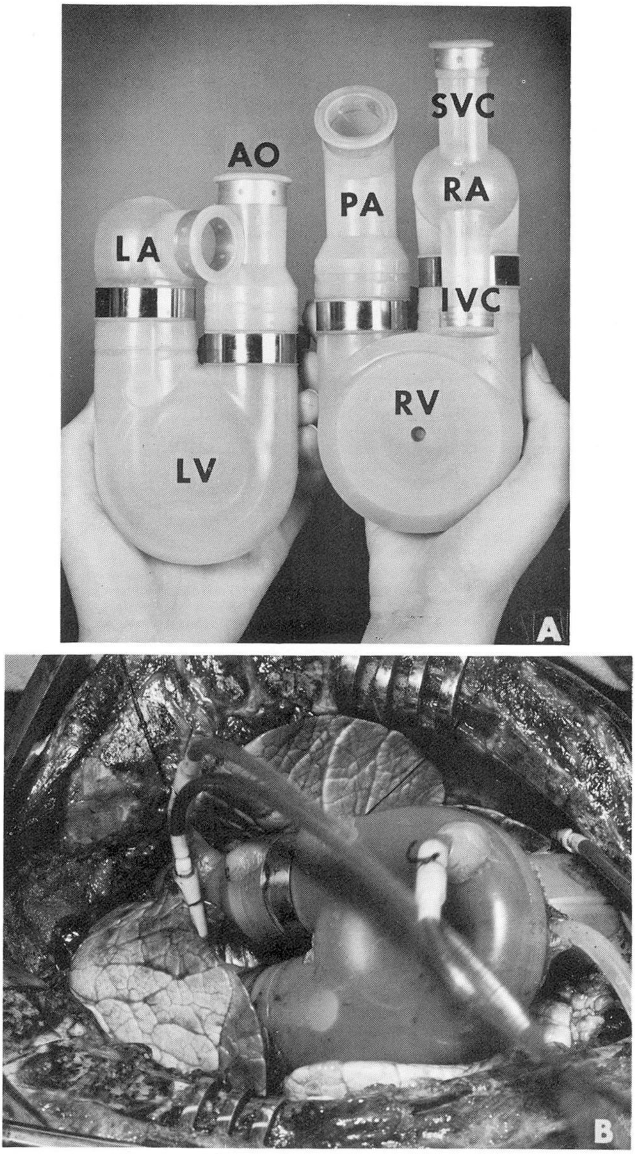

Fig. 4. A, Silastic hearts made by the injection mold technic by The Holter Co.: (LA) left atrium, (AO) aorta, (PA) pulmonary artery, (SVC) superior vena cava, (LV) left ventricle, (RV) right ventricle, and (RA) right atrium, (IVC) inferior vena cava. B, Holter heart inserted into the chest of a calf, supporting calf's total circulation. The right heart is above the lower end of the left heart.

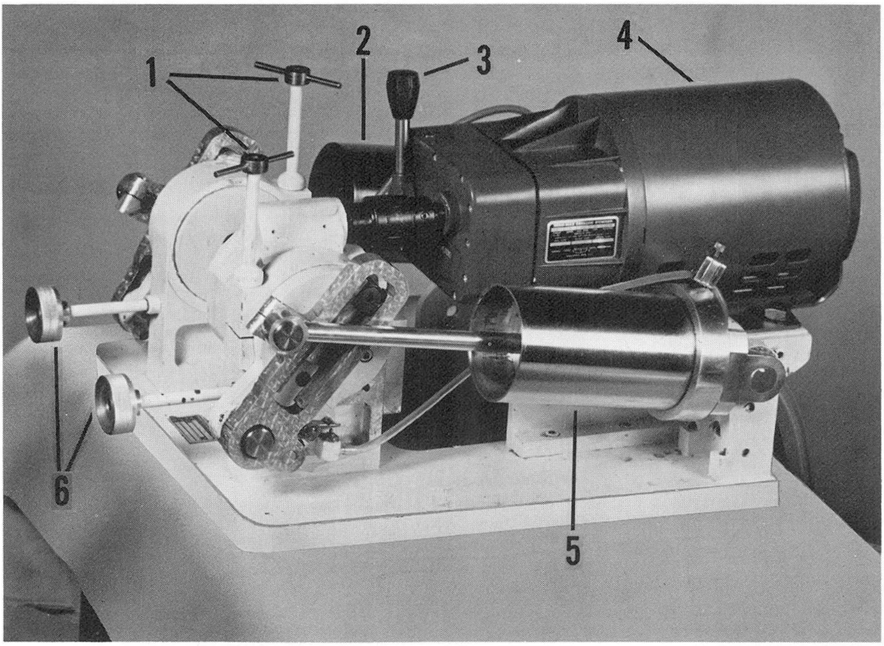

Fig. 5. T.R.W. reciprocating pump: (1) fixation screws to regulate stroke duration, (2) left heart cylinder, (3) handle to adjust rate of pumping, (4) motor, (5) right heart cylinder, and (6) knobs for adjusting stroke length. (Courtesy of Panayotopoulos, E. K.; Norton, S. H.; Akutsu, T., and Kolff, W. J.: Special reciprocating pump to drive artificial heart inside chest. J. Thoracic & Cardiovas. Surg. **48:** 844-849, 1964, and The C. V. Mosby Company, Publishers, Saint Louis, Missouri.)

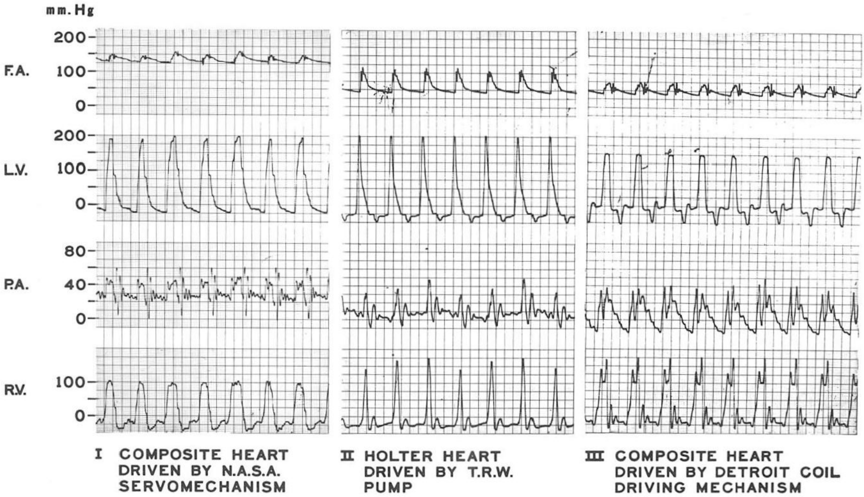

Fig. 6. Pressure curves from calves after total circulation was maintained by artificial hearts inside the chest; (F.A.) femoral artery, (P.A.) pulmonary artery, (L.V.) left ventricle, (R.V.) right ventricle.

hearts in calves is urgently needed. The calf has a heart of adult human size; its clotting problems are less complex than those occurring in dogs, and blood is abundantly available to prime the heart-lung machine. It is hoped that more laboratories in the United States will begin to participate in the studies, now that both mechanical hearts and driving mechanisms are available.

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