NASA TECHNICAL MEMORANDUM

NASA TM X-52408

NASA TM X-52408

GPO PRICE $

CSFTI PRICE(S) $

Hard copy (HC) 3.00

Microfiche (MF) .65

ff 653 July 65

N68-21237

(ACCESSION NUMBER) (THRU)

24 (PAGES) 1 (CODE)

TMX-52408 (NASA CR OR TMX OR AD NUMBER) 04 (CATEGORY)

FACILITY FORM 602

EXPLORING IN AEROSPACE ROCKETRY
21. BIOMEDICAL ENGINEERING

by Kirby W. Hiller
Lewis Research Center
Cleveland, Ohio

Presented to Lewis Aerospace Explorers
Cleveland, Ohio
1966-67

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION · WASHINGTON, D.C. · 1968

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Advisor, James F. Connors

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Chapter		NASA Technical Memorandum
1	AEROSPACE ENVIRONMENT John C. Evvard	X-52388
2	PROPULSION FUNDAMENTALS James F. Connors	X-52389
3	CALCULATION OF ROCKET VERTICAL-FLIGHT PERFORMANCE John C. Evvard	X-52390
4	THERMODYNAMICS Marshall C. Burrows	X-52391
5	MATERIALS William D. Klopp	X-52392
6	SOLID-PROPELLANT ROCKET SYSTEMS Joseph F. McBride	X-52393
7	LIQUID-PROPELLANT ROCKET SYSTEMS E. William Conrad	X-52394
8	ZERO-GRAVITY EFFECTS William J. Masica	X-52395
9	ROCKET TRAJECTORIES, DRAG, AND STABILITY Roger W. Luidens	X-52396
10	SPACE MISSIONS Richard J. Weber	X-52397
11	LAUNCH VEHICLES Arthur V. Zimmerman	X-52398
12	INERTIAL GUIDANCE SYSTEMS Daniel J. Shramo	X-52399
13	TRACKING John L. Pollack	X-52400
14	ROCKET LAUNCH PHOTOGRAPHY William A. Bowles	X-52401
15	ROCKET MEASUREMENTS AND INSTRUMENTATION Clarence C. Gettelman	X-52402
16	ELEMENTS OF COMPUTERS Robert L. Miller	X-52403
17	ROCKET TESTING AND EVALUATION IN GROUND FACILITIES John H. Povolny	X-52404
18	LAUNCH OPERATIONS Maynard I. Weston	X-52405
19	NUCLEAR ROCKETS A. F. Lietzke	X-52406
20	ELECTRIC PROPULSION Harold Kaufman	X-52407
21	BIOMEDICAL ENGINEERING Kirby W. Hiller	X-52408

21. BIOMEDICAL ENGINEERING

Kirby W. Hiller*

Listening to the heart by direct ear contact is said to have begun with Hippocrates in the late fourth century B.C. During the following 2200 years, the method was used with limited success for examining patients with suspected heart trouble. One of the main limitations was that the method could not be used on fat people because the fat muffled the sound. It was exactly this problem, a fat patient with suspected heart trouble, that faced Réné Laënnec in 1816, and his solution became an early example of the application of engineering principles to medicine. The following is a description of the incident in Laënnec's own words (ref. 1):

> I happened to recollect a simple and well-known fact in acoustics . . . the great distinctness with which we hear the scratch of a pin at one end of a piece of wood on applying our ear to the other. Immediately, . . . I rolled a quire of paper into a kind of cylinder and applied one end of it to the region of the heart and the other to my ear, and was not a little surprised and pleased to find that I could thereby perceive the action of the heart in a manner much more clear and distinct than I had ever been able to do by the immediate application of the ear.

Laënnec called his instrument a stethoscope and experimented with many materials and configurations to improve it.

The recent dramatic increase in the applications of aerospace engineering principles to medicine has given rise to a new field of engineering - biomedical engineering. Market survey organizations have been studying the prospects for this field, and they predict that it will grow into a young giant, becoming one of the seven new industries to surpass the billion dollar mark in the 1970's. It should be worthwhile to examine the nature of this new field and to consider what factors may be responsible for its growth.

Engineering principles are applied to biology and medicine in four main areas: diagnostics, treatment, prosthetics, and biological research. These areas are discussed in the following sections.

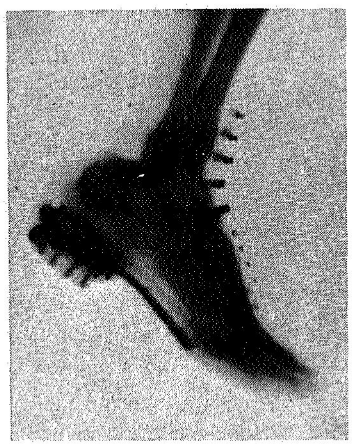
DIAGNOSTICS

Diagnosis is the process by which a disease is identified from its symptoms. Engi-

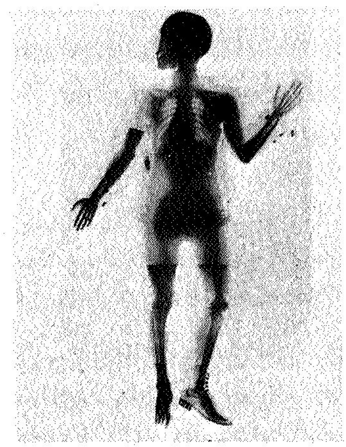
*Head, Airbreathing Engine Controls Section.

neering equipment lends itself to a wide variety of these applications. The following are some examples.

X-ray photography. - Almost as soon as it was discovered in 1895, X-ray photography (fig. 21-1) became one of the best known and most useful applications of engineering to medicine and has remained so ever since. The X-ray machine demonstrates one of the most desirable features of any diagnostic equipment: in operation, it affects neither the patient nor the pathological condition it must examine. (A glossary of medical terms is given at the end of this chapter, p. 21.) It depends entirely on the differences in opacity to X-rays of the various tissues for its success. Radiopaque substances, if swallowed or injected, follow the motion of fluids through the body and these can then

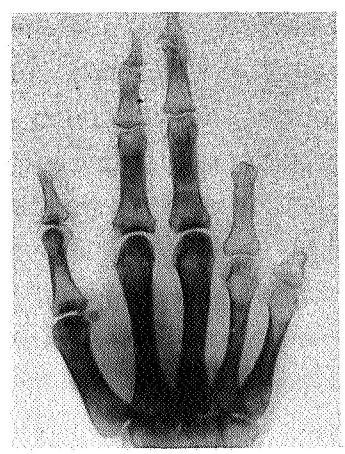


(a) Normal foot in shoe (taken by D. C. Miller, probably in early 1896).



