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Chapter 18

HEART FAILURE AND IMPLANTABLE INTRATHORACIC CIRCULATORY PUMPS: PHYSIOLOGY AND CLINICAL APPLICATION*

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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-

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Figure 1. Experimental chronic heart failure in a dog with arterial-venous fistula. Note the bulging left atrium.

tality standpoint, the best results were obtained by performing two A-V fistulas on one date, followed by a third fistula three to four weeks later.

Extracorporeal Bypass of the Left Ventricle

A left thoracotomy through the fifth intercostal space was performed. Respiration was maintained by a Bird* intermittent positive pressure respirator. Both femoral arteries and one femoral vein were exposed. After heparinization (2 mg/Kg), a partial left ventricular bypass from left atrium to femoral artery was performed, using a calibrated occlusive DeBakey roller pump. Pumping was continued for two hours, and pump speed was varied to keep the mean left atrial pressure slightly positive during expiration. The connection to the left atrium was either by the direct cannulation of the atrial appendage with the bypass tubing (internal connection) or by an external molded Silastic prosthesis (external connection) sutured to the atrium and then sealed with Eastman Adhesive 910.** When the external connection was used, the atrium was clamped and a small disc was excised for the blood to pass into the prosthesis. The external connection was then sealed to an adapter attached to the tubing.

*Manufactured by Bird Corporation, Palm Springs, California.
**Manufactured by Ethicon, Inc., Somerville, New Jersey.

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 preselected 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 CO_2 entering the gas chamber compresses the blood chamber thereby expelling its contents. Ball valves guarding the inlet and outlet cause unidirectional blood flow. The

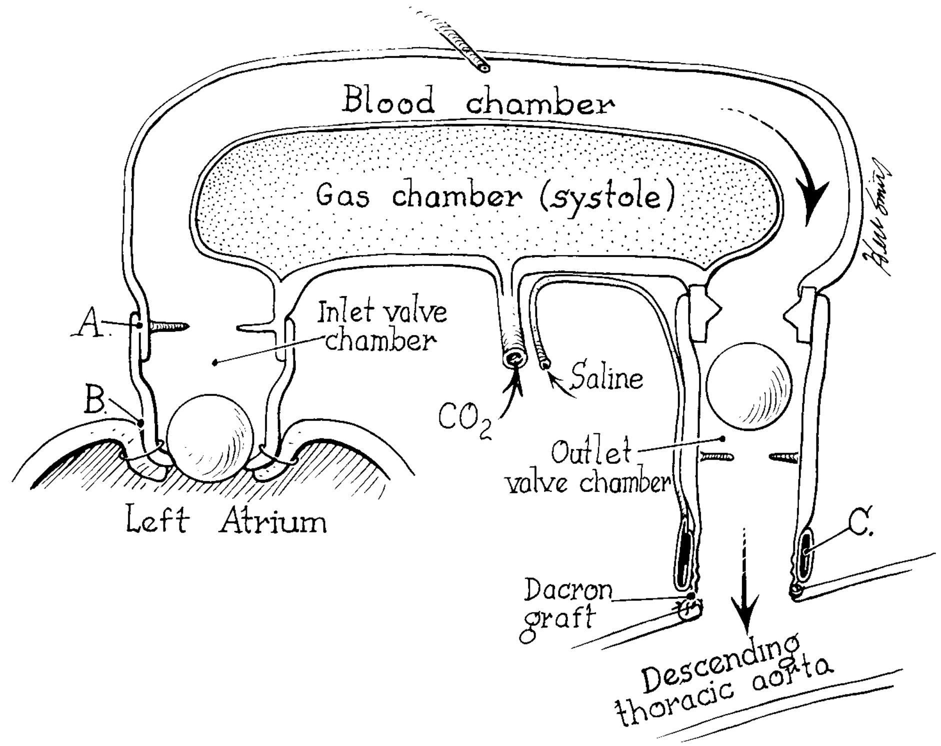

Figure 2. Schematic representation of the implantable pump. A. The inlet valve chamber is sealed to the body of the pump with Eastman Adhesive 910. B. The same adhesive makes the suture line of the inlet valve chamber and the left atrium air-tight. C. Inflatable chamber for occluding the outlet connection, allowing the isolation of the pump from the systemic circulation.

