PROLONGED PARTIAL LEFT VENTRICULAR BYPASS BY MEANS OF AN INTRATHORACIC PUMP IMPLANTED IN THE LEFT CHEST

Domingo Liotta, E. Stanley Crawford, Denton A. Cooley, Michael E. DeBakey, Miguel de Urquia and Louis Feldman

Of vital importance during the early postoperative period after cardiac or aortic surgery is the maintenance of an adequate arterial pressure without overloading the left ventricle. In this regard, it is possible to maintain a bypass of the left ventricle for a short period of time by performing a left atrial-femoral or subclavian arterial shunt with the aid of an extracorporeal circulatory pump.

Since the time of maintenance of this type of shunt is necessarily limited, it seemed advisable to design an intrathoracic pump which could maintain a sufficient general circulation for longer periods of time without placing undue strain on the left ventricle. This pump, which might be referred to as an artificial corollary left ventricle, should be capable of supporting artificial intracorporeal circulation for several days or weeks after closure.

Experimentally, 52 mongrel dogs weighing from 13 to 23 Kg. were employed. In 47 dogs the bypass was maintained without ill effects from 5 to 44 hr. Five dogs (circa 10%) succumbed in the initial stages of the experiments due to technical problems.

PROCEDURE

Following anesthesia with Nembutal I. V. (25 mg. /Kg.) and endotracheal cannulation, 100 % oxygen was administered with an intermittent positive pressure automatic respirator. The left femoral vein and artery were dissected free to administer drugs and blood and to check the arterial pressure. A left thoracotomy was performed through the third intercostal space, a wide opening was made in the pericardium and the aortic root dissected free from the surrounding tissue. A non-occlusive tangential arterial clamp was placed on the ascending aorta 1-2 cm. from the coronary ostium; a longitudinal aortotomy was made, and a 14 mm. woven dacron arterial graft was attached by end-to-side anastomosis. A purse-string ligature was placed around the proximal end of the left atrial appendage. The air tube of the pump was passed through the thoracic wall in the seventh intercostal space. The inlet piece of the pump was inserted into the left atrium through the appendage and tied with a ligature   sutured. The pump which previously had been prepared with 5 mg. of heparin was then connected to the inlet piece.

The outlet of the pump was connected to the graft and bound with a ligature. The air was aspirated from inside the pump through a thin tube; the arterial clamp was released; and the pump began functioning.

At this point, the position of the arterial piece inside the left atrium was adjusted to assure a good pump inflow and to avoid any compression on the circumflex coronary vessels. When the correct position was attained, the pump was fixed to the fourth rib, and the air tube was fixed to the muscle and skin in the seventh intercostal space.

Experiments are in progress whereby the anastomoses of this bypass are accomplished through a right thoracotomy. The descending aorta is utilized rather than the ascending aorta for the arterial junction.

In the majority of experiments, the heparin was neutralized with Polybrene I. V. (1-2 mg. / 1 mg. heparin). Following temporary suspension of the pump's function for the purpose of obtaining data, reheparinization of the pump was made through the thin tube. Various measurements and explorations were carried out with the pump in situ, functioning and non-functioning. During a non-function, the graft was occluded with an arterial clamp.

Pressure Control. An eight-channel Research Recorder* with 3 pressure transducers was employed to determine the following:

Systemic arterial pressure, controlled through a catheter placed inside the femoral artery;

Left intraventricular pressure, recorded in several experiments following either direct puncture of the myocardium with an 18 gauge needle or insertion of a catheter into the left ventricle through the ventricular wall;

Left atrial pressure, recorded in a number of experiments by direct puncture with an 18 gauge needle;

Inner pump pressure, determined in several instances by connecting the thin tube of the pump to the electrical transducer.

Flow Control. A Microflo Medicon Division Model FM-6 flowmeter, previously calibrated was employed to measure blood flow. Prior to each measurement the electrical and biological zero were corrected with the thorax filled with physiological saline.

