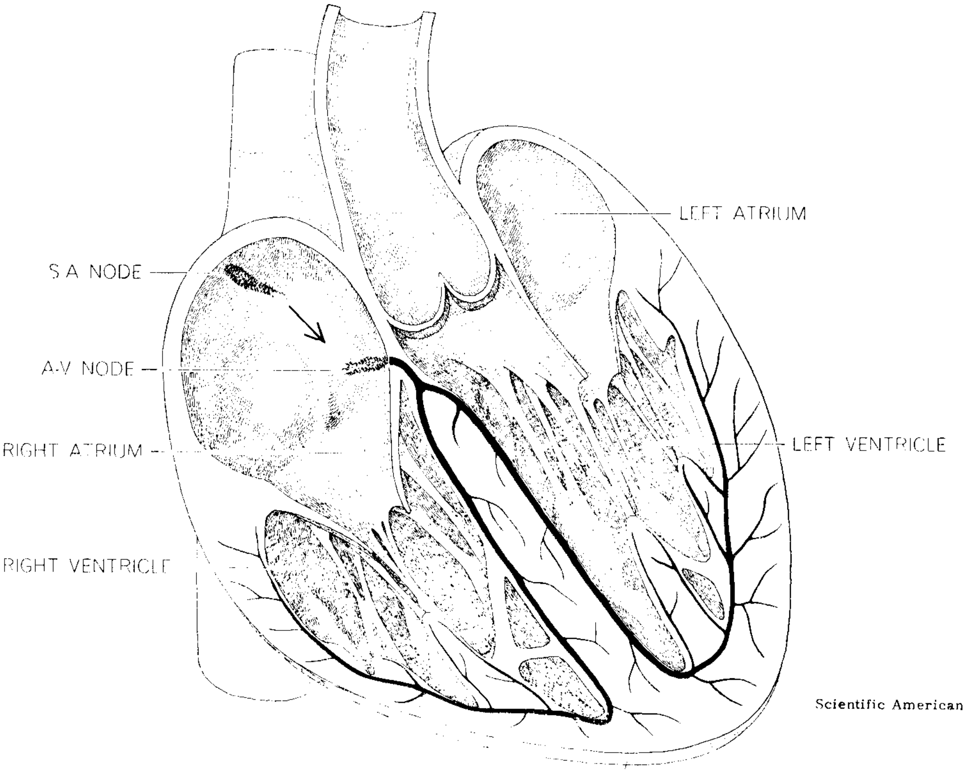


NEUROMUSCULAR CONDUCTION SYSTEM — Heartbeat is controlled primarily by specialized "neuromuscular" tissue within the heart. The beating impulse is generated in the sinoatrial (S-A) node and travels over the surface of the atria to initiate their contraction. It also travels (arrow) to the atrioventricular (A-V) node. From there, after a short delay, it is conducted by the branching Purkinje fibers throughout the two ventricles.

# heart pacing

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THE application of the principles of electronics to assist in the solution of medical problems has grown to enormous proportions within the past decade. Not the least of these is the use of electronic equipment in the treatment of cardiac standstill and heart block, a defect of cardiac conduction.

Being primarily a hollow muscle whose purpose is to act as a reciprocating pump, the four-chambered human heart is endowed with special properties to enable it to fulfill its role in the maintenance of life. Rhythmicity, which is the ability of cardiac muscle tissue to originate within itself the impulse that makes it contract, is the first of these. The second, conductivity, is the ability to distribute this impulse to every muscle fiber. Thirdly, the ability to respond to external stimuli, whether it be mechanical, chemical, or electrical, is known as the property of excitability. The last, contractility, is the ability of cardiac muscle tissue (or myocardium) to contract.

