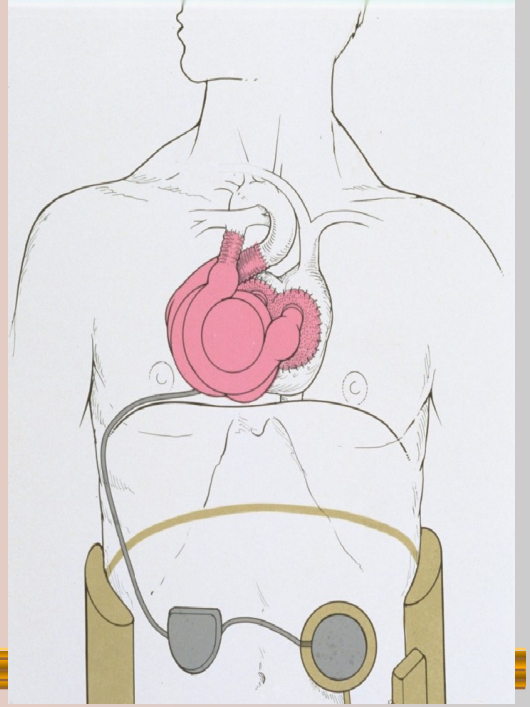
AbioCor Implantable Replacement Heart

Total Artificial Heart



From 1988 to 1991, I was Principal Scientist at Abiomed, Inc. and Principal Investigator on a project to develop a total artificial heart (TAH) later named the AbioCor. The following information is available in the public domain concerning that development.

Alan Millner 2005

The History

- Over 100,000 Americans could benefit from an artificial heart each year.
- Fewer than 20,000 hearts are available for transplant each year.
- During the 1960's, Robert Jarvik was part of a team of researchers developing an artificial heart driven by compressed air.
- Many patients were implanted, the most well known long term patient being Barney Clark.
- Most long term patients suffered strokes due to blood clots forming in the heart.
- The Jarvik heart was used extensively for short term heart replacement while awaiting a transplant, but no device since that time has been available for long term total replacement of the heart.

The Opportunity

Blood will clot if it sees too low or too high a shear, or incompatible surface chemistry, or systemic problems.

- Abiomed was one of 4 groups funded by the NIH to develop a total artificial heart. It was the only one to reach human trials.
- Abiomed brought to the problem:
  - A blood compatible polyether-urethane plastic with very long flex life.
  - Trileaflet heart valves made of the plastic, tested in animals and short term in humans.
  - Technology for casting blood pumps from the plastic, tested in animals and short term in humans.
  - Experience manufacturing and clinically managing air driven devices for temporary heart assist.
  - A multi-regional supporting medical team.
  - A will to create a useful product from the difficult science.

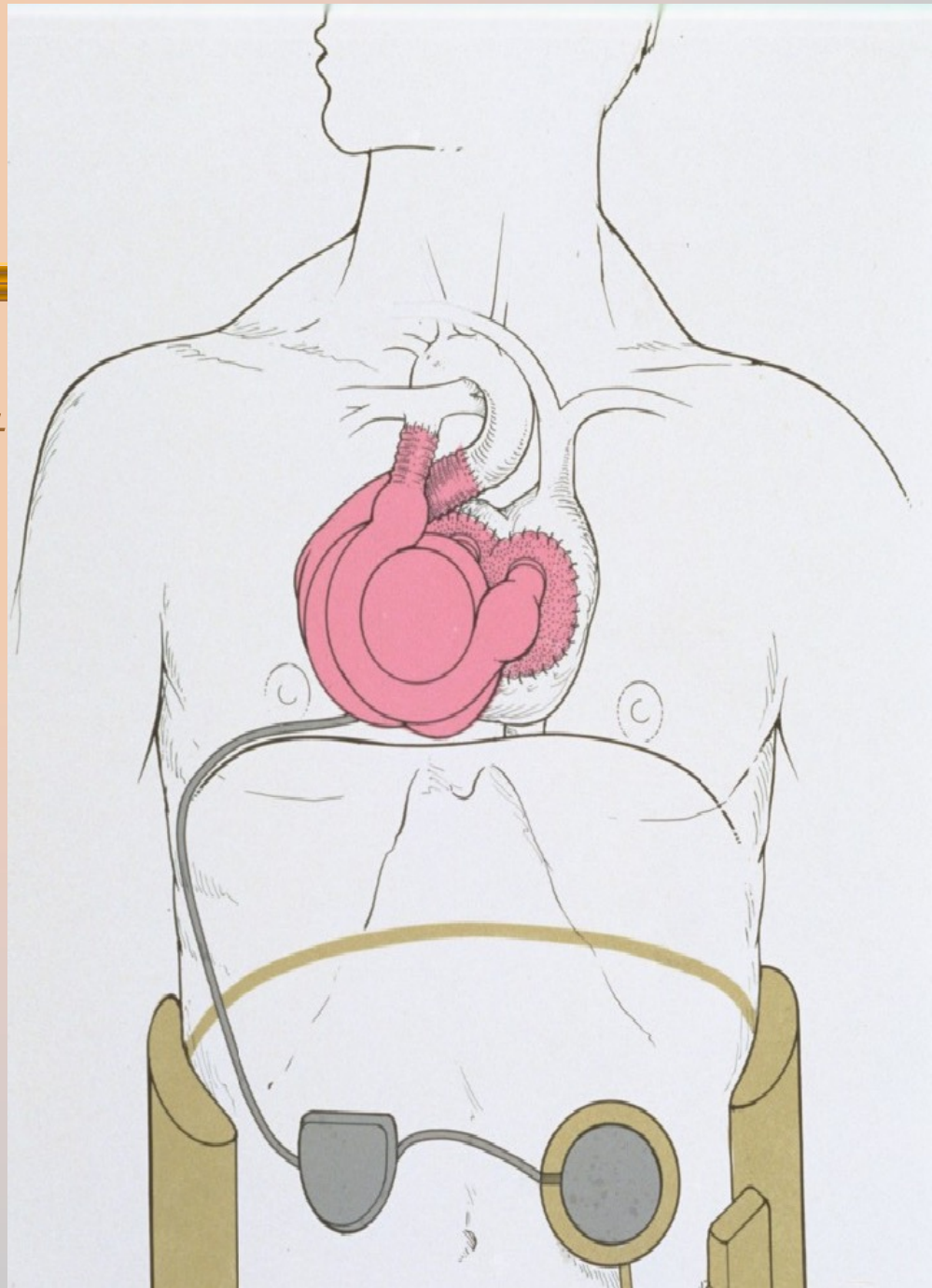
Engineering Design Steps

- Specify the requirements
- Translate them into the critical functional engineering parameters
- Identify candidate design approaches
- Develop the design details
- Test each critical parameter
- Improve the design to meet the need

Specifications

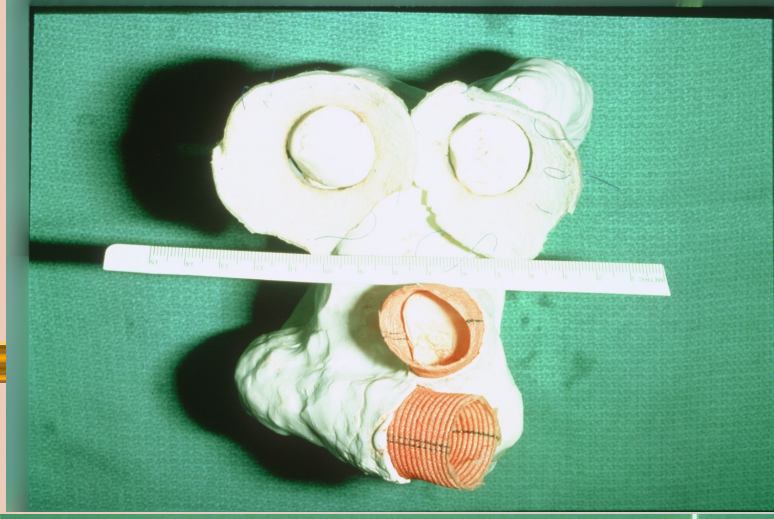
- Fundamental decision by the NIH: the heart is targeted for adult U.S. males.
- Many women have lower blood flow and volume, smaller thoracic cavity.
- Required flow: 4 to 8 liters/minute.
- Nominal pressure: 105 mm Hg aortic, 25 mm Hg pulmonary.
- Maximum Pressure: 150 mm Hg aortic, 80 mm Hg pulmonary.
- Pulse rate: 60 to 120 BPM (pulsatile pressure probably aids organ perfusion).