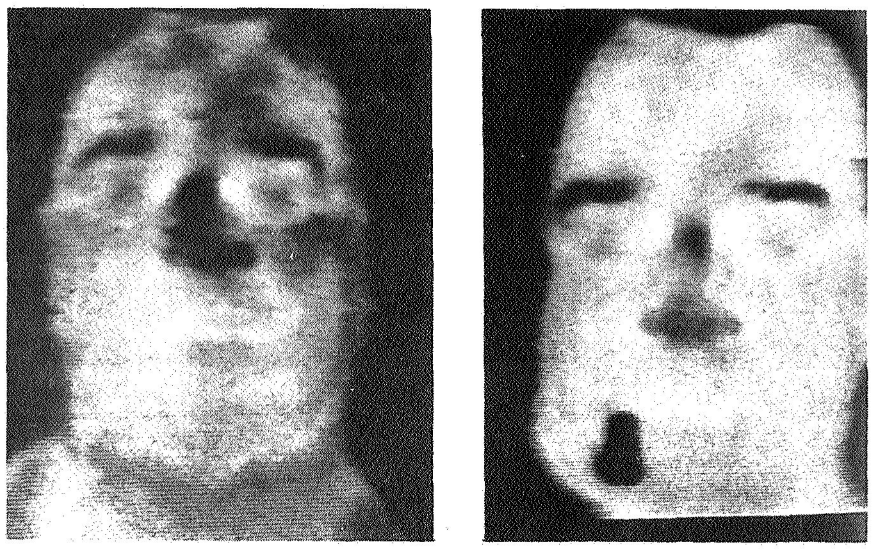
(b) Composite self-portrait of D. C. Miller (probably taken in early 1896).

(c) Dislocated thumb (taken by D. C. Miller on March 13, 1896).



(d) Hand with parts of fourth and fifth fingers removed by buzz saw (taken in April 1922). Note improvement in X-ray technique.

Figure 21-1. - Early examples of X-ray photography. (Original plates loaned to NASA by Professor Robert S. Shankland, Case Western Reserve University.)



(a) Before surgery. (b) After surgery. (The dark area at the patient's mouth is a pipe.)

Figure 21-2. - Infrared photographs showing variation in skin temperature of patient with blocked carotid artery. Dark areas indicate lower temperatures. (Courtesy of Dr. Warren Zeph Lane, Norwalk Hospital, Norwalk, Conn.)

be studied. For rapid motion, as in the circulatory system, X-ray motion pictures are taken.

Infrared photography. - If infrared-sensitive film is used to photograph a patient, the resulting image indicates variations in skin temperature. The presence of cancer, for example, may show up as a slight decrease in temperature over the afflicted area of the body. Figure 21-2 is an example of an infrared photograph. Figure 21-2(a) shows the facial temperature pattern of a patient who has a blocked carotid artery (the principal artery of the neck). Before surgery, the patient's average facial temperature is about 94.3° F, and his nose is particularly cold. After surgical removal of the blockage (fig. 21-2(b)), the patient's average facial temperature is about 0.5° warmer. (The dark area at the side of the patient's mouth is a pipe.)

Blood-sample diagnosis. - A typical large hospital performs thousands of chemical analyses per week on blood samples from patients. These analyses are slow and subject to human error. A machine is now available that automatically separates a blood sample into a dozen or so subsamples which are fed into analysis modules. Reagents are added automatically, the mixture may be heated or filtered, the results are analyzed optically by photocells, and the results are printed.

Patient monitoring. - Automatic monitoring equipment in use for intensive-care patients provides continuous electronic sensing of the electrocardiogram (EKG) signal, pulse rate, blood pressure, and respiration rate. When one of these parameters falls outside of normal limits, an alarm is automatically sounded and an automatic chart printout is initiated.

Telemetry. - Small transmitters, in combination with patient monitoring sensors, can be carried on or in the patient and make it possible to monitor the patient in action. Microelectronic devices developed for space programs have advanced this field. It is possible to monitor the blood pressure and heartbeat of a patient while he is climbing stairs. A small capsule is available which, when swallowed, telemeters back a signal indicative of the temperature in the alimentary canal.

Computer diagnosis. - Today, one of the most common uses of computers is in the maintenance of centralized records and medical information. A knowledge of past medical history is often valuable in treating a specific illness, and with people traveling more, centralized records can make their medical history available to physicians all over the country. Travel, by exposing people to a wider variety of diseases, introduces another medical problem which computers are able to help solve: although a doctor in Colorado, for example, may be very familiar with tick fever, he seldom encounters a case of malaria; for a doctor in another place, the reverse may be true. Centralized medical information makes it easier for each doctor to use the experiences of the other.

Diagnostics summary. - The many fruitful techniques for applying engineering to diagnosis gives this branch of biomedical engineering a bright future. It will grow rapidly and, in so doing, will rely on miniature instruments to probe into hitherto inaccessible areas of the body. Automated medical analysis will encourage the clinical approach, in which the patient will be given a comprehensive series of tests that will then be interpreted by computers. The role of the physician will change; instead of a man who makes a diagnosis on the basis of broad experience and a few well-selected tests, he will become increasingly concerned with using and improving diagnostic equipment.

The education and experience requirements of the physician will change. There will be opportunities for physicians who are very knowledgeable about engineering equipment and for engineers who are well versed in anatomy and physiology.

TREATMENT

Medical engineering equipment is being developed which makes new treatment techniques possible. Some examples are now presented.

Heart-lung machine. - In the human circulatory system (fig. 21-3), blood returns from the body to the right atrium of the heart; from there, it passes into the right ventricle, which pumps it to the lungs for oxygenation. Following this, the blood reenters the heart at the left atrium, moves to the left ventricle, and is pumped back into the body.

During operations on the heart or lungs, it is generally dangerous to expect them to continue functioning normally. Moreover, even if they do, such activity may easily com-

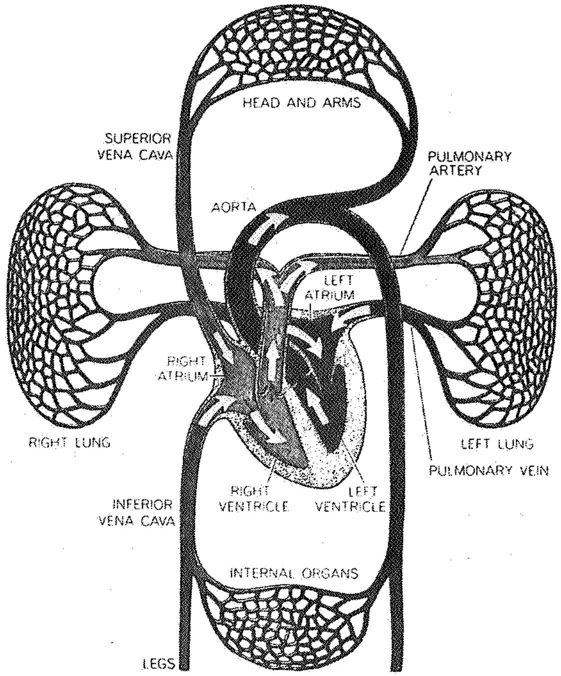


Figure 21-3. - Human circulatory system. (Courtesy of W. H. Freeman & Co., Publishers.)