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 initate 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.

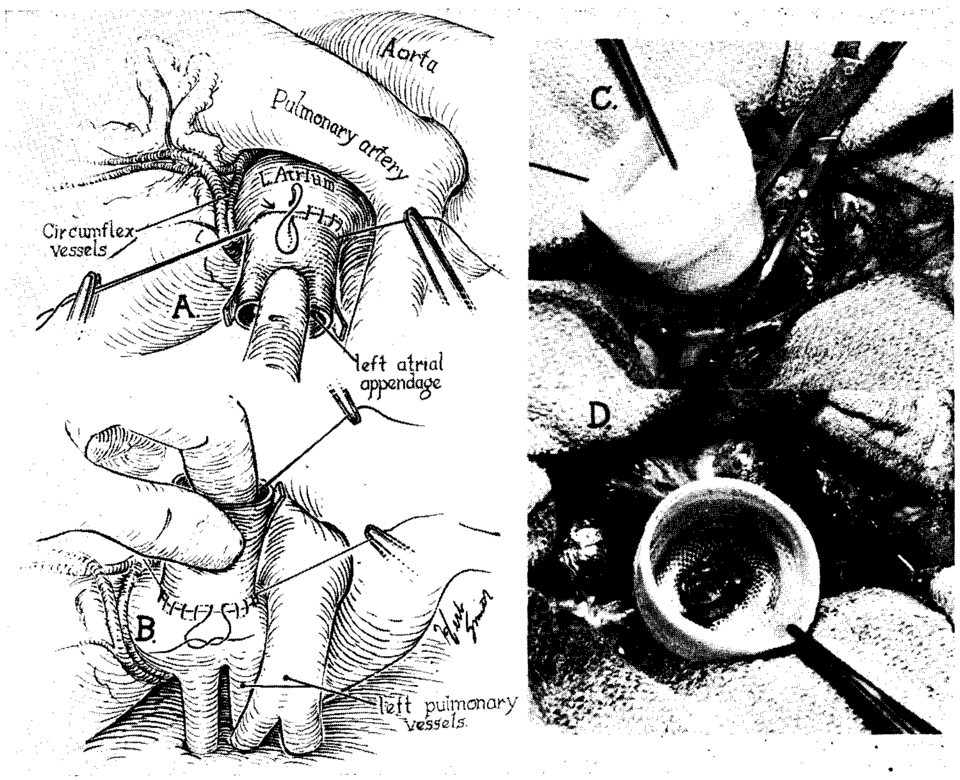

Figure 3. Technique of implantation of the external left atrial connector: The external connector is sutured medially to the appendage base (A), and laterally to the atrial wall (B). Care should be taken to allow an atrial clamp to be placed proximal to this anastomosis without encroaching upon the circumflex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

