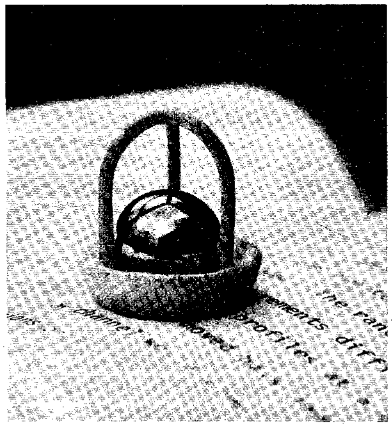
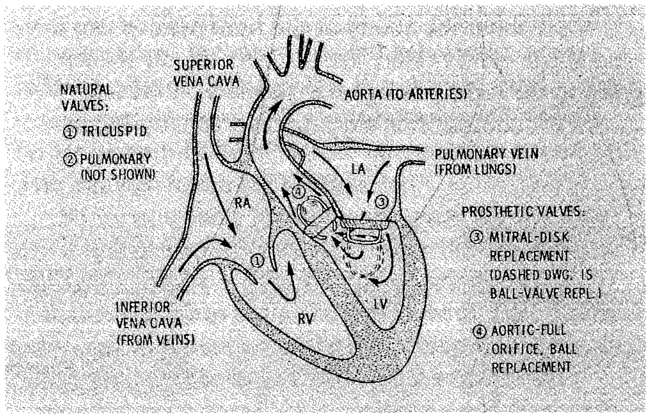
Progress in Artificial Heart Valves

In the 18 years since the development of the heart-lung machine made open-heart surgery possible, more than 500,000 artificial heart valves have been implanted in people whose own heart valves were defective. For most of those people, the quality of life has been improved and its length extended.

Encouraging as this record is, artificial heart valves are far from problem-free, and a team of southern California cardiologists and chemical engineers is working, first, to understand more about the nature of the cardiovascular system and, second, to apply that understanding to solving some of the problems created by the placing of a prosthesis in the human body. Dr. Earl C. Harrison of the USC-County Medical Center and Dr. Richard Bing of the Huntington Institute of Applied Medical Research are the cardiologists; Caltech's Professor William H. Corcoran and Research Fellow Ajit P. Yoganathan are contributing chemical engineering expertise.



The ball-shaped check element in this artificial heart valve moves up and down inside a Dacron-covered cage.



This schematic drawing shows the chambers of the heart and how blood flows through them (except from the right ventricle through the pulmonary artery); it also indicates where prosthetic valves could be implanted.

Heart valves—artificial or natural—operate like check valves in any chemical process system. They automatically limit the flow in a pipe or set of pipes to a single direction. Like natural valves, artificial valves are made in several configurations to accomplish this function. One is a tilting disk that flaps up to allow blood to flow through and down to shut off the flow and prevent regurgitation. Another type of disk valve operates similarly, but the disk moves straight up and down rather than tilting. There are also check elements shaped like balls that move up and down in a metal cage. All of the valve structures incorporate cloth (usually Dacron) sewing rings by which the surgeon sutures the valves into place in the heart. Each valve must, of course, operate dependably, and it must be fabricated of material that will not interact with the body in any harmful way and that will last for the normal life span of the patient.

The pump in the chemical process system of the human is the heart, which in the adult is a muscular organ about 5 inches long, 3 inches wide at the maximum width, and 2½ inches thick. It has four major chambers (two auricles and two ventricles), a number of valves, and associated arteries and veins that act as the pipes, or ducts, of the circulatory system. Briefly, and much simplified, the flow pattern of blood through the heart is as follows.