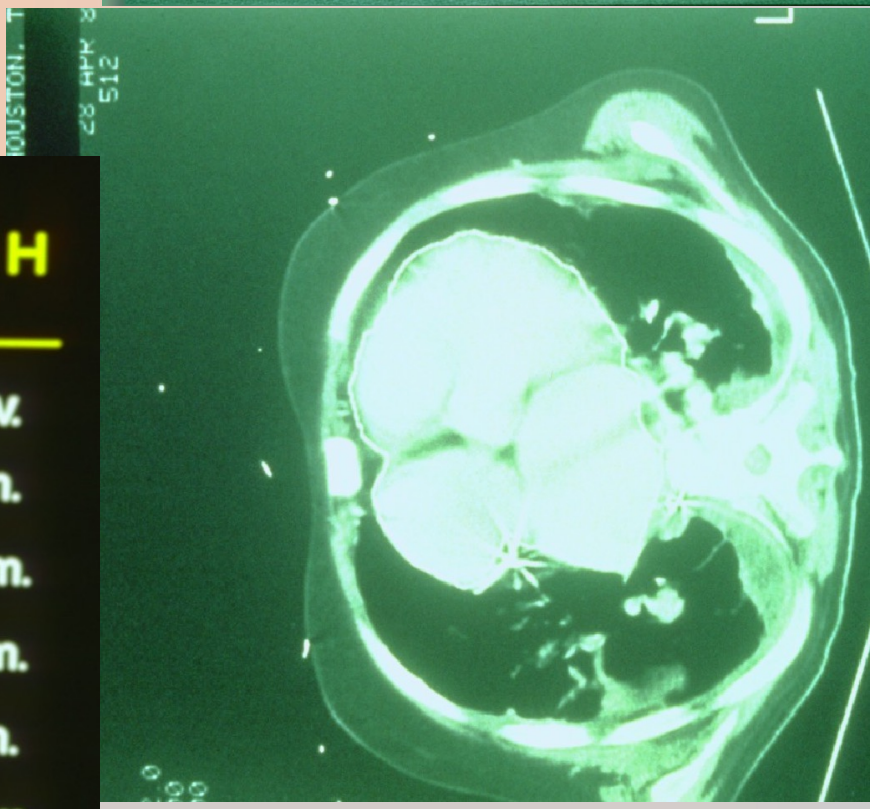
Totally implanted (no skin penetration) heart replacement, in the heart's normal chest position. Target life: 5 years.



Fit requirements

- Blood pumps, energy converter, and control electronics must fit in the chest space available.

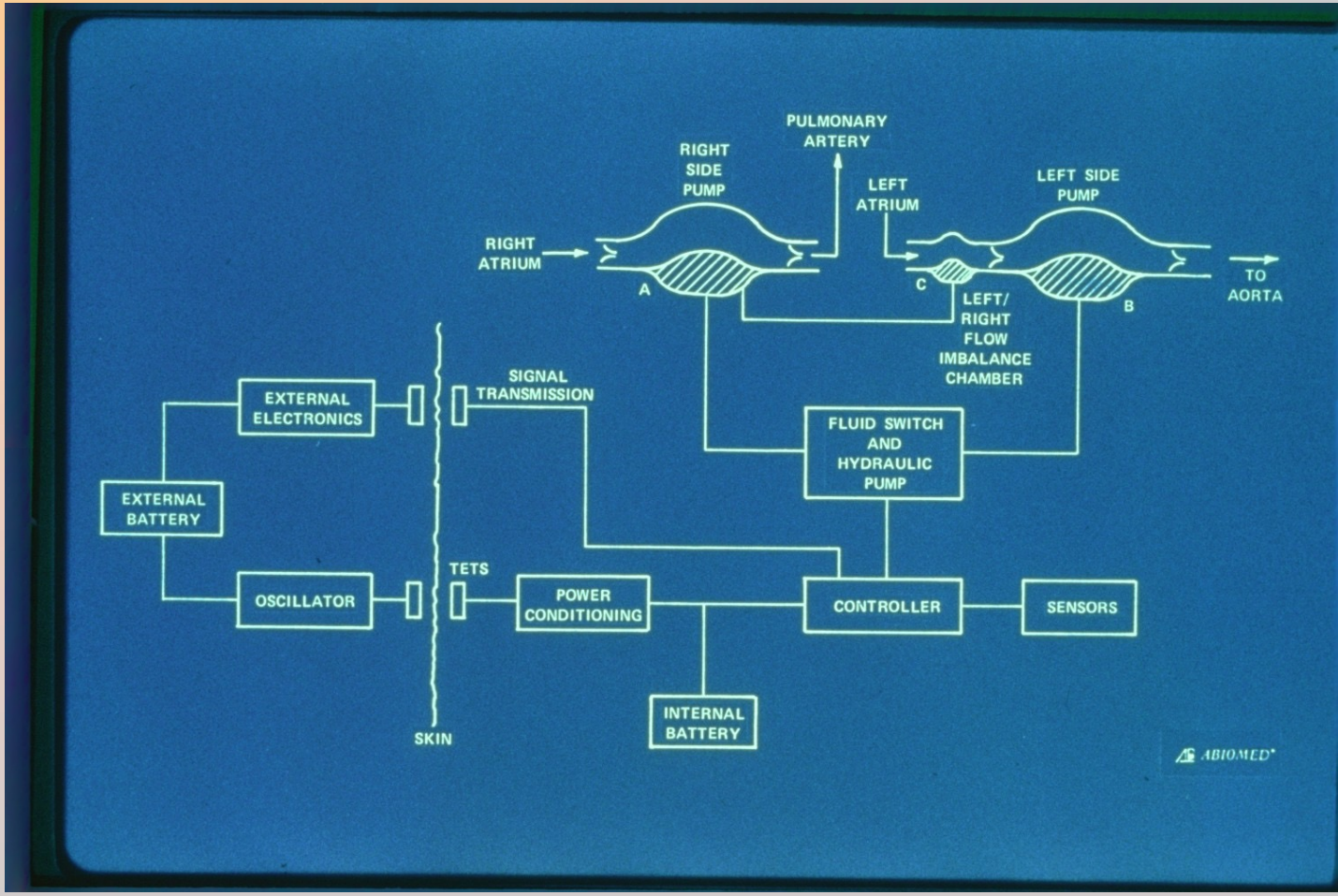




AVAILABLE THORACIC SPACE Cardiomyopathic Patients	T A H
Parameter	Mean +/–Dev.
Sternum to Thoracic Spine	12.7+/-1.7 cm.
Left lateral chest wall to ctr.	13.6+/-1.7 cm.
Ventricular length (AV to apex)	9.2+/-1.0 cm.
Ventr. width (perp.to septum)	12.7+/-1.8 cm.
Ventr. depth (along septum)	11.6+/-0.8 cm.
Ventricular volume	955+/-186 cc.

