Irreversible heart failure is focusing attention to the need for mechanical assistance, not only for a short period of time, but for long-term support. We have previously reported on the implantable left ventricular bypass pump which requires no anticoagulants (1, 2, 3, 4). The pump was designed to maintain support for periods of weeks or months.

The prerequisites of an implantable circulatory pump to support left ventricular function have likewise been outlined and previously reported (3). They are as follows:

1. Long-term support of ventricular function (weeks, months?).
2. Avoidance of heparinizing the patient.
3. Minimal amount of blood trauma.
4. Feasibility of discontinued function of the implantable pump for certain time intervals (hours, days) with normal resumption of its function afterwards. This should be accomplished without general heparinization of the patient and without danger of clotting the pump.
5. Possibility of pumping being synchronized with any preselected time of the cardiac cycle.
6. Surgical technique of implantation which is simple and safe for the patient.

In this report, preliminary physiological observations and clinical comment are presented from the initial phase of an active study in progress.

The physiology of the left ventricular extracorporeal bypass was studied, and compared with similar observations obtained from implanted intrathoracic circulatory pumps.

METHODS

Fifty mongrel dogs were used for the left ventricular extracorporeal bypass and twelve for the implanted intrathoracic circulatory pump. Included are data from the initial phase of a physiological study of experimental chronic heart failure (E.C.H.F.) (Fig. 1). This study involved (1) arterial-venous fistulas; (2) aortic insufficiency, and (3) mitral insufficiency. From the mor-
A specially designed tubing stand attached to the operating table was used to hold the inlet and intrathoracic segments of the tubing in a constant pre-selected position during the procedure. Blood was returned to a femoral artery through a tapered plastic catheter.

Intracorporeal Bypass of the Left Ventricle

Early models have been previously described (1, 2). The pump consists of (1) an implantable intrathoracic pump (Fig. 2) and (2) an external gas energizing and controlling system. The intrathoracic pump is made of 0.040 inch thick Dacron-reinforced Silastic and consists of a blood chamber surrounded by a gas chamber. The implanted pump is coupled to the external gas system by a small tube brought out through the chest wall. Pressurized CO₂ entering the gas chamber compresses the blood chamber thereby expelling its contents. Ball valves guarding the inlet and outlet cause unidirectional blood flow. The
inlet of the blood chamber is connected to the left atrium (external atrial connection) (Fig. 3) and the outlet to the descending thoracic aorta. Technical details of implantation are reported elsewhere (3).

The external gas system consists of a Teflon bellows powered by an electric motor. A control system has been developed to initiate a pump cycle in response to an EKG signal (Fig. 4). Motor speed control is provided by phase variable firing of silicon controlled rectifiers and has a dynamic braking circuit to bring the motor to a complete stop at the end of each stroke. By adjusting the maximum and minimum speed override circuits, the system maintains synchronization by initiating a stroke from either each EKG signal, every second signal, or every third signal. The speed override circuit also insures continuous operation (not necessarily synchronized) in the event that the EKG rate becomes very high, or is interrupted. Electrocardiographic synchronization can be substituted by a system dependent upon the mean left atrial pressure.

Figure 3. Technique of implantation of the external left atrial connector: The external connector is sutured medially to the appendage base (A), and laterally to the atrial wall (B). Care should be taken to allow an atrial clamp to be placed proximal to this anastomosis without encroaching upon the circumflex vessels (C). D. The atrial appendage and part of the atrial wall was excised.

Figure 4. The tracing shows a diastolic synchronization of an implantable intrathoracic circulatory pump with the electrocardiogram.
The control system is transistorized and employs a minimum of switch and relay contacts. An independent power supply provides for operating the system without synchronization, and a battery powered converter is used to make the entire system portable for periods up to 1 hour.

The following physiological measurements were made (Fig. 5):

- Femoral artery pressure
- Right atrial pressure
- Ascending aortic pressure
- Left intraventricular pressure
- Left atrial pressure

All pressure transducers were calibrated to a baseline by placing the tip of a catheter 0.5 cm below the point of entrance of the left superior pulmonary vein into the left atrium with the dog in right lateral position.

Mean left atrial pressure values were determined during expiration.

Pulmonary Flow Control. A Microflo Medicon Division Model FM-6 flowmeter was employed to measure pulmonary flow using a 14 or 16 mm probe. Prior to each measurement, the electrical zero was corrected and the biological zero was determined by clamping the artery distal to the probe while the probe was surrounded with physiological saline.

Tension-time Index: The Tension-time index was determined by planimetrically integrating in mm Hg secs. the area beneath the systolic portion of the left intraventricular pressure curve which starts with the beginning of the isometric contraction and ends at the point which corresponds with the aortic incisure. All measurements were made on tracings taken at a paper speed of 50 mm/sec.

Ejection-time Index: The Ejection-time Index is a measurement of the amount of tension developed in the myocardium of the left ventricle during the ejection period of systole. As such, it is an indication of the stroke volume of the ventricle. This value was determined by planimetrically integrating the area under the systolic portion of the aortic pressure curve, beginning with the opening of the aortic valve and ending at the aortic incisure. Values are stated in mm Hg secs., and are from tracings taken at 50 mm/sec. paper speed.

RESULTS

Left Atrial Pressure

Left ventricular extracorporeal bypass in each case decreased the mean left atrial pressure. Pump speed was varied to keep mean left atrial pressure (MLAP) slightly positive during expiration. Without constant attention to the pump speed and MLAP, negative pressure developed and resulted in dangerous left atrial suction. Average mean pressure decrease in normal dogs was 2.3 mm Hg (50 per cent). In experimental chronic heart failure dogs, the decrease was 5.7 mm Hg (46 per cent).