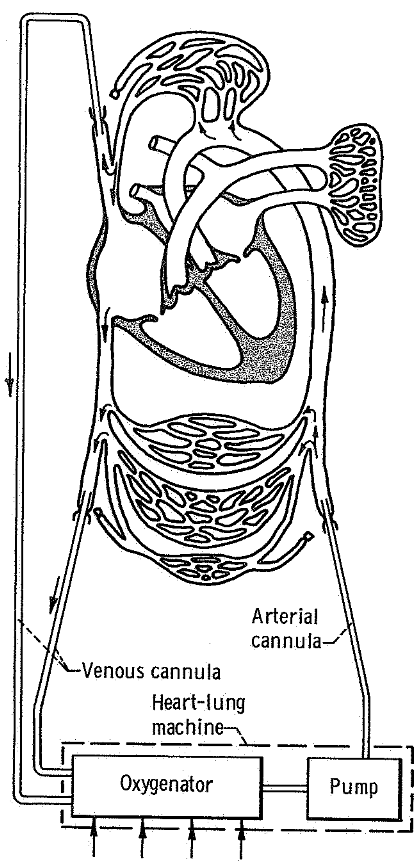


Figure 21-4. - Human circulatory system with heart-lung machine.

plicate the surgeon's problems. Surgery in this region of the body is much simpler when the heart and lungs can be inactivated without danger to the patient. This is the job of the heart-lung machine (fig. 21-4).

While the blood is outside the body for oxygenation and pumping, it is cooled by being run through a heat exchanger to reduce the patient's body temperature quickly to a state of deep hypothermia. This permits dry field surgery because cold tissues use oxygen at a lower rate and can live without circulation for a longer period.

Heart assist pump. - A person recovers much more quickly from a heart attack if his heart has a chance to rest for a while; the heart assist pump makes this possible. One of the major problems in developing this device was synchronizing the artificial pumping action with the natural heartbeat. This was solved by NASA engineers by allowing the patient's own heart to stimulate the artificial one through an electropneumatic relay which responds to myopotentials. Thus, an electrical signal as low as 1 millivolt, produced at the skin by a feeble natural heartbeat, is sufficient to trigger the heart assist pump.

According to the nature of the problem, several types of heart assist pumps are available. One is the left-heart bypass. It pumps blood in parallel with the left heart. Another is the counter-pulsation pump, which pushes blood in and out of the aorta in synchronization with the heartbeat. Both devices reduce the workload of the heart and hence are useful in helping a patient recover from open-heart surgery as well as from heart attacks.

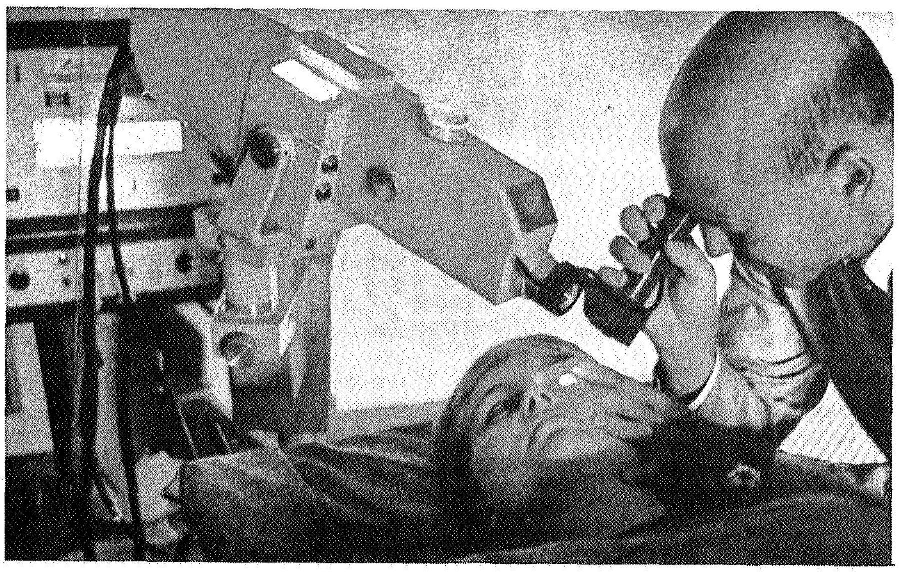


Figure 21-5. - Laser eye surgery. (Courtesy of Archie Liebermann.)

Laser. - The recent development of the laser device has created the new field of bloodless laser surgery. Ultraviolet lasers have been used to remove tumors. Lasers are also used for delicate eye surgery, as shown in figure 21-5. Here the surgeon aims a concentrated laser beam onto the back of the patient's eye. The resulting burn forms a pinpoint scar to seal down a dangerous tear of the retina.

Cryogenic probe. - The application of the cryogenic probe to the field of surgery has resulted in the technique of cryosurgery, which is the process of destroying diseased tissue by freezing. Cryogenic probes can be used to freeze the lens of an eye before removal of a cataract or to make a therapeutic lesion. Certain diseased areas of the brain can be killed by inserting a cryogenic probe to the proper depth and freezing the tissue (fig. 21-6).

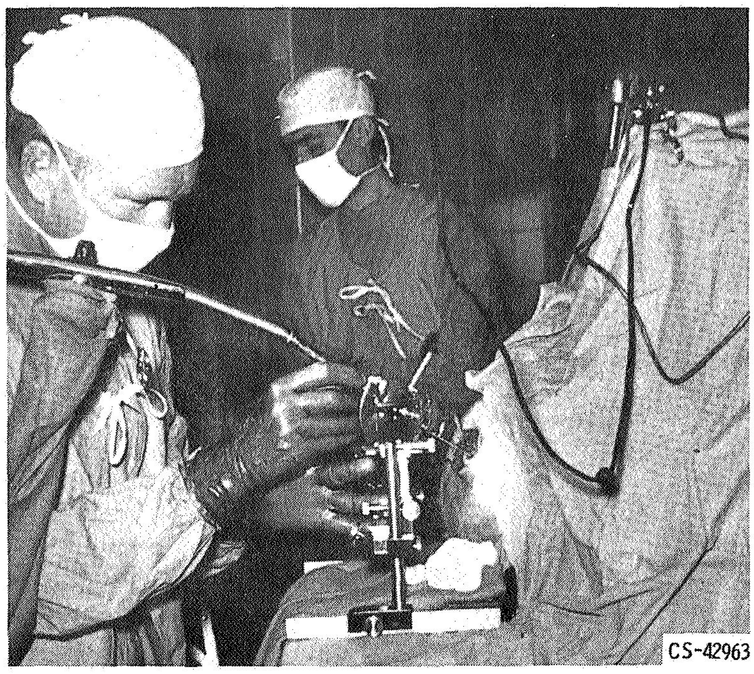


Figure 21-6. - Cryogenic brain surgery.

