THE CURRENT STATUS OF BIOMEDICAL ENGINEERING IN THE USA

John G. Webster
Department of Electrical and Computer Engineering
University of Wisconsin-Madison
1415 Johnson Drive
Madison, WI 53706 USA

ABSTRACT

Engineers have developed new instruments that aid in diagnosis and therapy. Ultrasonic imaging has provided a nondamaging method of imaging internal organs. A complex transducer emits ultrasonic waves at many angles and reconstructs a map of internal anatomy and also velocities of blood in vessels.

Fast computed tomography permits reconstruction of the 3-dimensional anatomy and perfusion of the heart at 20-Hz rates. Positron emission tomography uses certain isotopes that produce positrons that react with electrons to simultaneously emit two gamma rays in opposite directions. It locates the region of origin by using a ring of discrete scintillation detectors, each in electronic coincidence with an opposing detector.

In magnetic resonance imaging, the patient is placed in a very strong magnetic field. The precessing of the hydrogen atoms is perturbed by an interrogating field to yield two-dimensional images of soft tissue having exceptional clarity. As an alternative to radiology image processing, film archiving, and retrieval, picture archiving and communication systems (PACS) are being implemented. Images from computed radiography, magnetic resonance imaging (MRI), nuclear medicine, and ultrasound are digitized, transmitted, and stored in computers for retrieval at distributed work stations.

In electrical impedance tomography, electrodes are placed around the thorax. 50-kHz current is injected between two electrodes and voltages are measured on all other electrodes. A computer processes the data to yield an image of the resistivity of a 2-dimensional slice of the thorax. During fetal monitoring, a corkscrew electrode is screwed into the fetal scalp to measure the fetal electrocardiogram. Correlations with uterine contractions yield information on the status of the fetus during delivery.

To measure cardiac output by thermodilution, cold saline is injected into the right atrium. A thermistor in the right pulmonary artery yields temperature measurements, from which we can calculate cardiac output. In impedance cardiography, we measure the changes in electrical impedance as the heart ejects blood into the arteries. Motion artifacts are large, so signal averaging is useful during monitoring.

An intraarterial blood gas monitoring system permits monitoring in real time. Light is sent down optical fibers inserted into the radial artery, where it is absorbed by dyes, which reemit the light at a different wavelength. The emitted light travels up optical fibers where an external instrument determines O2, CO2, and pH.

Therapeutic devices include the electrosurgical unit. A high-frequency electric arc is drawn between the knife and the tissue. The arc cuts and the heat coagulates, thus preventing blood loss. Hyperthermia has demonstrated antitumor effects in patients in whom all conventional modes of therapy have failed. Methods of raising tumor temperature include focused ultrasound, radio-frequency power through needles, or microwaves.

When the heart stops pumping, we use the defibrillator to restore normal pumping. A

brief, high-current pulse through the heart synchronizes all cardiac fibers to restore normal rhythm.

When the cardiac rhythm is too slow, we implant the cardiac pacemaker. An electrode within the heart stimulates the cardiac muscle to contract at the normal rate. When the cardiac valves are narrowed or leak, we implant an artificial valve. Silicone rubber and Teflon are used for biocompatibility. Artificial hearts powered by pneumatic hoses have been implanted in humans. However, the quality of life gradually degrades, and death ensues.

When kidney stones develop, lithotripsy is used. A spark creates a pressure wave, which is focused on the stone and fragments it. The pieces pass out normally. When kidneys fail, the blood is cleansed during hemodialysis. Urea passes through a porous membrane to a dialysate bath to lower its concentration in the blood.

The blind are able to read by scanning the Optacon with their fingertips. A camera scans letters and converts them to an array of vibrating pins. The deaf are able to hear using a cochlear implant. A microphone detects sound and divides it into frequency bands. 22 electrodes within the cochlea stimulate the acoustic nerve to provide sound patterns.

For those who have lost muscle function in the limbs, researchers are implanting electrodes to stimulate the muscle. Sensors in the legs and arms feed back signals to a computer that coordinates the stimulators to provide limb motion. For those with high spinal cord injury, a puff and sip switch can control a computer and permit the disabled person operate the computer and communicate with the outside world.

INTRODUCTION

What can engineers do to improve health care? Before we answer that question, we should acknowledge the great debt we owe to civil engineers. They have provided us with pure drinking water and disposed of sewage in sanitary systems so that infant mortality is very low.

We owe a great debt to the inventors of vaccines and drugs that have greatly lowered mortality from infectious diseases.

Thus the greatest effort of physicians and biomedical engineers that work with them is directed toward the chronic diseases that increase with age, such as atherosclerosis, cancer, kidney failure, and the like.

Today I will first give examples of how engineers have developed new instruments that aid in diagnosis. After the medical problem has been diagnosed, I will give examples of how engineers have developed devices for therapy. Then I will give examples from rehabilitation engineering for the alleviation of those with disabilities.

ULTRASONIC IMAGING

When a single electric pulse energizes a piezoelectric transducer, it emits an acoustic pulse. This travels to an internal organ, which reflects it back to the transducer. The received signal is processed for time-of-flight, which indicates range, and amplitude, which indicates change of density at the organ interface.

In one method, the operator rocks the transducer on the skin to paint a fan-shaped image of internal organs. Figure 1 shows a second method, in which a linear multielement array emits sequential pulses, each delayed a constant amount from the previous pulse. These combine to produce a single wavefront that propagates at an angle.

Figure 2 shows a typical ultrasonic gray scale image with the liver, with several vessels, the kidney and the curved diaphragm.

Unlike x rays, ultrasound does not harm tissues. Thus ultrasonic images are very useful for defining the size and orientation of the fetus prior to birth.

In the same way that moving trains produce a Doppler frequency shift for sound, moving blood cells produce a Doppler frequency shift for ultrasound. Modern ultrasonic imagers use this frequency shift to produce images of the velocity of blood in arteries.

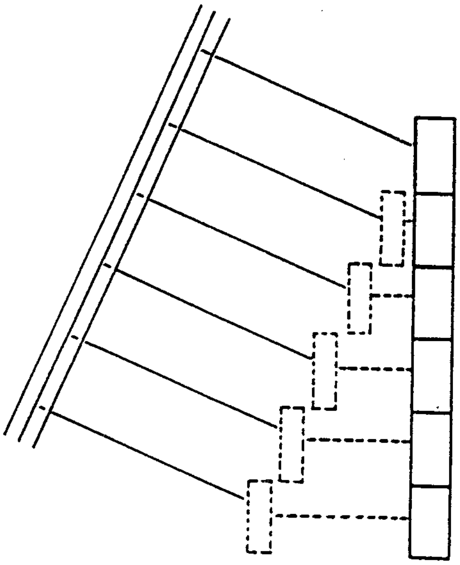


Figure 1 In ultrasonic imaging, electrical pulses to piezoelectric transducers cause them to emit acoustic pulses. The direction and time-of-flight of reflections localize internal organs. A linear multielement array permits electronic beam steering.