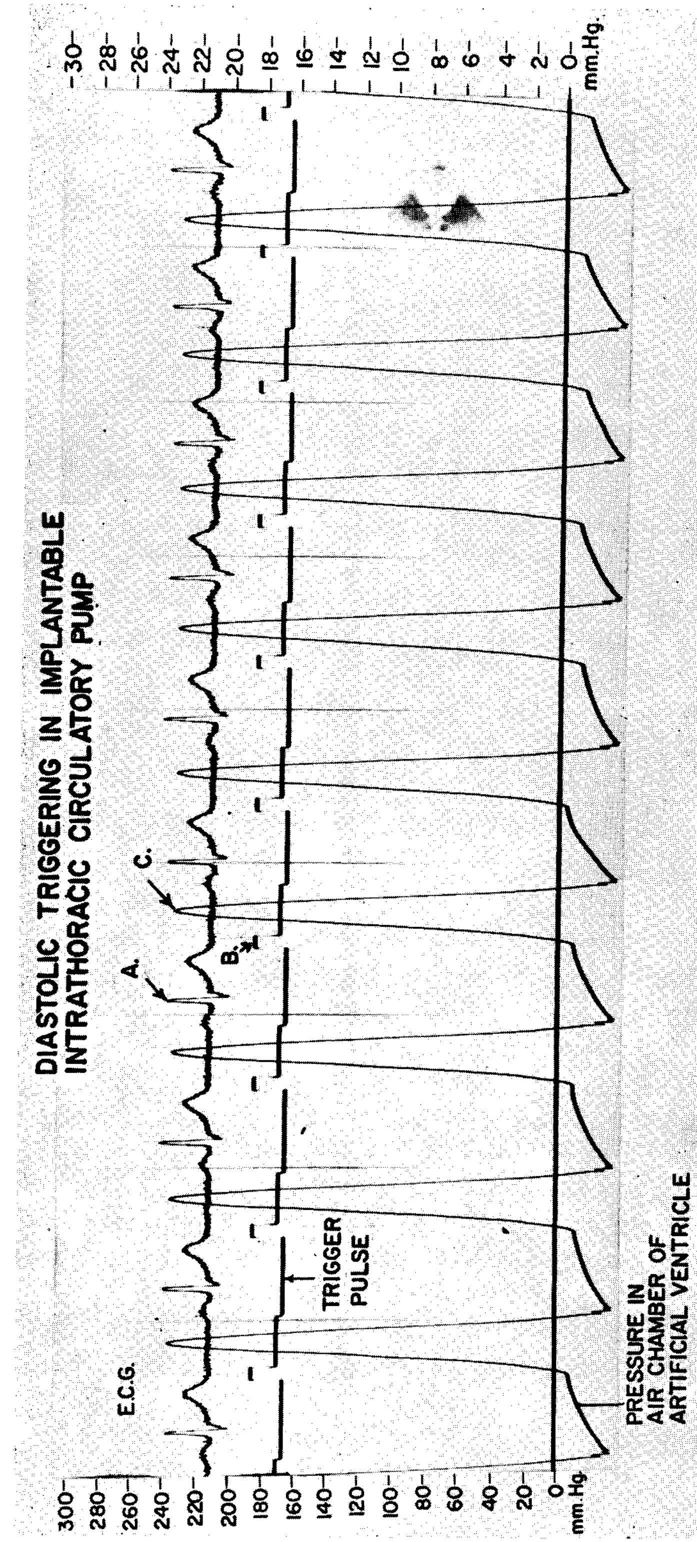

Figure 4. The tracing shows a diastolic synchronization of an implantable pump with the electrocardiogram.

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):