Air-inflated Hoverbed. - The principle and the technology of the Hovercraft, resulting from aeronautical research, have been applied in the development of the air-inflated Hoverbed, shown in figure 21-7. This bed is used for treating burn victims. The bag is pressurized by air from a compressor. The upper surface of the bag consists of segments of porous, light fabric. The pressure difference between the inside of the bag and the outside causes the upper surface to billow up. If an object is placed on the bag, a seal is made at the periphery of the object. Now the pressure on the bottom of the object becomes as high as the pressure inside the bag. Since a pressure difference

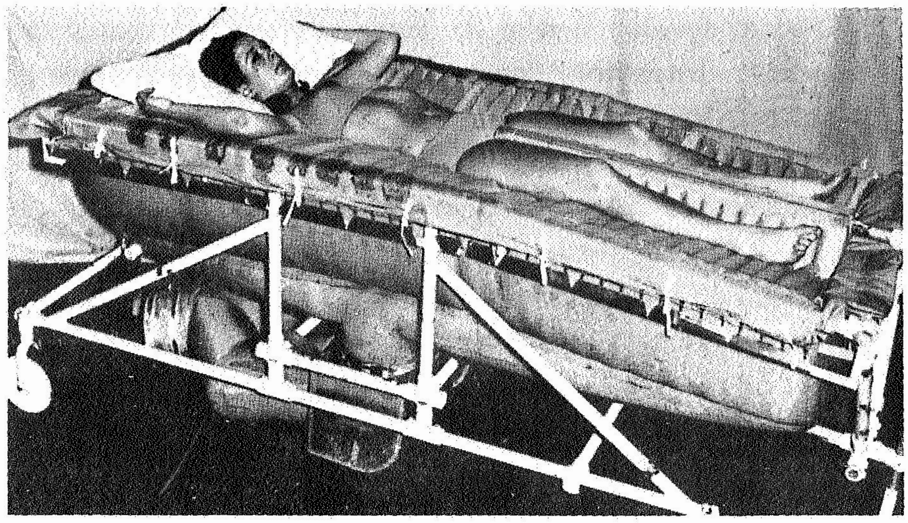


Figure 21-7. - Air-inflated Hoverbed. (Reprinted with the permission of Industrial Research, Inc.)

no longer exists across the fabric, it falls limply away. Now the object is essentially floating on air, except for a line of contact at its periphery. (This is the principle of Hovercraft.) The same thing happens when a patient lies down on the bag; the patient becomes almost completely airborne. Under this kind of treatment the weeping areas of burns dry rapidly.

Treatment summary. - Through the use of engineering equipment, entirely new treatment techniques, as well as better ways of doing the old jobs, have been made possible. As in diagnostics, the need for physicians who can deal with complicated engineering equipment is increasing. For the engineer, the design of equipment which will solve the needs of the physician is important. This field is already well underway with many fruitful applications.

PROSTHETICS

Prosthetics is the specialty which is concerned with the replacement of organs of the body with artificial devices. Some examples are now discussed.

Artificial heart. - The human heart is a four-chambered pump equipped with four valves (see fig. 21-3, p. 5). Recently, medical engineers have developed lightweight plastic pumps which can be substituted for the chambers of the heart. Figure 21-8 is a schematic diagram of one of these pumps. When pneumatic pressure in the drive line is reduced, blood pressure in the vein causes blood to open the inflow valve and fill the artificial ventricle. When pneumatic pressure in the drive line is increased, the resulting increased blood pressure in the ventricle closes the inflow valve, opens the outflow valve, and causes the blood to discharge into the artery.

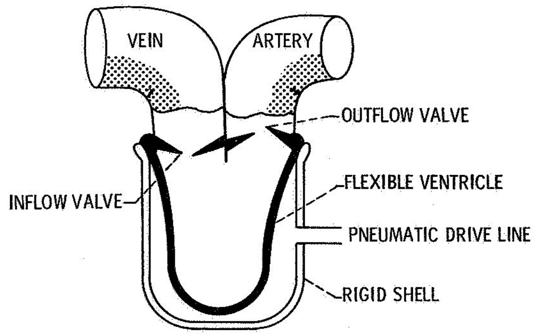
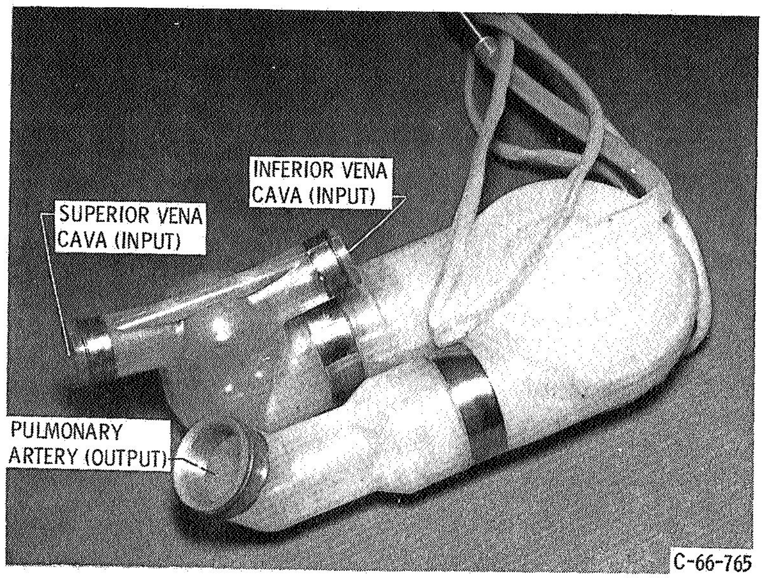
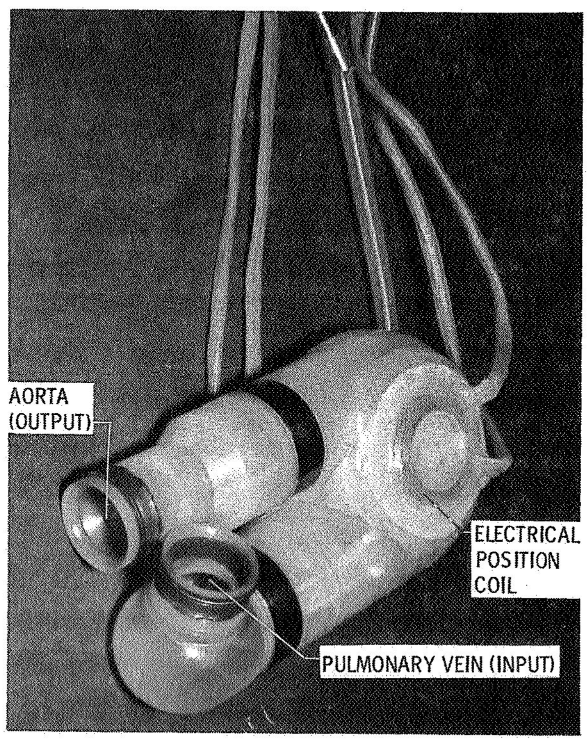


Figure 21-8. - Sac-type pneumatic artificial ventricle.