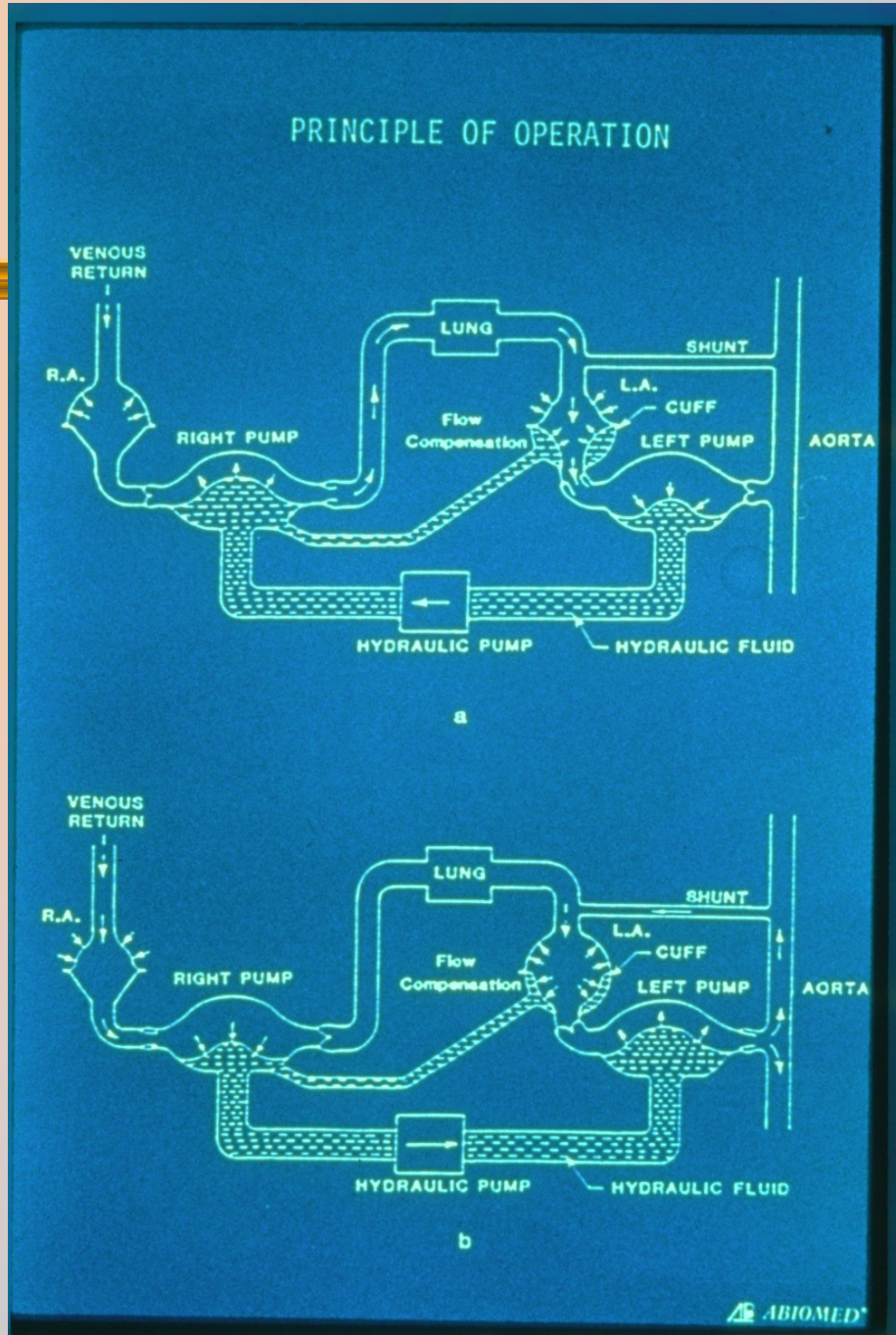
System diagram

- Electro-hydraulic design converts electric power to hydraulic blood pumping.



Operation

- Alternating sides pump blood out.
- Pulmonary systole (a) pumps to the lungs.
- Aortic systole (b) pumps to the body.
- Note flow compensation in left atrial cuff, adjusted by pulmonary pressure.

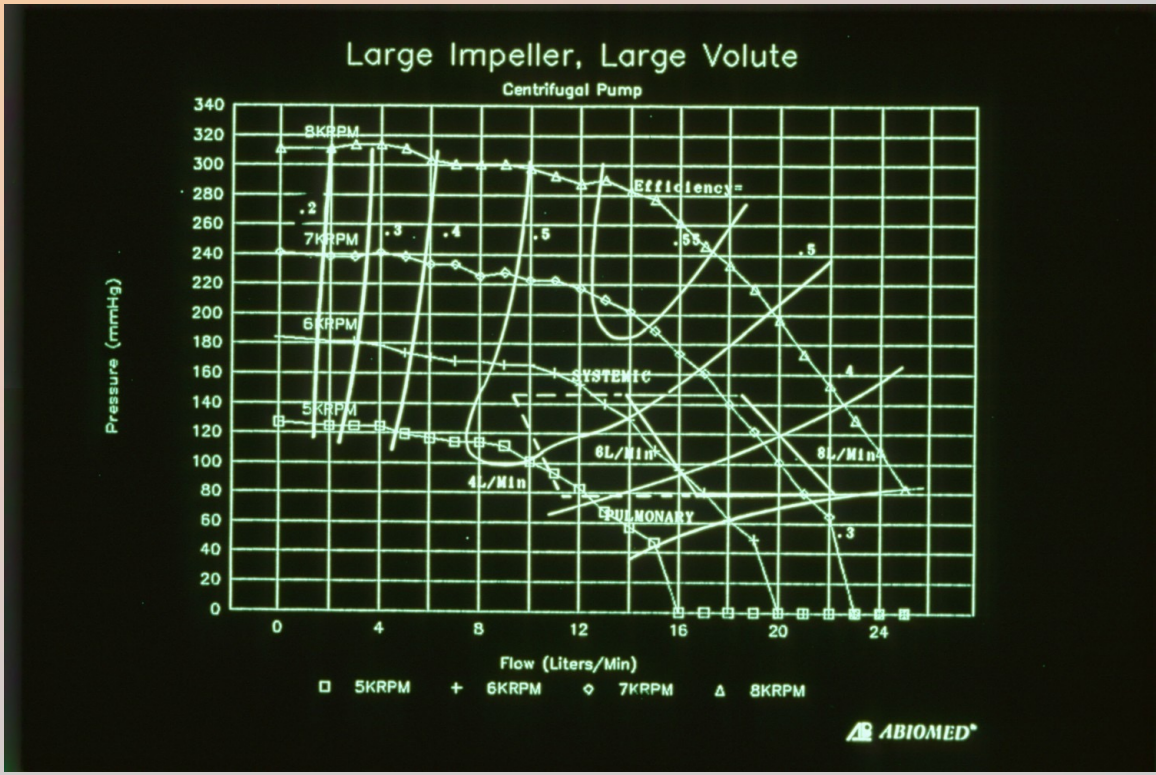


Left-right imbalance

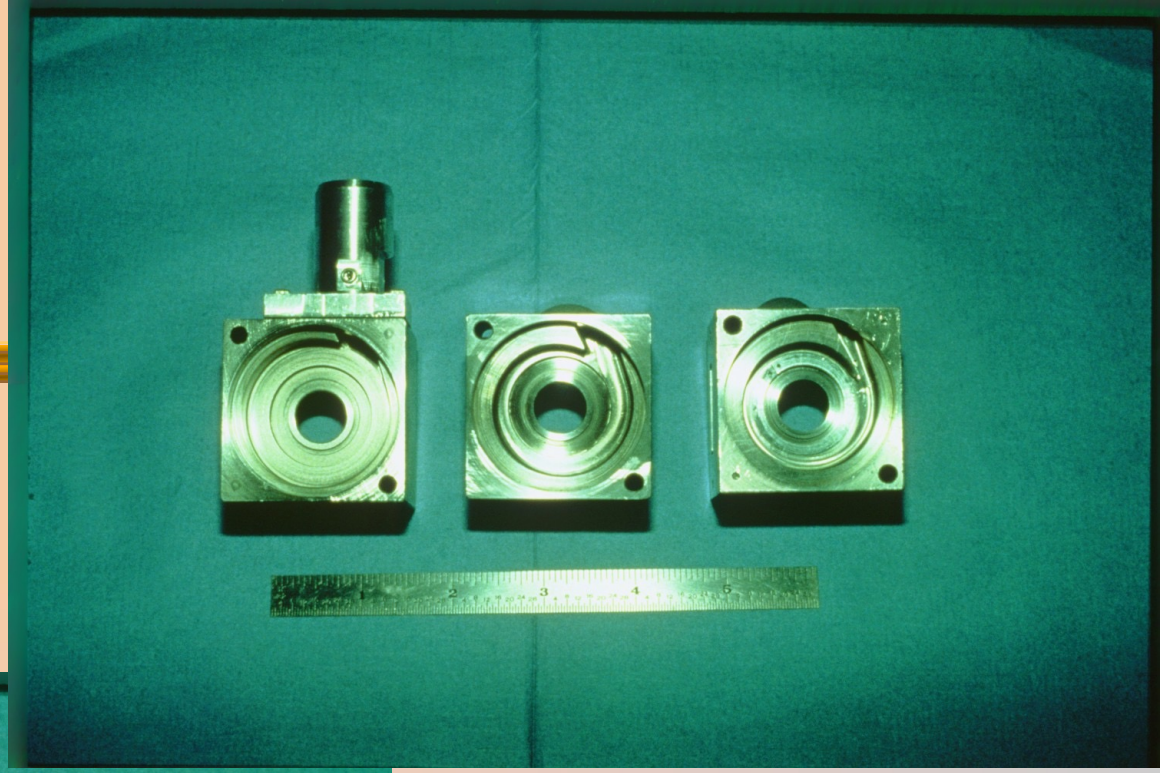
- Note the body has two circulatory paths, aortic and pulmonary.
- A small amount of the aortic flow returns to the left atrium instead of the veins, so the left side of the heart must pump a little more than the right side.
- This imbalance must be maintained or pulmonary hypertension results.