The ability to initiate and conduct an electrical impulse which will result in an effective mechanical cardiac contraction is related to a system of specialized muscle tissue contained within the organ itself. Composed of several distinct parts, the primary component of this system is the sino-atrial node, also referred to as the S-A node or the sinus node. Described by Keith and Flack in 1907, it possesses the attribute of rhythmicity to an extraordinary degree. Early experimentation demonstrated that touching this node with a hot probe would speed the heart rate while contact with a cold probe would slow it. The node, about the size of a thumb-nail, is located at the sulcus terminalis where the superior vena cava joins the posterior wall of the right atrium. This node normally generates the impulse which stimulates the myocardium to contract. Since this determines the rate for the entire heart it is called the normal pacemaker and its rhythm is called sinus rhythm.

*(See Figure 1 above)*

The sino-atrial impulse passes through the atrium to reach the atrioventricular node which is located near where the coronary sinus drains int the right atrium. The atrio-ventricular node was discovered by Aschoff and Tawara in 1908 and consists of two distinct parts. Containing little glycogen, the atrial portion seems to act as a receiver for the impulse transmitted by the S-A node, somewhat like the micro-wave relay of television; the ventricular portion, which lies in the membranous ventricular septum and contains considerable glycogen, possibly amplifies the signal as it passes the impulse to the bundle of His for distribution to the ventricular myocardium.

### Highly Conductive Tissue

The bundle of His can be easily demonstrated by Lugol's solution and is highly conductive tissue. The bundle is continuous with the ventricular portion of the A-V node, and consists of a main body in the membranous septum together with branches straddling either side of the muscular ventricular septum, like a cowboy astride a horse. These branches terminate in groups of specialized fibers, known as the Purkinje system, which carry the impulse to the individual muscle fibers.

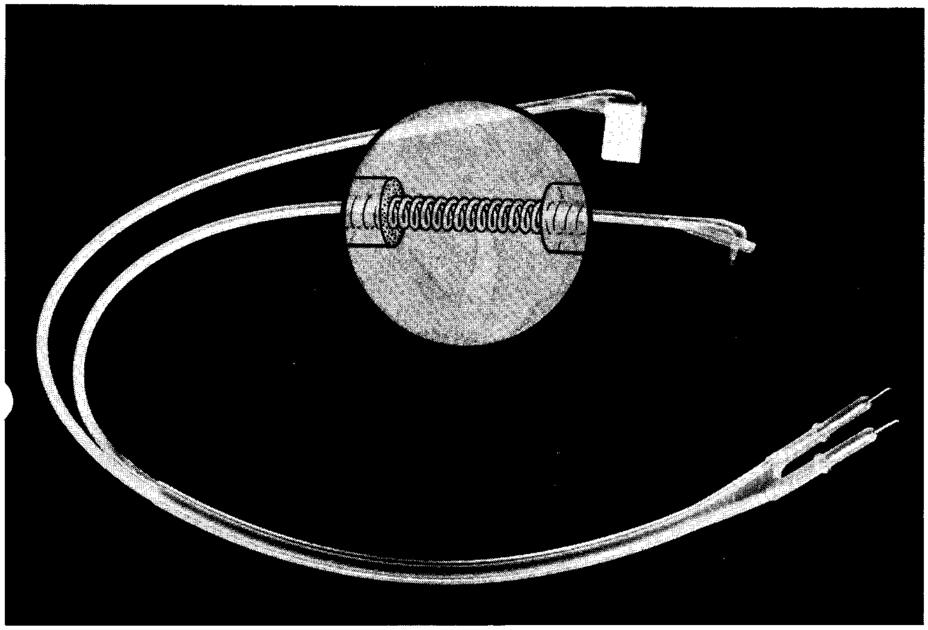
In addition to the heart's inherent ability to control itself, external influence is brought to bear upon it through various nerve connections. The role of the vagus nerve is of special interest. A greater number of the fibers of the left vagus end in the A-V node and uppress that segment of the impulse, while a greater number of the fibers from the right vagas terminate in the S-A node suppressing the primary portion of the impulse. Therefore, stimulation of the *right* vagas has a greater effect on the overall heart rhythm whereas stimulation of the left vagus may cause heart block. Vagal stimulation depresses rhythmicity directly at the nodes and in this way may indirectly depress conductivity and contractility.