(a) Left chamber.



(b) Right chamber.

Figure 21-9. - Chambers of artificial heart.

Two such prosthetic ventricles (fig. 21-9) are required to replace a human heart. These ventricles, or chambers, are made of silicone rubber, a flexible material that is compatible with body fluids. The doughnut-shaped object on the side of the right chamber in figure 21-9 is an electrical position coil used to detect the blood volume in the artificial ventricle.

NASA engineers have contributed to the development of artificial heart systems, first by suggesting in 1960 the possibility of using air as an energy transfer medium for driving artificial hearts, and later by designing pneumatic control devices capable of reproducing physiologic pressure waveforms and pulse rates.

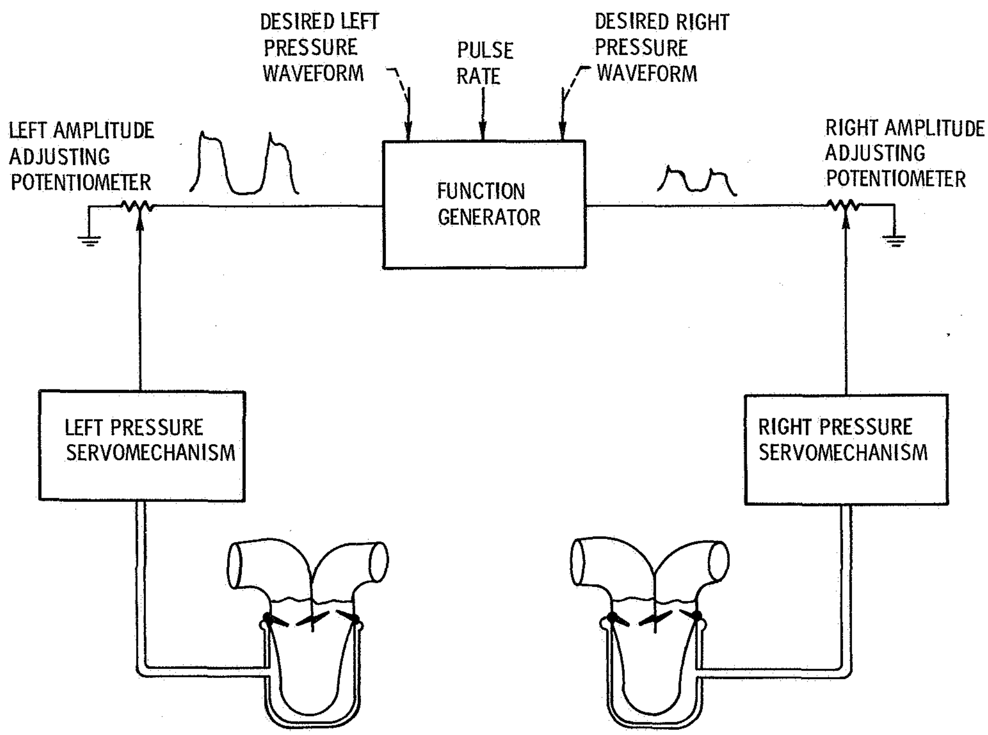


Figure 21-10. - Block diagram of artificial heart control system.

A block diagram of this NASA-developed control system for the artificial heart is shown in figure 21-10. The function generator is an electronic device which repetitively produces electrical voltages indicative of the desired left and right ventricular pressures. Since it is an electronic device, its waveforms can be adjusted to any desired functions of time, and it can be sped up or slowed down to provide variable pulse rates.

A desired fraction of the left and right voltages can be selected by means of the two amplitude adjusting potentiometers and fed to two pressure servomechanisms. These servos are slave devices which faithfully reproduce the voltages as pneumatic pressures.

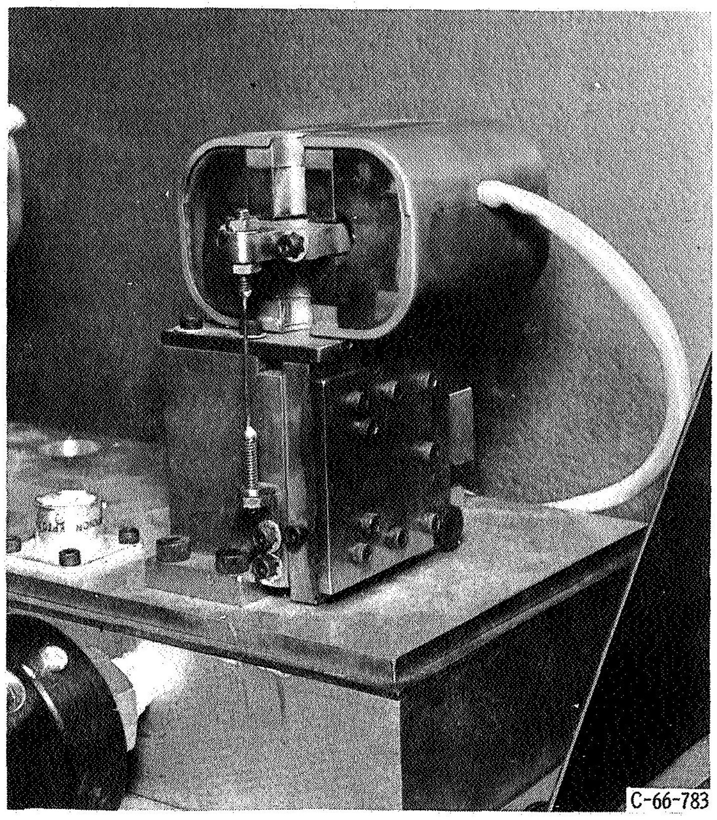


Figure 21-11. - Pneumatic servovalve for artificial heart.

Within each pressure servomechanism the electrical signal is transduced to a pneumatic pressure by a servovalve, shown in figure 21-11. The operating principle of the servovalve is similar to that of an electrical solenoid. An electrical current produces a motion of an armature. Through the use of a restraining spring, the motion of the armature is rendered proportional to the current in the coil. A valve element is connected to the armature by means of the long, thin drive rod shown in figure 21-11.