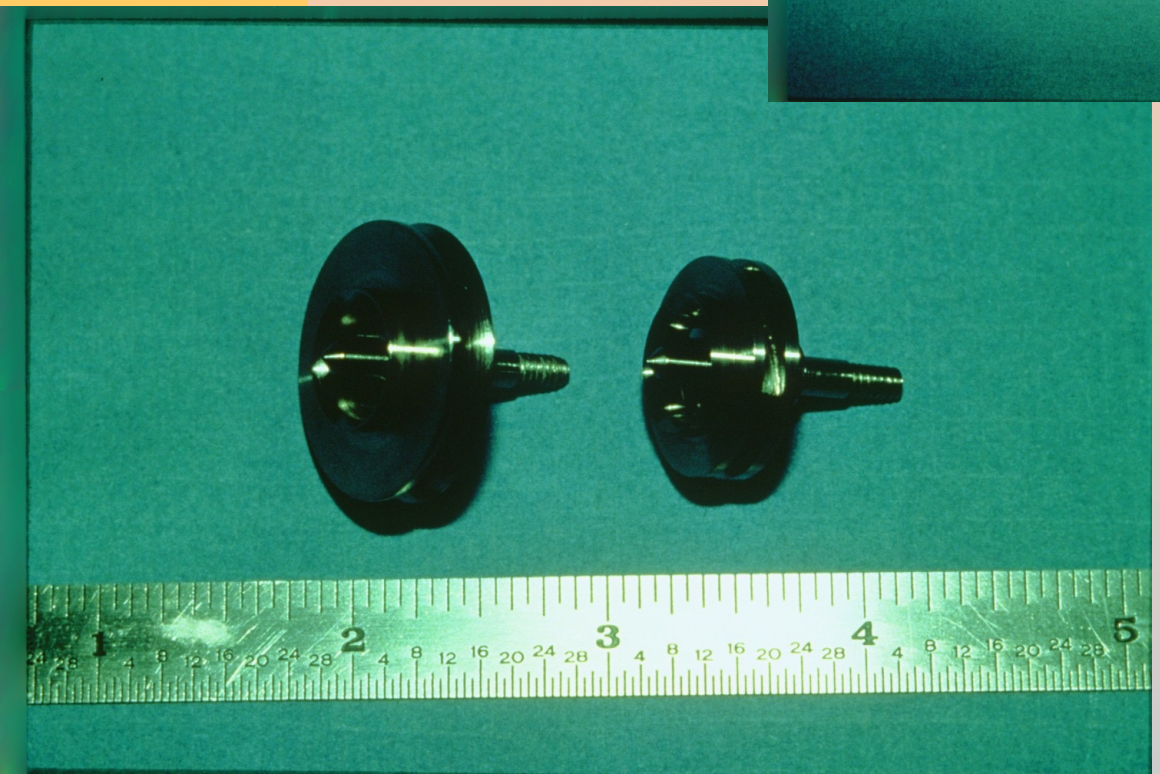
Hydraulic pump requirements

- Must match needs for both left and right systole.
- A centrifugal pump was designed for silicone oil as hydraulic fluid.
- Operation 5000-7000 RPM



Pump design





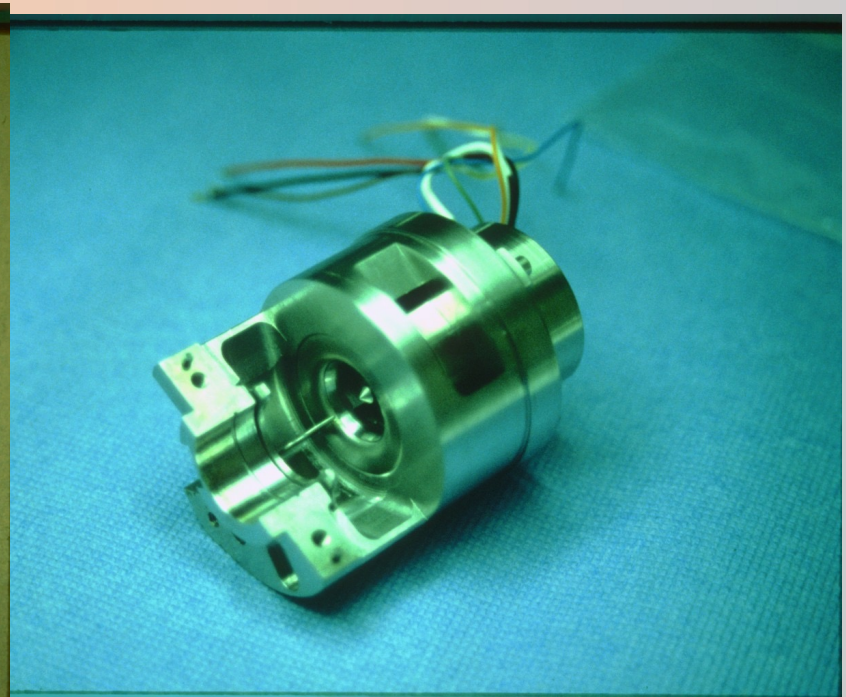
Volute and impeller shown.

Driven by a brushless DC variable speed permanent magnet motor

12 to 21 L/min instantaneous flows

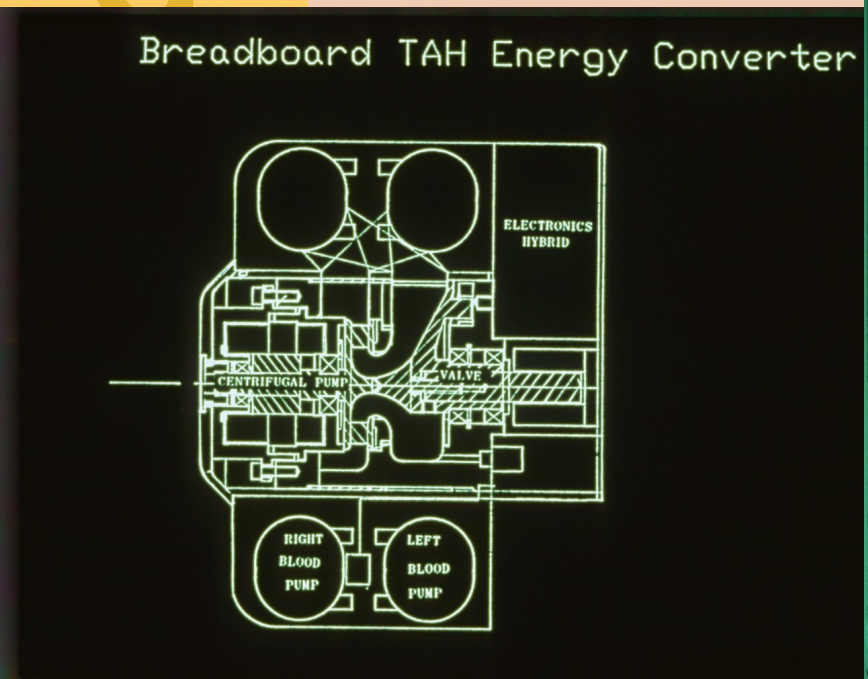
Hydraulic valve assembly around the pump

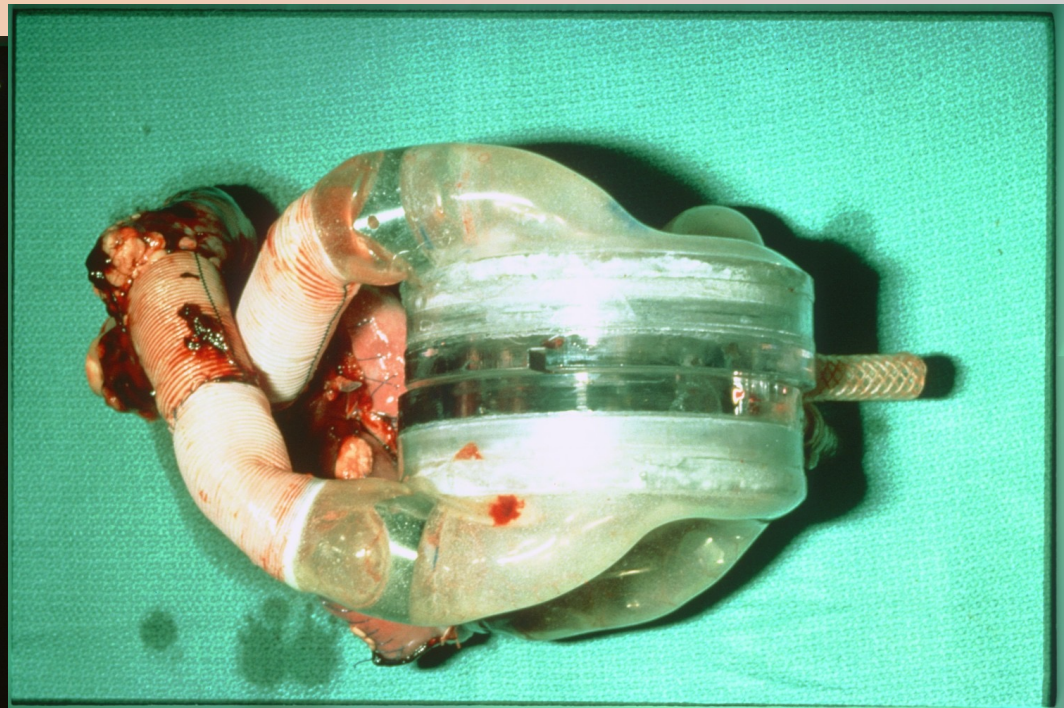
- Alternates positions by rotation for left and right systole.
- Driven by a small permanent magnet torque motor.