1. Anterior descending coronary artery flow. This artery was exposed as high as possible for 1-2 cm. and a 2 mm. electromagnet was placed around it.

2. Left main coronary artery flow. A 3 mm. electromagnet was placed around this artery which had been dissected close to the aortic wall before the bypass was performed. Due to shortness of the vessel in an occasional dog, it was not always possible to record this measurement. Prerequisite to easy maneuverability for placement of the electromagnet is a large dog with a long anatomical segment proximal to the bifurcation of the artery.

3. Left circumflex artery flow. A 2 or 3 mm. electromagnet was placed before the bypass was performed.

4. Pump output. In experiments in which this measurement was to be determined, a fresh aortic homograft was used between the outlet of the pump and the ascending aorta and a 14 mm. electromagnet was placed around it.

5. Cardiac output. A 14 mm. electromagnet was placed around the aortic root. This measurement was made for the purpose of calculating the myocardial oxygen consumption and external cardiac efficiency.

Anterior Descending Coronary Artery (distal segment) Backflow Measurement. With some modifications, the technique originated by Mautz and Gregg[1] was employed. The dog was heparinized with 2 mg. /Kg. I. V. The distal segment of the anterior descending coronary artery was exposed about 3 cm. from its origin and tied. Five minutes later a thin catheter (.034" I. D.) was introduced distally into the artery one-half to one centimeter from the previous arterial ligation and tied. The peripheral arterial blood was collected in a reservoir placed 15 cm. below the heart level and measured for 5 min. periods. The first control was made before the pump began to function; the second one hour later

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* Manufactured by Electronics for Medicine.

and the third, one hour after the pump was stopped. The systemic arterial pressure was kept at the same level during the 3 measurements.

Aortogram and Coronary Arteriogram. Visualization of the aorta, systemic arteries and coronary tree was accomplished by the injection of 30 ml. of 75% Hypaque through the thin tube into the pump and a single exposure roentgenogram was made in the lateral position.

PO_2 and PCO_2 and pH Control in Arterial and in Venous Coronary Blood. A Blood Parameter Analyzer Epsco Medical Yellow Springs Instrument was used. Samples were obtained under strict anaerobic conditions. For collection of the coronary venous samples a thin catheter was inserted into the distal segment of the circumflex vein and introduced as high as possible or the sample was obtained by direct puncture of the circumflex vein. These measurements were made for the purpose of calculating the myocardial oxygen consumption and external cardiac efficiency with the pump functioning and stopped.

Work of the Left Ventricle. The left ventricular work was calculated by the formula: $W = QR + \frac{wV^2}{2g}$. The kinetic energy content of the blood represented by the second symbol of the formula (about 5% under ordinary resting conditions) was disregarded as was the coronary flow calculation. Practically, left ventricular minute work in Kg.-M was calculated as the product of left ventricular output (aortic flow) in L./min. divided by 100 and the plane metrically-integrated mean systolic pressure recorded in cm. water (cm. of Hg per 13.6).

Myocardial oxygen consumption and CO_2 production. These were calculated as the product of coronary flow in ml./min. (left main corconary artery, or circumflex artery, or anterior descending coronary artery) and the difference between arterial and circumflex vein oxygen contents in vols. per cent.

External cardiac efficiency. This was calculated as the ratio of left ventricular minute work in Kg.-M. to the product of myocardial oxygen consumption in ml./min. using the conversion factor, 2.06.

Left Ventricular Bypass During Myocardial Stress. Myocardial stress was induced by the following methods:

1. Ligation of the anterior descending coronary artery (24 dogs). This artery was dissected free as high as possible (5-10 mm. below the origin of the circumflex artery) and tied. The ligation was performed at least 40 min. after the pump began functioning.

2. General hypoxia and CO_2 retention. A general hypoxia was effected 20-30 min. after ligation, either by respirating the dog for at least 15 min. with a mixture of 90% helium and 10% oxygen under closed circuit or by reducing oxygen consumption by disconnecting the respirator from the endotracheal cannula.