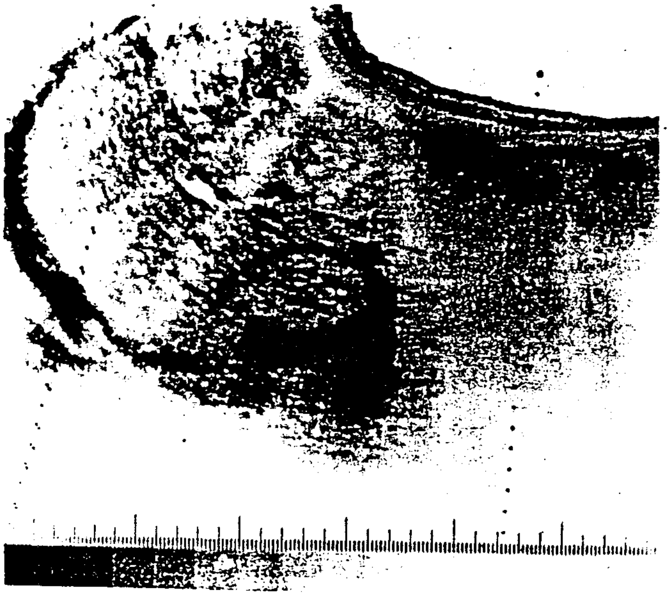


Figure 2 A typical ultrasonic gray scale image with the liver, with several vessels, the kidney and the curved diaphragm.

FAST COMPUTED TOMOGRAPHY

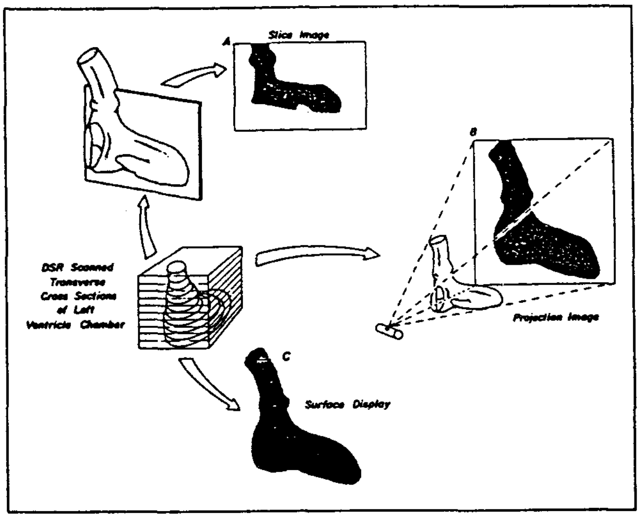


Figure 3 Multislice fast computed tomography yields slice images, projection images, and surface displays.

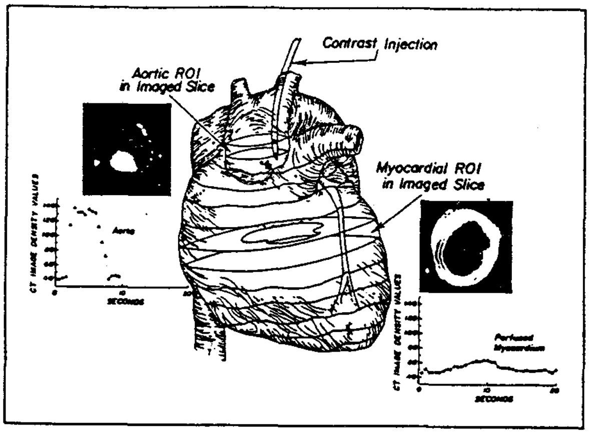


Figure 4 Multislice fast computed tomography can quantitate blood flow in the aorta and in perfused myocardium.

An engineer won the Nobel Prize for inventing CT (computerized tomography). A pencil-like beam of x rays passes through a body slice from all different angles. A computer uses all this information to reconstruct the image of internal attenuation.

Fast computed tomographs can complete scans at 0.05-s intervals, they can scan multiple adjacent 8-mm slices, and they can repeat these scans at frequent time intervals for a specified period. Figure 3 shows that multislice fast computed tomography yields slice images, projection images, and surface displays. Thus they can produce accurate images of the geometry of rapidly moving cardiovascular structures and apply a wide range of indicator dilution studies used for microcirculation studies inaccessible to conventional CT scanners. Figure 4 shows that multislice fast computed tomography can quantitate blood flow in the aorta and in perfused myocardium.

Unlike conventional angiography, numerical projection can be used to create a display from any conceivable angle of view by using only one set of volume image data. The original data set can be mathematically manipulated to "dissolve" or "dissect" away unwanted superposing tissues.

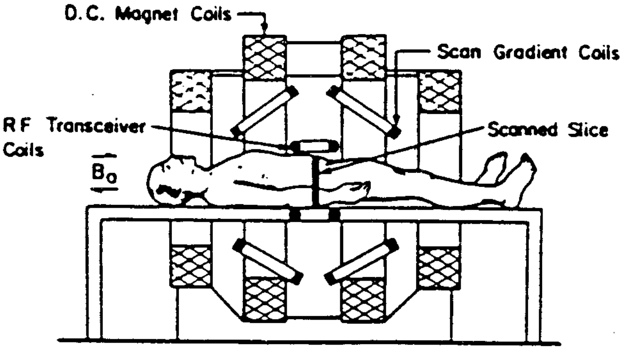

MAGNETIC RESONANCE IMAGING

Figure 5 Magnetic resonance imaging uses a strong dc magnet to precess hydrogen nuclei. An RF pulse causes an exponential decay in a receiving coil. A gradient magnet selects a single slice for imaging.

MRI, Magnetic Resonance Imaging, produces images of hydrogen concentration. Figure 5 shows that a very strong dc magnet causes precession of hydrogen nuclei. A gradient magnet varies the net magnetic field, thus varying the precessing frequency and selecting a single slice through the body.

An RF (radio frequency) pulse causes an exponential decay in a receiving coil, which provides information for reconstructing the image. The equipment is large and expensive, about $1,000,000. In some cities the equipment is on a moveable trailer and is shared by several hospitals on different days of the week. The cost to the patient is about $200 for a set of images.

Figure 6 A magnetic resonance image of the human brain shows the high soft tissue contrast that is not available with other imaging techniques.

Figure 6 shows that excellent detail can be observed in the soft tissue of the brain. Such images are well worth the cost if they prevent the need for an operation.

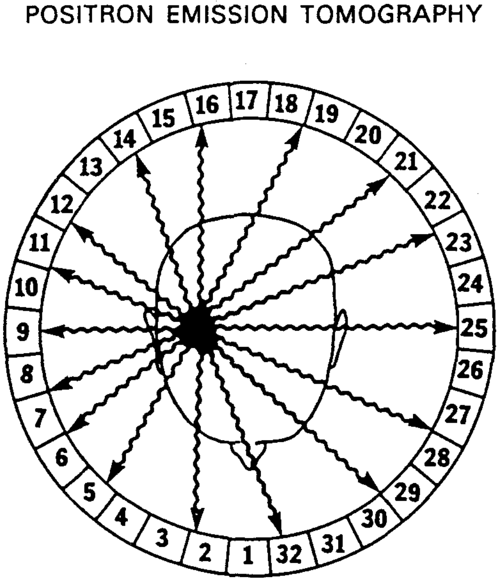


Figure 7 A cross-sectional view of a positron emission tomography (PET) scanner consists of a ring of discrete detectors, each in electronic coincidence with an opposing detector.