The complete control system, shown in figure 21-12, employs many sophistications necessitated by the nature of this medical research. The small analog computer at the top of the left console is used to lend flexibility to the control system. For example, the computer permits automatic adjustment of the amplitudes of the voltages going to the left and right pressure servos and eliminates the need for manual adjustment of the potentiometers shown in figure 21-10. This feature allows heart flow rate to respond to the body's needs through electronic sensing of physiological signals. Thus, the need for continual operator adjustment is reduced, and the system essentially makes its own adjustments. The bank of potentiometers in the lower portion of the left console (fig. 21-12)

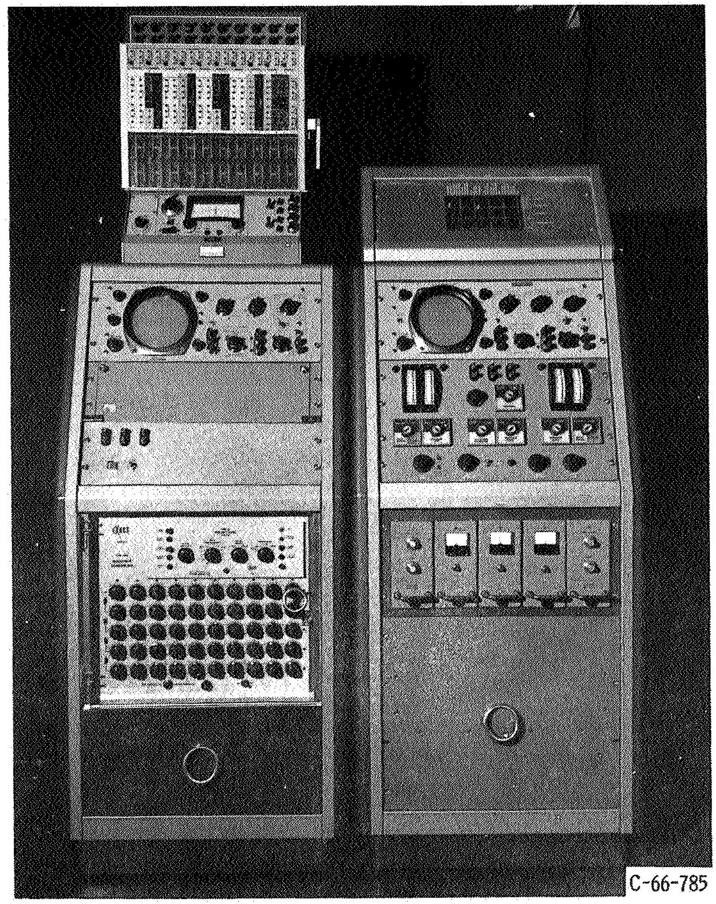


Figure 21-12. - Control system for artificial heart.

is used to set up the left and right heart pressure waveforms. The use of these 50 dual potentiometers permits a relatively exact setting of the desired waveforms.

The three electronic modules with square meters in the lower portion of the right console (fig. 21-12) are servoamplifiers for the pneumatic servovalves that are located in the pull-out drawer at the bottom of the console. Three channels of servosystems permit one to serve as a spare in case either the left or right channel fails. Automatic sensing of a failure and automatic substitution of the spare channel is accomplished by the large panel under the oscilloscope in the right console.

This control system is being used in a medical research program to develop artificial hearts for total heart replacement in humans. Present experimental work is being done with sheep and calves.

Pacemaker. - The pacemaker is an electronic heart-shocking device that replaces the nervous impulse that initiates the beat of the heart. Most pacemakers operate at a fixed pulse rate and consist of a free-running oscillator, a power amplifier, and batteries. Recently, the battery life has been increased, and the units can be implanted under the skin; the requirements for electrical leads that penetrate the skin are thus eliminated.

Artificial kidney. - The artificial kidney is based on the principle of dialysis, which is the separation of substances in solution by means of differential diffusion through a semipermeable membrane. In the artificial kidney (fig. 21-13), blood from the body flows past semipermeable plastic membranes that are bathed by a dialyzing fluid. Impurities are removed from the blood by their diffusion through the membranes into the dialyzing solution. The artificial kidney shown in the figure was designed for home use to minimize cost to the patient.

Figure 21-13. - Artificial kidney for home use. (Courtesy of Dr. Yukihiko Nosé, Cleveland Clinic.)

Artificial limbs. - Work is being done in several organizations to develop powered artificial arms or legs. An artificial arm requires many degrees of freedom, and electric or hydraulic actuators with position or force feedback are required for each degree of freedom. Packaging all of this into a size compatible with the limb to be replaced presents a real engineering challenge. A variety of ways are available for obtaining the command signals. One way is to use biological electric signals caused by muscle contractions and called myopotentials. These signals from even minute muscle motions can be picked up on the skin's surface by electrodes, amplified, fed to a pattern-recognition computer similar to that used in recognizing aerial reconnaissance photos, and used to drive the actuators.

Prosthetics summary. - The ease with which engineering has been applied to diagnostics and treatment has not held true for prosthetics. One difficulty is that prosthetic devices must serve as complete replacements for human organs during the remaining life of the patient. In the case of the artificial heart, for example, this requires approximately 100 000 beats a day, 3.6 million a year, or 720 million in 20 years. In contrast to this, the heart-lung machine, an operating-room device, need only function for about 6 hours, or about 25 000 beats. The researchers in prosthetics find themselves competing with nature in trying, in a few years, to develop an artificial organ as good as the natural one that developed over millions of years. The researcher gains a new respect for the capabilities of the human body. He also may find that the organ he is trying to replace was performing a function only partly understood by the physiologists. If the life of a patient depends on an artificial organ, the researcher is faced with several moral and legal problems. For example, if the artificial organ costs $100 000 and requires a team of six experts to maintain it, could the resources being expended to keep one man alive keep several alive? If the machine fails because a simple part breaks, who is responsible? These are not arguments against working in this field, but they are arguments for working carefully. Moreover, advancing technology will solve many problems - new power sources, increased reliability, lower costs, and stronger materials are exactly what workers in this field are seeking.

BIOLOGICAL RESEARCH AND MAN-AUGMENTATION

The use of scientific and engineering equipment enables us to study the basic processes of nature, thereby expanding our knowledge of man. Special microscopes, electronic detectors, and chemical analysis techniques can be used in these studies. As this field expands, researchers may discover, on the molecular level, how the basic process of life takes place. The factors which determine and control intelligence, the basic nature of the thought process, heredity, aging, and disease will all become better understood.