The Intrathoracic Pump. The Tube Type Pump[*] (Figures 1-3) employed in this work belongs to the "Air Driven Systems"[2-4]. A tricuspid valve is located at both the inlet and outlet connections of the pump (Figure 3). Blood is pumped by displacement of an internal elastic tube against a rigid external housing, the valves maintaining the blood in the proper direction. Polyurethane[+] was used to build the rigid housing and valves. The internal elastic tube is made of natural rubber, Silastic[#] or natural rubber externally covered with Silastic[x].

A thin catheter attached to the bottom of the pump is used to aspirate air during the insertion procedure, to record inner pump pressure, to obtain samples of arterial blood and for reheparinization during arrest of the pump for experimental purposes.

* Constructed and developed at Baylor University College of Medicine, Houston, Texas.
+ Estane 5700 x 101, the B. F. Goodrich Company, Research Center, Brecksville, Ohio.
# Prepared for us by Dow Corning, Research Center, Midland, Michigan.
x Prepared at Baylor University College of Medicine, Houston, Texas.

The pumps employed in our experiments have capacities of 70, 50, 30, 20 and 15 ml. of blood output per stroke, respectively, and have systolic residues of from 5 to 15 ml.

In the Air Driven System, the internal elastic tube is inflated and deflated by an air stream introduced into the tube through a catheter 3 mm. inside diameter.

Air is pumped by two methods:

1. The "closed system" in which a rolling diaphragm pump, driven by a small electric motor, pumps air in alternate directions.

2. The "open system" in which the power is derived from a compressed air line or an oxygen tank, the systolic and diastolic times regulated by two electric valves driven by an electronic device[*].

In the "closed system", the same volume of air is repeatedly displaced. The systolic and diastolic times can be regulated by an electronic device[+] which also allows this system to be triggered with the R wave of the electrocardiogram of the dog. This same mechanism is used to maintain blood ejection during the diastolic period of the natural heart. For these determinations, the small motor is replaced by the electromagnet which moves the pump and is triggered by the electrocardiogram through the electronic device.

The "open system" works under high pressure. It is so named because, during the diastolic time, the volume of air used during systole escapes from the intrathoracic pump.

In the left ventricular bypass, approximately 50, 60, or 70% of the total ventricular output per minute, which has been previously calculated for each dog, is taken from the left atrium. Consequently, in this partial bypass there is no problem of atrial suction. The "closed system" is probably the more nearly ideal. In total ventricular replacement atrial suction is a primary problem[5]. The pumps previously were tested in an artificial circulatory system[5, 6].

RESULTS

Left partial ventricular bypass was performed successfully in 47 dogs, with the pump functioning for 5 to 44 hr., depending upon the purpose of each experiment. Five dogs were lost at the beginning because of technical failures and had to be excluded from further consideration. Maximum survival with perfect tolerance was obtained for 44 hr., after which time the dog was sacrificed. Currently, adequate maintenance facilities are being prepared to permit longer survival periods. In 29 dogs the "open system" was employed, triggered with the electrocardiogram in 7 of the animals. The "closed system" was utilized in 18 dogs. In some experiments both systems were used. No attempt has been made to assess the effect of long-term assistance on the formed elements of the blood or on fluid electrolyte acid-base balance.

Systemic arterial pressure. The arterial pressure curve is mainly created by the pump. Waves caused by the cardiac contractions are generally hidden (Figure 4, 5). These phenomena are more readily discerned when records taken during function of the pump are compared with those taken during non-function.

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* Electronic timing controls, G. D. Wilson & Company, Huntington, West Virginia.

+ Prepared by the Bioelectronics Division of the Department of Surgery, Baylor University College of Medicine, Houston, Texas.

All systems create similar arterial profiles. With the "closed system", the action of the pump is more apparent (Figure 4). The systolic arterial pressure increases by several millimeters while the diastolic tends to decrease proportionally. The main arterial pressure remains constant (Figure 6).