Positron emission tomography (PET) uses certain isotopes that produce positrons that react with electrons to simultaneously emit two gamma rays at 511 keV in opposite directions. Figure 7 shows that PET has the ability to locate the region of origin by using a ring of discrete scintillation detectors, each in electronic coincidence with an opposing detector.

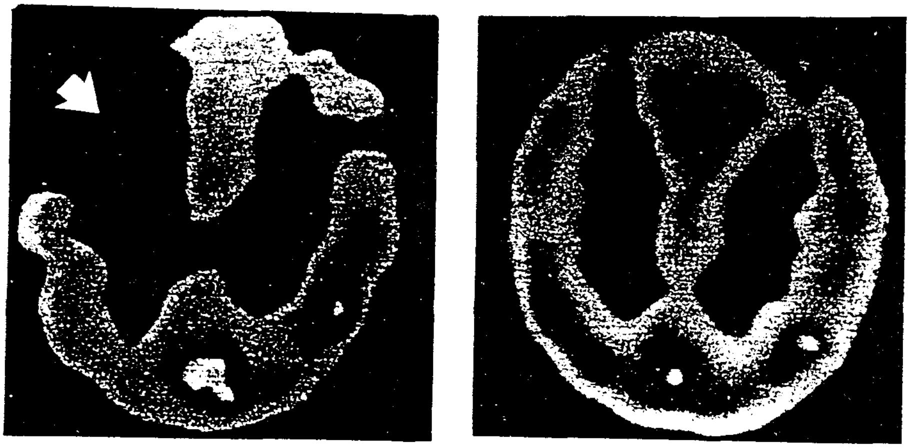


Figure 8 PET scans of brains of a normal person (lower) and a patient with AlzheimerUs disease (upper) taken with 18F-labeled analog of glucose.

A computer processes the information and displays the 2-dimensional slice. Figure 8 shoshows that it is possible to map metabolic activity in the brain by using tagged compounds to observe uptake and clearance.

PICTURE ARCHIVING AND COMMUNICATION SYSTEM

As an alternative to radiology image processing, film archiving, and retrieval, picture archiving and communication systems (PACS) are being implemented. Figure 9 shows that images from computed radiography, magnetic resonance imaging (MRI), nuclear medicine, and ultrasound are digitized, transmitted, and stored in computers for retrieval at distributed work stations. Systems use a network of computers, optical-disk archiving devices,and long-line image transmission. A workstation replaces the lightbox that is used in a film-based department. Connectivity is provided by the installed network and communication protocols. A PACS opens the possibility to include images in patient reports. Patient privacy and data security must be provided.

While complete elimination of film is very unlikely to occur, PACS should reduce archiving personnel and space. Delays in and costs of retrieval of images should be reduced. An operator can call any image and text file anywhere in the system for interactive display. This enables a radiologist or other specialist at a distant site to view an image and make a diagnosis.

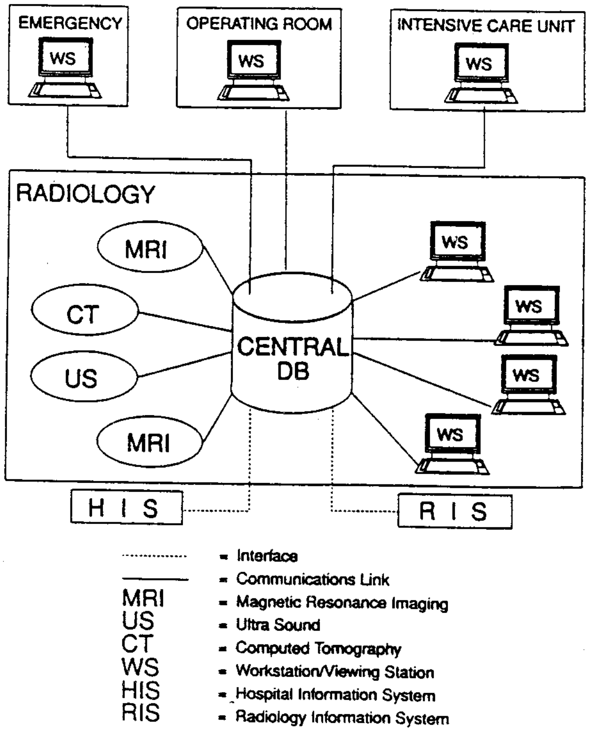


Figure 9 Picture archiving and communication systems (PACS) integrates MRI, CT, and US images into a totally digital radiology department.

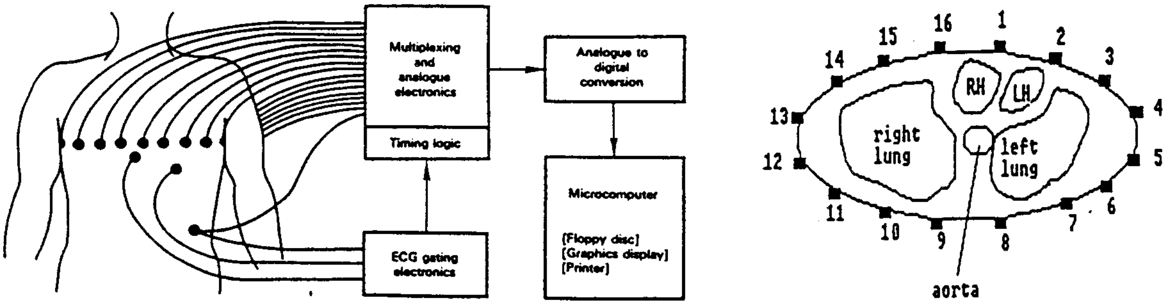


Figure 10 In electrical impedance tomography, impedance between all possible pairs of electrodes is processed to yield an image of resistivity.

Figure 10 shows that in electrical impedance tomography, 16 or 32 electrodes are placed around the thorax. 50-kHz current is injected between two electrodes and voltages are measured on all other electrodes. This is repeated for all possible pairs of injection electrodes. A computer processes the data to yield an image of the resistivity of a 2-dimensional slice of the thorax. Improved systems inject current patterns through all electrodes.

Problems are that the current flows out of the plane of measurement, the spatial resolution is poor at about 10% of the diameter, and while it is easy to obtain dynamic images, it is difficult to obtain static images. Applications exist in ventilation monitoring, cardiac output, stomach emptying, and breast tissue analysis.

FETAL MONITORING

Figure 11 shows that one form of fetal monitoring uses a corkscrew electrode that is screwed into the scalp as soon as it shows. This permits reliable measurement of the tiny fetal heart signals (electrocardiogram) without interference from the large maternal electrocardiogram.

A separate pressure transducer strapped around the abdomen measures uterine contractions, which peak every four minutes. The fetal heart rate may slow from 150 per minute to 100 per minutes late in the uterine contraction cycle. This indicates fetal distress and may prompt the obstetrician to remove the fetus by Caesarean operation.