### The QRS Complex

A graphic record of the stimulatory impulse of the heart is the electrocardiogram (EKG or ECG) which depicts the electrical force of the cardiac cycle on paper at a standard recording speed. First demonstrated by Kolliker and Mueller in 1856, the configuration of a single cardiac cycle consists of a series of waves (named by Einthoven), some positive and others negative, in relation to an isoelectric baseline of zero. The P wave is usually positive and depicts the atrial contraction. The ventricular contraction is associated with a small, negative Q wave, a large, positive R wave, and a small, negative S wave. This is called the QRS complex. Following the ventricular contraction, the heart repolarizes and this is expressed by the T wave, which is usually positive.

The chart paper is marked in one millimeter squares so that, at a standard recording speed of 25 millimeters per second, each millimeter of length equals 0.04 seconds in time. The sensitivity of the ECG recorder is adjusted so that each centimeter of deflection equals one millivolt (0.001 volts) of electrical force. From this calibrated chart various interval and amplitude measurements are made which are of importance to the cardiologist. The P wave is normally 0.1 second long and 0.2 millivolt in strength while the R wave is from 0.7 to 1.7 millivolts and lasts a maximum of 0.1 seconds. The P-R interval is measured from the beginning of the P wave to the start of the Q wave and is normally from 0.13 to 0.18 seconds long. These electrocardiographic events precede the actual myocardial contraction by 0.01 to 0.03 seconds.

Although an electrocardiogram can theoretically be recorded from an infinite number of points on the body, the twelve lead electrocardiogram is now considered as standard.



Chardack coiled platinum myocardial electrodes.

### Possible Impairment

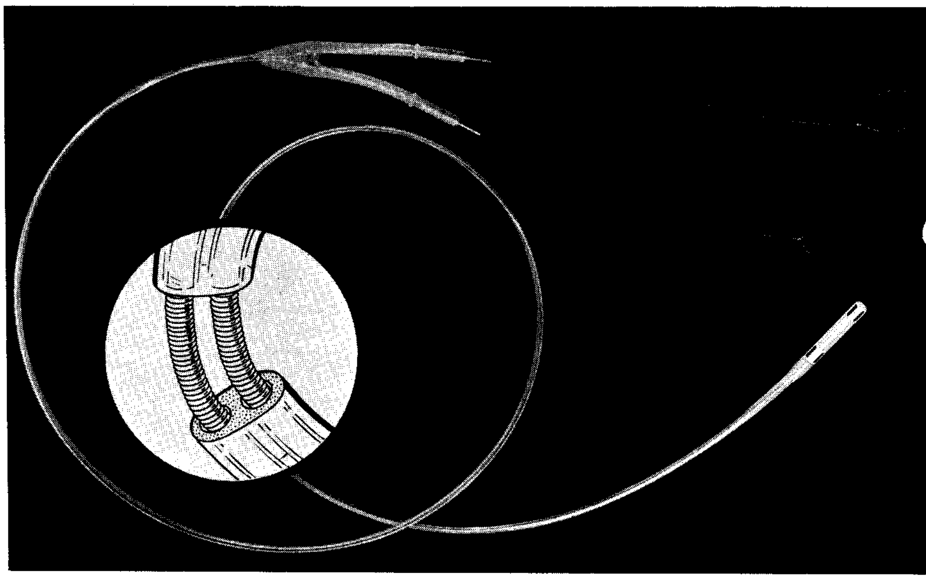
The passage of the impulse through the heart may be impaired by injury to or suppression of the cardiac conductive system, the complete interruption of the conduction of the impulses is called heart block. Heart block can occur in congenital cardiac disease but here the primary concern is the co-existence of other developmental abnormalities for other areas of rhythmicity will take over the pacemaker function.