Blood pumps (one version)after animal implant

- A polyether-urethane blood container and trileaflet valves, very blood compatible
- Long flex life to avoid tearing





Pressure and stroke sensors

STROKE SENSOR | TAH

- Infrared optical sensor selected, signal propagates through hydraulic fluid
- Reflective target, part of blood pump membrane
- Left pump master, right slave
- Self calibrating algorithm
- Customized package for mechanical integration
- Systole and diastole of the left pump sensed by one detector

ABIOMED

PRESSURE SENSOR | TAH

- One year in vitro test: ‹2mmHg drift
- One sensor placed at the pump inflow measures both atrial pressures alternately
- A customized gauge sensor eases packaging
- Constant flow mode backup for sensor failure
- Electronics interfaces are simplified

ABIOMED

- Stroke sensor regulates 60CC stroke volume
- Pressure sensor regulates venous pressure

Other components

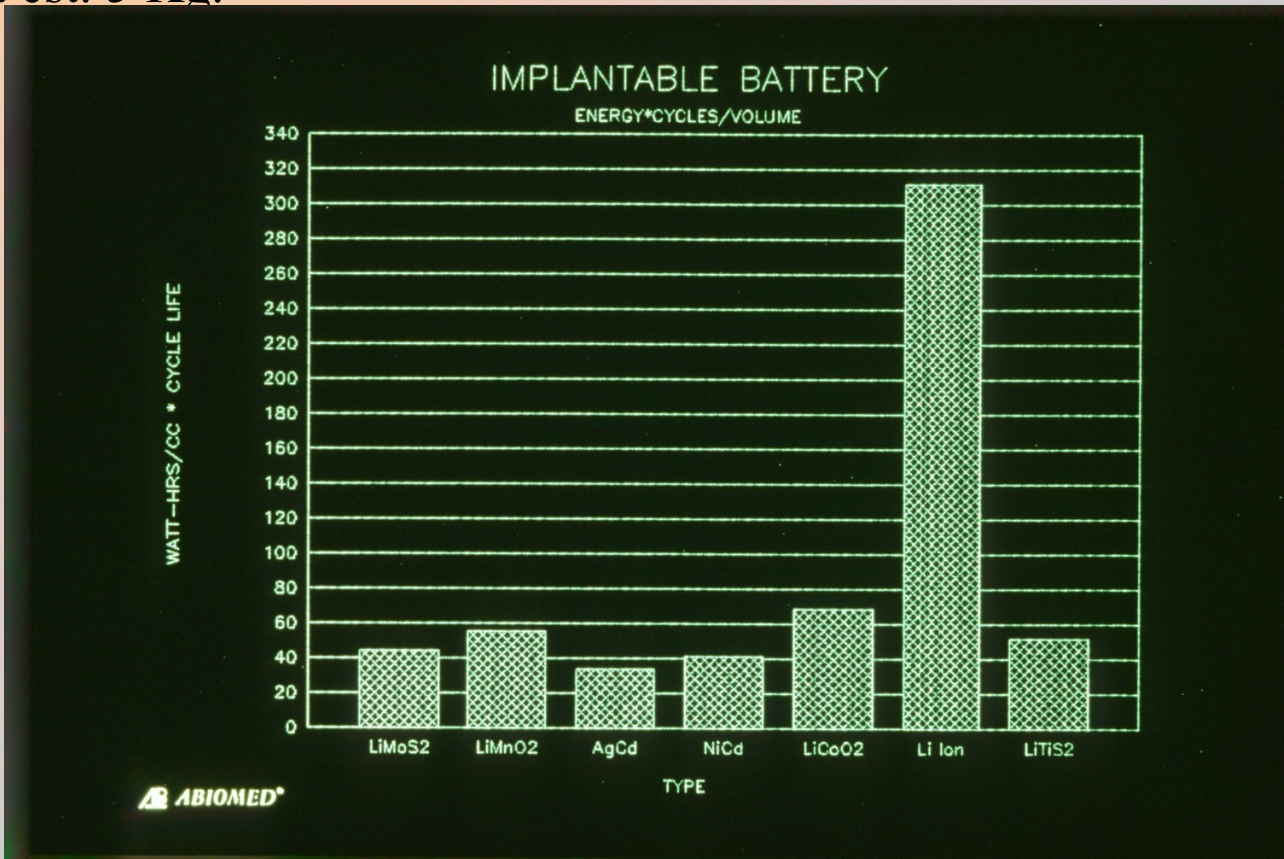
- A transcutaneous energy transmitter couples power through the skin via an air core transformer, primary outside and secondary inside.
- An implanted abdominal power pack has a small battery for under 1 hour use.
- A vest with 8 hour battery pack allows mobility.

Implanted size and weight

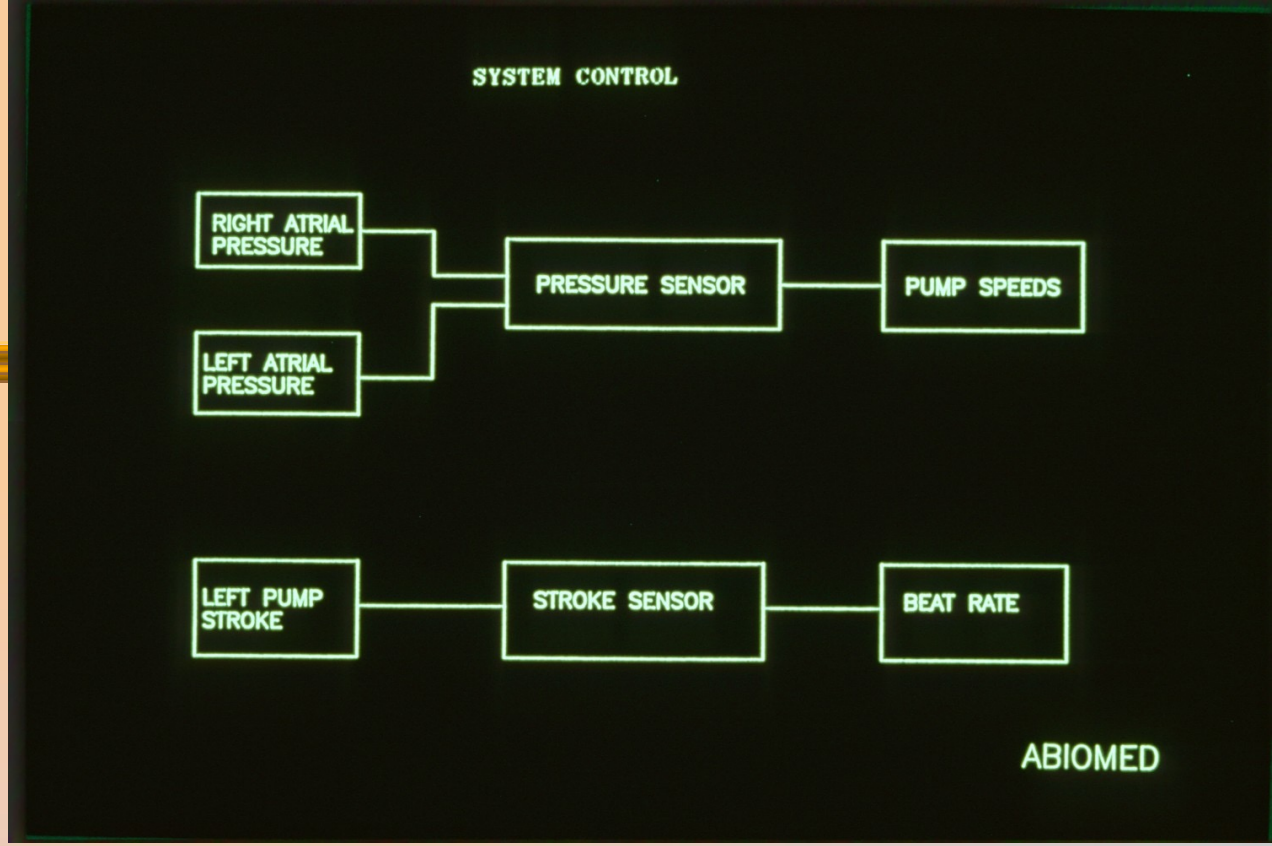
- Thoracic 868cc, 1100g.
- Abdominal 234cc, 550g.
- External vest est. 5 Kg.