In some medical centers, the Caesarean operation rate has reached 20%, which some observers feel is too high. Thus we must perform careful studies to determine if the benefits of monitoring to mother and child exceed those without monitoring.

In like manner, by heroic measures, it is possible to keep extremely low birth weight babies alive. Many of these will not live normal lives, which prompts difficult ethical questions. With limited medical resources available, society must decide the best allocation of these resources.

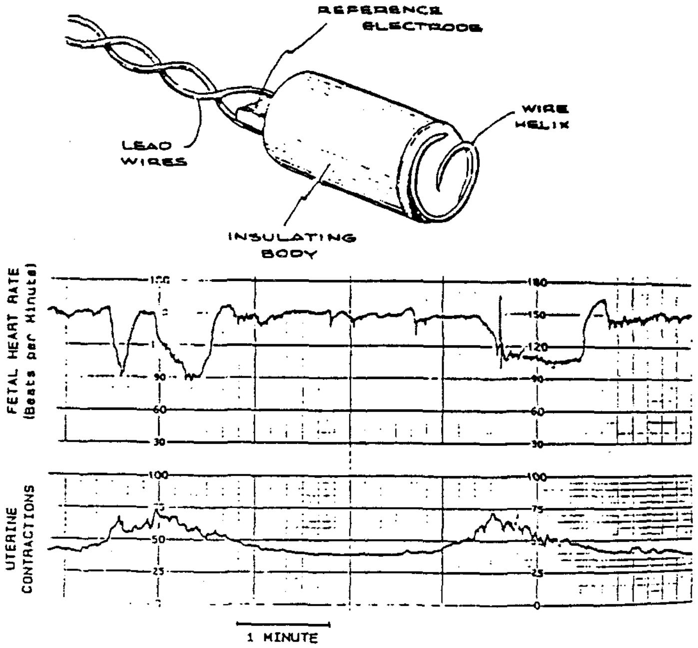


Figure 11 During birth, a corkscrew electrode permits fetal monitoring of the electrocardiogram (ECG). An abdominal transducer measures uterine contractions. Excessive slowing of the fetal heart rate late in the contraction cycle indicates fetal distress.

CARDIAC OUTPUT

During an operation, the anesthesiologist monitors the health of the patient. In order to measure cardiac output (flow), a catheter tube is threaded through a vein in the arm into the heart. Ten milliliters of cold saline is injected at the entrance of the heart.

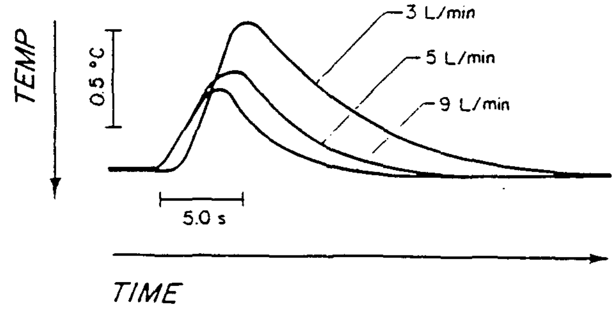


Figure 12 A catheter tube in the heart can measure cardiac output(flow). Cold saline is injected and temperature measured by a thermistor. High flow moves the cold injectate through quickly.

Figure 12 shows that if cardiac output is high at 9 liters per minute, the cold injectate moves through the heart quickly. Then the thermistor at the exit of the heart measures a short transient decrease of temperature and the area under the curve is small.

If cardiac output is low at 3 liters per minute, the cold injectate moves through the heart slowly. Then the area under the curve is large. Electronic integrators measure the area under the curve and calculate cardiac output.

The saline does not harm the body so repeated measurements can be made. The special multilumen catheter tube costs $100 and is discarded after one use to prevent cross infection. Thus the cost of medical care increases as we invent new ways of acquiring diagnostic information and make use of them.

Actually the method is not so new. In the last century, the Paris city engineer dropped colored dye into the sewer system at one point and measured its concentration downstream. Using this same indicator dilution technique, he estimated flow.

IMPEDANCE CARDIOGRAPHY

To measure cardiac output, it is desirable not to invade the body. Figure 13 shows that we can inject 100-kHz current through electrodes on the neck and back. We can measure voltage between electrodes on the neck and chest. From the resulting electrical impedance we can calculate stroke volume, and then cardiac output. Thus this seems better than thermodilution.

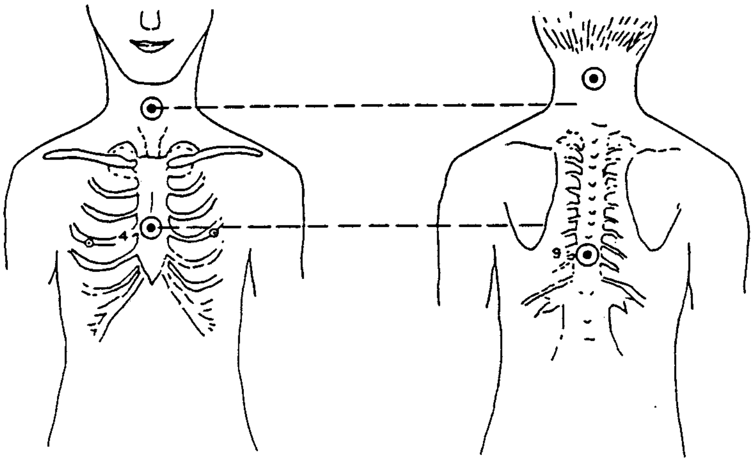


Figure 13 Each beat, the heart ejects high-conductivity blood into the pulsating arteries. This lowers the 100-kHz impedance of the chest, which yields cardiac output. By synchronizing the impedance changes with the ECG, we can average responses to minimize errors caused by motion.
$SV = r(L/Z0)2(dZ/dt)mT$.

But the method is controversial. Many studies show good correlation between this impedance cardiography and other methods. Other studies show that the correlation is poor for very sick patients--just those you need to measure most. Perhaps future work by biomedical engineers can invent superior electrode locations, more than four electrodes, and improved signal processing.

In our laboratory we have used spot electrodes to reduce interference from movements. Then we synchronize the impedance changes with the ECG and average 64 beats. Then it is possible to obtain a 24-hour record of cardiac output from an ambulatory subject.

Similar impedance apnea monitors measure respiration in infants, can set off an alarm if respiration stops, and alert the parents to resuscitate and prevent crib death.

BLOOD GAS MONITORING

Most blood gas monitoring is performed by withdrawing periodic samples of blood and analyzing them in external analyzers. Figure 14 shows that in new blood gas analyzers, light is sent down optical fibers inserted into the radial artery through a 1-millimeter diameter catheter. Light is absorbed by dyes, which reemit the light at a different wavelength. The intensity of the light is changed by the concentration of oxygen, carbon dioxide, and hydrogen ions. The emitted light travels up optical fibers where an external instrument determines O2, CO2, and pH. This intraarterial blood gas monitoring system permits monitoring in real time.