When these basic biological subjects are understood in depth, improvements will be easier to make. A hint comes from Philco's Communications and Electronic Division. where work on the artificial limb control mentioned earlier has made it possible for man's nervous system to communicate directly with a computer by means of sensing myopotentials. At the same time, it is possible to communicate back to man's nervous system by electronics; experiments have been conducted in which electrodes have been implanted deep in the brains of monkeys. This has permitted stimulation of the monkeys that induced pleasure responses so great that the monkeys preferred pushing a lever to eating or sleeping - hence they levered themselves to exhaustion. A possible application of the myopotential work is remote control of industrial machines. It is hoped that a digging machine can be made to follow the arm motions of the operator. If detailed intelligence-bearing information could be conveyed to and from the nervous system by electronics, the consequences to our society would be great. For example, speech at 200 words per minute is an awkward way to supply information to a computer, but electrical communication with the nervous system of man would permit individuals to communicate by electronics at speeds in excess of 1000 words per minute.

Electronic communication between man's mental processes and computers illustrates what may come about through the application of engineering principles to man himself. As technological development has advanced, man has produced sizable changes in his environment. He has surrounded himself with equipment that permits him to travel very fast, to speak over long distances, to raise crops, and to build roads with little expenditure of human energy. But, man's personal attributes have remained relatively unaffected. He still communicates verbally or in writing, the way men did when they thought that arteries were filled with air and that the heart was the body's source of heat, the site of love, and the habitat of the soul. During this time, man's machines have outstripped him. Technology has become so extensive that man, who still communicates and learns with the same old techniques, must spend an increasingly long time to learn enough to be useful; some professionals, like the surgeons, do not complete their education until they are past 30, or nearly at the chronological midpoint of their lives.

A further illustration of the incompatibility of man and his machine is the automobile. Each year, cars become faster and traffic patterns become more complicated. The proportion of people who are really capable of driving safely under these more difficult conditions is getting smaller. The need for an automobile control system using electronic sensors and computers which will augment the driver's sensory and decision-making capability is becoming very acute and is a fruitful area for future research.

Thus, a field which might be called man-augmentation is ready to be developed. It will bring man back into harmony with his machines. This will be done by both changing the machines so they are right for man and, through biological research, changing man so he can handle his new role in life. When this work is successful, man will become the master of his technology rather than a slave to it. Beyond these immediate goals, advances in basic biological research may, in the future, permit profound changes in man's physiology. It may be possible to regenerate diseased tissue, to enhance intelligence, to select the sex of progeny, or to slow down the aging process.

As with prosthetics, biological research and man-augmentation tends to be a more futuristic field than diagnostics and treatment. The idea of extending man's basic personal capabilities is far from present practice, but the future potential of this field is very great.

APPENDIX - CIRCULATORY SYSTEM PHYSIOLOGY

Purpose of Circulatory System

Any living organism depends for its existence on the exchange of material between itself and its surroundings. A spherical object like a single cell of radius R has a surface area of $4\pi R^2$ and a volume of $4\pi R^3/3$. Its surface-to-volume ratio is given by

$$\frac{S}{V} = \frac{3}{R} = \frac{6}{D}$$

This is the familiar surface-to-volume ratio which gives an insight into many phenomena of nature. It shows why larger plants and animals have had to develop specialized organisms for exchanging material with their surroundings. On a linear scale basis, man is about 5000 times as large as a single cell, so his material exchange problem, being a volume-to-surface-area related phenomenon, is 5000 times more difficult. To make life possible, organs like the lungs and digestive system have been developed with folded, crinkled surfaces to maximize their surface area. The circulatory system conducts materials around the body in liquid solution from these organs to nourish the cells of the body. These cells live in the interstitial fluid whose chemical composition is constantly maintained by the circulation of blood. Some reference numbers for man are as follows:

Body weight, kg (lb)	70 (155)
Body volume, liters (qt)	85 (89.7)
Interstitial fluid volume, liters (qt)	14 (14.8)
Blood volume, liters (qt)	5.3 (5.6)
Skin surface area, m^2 (ft^2)	1.7 (18.3)
Lung effective surface area, m^2 (ft^2)	90 (970)
Intestine effective surface area, m^2 (ft^2)	10 (107)
Kidney effective surface area, m^2 (ft^2)	1 (10.7)

Function of Circulatory System

The circulatory system is composed primarily of the heart and a number of blood vessels. Figure 21-3 (p. 5) shows a diagram of the system. The heart's only known function is to pump blood. The blood vessels essentially conduct blood to and away from the heart. The action of the heart is as follows: On diastole, the top part of the heart contracts (the two atria) and the bottom relaxes (the two ventricles). This causes blood to enter the two inflow valves and fill the ventricles. On systole, the bottom part of the heart contracts (the ventricles) and the top part relaxes (the atria). This causes blood to leave the heart through the two outflow valves. Thus, the heart is a four-chambered pump with four valves, two for each ventricle. Its external connections are four large veins and two large arteries, or six vessels in all. As the heart accepts blood on diastole and discharges it on systole, it exhibits an up-and-down motion because of the momentum of the entering and leaving blood. This motion, together with the pulsatile pressurization of the circulatory system which it causes, produces a two-pulsed sound on each beat. It also exerts a pulsating force on its owner. These sounds and motions are normally indicative of the presence or absence of life.

The flow path of blood in the circulatory system can be deduced by observing the vessel connections and knowing that the heart induces pulsatile, unidirectional flow of blood in its six connecting vessels. Starting from the superior and inferior venae cavae, blood enters the right atrium. On diastole, it enters the right ventricle through the tricuspid valve. On systole, blood leaves the right ventricle through the semilunar valve and enters the pulmonary artery. This artery divides to carry the blue blood to the two lungs. Red oxygenated blood returns from the lungs through the pulmonary veins to the left atrium. On diastole, it enters the left ventricle through the mitral valve. On systole, blood leaves the left heart through the aortic valve and enters the aorta. The ascending aorta divides to provide flows to the head and upper extremities while the remainder flows down the descending aorta to the trunk and lower extremities. The two sides of the circulatory system are the pulmonary system, and the systemic system.

The overall action of the heart and circulatory system is a fairly complex, ever-changing phenomenon. Pressures and flows in the vessels are not steady but pulsating. At locations near the heart, the amplitude of these pulsations are large, while at the ends of the small arteries the pulsations have been filtered, leaving steady flow conditions. In addition to the pulsatile conditions that exist in the circulatory system, the net overall flow rate, pulse rate, and pressure level change in response to stimulation of the organism. It has been found that both heart and blood vessels work together to produce these changes.

A graph of the time sequence of events in the left heart is shown in figure 21-14. The solid curve in the upper part of the figure shows pressure inside the ventricle. The upper dotted curve shows pressure in the aorta, while the lower dotted curve shows pressure in the left atrium. The next curve down shows a graph of heart sound output; the next curve shows the ventricular volume, and the last, the electrocardiogram (EKG).