Intraventricular pressure. Since this bypass is actuated only by diminution of the left ventricular output, the intraventricular pressure should not change. When, however, the diminution of the ventricular output is excessive, the intraventricular pressure wave tends to decrease or becomes characteristically alternate (Figure 5), depending upon the amount of blood entering the left ventricle. The "closed system" does not, however, produce excessive elevation in arterial pressure, since the systolic stroke is regulated by the actual arterial pressure (self regulation). The "open system" requires constant regulation.

Left atrial pressure. Generally, the mean atrial pressure decreases by approximately 2 mm. Hg, according to the rate and output of the pump.

Inner pump pressure. In the "closed system" this is equivalent to the arterial pressure. In the "open system" it depends upon the pressure delivered by the high pressure air line.

Coronary flow. Measurements of coronary flow were taken and compared during function and non-function of the pump. Comparison of the different systems may be seen in Table 1. In all the experiments there was an increase in the coronary flow. In some instances, a marked increase was evident. For example, during non-function of the pump, the blood flow through the left circumflex artery measured 105 ml./M. and, during function, 250 ml./M. In Figure 7, the recordings of Experiment #41 show the striking difference in the coronary flow at the anterior descending coronary artery during function and non-function of the pump.

Anterior descending coronary artery (distal segment) backflow measurement. An increase in the backflow measurement was seen with the pump functioning. In one experiment, the increase was as high as 50%. In the experimental conditions described above, this interesting technique reveals the flow through the anastomotic channels distal to the arterial ligation.

A comparison of the 2 experiments may be seen in Table 3, with and without functioning of the pump.

Pump output. The capacity and rate of the pump are indicative of its possible future performance, and the test in the artificial circulatory systems[5, 6] affords still more accurate information. Control of these measures in the dog supplies real knowledge of the pump's output. In Table 2 the results of Experiment #43 are shown, with a comparison of the closed and open systems. About 60 to 70% of the blood was taken out of the left atrium by the pump.

Aortogram. The dye was injected inside the pump during function. It was thus possible to visualize the coronary tree and the systemic circulation (Figure 8). The absence of dye in the left atrium proved that valvular function was effective.

Work of the Left Ventricle with the Pump Functioning and Non-functioning. The reduction of the work, computed by formula, was proportional to the reduction of the left ventricular output. In general, a left ventricular work of 2-2.5 Kg.-M./min. was reduced to 1-1.5 Kg.-M./min. when the pump was functioning. Conversely, it was possible with the same formula to calculate the pump's work (from 1 to 6 Kg.-M./min., according to rate and pump's capacities).

Myocardial oxygen consumption, CO_2 production, and external cardiac efficiency are being studied, and some preliminary results are available; however, even with the increase in the coronary circulation, there are no important changes

in myocardial oxygen consumption and CO_2 production. External cardiac efficiency tends, paradoxically, to decrease with diminished left ventricular output and with no variation in myocardial oxygen consumption.

Ligation of Anterior Descending Coronary Artery. This was performed in 25 dogs.

General hypoxia with helium	11
With CO_2 retention	5
Without helium or CO_2 retention	7
Pump inserted in usual manner and then stopped	2

The results were: one ventricular fibrillation at 6 min. from the ligation (Experiment #33), and one doubtful result because the ventricular fibrillation was provoked after 30 min. from the ligation when another left descending coronary artery was ligated (Experiment #25).

In 2 experiments the pump was inserted but not functioning. In both cases, ventricular fibrillation occurred at 10 min. (Experiment #23) and 7 min. (Experiment #24), respectively, from the ligation. If the doubtful experiment is excluded, 4% of ventricular fibrillation was obtained in this series under the described experimental conditions.

DISCUSSION

The tube type pump employed in these experiments has the advantages of small volume, light weight, and lack of heat production during function. This type of pump is ideal for a temporary bypass. Since atrial suction is avoided in the partial bypass, the closed air-driven system with a diastolic injection, with temporary triggering by the electrocardiogram, is preferable.