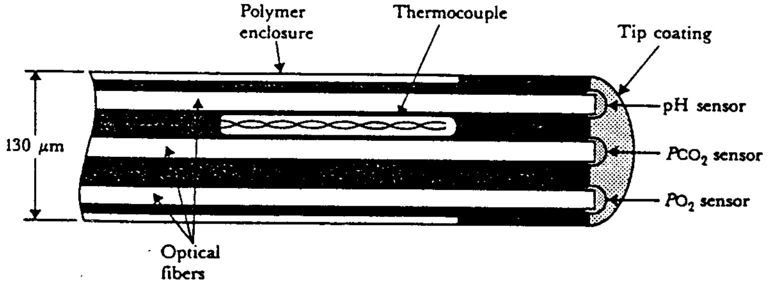


Figure 14 An intravascular blood-gas probe measures pH, PCO2, and PO2 by means of single fiber-optic fluorescent sensors. Light is absorbed by dyes, which reemit at different wavelengths.

ELECTROSURGICAL UINT

Now we will leave diagnostic instruments and turn to therapeutic devices.

The surgical scalpel causes bleeding in vascular organs such as the brain, liver, and spleen. About 1930 an engineer invented the electrosurgical unit (surgical diathermy), shown in Figure 15. A 500-W, 1-MHz arc is drawn between a knife and the tissue.

This makes cutting the tissue much easier. The heat generated simultaneously coagulates the tissue and prevents bleeding. This permits surgery on vascular organs.

The spark gap generates ferocious interference and prevents simultaneous measurement of the electrocardiogram (ECG).

One solution is to sample the ECG only when the electrosurgical unit is not operating; that is, at the end of each half wave of the line power when the line voltage equals zero.

Another solution is adaptive filtering. We pick up a second signal from the arm, where there is no ECG. We subtract this from the first signal, which contains ECG. By adjusting the gain of the two channels, the interference subtracts to zero. Only the ECG remains.

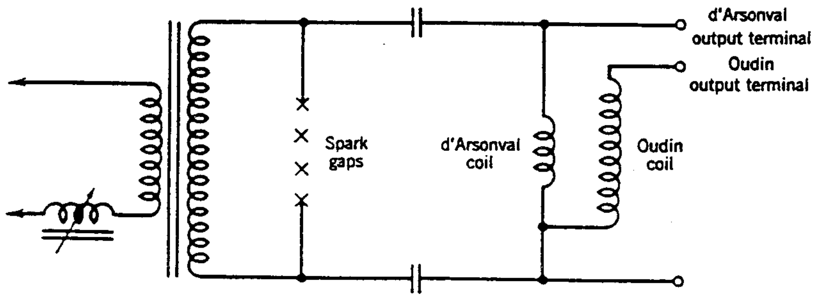
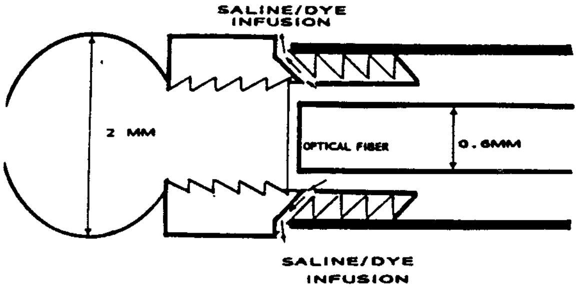


Figure 15 An electrosurgical unit is a 500-W spark-gap radio transmitter similar to that used by Marconi. The heat generated by an electric arc drawn between a knife and tissue cuts easily and coagulates simultaneously. The ferocious interference prevents simultaneous measurement of the ECG. One solution is synchronous sampling. Another solution is adaptive filtering.

LASER ANGIOGRAPHY



SAPPHIRE-TIP CATHETER IS CONNECTED TO
A ND-YAG LASER

Figure 16 A sapphire tip emits 5-40 W of focused 1020-nm light from a Nd-YAG laser through a 600-nm optical fiber in a Teflon tube. Atherosclerotic plaque is vaporized just beyond the tip.

When sclerotic plaque obstructs arteries, surgeons attempt to remove it. Figure 16 shows that rounded tip laser fibers can be introduced through the skin into the artery and the power can remove the plaque. Continuous wave infrared Nd:YAG or Argon lasers yield thermal effects, which vaporize the tissue. Blackening the tip makes it self-absorbent so it can reach the high temperatures necessary to vaporize vessel material. A totally encapsulating distal metal tip ablates vascular obstructions with circumferentially distributed heat, which diminishes the incidence of thermal perforations. These hot-tip lasers permit the recanalization of noncalcified blockages with low damage risk.

Figure 17 shows the photoablation induced by the ultraviolet 308-nm high-power short-pulse excimer laser. This athermic process is more effective for ablation of heavily calcified lesions. The disadvantage is that the achieved size of the channel is not significantly larger than the core diameter of the fiber and effectiveness on calcium deposits is limited.

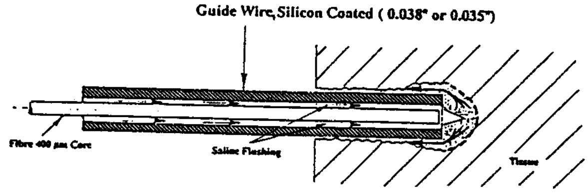


Figure 17 An excimer laser emits light through a 400-um Q/Q fiber into an open-ended guide wire. Atherosclerotic plaque is vaporized with a channel diameter of 1.0-1.2 mm.

HYPERTHERMIA

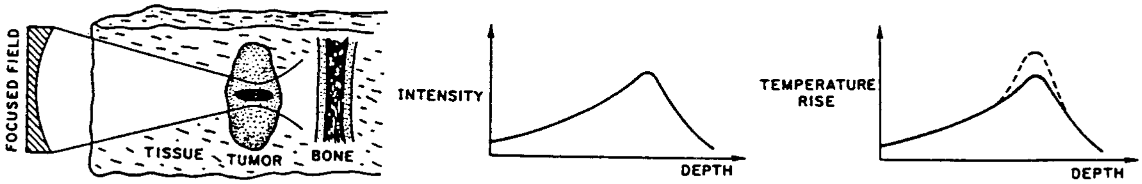


Figure 18 Hyperthermia has demonstrated antitumor effects. Focused field ultrasound delivers heating to a deep tumor while minimizing heating in overlying tissue.

Hyperthermia has demonstrated antitumor effects in patients in whom all conventional modes of therapy has failed. Tumors exhibit greater heat sensitivity than normal tissues. Figure 18 shows that a common method of raising tumor temperature is using multiple or focused ultrasound to achieve heating in a deep tumor. This minimizes heating in overlying tissue.

Alternatively radio-frequency power can deliver localized heat through needles implanted in the tumor or by an interstitial microwave antenna. Thermoseeds can absorb power from an externally applied magnetic induction field in a contactless manner, with each seed acting as an independent and self-contained heating element. Thermocouple or thermistor temperature sensors are used to monitor temperature distribution.

DEFIBRILLATOR

My grandmother was 84 when she died of heart failure in her bed at home. She was not monitored because if there is no therapy, there is no need to monitor. Since 1946, engineers have developed the defibrillator. Figure 19 shows that it charges up a capacitor, then discharges a 20-A, 10-ms pulse through the chest. This contracts all heart fibers simultaneously and permits the heart to resume normal rhythm.