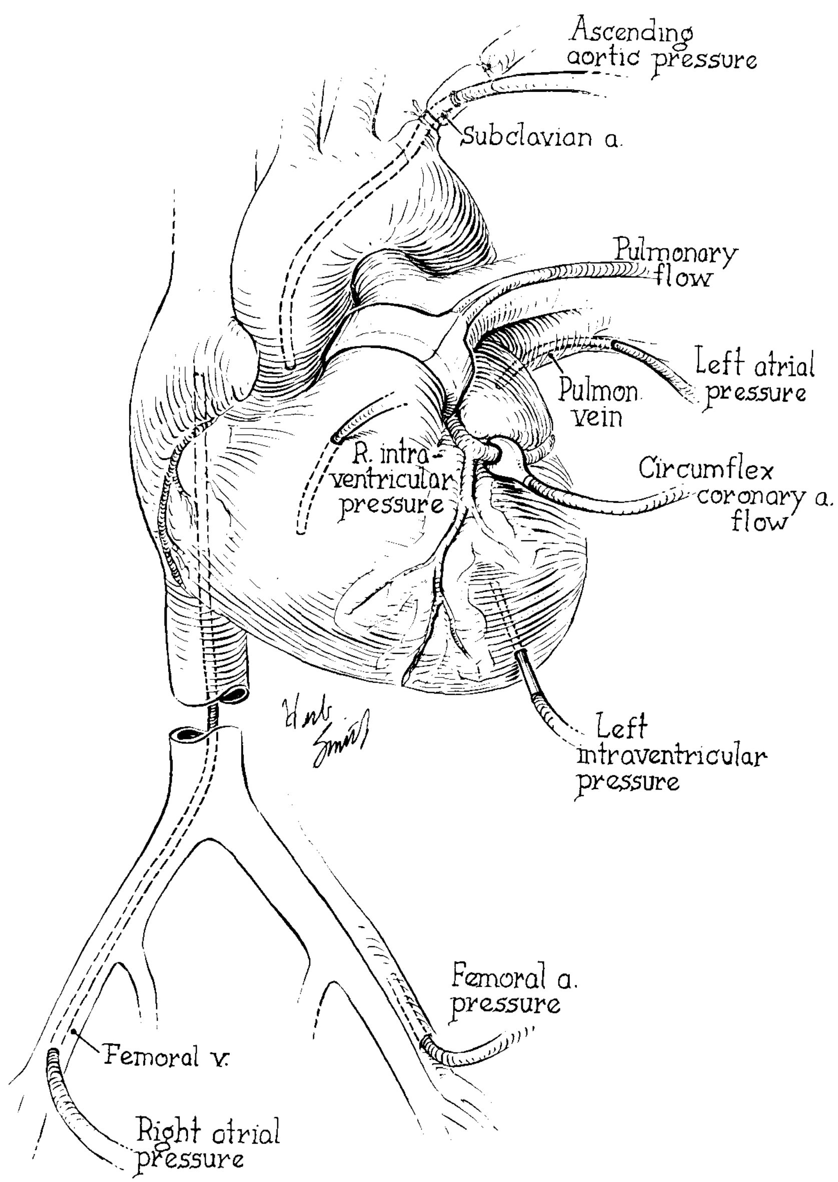

Figure 5. Schematic diagram showing the physiological parameters explored during the present investigation.

PRESSURE CONTROL. An eight-channel recorder* with four pressure transducers was employed to determine the following:

1. Femoral artery pressure.
2. Right atrial pressure.
3. Ascending aortic pressure.
4. Left intraventricular pressure.
5. 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 incisura. 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-

*Manufactured by Electronics for Medicine.

diastolic left intraventricular pressure) and the systolic peak of left intraventricular pressure. The changes in the systolic peak were classified as: (1) alternans, (2) irregular decrease, and (3) uniform decrease. In seventeen normal dogs studied, the average MLAP and the decrease during pumping was 4 and 2.5 mm Hg, respectively. The irregularities noted in the systolic peak were probably due to the decreased intraventricular blood volume and decreased stimulus to the end diastolic stretch reflex.