Energy converter length 8.7cm. (spinal-sternal)

Implanted battery best choice is Li Ion

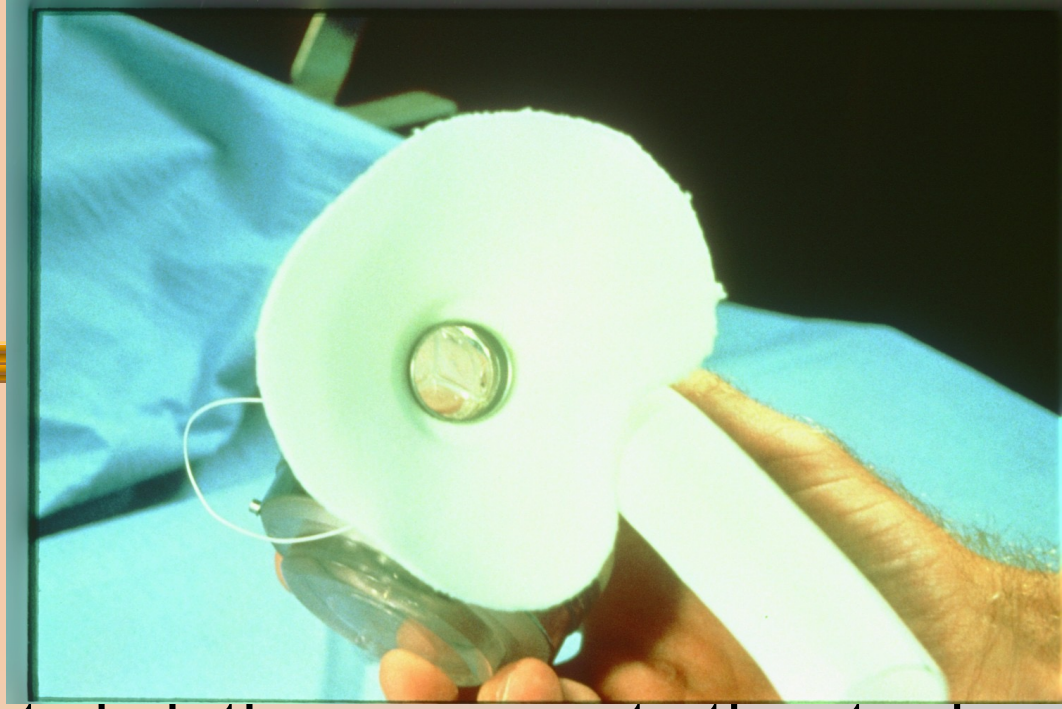


Control



- Pump speed is proportional to blood flow.
- When the body exercises, the resistance to flow of the capillaries is reduced, and more blood transfers from the arteries into the veins, raising the venous pressure.
- Regulating the venous pressure by varying the flow rate is very stable, since higher flow rate changes the rate of change of venous pressure (higher flow = lower venous pressure).
- The stroke sensor senses full stroke volume on the blood pump sack by reflection from a white spot on the surface, avoiding abrasion of the polymer.

Atrial cuff and connector



Note tri-leaflet valve

One of four

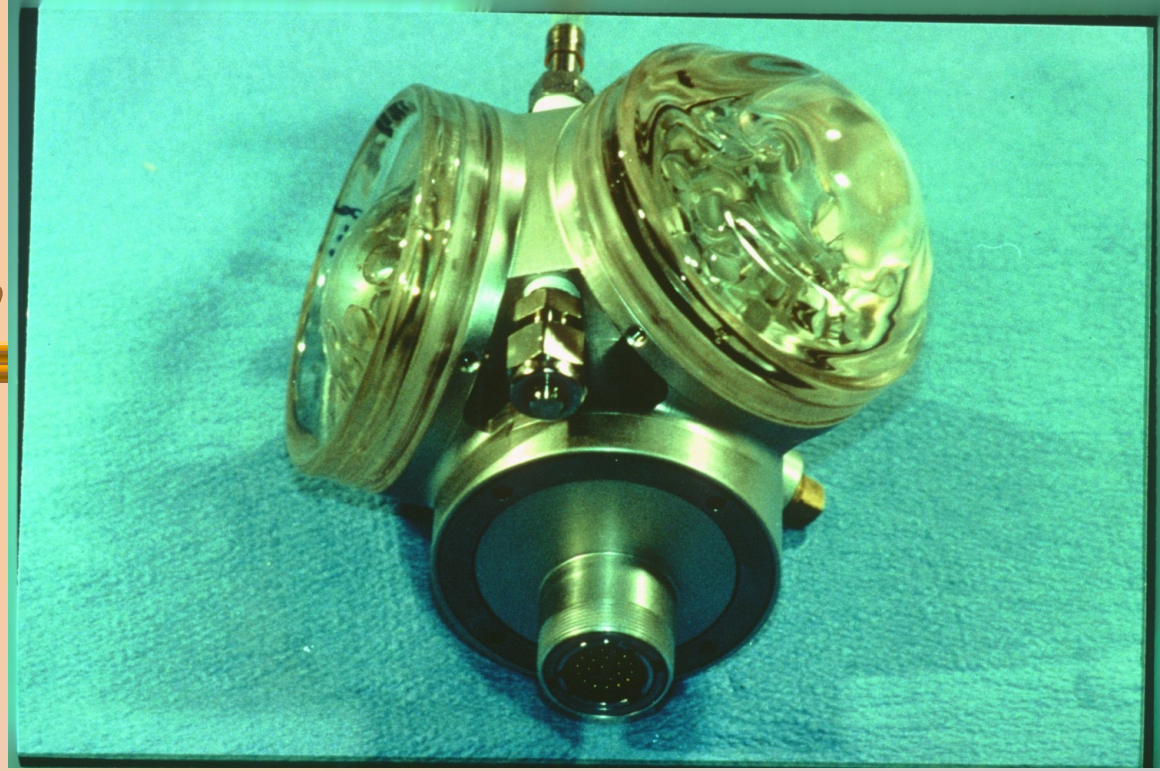
- The atrial cuffs are a coated cloth cone sewn to the atrial remnants by the surgeon, as in a heart transplant.
- The rest of the heart connects to the cuffs with a plastic snap connector.
- To keep tissue from growing down blood streamlines into the connector and clogging it, the inlet of the connector is raised above the lower edge of the cuff.
- The ventricular outlets are also cloth sewn to the arteries.

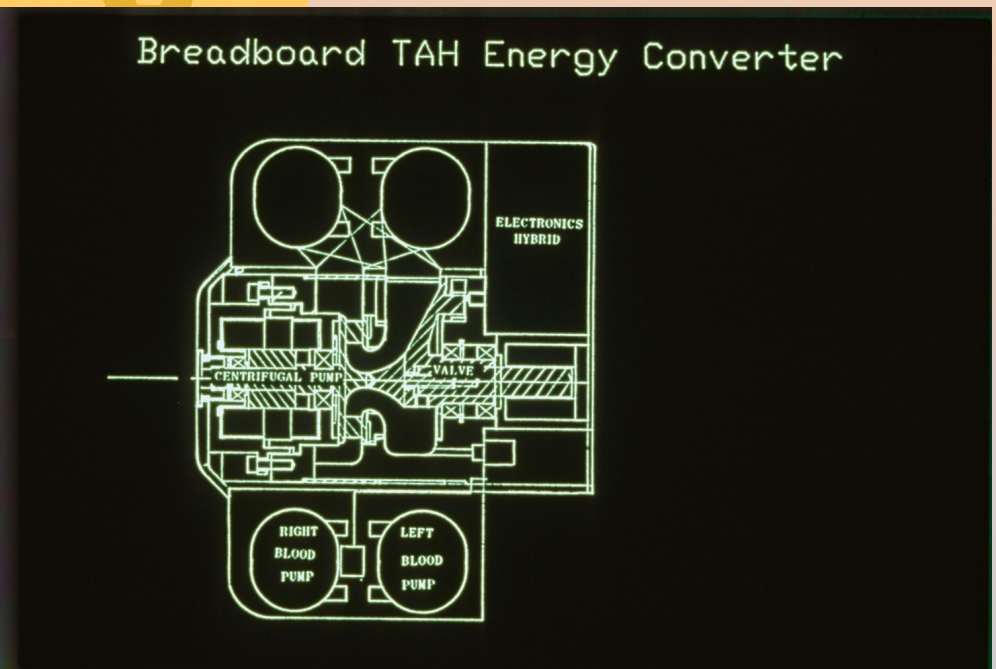
Energy balance

- Mechanics: ½ MV^2+Mgh=constant energy.
- Fluids: ½ ρv^2 +ρgh + p = p_0 along stream lines (Bernoulli's equation).
- Energy density times volume = energy.
- Energy / time = power = energy density times volume flow rate Q.
- (150mmHg + 80mmHg) *8 L/min * (13.6 Kg/m2/mmHg) *(10^{-3} m^3/L)*(1 min/60sec) = 0.42 watts output.
- The AbioCor draws 14 to 19 watts input.
- Direct mechanical drive is more efficient.