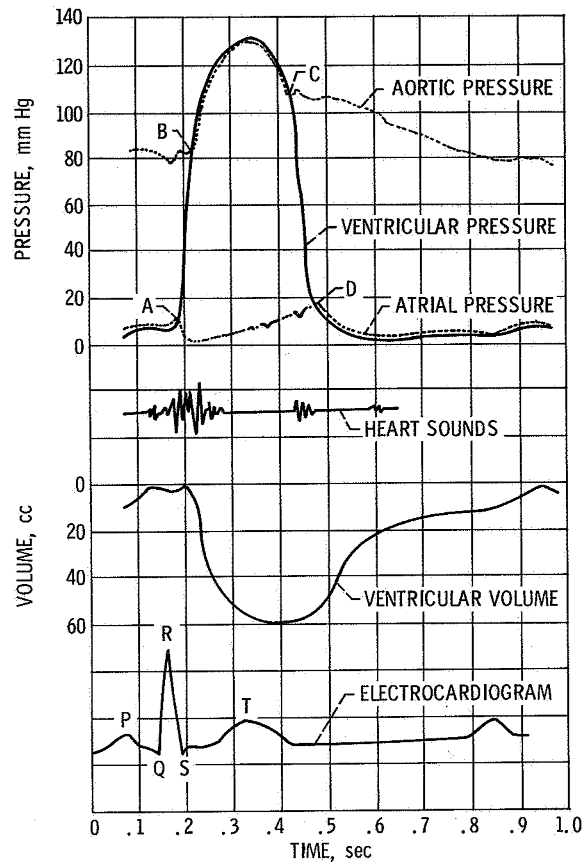


Figure 21-14. - Time history for left heart. (Based on Physiology in Health and Disease by C. J. Wiggers, Lea & Febiger, Publishers, 1949.)

At time 0.15 second on the graph, the heart gets a nervous impulse to beat. This causes a depolarization wave to sweep through the muscle cells of the heart, giving rise to the "QRS complex" part of the EKG signal and initiating contraction of the ventricles (systole). Shortly after this, the ventricle starts to contract. At point A (time = 0.18 sec) on the pressure curve, ventricular pressure exceeds atrial pressure and causes the mitral valve to close. Ventricular pressure rises rapidly from point A to point B (0.21 sec), at which point ventricular pressure exceeds aortic pressure and causes the aortic valve to open and outflow to begin. On the sound trace, it is seen that a fair amount of noise is associated with the rapid pressurization of the circulatory system and the action of the valves at points A and B.

From point B (0.21 sec) to point C (0.42 sec), ventricular pressure exceeds aortic pressure to cause outflow through the aortic valve. At point C, contraction of the ventricle is complete. This is the beginning of diastole. Ventricular pressure drops, thereby allowing the aortic valve to close. The heart first relaxes isometrically (i.e., without blood flow) from point C (0.42 sec) to point D (0.48 sec), both valves being closed. At point D, ventricular pressure drops below atrial pressure to cause the mitral valve to open. This is followed by a relatively long inflow phase from point D (0.48 sec) to the beginning of the next systole, at about 0.98 second.

It is seen that the duration of systole is 0.24 second while that of diastole is 0.56 second. The period is 0.80 second, which corresponds to a pulse rate of 75 beats per minute. The percentage of the period for systole is 30 percent, with 70 percent of the time left for diastole.

The relatively short duration of systole is of interest. Since the entire outflow of the heart must be accomplished during this time, the peak instantaneous flow rate during systole is of the order of six times the average blood flow rate. Typical numbers are 30 liters per minute for peak instantaneous flow rate and 5 liters per minute for average flow rate.

Since 30 liters per minute equals about 8 gallons per minute, this peak flow rate is appreciable. (A typical flow rate from an open-ended garden hose is 5 gal/min.) One might wonder how high this peak flow rate might become during exercise. The situation is not as extreme as might be expected because the heart increases its rate mainly by shortening diastole. At very high pulse rates, systole and diastole are about equal in duration. This causes about a 4 to 1 ratio of peak instantaneous flow rate to average flow rate. At an average flow rate of 15 liters per minute, the peak value would be 60 liters per minute, or, at that instant, about three times the flow rate out of a garden hose.

A subject of additional interest is the power consumed by the human heart. Hydraulic power is found by multiplying pressure by flow rate and using the proper conversion factor. The following is a summary of average pressures in the circulatory system:

Location	Pressure	
	mm Hg	psi
Right atrium	1.5	0.03
Pulmonary artery	15	.3
Left atrium	5	.1
Aorta	100	1.9

The right heart has to cause a pressure rise of 13.5 mm Hg (0.27 psi) while the left heart, 95 mm Hg (1.8 psi). With average flow rates of 5 liters per minute (resting) and 15 liters per minute (maximum), the hydraulic power outputs for the heart are as follows:

	Output, W	
	Rest	Exertion
Right heart	0.16	0.48
Left heart	1.03	3.09
Total	1.19	3.57

This section has been a description of circulatory system physiology from the engineer's point of view. Special attention has been given to the timing of the heart's beat, the waveform of ventricular pressure, and hydraulic pumping power requirements.

GLOSSARY

anatomy. The science dealing with the structure of plants and animals.

aorta. The principal artery by which the blood leaves the heart and passes to the body.

aortic valve. The outflow valve from the left ventricle.

atrium. One of the two chambers of the heart by which the blood is received from the veins and forced into the ventricles. (The terms atrium and auricle are used interchangeably.)

cannula. A tube that is inserted into the body or into an organ for injecting or removing fluid.

depolarization. An object is polarized when it is charged electrically. A nervous impulse that depolarizes (discharges) the cells of a muscle causes that muscle to contract. This depolarization also induces a voltage (myopotential) that can be measured on the skin. The electrocardiogram (EKG) is a record of one of these voltages.

dialysis. The separation of substances in solution by means of their unequal diffusion through semipermeable membranes.

diastole. The period during which the heart muscle relaxes and the heart dilates. During this period the chambers of the heart fill with blood.

electropneumatic. Of or relating to a combination of electrical and pneumatic effects.

hypothermia. The state or conditon of having a subnormal body temperature.

lesion. An injury to an organ or tissue.

mitral valve. The inflow valve to the left ventricle.

myopotential. A small electrical signal caused by the contraction of a muscle.

pathology. The study of the nature and progress of disease and of the changes it produces in structure and function. Thus, a pathological condition is the result of a disease.

physiology. The science dealing with the processes, activities, and phenomena characteristic of life.

radiopaque. Impenetrable to X-rays or other forms of radiation.

semilunar valve. The outflow valve from the right ventricle.

systole. The period during which the heart muscle is contracting and blood is expelled from the ventricles into the aorta and the arterial system.

therapeutic. Serving to cure or to heal.

tricuspid valve. The inflow valve to the right ventricle.

REFERENCE

1. Laënnec, R. T. H. (John Forbes, trans.): A Treatise on the Diseases of the Chest and on Mediate Auscultation. Classics of Medicine and Surgery. C. N. B. Camac, ed., Dover Publ., Inc., 1959, pp. 157-204 (originally published by W. B. Saunders Co., 1909).

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