An electromagnetic system is currently under study, and it is also recognized that the quality of the plastics used, at present, for experimental purposes could be improved.

In some of these experiments, partial measurements were taken of coronary flow, O_2, and CO_2 solely to establish a means of comparison during function and non-function of the pump - for example, at the anterior descending coronary artery.

The bypass decreases the heart's work by diminishing the left ventricular output. This is in opposition to the action of the special extracorporeal pump, which decreases the heart's work by diminishing the systolic pressure[7-9]. When, however, the bypass is almost total, the left intraventricular pressure tends to decrease in direct relationship to the diminished amount of blood received by the left ventricle. At this point, the left ventricular wall tension also decreases, because it is dependent on the intraventricular pressure and the volume per stroke (measured by systolic duration). This bypass reduces the volume per stroke and, consequently, reduces the volume of the left ventricle. The left ventricular wall tension decreases according to Laplace's Law: $P = \frac{T}{R}$ (when the pressure, P, developed by a particular level of wall tension, T, is inversely proportional to the radius, R, of the chamber). In other words, the myocardial fibers must develop higher tension to produce the same level of intraventricular pressure when the left ventricular diameter is larger. The ventricular wall tension is considered to be a primary factor in myocardial oxygen consumption[11].

The bypass is probably more effective when the left ventricle is dilated. It is possible to assume that the bypass decreases the pressure or eventually effects a decompression on the pulmonary vein system, left atrium, and left ventricle. In the last-named, it provokes a reduction of end-diastolic pressure with shortening of the myocardial fibers.

The importance of the radius of the left ventricle as a vital factor in the myocardial oxygen consumption has been pointed out recently by Levine and Wagman[12]. They found that the normal left ventricle oxygen consumption is about 5% of the total body oxygen consumption. This situation differs in patients with large failing hearts where values as high as 27% of the total body oxygen consumption were observed.

On the other hand, an increase in the coronary circulation was evident in these experiments despite remarkable reduction in the work of the left ventricle. This same observation was made by Watkins and Duchesne[9]. It is possible that in special experimental situations when the circulation is assisted by means of a pump, the results are not really comparable with experiments in other or natural circulatory conditions[10-13]. In these instances, a definite slowing down of heart rate was observed with the pump in operation, but no attempt was made to investigate it.

Although the experimental results reported of the anterior descending coronary artery ligation were doubtful, this test was chosen to cause acute left ventricular stress during the bypass. The 4% fibrillation obtained in anterior descending coronary artery ligation constitutes a satisfactory result, especially if the previous long surgical procedure and the general hypoxia that is effected (2 factors pointed out as the primary causes of ventricular fibrillation in the anterior descending coronary artery ligation) are considered[14-16]. This bypass avoids the overfilling of the left ventricle that occurs with partial myocardial paralysis after ligation of the anterior descending coronary artery.

Experiments are in progress with this bypass in cases of acute and chronic myocardial infarctions with microspheres and in subvalvular aortic stenosis.

CONCLUSION

Left ventricular bypass as described here reduces the left ventricular work and the left ventricular wall tension while at the same time it increases the coronary circulation.

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TABLE 1

MEASUREMENT OF BLOOD FLOW THROUGH THE ANTERIOR DESCENDING CORONARY ARTERY

System employed*		Without pump		With pump	
		Volts	ml. /M.	Volts	ml. /M.
Closed system	1st. Meas.	1.7	15.13	2.4	21.36
	2nd. Meas.	1.9	16.91	2.2	19.58
Open System triggering with the EKG		1.7	15.13	1.9	16.91
Open System without triggering		1.9	16.91	1.9	16.91

* Probe 2-1
  Gain 2.0
  Integrator 3

TABLE 2

MEASUREMENT OF THE PUMP'S OUTPUT

System employed*	Volts	ml. /M.
Closed System (pump's rate: 80/M.)	2.6	1165.06
Open System without triggering (pump's rate: 80/M.)	1.2	537.72

* Probe 14-1
  Gain 1
  Integrator 3

TABLE 3

ANTERIOR DESCENDING CORONARY ARTERY (DISTAL SEGMENT) BACK FLOW MEASUREMENT WITH AND WITHOUT PUMP FUNCTIONING. PERIOD OF TIME FOR EACH CONTROL: 5 MINUTES

	without pump	with pump
Dog #1	1.8 ml.	3.2 ml.
Dog #2	3.3 ml.	3.7 ml.