The defibrillator is excellent therapy for middle aged patients with "hearts too young to die". It may get the heart through an acute episode and add decades to the life of the patient.

However, when my father had a stroke, he was in a hospital and was failing fast, his heart went into fibrillation. The physician asked my mother if he should resuscitate. My mother said, "No, he's 85, has had a good life, and will never recover from this."

Sometimes the devices built by biomedical engineers are not wanted and frustrate the graceful death we would all hope for. Now totally implantable defibrillators are available for high-risk patients. Each of you should ask yourself the question, "Would I want a defibrillator implanted in me?"

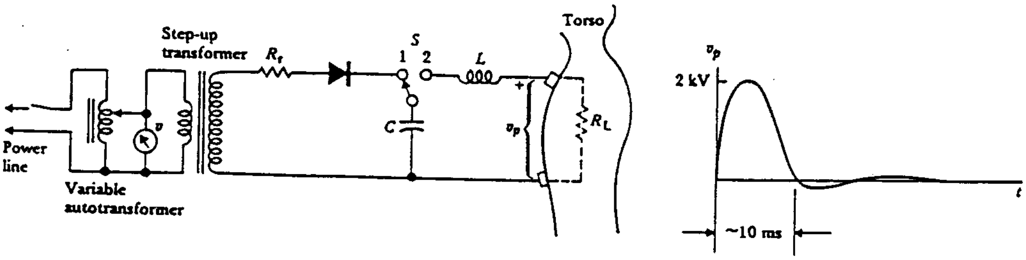


Figure 19 A heart attack may cause ventricular fibrillation and death. A defibrillator discharges a 20-A, 10-ms pulse through the chest, which contracts all heart fibers simultaneously.

PACEMAKER

The normal pacing pulse of 70 beats per minute, travels from the top of the heart to the bottom of the heart to cause ejection of blood into the body. Blockage of this pulse yields a very slow heart rate of 35 beats per minute. The patient may be an invalid or have fainting spells.

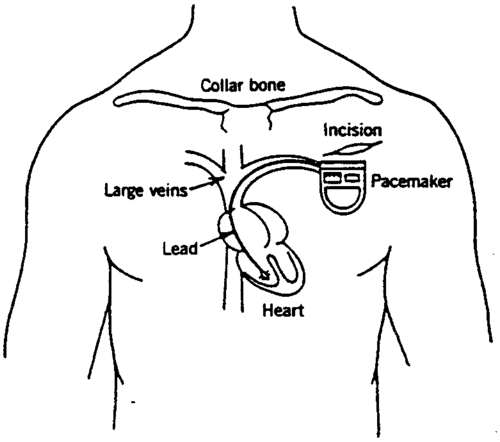


Figure 20 Blockage of the normal pacing pulse from the top to the bottom of the heart yields a very slow heart rate of 35 beats/min. An implanted heart pacemaker can restore a normal rate of 70 beats/min.

Figure 20 shows that under local anesthesia, the pacemaker is implanted under the collarbone and an electrode threaded through a vein to the bottom of the heart. An electrical pulse at 70 beats per minute restores normal heart rate and normal health.

For less than the price of an automobile, the patient achieves a tremendous improvement in health. I feel this is one of the real achievements of biomedical engineers and is one of the most cost effective therapies.

Newer pacemakers can increase the heart rate in response to exercise. Chest muscle movement bends the container. In it a bonded piezoelectric sensor yields a signal that increases the rate. Some pacemakers are programmable by transmitting codes signals into the body. Other can store information as to the function of the heart over a day and transmit it out on demand for use in diagnosis.

ARTIFICIAL VALVES FOR THE HEART

The valves of the heart may be damaged because of genetic abnormalities or by disease. They may not open sufficiently, which causes a large pressure drop across the valve and makes the heart work harder. They may leak when closed, which causes the heart to pump the additional leaked blood.

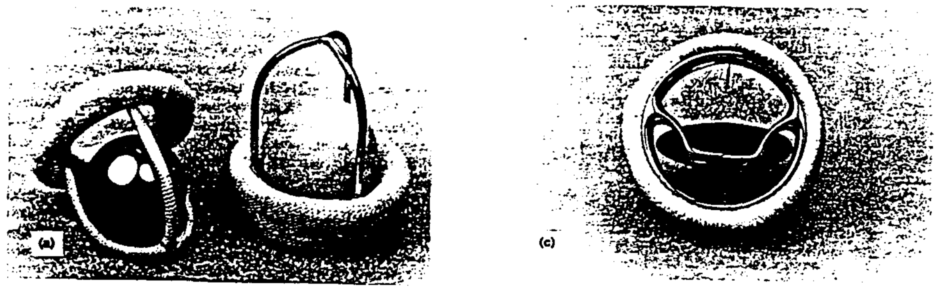


Figure 21 100,000 heart valves are implanted each year. The silicone rubber ball in cage is anchored by knitted Teflon cloth. The tilting disk is made of pyrolytic carbon.

Biomedical engineers with materials science backgrounds have developed replacement heart valves. Figure 21 shows that the ball is made of silicone rubber, which is tolerated by the body. The knitted Teflon cloth provides an anchoring ring for suturing to the heart. The metal cage prevents the ball from escaping.

An alternative valve has a disk that tilts open and closed. It is made of pyrolytic carbon which is tolerated by the body. One-hundred thousand heart valves are implanted each year. The patient must take drugs to prevent clots from forming.

ARTIFICIAL HEART

Biomedical engineers have dreamed of a totally implantable artificial heart, but have not succeeded. Any violent pumping action damages the blood cells so pumps use a flexible diaphragm. Figure 22 shows that an external compressor blows air through tubes that pass through the chest wall and pneumatically inflate the air chamber. The diaphragm pushes up to eject the blood through the outflow valve. This gentle peristaltic pumping causes the least cell damage.

However, patients on this implanted artificial heart have had a poor quality of life. Their physical and mental state degrades and finally death occurs.

While future improvements may solve some of these problems, patients still must be tied to their external power source. Each one of us should answer the question, "Am I prepared to accept death gracefully, or would I wish to extend it at enormous expense by having an implanted artificial heart?"

Jarvik elliptical artificial heart (1974)

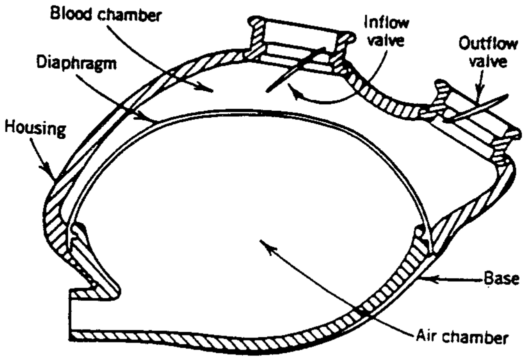


Figure 22 The artificial heart is pneumatically driven from an external compressor. Five patients with permanent implants lived from 10 to 620 days. 35 patients have used the implant as a bridge to transplantation.