Heart Assembly

- Outside of device is a rigid biocompatible coating





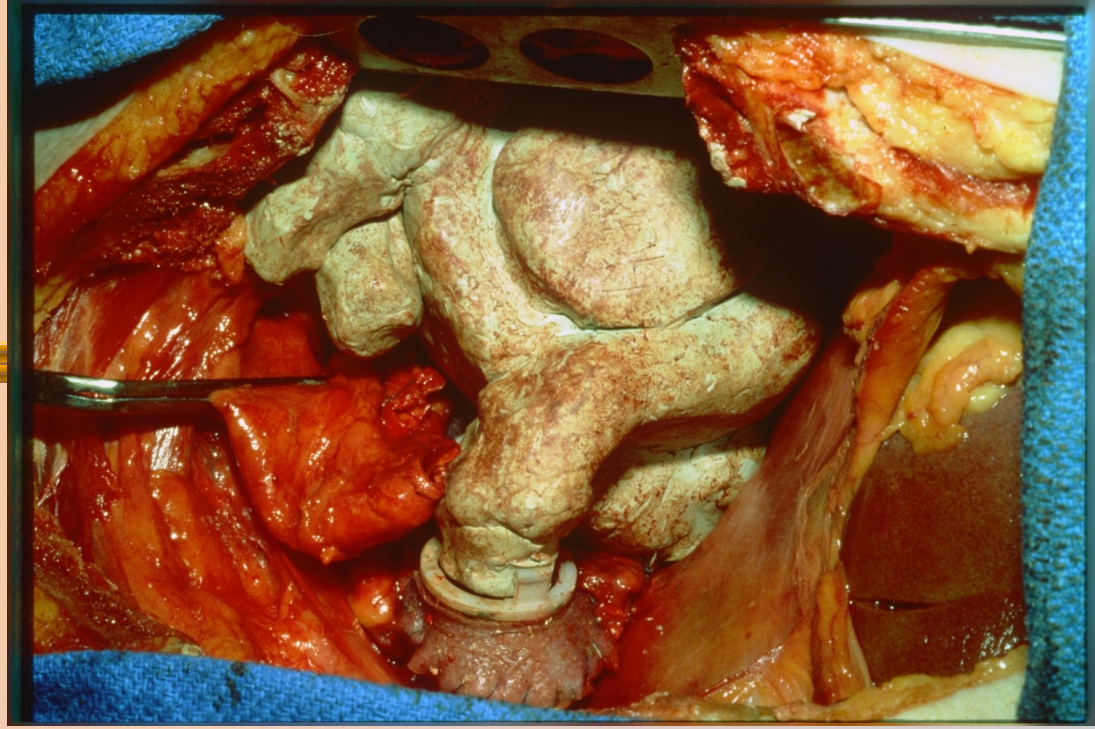
- Blood pumps either toroidal or elipsoidal
- Energy converter at the center with rotating valve
- Electronics hybrid attached

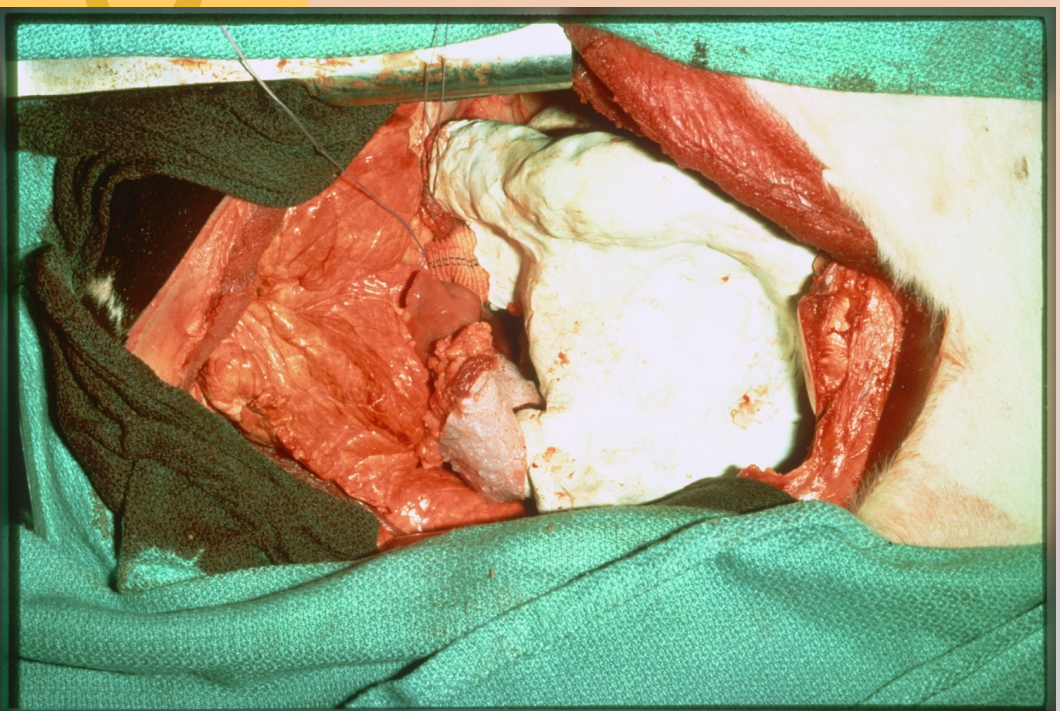
Shape

- The device must fit the contours in the chest.
- Many models of different materials allowed sculpting and molding and fit testing.
- The atrial cuffs and arterial connections are flexible and may be cut by the surgeon to allow adjustment

Fit checks and tests

- Calf fit study (r), note aorta connection.
- Many functional tests in calves.

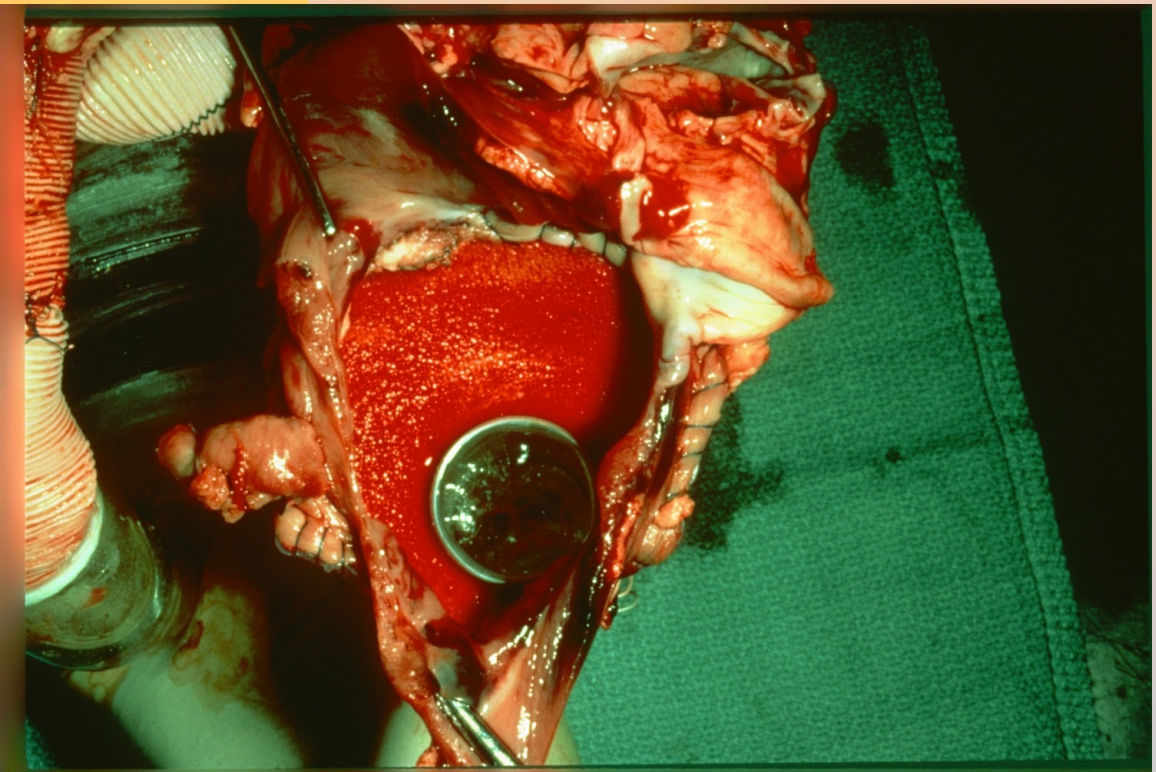




- Cadaver fit study (l)
- Tight but OK.