Figure 1. Diagram of the tube type pump (air-driven system). A - Inlet valve. B - Outlet valve. C - Air line. D - Rigid housing. E - Elastic internal tube.
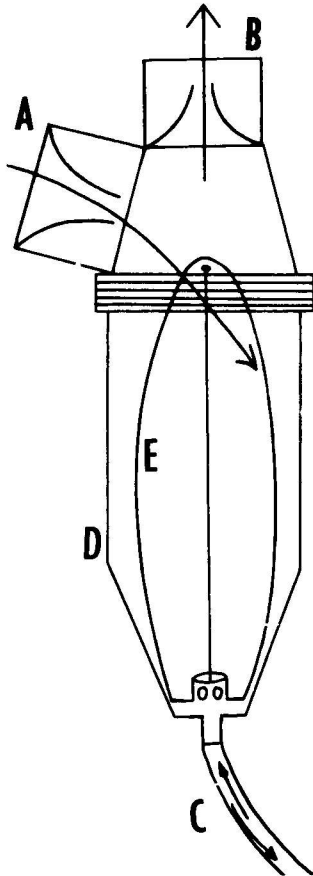
Figure 2. Comparison of 2 model sizes of the tube type pump.

Figure 3. Top of pump with valvular system. Valves are of the tricuspid type, and between them is a sort of crista (C).
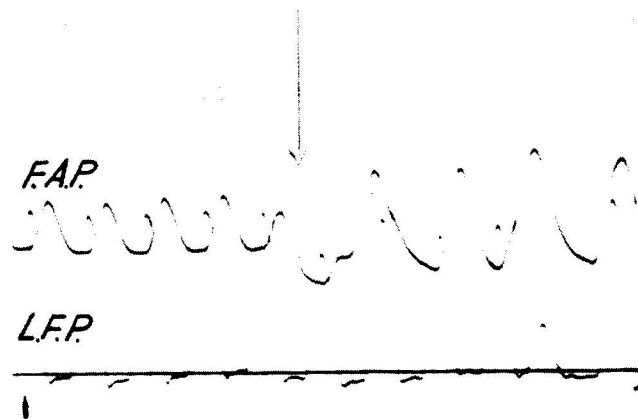
Figure 4. Tube type pump (closed system). F.A.P. - Femoral arterial pressure. L.V.P. - Left intraventricular pressure. Pump starts at S. There is visible change in the L.V.P. tracing.
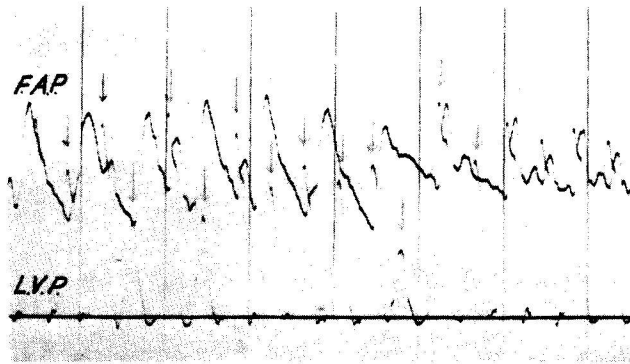
Figure 5. Tube type pump (open system). F.A.P. - Femoral arterial pressure. L.V.P. - Left intraventricular pressure. S-S space - When the pump is non-functioning. When the pump is functioning, the L.V.P. curve alternates (arrows).
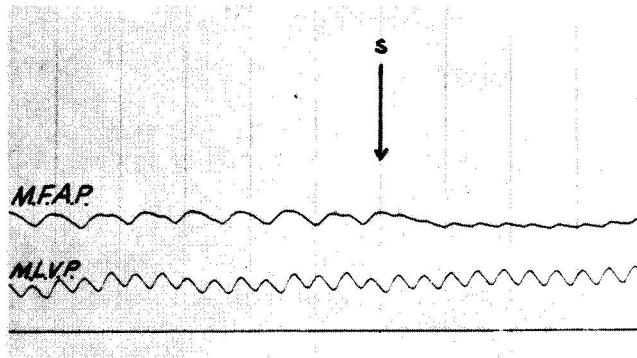