LITHOTRIPSY

In two to four percent of people, stones form within the kidney, and they will not pass out. Formerly an abdominal operation was required to surgically remove the stones.

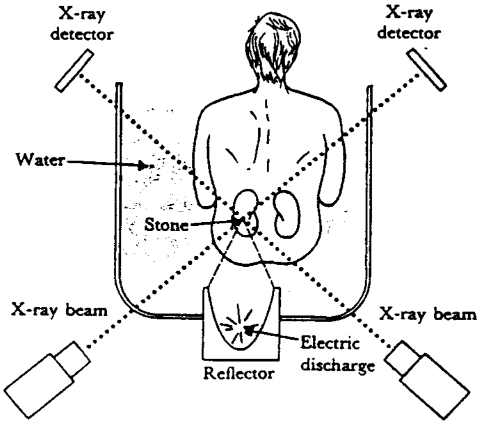


Figure 23 2-4% form kidney stones by age 70. In extracorporeal shock-wave lithotripsy, a biplane x-ray apparatus is used to make sure the stone is at the focal point of 18-kV spark-generated 50 MPa shock waves from the ellipsoidal reflector, which fragment the stone.

Figure 23 shows that in extracorporeal shock wave lithotripsy, the patient is placed in a water bath. The stone is located using x-ray machines. The ellipsoidal reflector is focused on the stone.

Then an 18-kV spark between two electrodes creates an instantaneous gas bubble. It sends a pressure shock wave to the reflector, which focuses all the pressure on the stone. The 50 MPa pressure fragments the stone and the pieces pass out. Note that the pressure density in all regions away from the stone is low, which prevents damage to healthy tissue. Noninvasive therapy like this is an excellent result of biomedical engineering.

HEMODIALYSIS

Although we can survive nicely with only five percent of kidney tissue functioning, when that last margin is destroyed by infection, urea builds up in the blood and death occurs within a week.

After genetic matching, kidney transplants from a healthy donor provide dramatic restoration of health. But there are not enough donors. A surviving relative must give permission within two hours after a traffic accident for the kidney to be viable. Most relatives are too upset to agree. This is one reason I carry a witnessed anatomical gift certificate on the back of my drivers license.

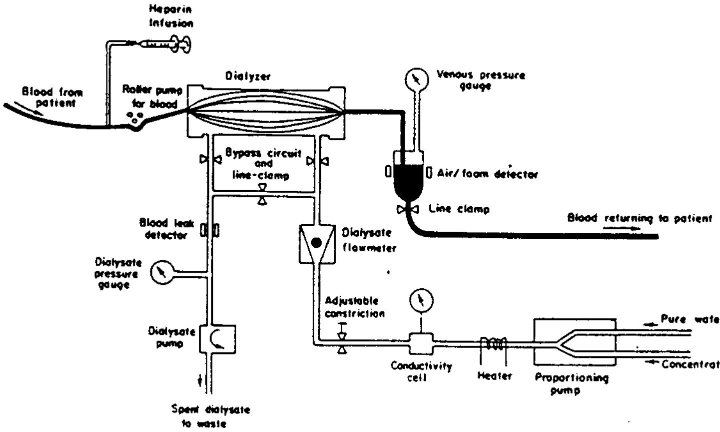


Figure 24 Urea must be removed from patients who have kidney failure. During hemodialysis, urea diffuses through Cellophane into a dialysate bath. Dialysis can be done at home. A wearable dialysis system is possible.

For those on the lengthy waiting list for a kidney transplant, the chemical engineers provide kidney dialysis. Figure 24 shows that blood is pumped from the wrist past a cellophane membrane, where urea diffuses into a dialysate bath. Three hours of rinsing two times each week is sufficient to keep the patient alive, even though feeling poorly. The U.S. government pays more than $2 billion each year to provide this treatment to all who need it. Dialysis can be done at home to reduce the costs and a wearable dialysis system is possible.

READING MACHINE FOR THE BLIND

Now we change from problems that are life-threatening to how biomedical engineers can help those who have sensory loss. The blind can learn to read raised, embossed letters using Braille on previously prepared text. To meet the need for reading any available text, the Optacon reading machine was developed. Figure 25 shows that with one hand, the blind person scans the text with a miniature, solid-state camera. He places one fingertip on a 6 by 24 element array of piezoelectric vibrators. As he scans a letter he feels the image of the letter moving under his fingertip. The vibrators vibrate at 250Hz, where vibratory perception is optimal.

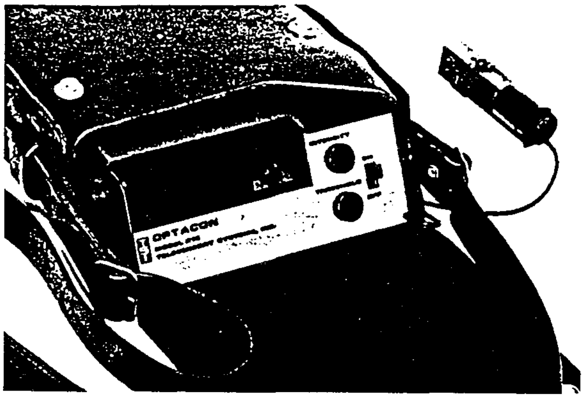


Figure 25 The Optacon reading machine for blind persons uses a solid-state camera to image characters. 144 piezoelectric vibrators reproduce the image on the fingertip for tactile perception.

Experienced users can read at rates up to 30 words per minute. However, reading in this manner is difficult and only a few blind persons are willing to expend the effort to learn. Also many persons are blind because of diabetes. They usually have reduced sensation in the fingertips and cannot use the Optacon.

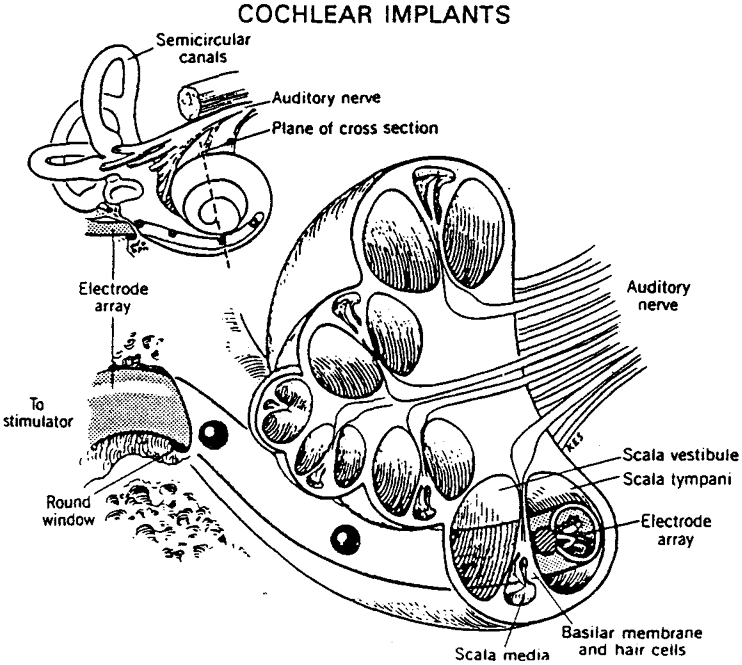


Figure 26 A profoundly deaf patient may retain auditory nerve fibers. A silicone rubber prosthesis contains 22 electrodes. Cochlear stimulation produces acoustic sensations at different frequencies. Some patients can understand speech.