Experimental results

- Many experiments in calves and a few goats showed the device can sustain life.



- Inner surfaces must remain free of clots to avoid strokes.

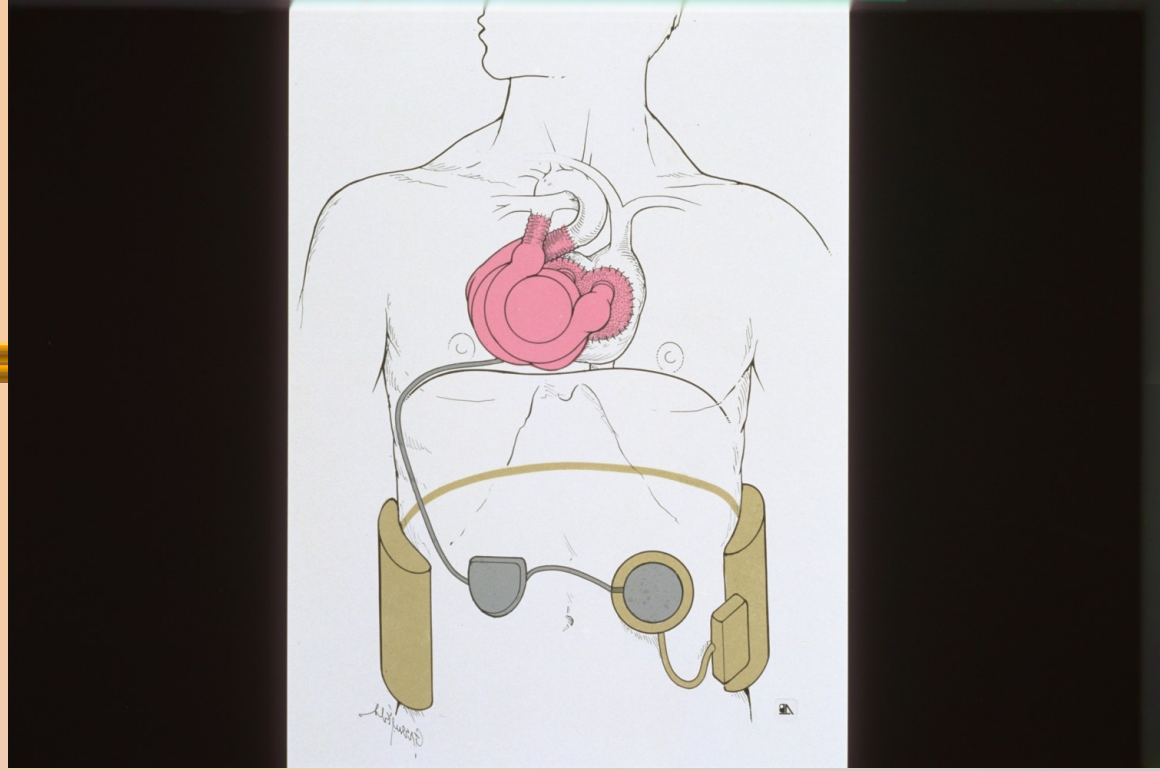
2004 Initial experience with the AbioCor implantable replacement heart system

Robert D Dowling [1], Laman A Gray Jr, Steven W Etoch, Hillel Laks, Daniel Marelli, Louis Samuels, John Entwistle, Greg Couper, Gus J Vlahakes, O H Frazier

- **Objective:** We sought to evaluate the safety and efficacy of the first available totally implantable replacement heart in the treatment of severe, irreversible biventricular heart failure in human patients.
- **Methods:** Seven male adult patients with severe, irreversible biventricular failure (>70% thirty-day predicted mortality) who were not candidates for transplantation had placement of the AbioCor Implantable Replacement Heart. All were in cardiogenic shock despite maximal medical therapy, including inotropes and intra-aortic balloon pumps. Mean age was 66.7 +/- 10.4 years (range, 51-79 years). At the time of the operation, the internal transcutaneous energy transfer coil, battery, and controller were placed. Biventriculectomy was then performed, and the thoracic unit was placed in an orthotopic position and attached to the atrial cuffs and outflow conduits with quick-connects. The flow was adjusted to 4 to 8 L/min. Central venous and left atrial pressures were maintained at 5 to 15 mm Hg.

Results

AbioCor Implantable Replacement Heart



14 near-death patients supported by AbioCor 1.

One lived 166 days, death 11/04 not related to the device.

Rights to a smaller mechanical heart, developed by Penn State, acquired by Abiomed in 2005.

Further clinical use being considered by the FDA; advisory committee reported a closely split negative 6/05.

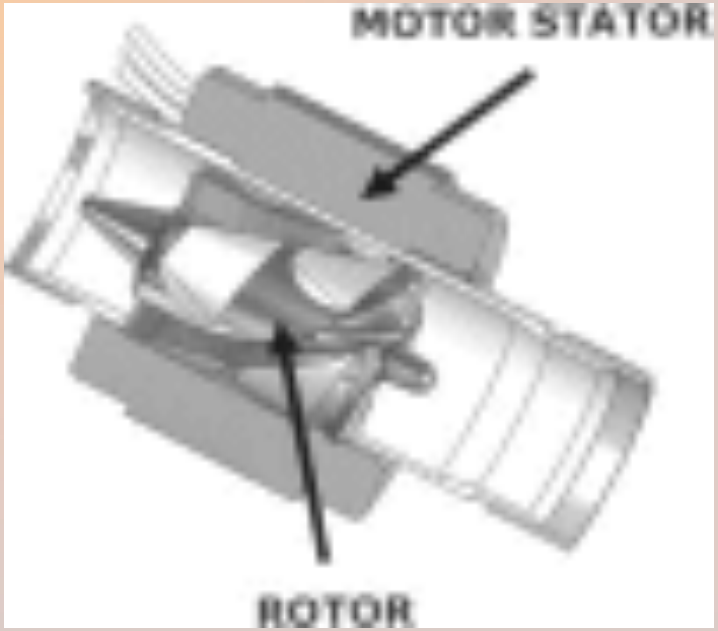
The future of the artificial heart

AbioCor Implantable Replacement Heart

AbioCor II

- Breaking news 2006! FDA has approved up to 2000 patients to receive AbioCor
- A smaller unit is being developed.
- This would fit women better.
- Again, testing in animal trials.
- Regulatory review will determine the future.
- The technology exists.

Axial Flow VAD 1 inch long



Ventricular Assist Devices

circumferential and axial

- Circumferential: The HeartMate II™ LVAD is designed to provide short- or long-term circulatory support for advanced heart failure patients and is indicated for both destination therapy and bridge-to-transplantation in the United States. Backed by more than 10 years of data, the HeartMate II LVAD is the most widely used and extensively studied LVAD in the world, with more than 27,000 patients implanted worldwide.
- Axial: The HeartMate 3™ Left Ventricular Assist Device is indicated for short- and long-term mechanical circulatory support (e.g., as bridge to transplant or myocardial recovery, or destination therapy) in patients with advanced refractory left ventricular heart failure. HeartMate 3 LVAD with Full MagLev™ Flow Technology delivers unprecedented* survival and safety outcomes as demonstrated in the MOMENTUM 3 Trial at 2 years.

Abiocor Future

- **Abiocor Conclusion:** The initial clinical experience suggests that the AbioCor might be effective therapy in patients with advanced biventricular failure. There have been no significant device malfunctions. Two of these patients have been discharged from the hospital.
- Impella is the next generation cardiac device from J&J Abiomed. It is inserted through a cannula into the aorta or pulmonary artery.
- **More than 300,000 patients have been supported with Impella® heart pumps**
- **Abiomed Recalls the Instructions for Use for Impella Left Sided Blood Pumps due to Perforation Risks - 2023**
- The work continues