These changes in the ventricular contraction were unpredictable when the

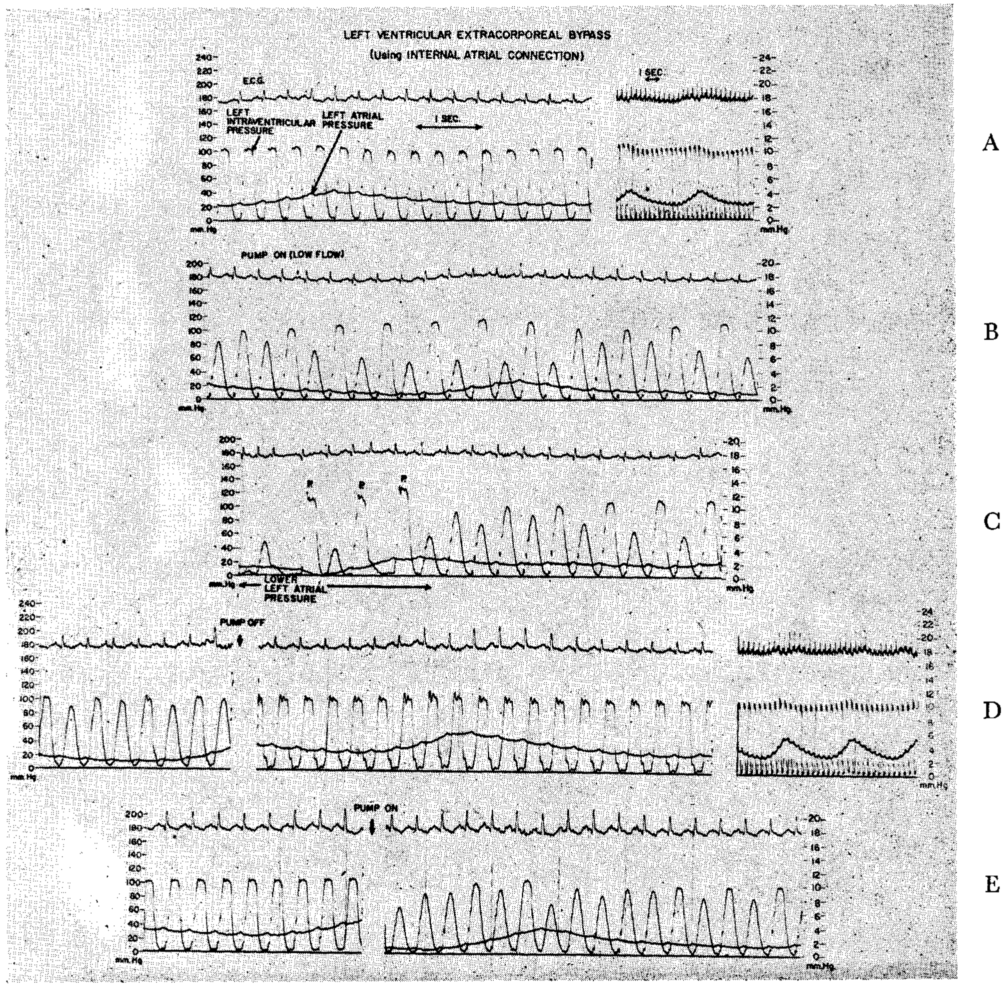

Figure 6. Pressure tracings taken during extracorporeal bypass. A. Before bypass. B. During bypass—note marked alternans coincident with the decrease of MLAP. C. Note the peak (P) of systolic contraction when MLAP reached zero, reflecting impairment of myocardial contractility. D. The first part shows a mild alternans during pumping; in the second part the pump is off. E. Marked irregular decrease in the systolic peak of the left ventricle when the pump is on.

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.