Hearing aids cannot help those who have no residual hearing. About 500 people are now wearing cochlear implants in their ears. An external microphone detects speech and divides its frequencies into 22 frequency bands. This information is transmitted across the skin behind the ear to a receiver under the skin. Figure 26 shows that these signals flow through wires in a silicone rubber tube inserted into the cochlea of the ear. 22 electrodes stimulate endings of the auditory nerve. The patient perceives sounds at different frequencies, something like banging of cymbals. With training, a few star patients can interpret speech. Most patients have considerably improved correct responses during lip reading. Acceptance of the cochlear implant is very high. It seems likely that future improvements will increase its utility.

STIMULATION OF MUSCLE

Paraplegics have lost use of their legs because of spinal cord injury. Figure 27 shows that electrodes on the skin can cause muscle contraction, but it is not well controlled because some muscles overlie other muscles.

Stimulating a large nerve bundle provides poor control because it stimulates many muscles simultaneously. Best control is achieved by stimulating the individual terminal branches that lead to individual muscles.

Researchers have implanted 27 radio-controlled stimulators to produce walking movements. The patient uses the strength of his arm muscles to support his torso on a wheeled walker. Then the stimulated leg muscles provide the propulsion. Star patients are exhausted after 100 m.

The task of restoring function to muscles that have lost stimulation is a very difficult task, but each year brings new progress.

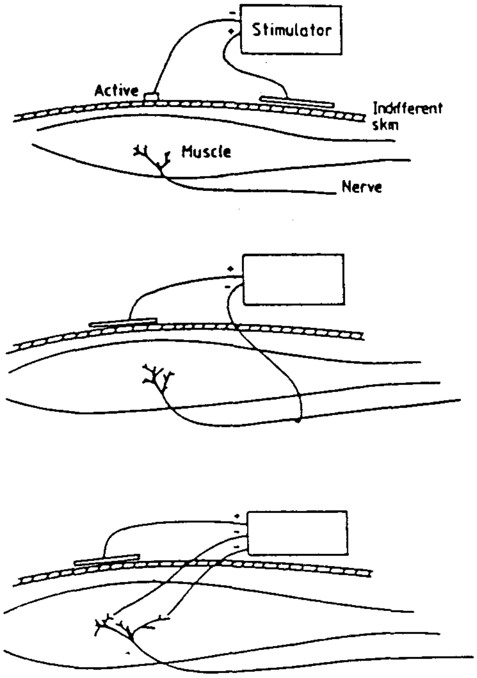


Figure 27 Spinal cord injured patients cannot move their limbs. Electric stimulators can cause muscle contraction. 27 radio-controlled implanted stimulators have permitted a patient holding a wheeled walker to stand and walk.

ARTIFICIAL HANDS

Where limbs are lost, rehabilitation engineers can replace them. Usually these are passive prostheses with perhaps a single pinch motion.

Figure 28 shows that mechanical engineers have designed artificial hands with several degrees of freedom. But these require many electric motors, which require much space and power. As motors become smaller and more efficient, such a mechanical artificial hand may become practical. Signals from the muscles in the shoulder or stump can be used to provide voluntary control.

However, today, passive prostheses are much more reliable and accepted.

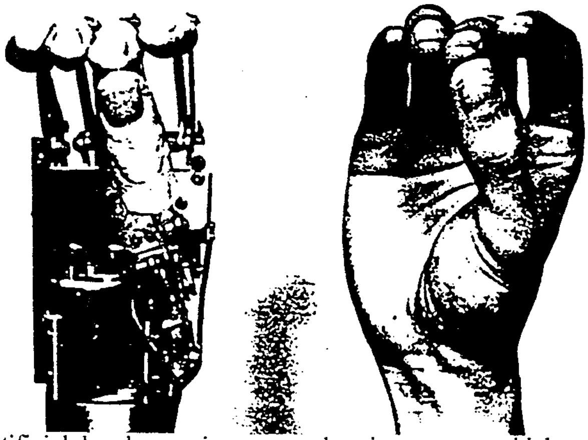


Figure 28 Artificial hands require many electric motors, which require much space and power. Signals from existing muscle contractions can control the hand. Passive prostheses are much more reliable and accepted.

SPINAL CORD INJURIES

Some spinal cord injuries are so high that the patient cannot move any limb. Figure 29 shows that a switch permits the patient to sip and puff to provide Morse code signals to a computer interface. Then the patient can write letters, program the computer, and use all available software.

For those patients who also cannot control their vocal cords, such a system provides a key method for communicating with the outside world.

Figure 29 Some injuries leave only respiration and head voluntary muscles. A Rsip and puffS system controls a computer using Morse code. The patient can control all software written for the computer.

PREVENTING MEDICAL PROBLEMS

We engineers pride ourselves on relating cause and effect. If a bridge falls down, we find the cause--a weak beam--and correct it.

In the health field, the people who find the cause are called epidemiologists. For example in the early days, a physician noted that all who died in a cholera epidemic used the same well. He correctly deduced that the cause of cholera was water borne, closed the well, and stopped the epidemic.

Today in developed countries, our major medical problems are heart disease and cancer. You have all known someone who died prematurely from these. The U.S. Surgeon General in his latest report gives the cause, which I reproduce here/

Do not smoke
Minimize food with fat (eggs, cheese, butter, red meat)
Maximize food with fiber (vegetables, grains, legumes, fruit)

It's not easy to follow this advice eating the U.S. diet but it can be done. The Japanese diet is somewhat better.

If everyone followed this advice, we could send most of the physicians and biomedical engineers off to do other work. In my mind this would be a great future for biomedical engineering.

REFERENCES

[1] Allen, L. and O. Frieder, Exploiting database technology in the medical arena: a critical assessment of picture archiving and communications, IEEE Eng. Med.Biol. Magazine, 11 (1), 42-49, 1992.

[2] Biamino, G., J. M. Isner, G. J. Muller, and M. Oeff (eds.), 2nd German symposium on laser angioplasty, G. J. Muller, H.-P. Berlien (eds.) Advances in Laser Medicine 4, SPIE Vol. 1462, 1990.

[3] Jost, R. G. (ed.), Medical imaging V: PACS design and evaluation, Proc. SPIE Vol.1446, 1991.

[4] Ritman, E. L., Fast computed tomography for quantitative cardiac analysis--state of the art and future perspectives, Mayo Clin. Proc., 65, 1336-1349,1990.

[5] Webster, J. G. (ed.), Encyclopedia of medical devices and instrumentation, John Wiley & Sons, New York, 1988.

[6] Webster, J. G. (ed.), Electrical impedance tomography, Adam Hilger, Bristol, England, 1990.

[7] Webster, J. G. (ed.), Medical instrumentation: application and design, second edition, Houghton Mifflin, Boston, 1992.