A correlation was made between mean left atrial pressure decrease (end-
MLAP was maintained above zero. However, when the MLAP reached zero or below, a succession of small beats in conjunction with abnormally high systolic peaks was observed (Fig. 6).

In fifteen experimental chronic heart failure animals the average MLAP was 16 mm Hg. In this group, the systolic peak of the left ventricle remained unchanged except in one instance when the flow through the bypass was extremely high.

The implantable intrathoracic circulatory pump in each case decreased the mean left atrial pressure. Average mean pressure decrease in normal dogs was 0.55 mm Hg (13 per cent). In experimental chronic heart failure dogs, the decrease was 8 mm Hg (50 per cent).

The correlation between the mean left atrial pressure decrease and the peak systolic intraventricular pressure depended upon the time of synchronization. During independent rate pumping and during systolic pumping, the systolic ventricular peak changed to a mild alternans or to a mild irregular decrease. When only every other R wave was synchronized, a mild alternans was a constant finding (Fig. 7).

**Systemic Pressure**

Left ventricular extracorporeal bypass usually increased mean systemic pressure, though this was not a constant finding. Average mean pressure increase in normal dogs was 1.2 mm Hg (0.6 per cent). In experimental chronic heart failure dogs, the increase was 4.3 mm Hg (7 per cent).

The implantable intrathoracic circulatory pump generally increased the mean systemic pressure. Again, this finding was inconstant. Average mean aortic pressure increase in normal dogs was 3.9 mm Hg (4 per cent); in experimental chronic heart failure dogs, 1.1 mm Hg (1 per cent).

**Tension-time Index**

The left ventricular extracorporeal bypass decreased TTI in all but one animal. The average decrease in normal dogs was 16 per cent; in those with experimental chronic heart failure, 8.2 per cent.

In all animals with the implantable intrathoracic circulatory pump, TTI was decreased. Average decrease in normal dogs was 15 per cent; in experimental chronic heart failure dogs, 3.8 per cent.

**Ejection-time Index**

A decrease in ETI was a constant finding with the left ventricular extracorporeal bypass. ETI in normal dogs decreased an average of 15 per cent; experimental chronic heart failure dogs, 43 per cent.

The implantable intrathoracic circulatory pump also caused an ETI decrease in each case. Normal animals demonstrated an average decrease of 25 per cent; experimental chronic heart failure animals, 36 per cent.
Figure 7. Pressure tracings taken during bypass with implantable pump. Note the mild decrease in MLAP. The pressure pulse from the pump is reflected in the aortic pressure at the same time that the gas system pressure reaches its systolic peak. A. During independent rate pumping. The pump rate is 76/min., and the heart rate is 153/min. Note the pressure pulse from the pump is unrelated to the cardiac cycle. B. During systolic pumping. Note that the pressure pulse from the pump is superimposed on the systolic aortic pressure curve. C. During diastolic pumping. Note that the pressure pulse from the pump occurs during diastole. ETI = crosshatched area; TTI = shaded area.

Pulmonary Flow

Pulmonary flow was measured in two animals with the implantable intrathoracic circulatory pump, and 4 with the extracorporeal bypass. All were normal dogs and no change was observed.

DISCUSSION

The constant observation in both extra- and intracorporeal bypasses has been a decrease in mean left atrial pressure (MLAP). Because they are functionally related, the left ventricular end-diastolic pressure (LVEDP), pulmonary capillary pressure, and pulmonary venous pressure were consequently decreased. However, the correlation between MLAP and the systolic peak of the left ventricular pressure demonstrated that there was a drastic change in myocardial contractility when MLAP was allowed to approach or reach negativity.

The intrathoracic pump avoided an important decrease in MLAP in normal dogs. Indeed, MLAP was constantly autoregulated (2,3). On the other hand, a striking contrast occurred when the bypass was performed in dogs with elevated MLAP (experimental chronic heart failure group). In this group, MLAP was decreased, but not to a pressure below normal, and only slight changes were occasionally detected in myocardial contractility.

There is a discrepancy in the reported results of complete left ventricular bypass when directed toward decreasing the myocardial oxygen consumption rather than allowing an effective myocardial contraction to occur. Unfortunately, the reported work on this bypass used normal dogs and an extracorporeal pump, overlooking the provision of an effective left ventricular filling pressure. It is also evident that the law of Starling (5), which has recently been confirmed in man (6-9), warrants consideration.

It appears that both factors (a decrease or an elevation of MLAP) may result in an impairment of left ventricular contractility.

It is apparent that a mechanism which could continue to maintain left ventricular end-diastolic pressure at a level adequate for an effective left ventricular contraction, and allow decompression of the left atrium and pulmonary venous system, would be of clinical interest (Fig. 8).

TTI showed a decrease during extra- and intracorporeal bypass. The myocardial wall tension (TTI) is the primary determinant of cardiac oxygen consumption (10). However, in both groups the ETI demonstrated an important decrease because the bypass affects predominantly the ejection phase of the left ventricular contraction.

Pulmonary flow remained unchanged except for a brief period at the beginning and end of the bypass. This observation indicated a blood redistribution rather than overload of the right ventricle.
Heart Failure and Implantable Pumps

2. Avoidance of heparinizing the patient;
3. Minimal amount of blood trauma;
4. Synchronization with a preselected time of the cardiac cycle;
5. Possibility of discontinuing the pump in order to correlate its effects;
6. Autoregulation of MLAP.

MLAP was shown to be critical in the provision of an effective ventricular contraction.

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