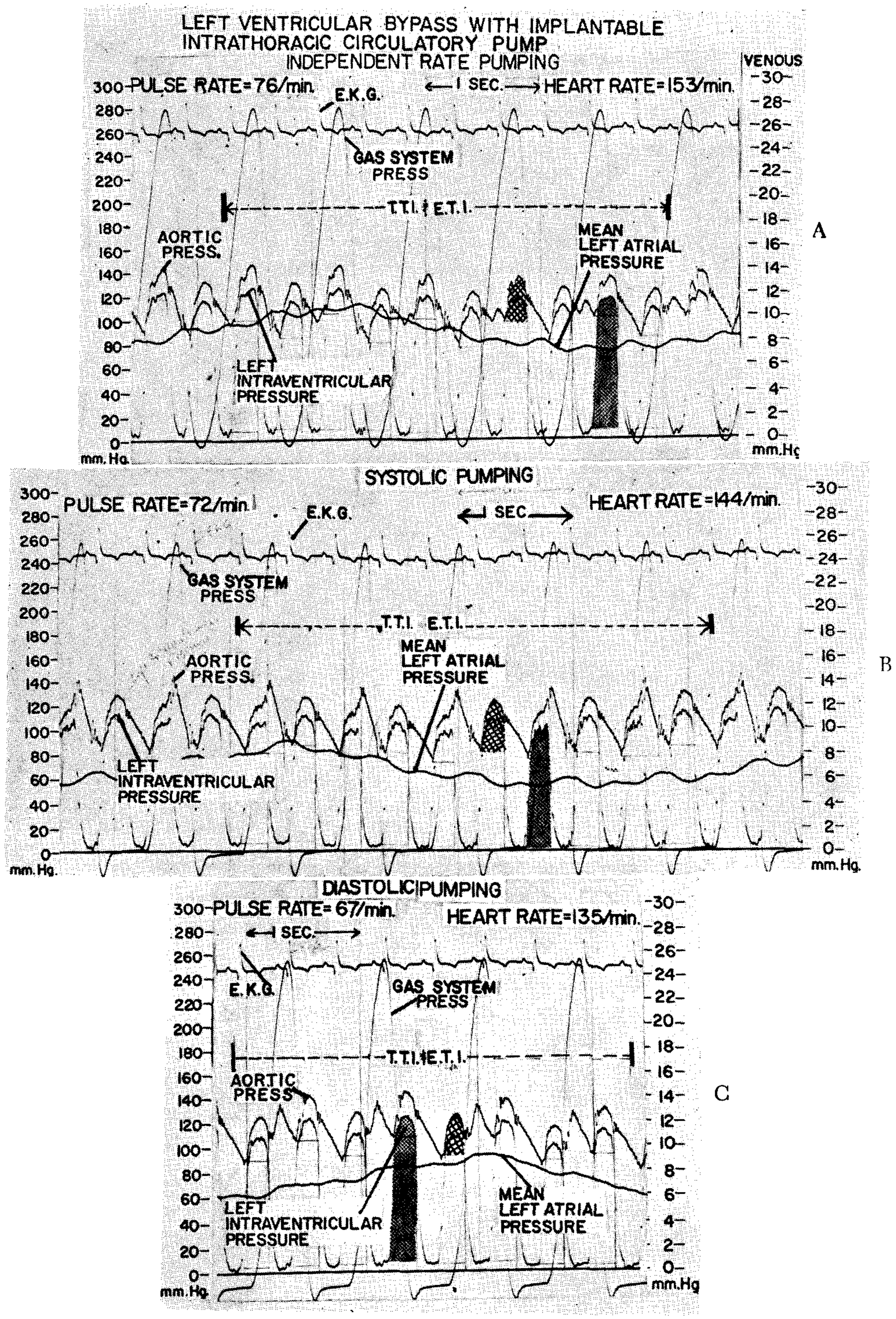

Figure 7. Pressure tracings taken during bypass with implantable pump. Note the mild decrease in MLAP. The pressure pulse from the pump is reflected in the aortic pressure at the same time that the gas system pressure reaches its systolic peak. A. During independent rate pumping. The pump rate is 76/min., 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 tention (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.

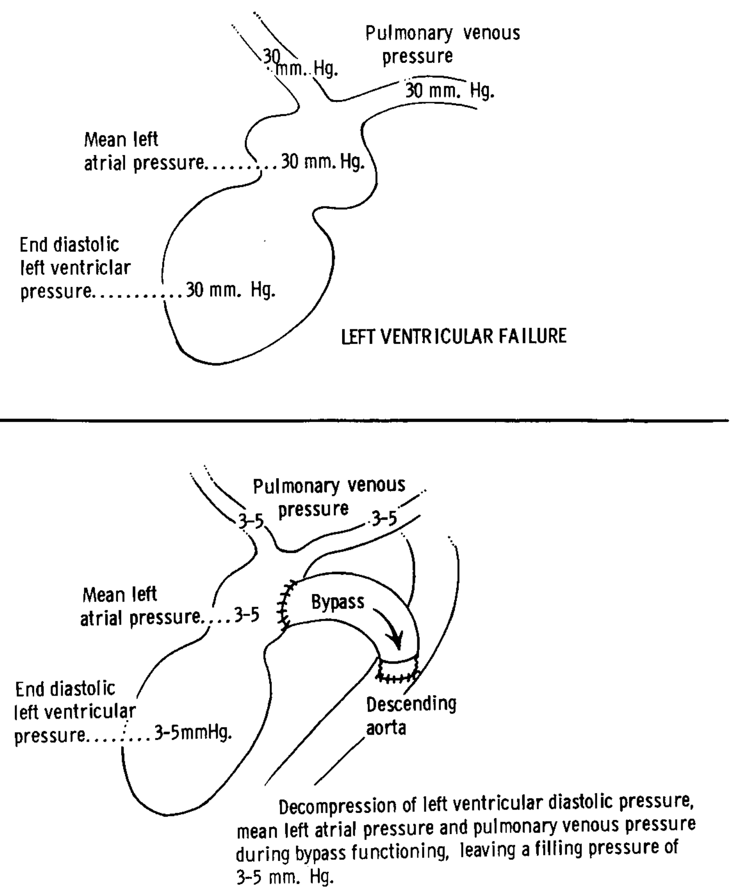

Figure 8. Diagram showing the concept of the decompression of MLAP, LVEDP, and pulmonary venous pressure during left ventricular bypass in left heart failure.

Negligible hemolysis was noted when a tubing support was used. This minimized turbulence and suction at the site of the left atrial connection. Hall (11) reported significant hemolysis during left ventricular bypass with the closed-chest technique, and one wonders whether placement of a cannula within the heart could ever overcome significant hemolysis.

Clinical application of the implantable pump has been temporarily suspended until we have a better understanding of its physiologic implications.

SUMMARY

A physiological evaluation was made of the left ventricular bypass using both extracorporeal and implantable intrathoracic pumps.

The features of the implantable pump were defined as:

1. Long-term circulatory support;

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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