Figure 6. Tube type pump (closed system). M.F.A.P. - Mean femoral arterial pressure. M.L.V.P. - Mean left intraventricular pressure. The pump is stopped at S. There is slight variation or none in the mean arterial and mean intraventricular pressure values.
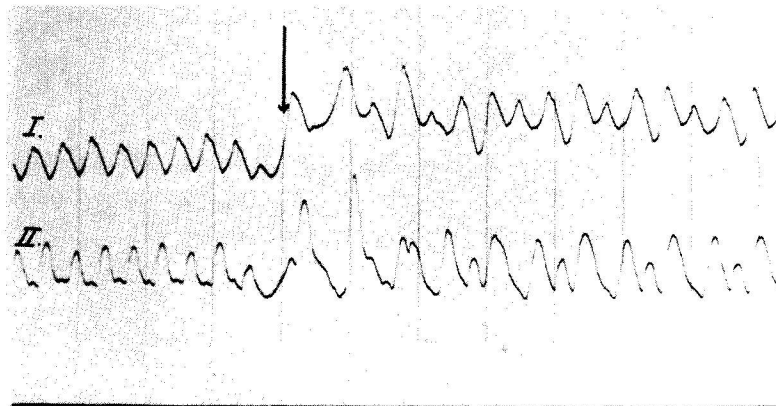

Figure 7. Tube type pump (closed system). I. Anterior descending coronary artery flow. II. Femoral arterial pressure. A marked increase in coronary flow is evident when the pump is functioning.
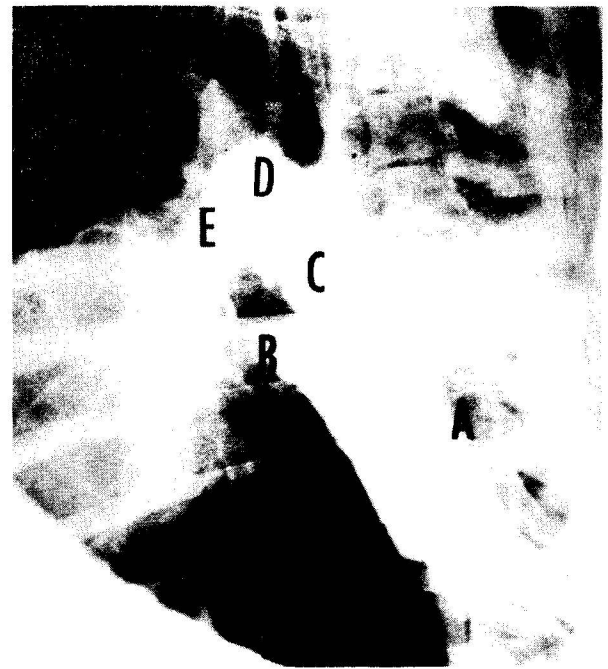

Figure 8. Tube type pump. Aortogram and coronary arteriogram. The dye is injected into the pump through the thin catheter. A - Body's pump (rigid housing). B - Atrial junction (inlet valve). C - Outlet valve. D - Arterial graft. E - Ascending aorta. The coronary tree is filled, as well as the peripheral arteries.

Figure 9. One experiment is shown. The pump has been implanted in the left chest.