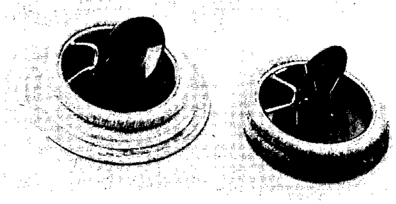
Blood enters the right auricle through the two largest veins in the body—the superior and inferior vena cavas. At this point, the blood is very low in oxygen, and the heart's first task is to help remedy this lack. In its role of circulating venous blood to the lungs, it takes blood from the right auricle in the diastolic beat into the right ventricle through a one-way valve—the tricuspid valve. The right ventricle contracts in the systolic beat to push the blood out. The tricuspid valve keeps the blood from flowing back into the auricle, and so it is forced out through the ventricle's only other opening and then into the pulmonary artery, which carries the blood to the lungs.

In the lungs the blood absorbs oxygen and then returns to the heart, entering the left auricle through the pulmonary vein. The heart in its diastolic beat sucks the oxygenated blood through the mitral valve into the left ventricle.

The left ventricle then contracts in the systolic beat. Again, the blood can flow in only one direction, so it is forced out of the heart, with a maximum flow rate of approximately 420 cc per second, through the aortic valve and into the largest artery of the body, the aorta. At this point the aorta is about one inch in diameter. The blood then makes a round trip through the body, and eventually returns to the heart through the vena cavas but with reduced oxygen content because of the amount left behind for the metabolic processes in the cells of the body.

Blood does not react in the same way with foreign substances like plastic or metal as it does with human tissues. Therefore, artificial heart valves are designed thinking of material requirements as well as those of structure. These valves share many of the design requirements of any flow system, but these must be met using available materials and keeping in mind maximum quality in performance. The research at Caltech focuses on understanding the flow and material characteristics.

In the flow studies, velocities, shear stresses, and pressure losses are investigated. Accurate, detailed observations of all these parameters in the human heart are not yet possible, but chemical engineers can build a model flow system in the laboratory—an artificial aorta, for example—with an artificial heart valve at its entrance, run a simulated blood fluid through it, and then make velocity measurements from point to point.



The tilting disks in these valves flap up to let blood flow through and down to shut it off.

To do this they use a laser-Doppler anemometer.

With this type of anemometer, crossed laser beams strike impurities in a stream of fluid flowing through a channel, and the light is scattered from them at a slightly different frequency than from the original source. From this displacement in frequency and the angle at which the laser beams pass through the system, calculations may be made of the exact velocity of the flow at a given point.

An understanding of the velocities is important for several reasons. Jet effects can, for example, damage the walls of the aorta. High shear stresses can damage blood cells, and regions of low flow can lead to clot formation. Under adverse circumstances endothelial cells of the aorta may be sheared off and scar tissue developed. Red cells may be fractured, allowing hemoglobin to leak out into the blood plasma. Platelets in the blood begin to sustain damage at stresses as low as 400 dynes per square centimeter. The result is loss of some of their chemicals, which can initiate clotting. When the velocity of the blood flow is too low, stagnation may take place in such areas as on the minor outflow side of a tilting disk valve, with consequent clotting or buildup of extra endothelial tissue. When the various problems are considered, the value of the research goals of learning more about shear and velocity fields along with pumping pressures becomes more apparent.

What are some of the other desirable features of artificial heart valves? They should be sterile, non-toxic, and surgically convenient to use. They should offer minimum resistance to flow and minimal reverse flow for maximum pumping efficiency. They should be long-lasting (say 25 years), with low mechanical and structural wear during all of that period. They should be reasonably quiet in operation, and it should be possible to manufacture them at a relatively low price.

At present, some 90,000 artificial heart valves are implanted in otherwise handicapped human beings each year, making possible longer and more active lives for the wearers. The failures and malfunctions of those valves—and they are surprisingly infrequent—have led to the cooperative effort to improve valve design and performance. Chemical engineers Corcoran and Yoganathan and doctors Harrison and Bing hope that a combination of meticulous observation of actual patients and careful laboratory research into the nature of the flow system will lead to reduction of the number and severity of the problems and to improvement of the quality and length of life. □