The most frequent cause of heart block is vascular disease. The muscle fibers composing the specialized conduction tissue are extremely susceptible to anoxia, much more so than is ordinary muscle tissue. Oxygenated blood is supplied to the bundle of His by the septal coronary artery which arises from the left main coronary artery near its origin. A blockage of this artery can deprive the bundle of oxygen and possibly damage it permanently, often without any apparent damage to the rest of the heart.

During intracardiac surgery, since the bundle is not visible, stitches may be placed in such a manner as to disrupt conduction. This can frequently occur (about one in ten) during closure of interventricular septal defects. Also, transient heart block may be produced by the stimulation of the left vagus or by an overdose of a cardiac depressant such as procaineamide hydrochloride.

## Sino-Atrial Block

From these four causes several different types of block can result depending upon where in the conductive system the block has occurred. In sinoatrial block, the impulse does not leave the node so neither the atria nor, therefore, the ventricles contract resulting in dropped or skipped beats. If this suppression becomes permanent, the A-V node establishes a rhythm (called nodal rhythm) in which the P waves may be absent and there may be splintering of the R waves.



Chardack coiled platinum endocardial cannulla electrode.

## Bundle-Branch Block

Bundle-branch block is caused by an interruption in conduction through the right or left branches of the bundle of His. This is characterized by a prolonged QRS complex usually accompanied by an inverted T wave. The duration of the R wave is increased beyond 0.1 second because of the time involved by the impulse searching for an alternate route.

## Atrio-Ventricular Block

Atrio-ventricular block results from the depression or destruction of the bundle of His. It is often accompanied by characteristic attacks of unconsciousness (with or without convulsions) known as Stokes-Adams syndrome. There are three classifications of A-V block, the first of which is called first degree block. This is characterized in the ECG by a P-R interval greater than 0.18 second.

In second degree block, some P waves are not followed by QRS complexes and there may be a progressively increasing P-R interval. Third degree or complete heart block is the condition in which *no* impulses reach the ventricles from the atria and each pair of chambers beats independently at its own rate.

## Third Degree Block

In cases of third degree block, for life to be maintained, the ventricular rate must be sufficiently frequent to circulate enough oxygenated blood to maintain the viability of vital organs. The inherent properties of cardiac tissue attempt to prolong cardiac action. A new center of rhythmicity arises in an area of the ventricle, usually the bundle of His below the block, and stimulates the ventricles to beat—this is called the idioventricular rhythm. This is a comparatively slow rate, about forty beats per minute or less.

In order to compensate for the decreased rate, the stroke volume of the ventricle is increased. Peak arterial (systolic) pressures in the high two hundreds (millimeters of mercury) are not uncommon and are often a basis for diagnosis in these patients. Eventually, in most cases, something more must be done to insure the output of sufficient quantities of blood.

The excitability of the heart allows the cardiologist to prescribe the assistance of chemical or electrical stimulation. Isoproterenol hydrochloride is an example of a sympathomimetic agent that increases the rhythmicity of the myocardium and, thus, increases the rate. However, proper control may be difficult and prolonged use may mean increasing the dosages to near toxic levels.

Cardiac contractions can be produced by stimulating the heart with pulsed direct electrical current of the proper rate and amplitude. Application of the pacing stimulus to the heart can be accomplished in a number of ways for emergency use and long or short term use. External pacing is attempted through simple plate electrodes pasted to the chest wall. Although it is the oldest method, it is probably ineffective.

Internal pacing is the preferred treatment for complete heart block and can be accomplished in two ways. Unipolar electrode placement requires one electrode to be in contact with ventricular myocardium and a second electrode to be in contact with the body at some other site. Bipolar pacing requires *both* electrodes to be in contact with ventricular myocardium. The latter allows the use of much less current and eliminates the possibility of discomfort due to muscle response at the site of the indifferent electrode.

*(See Figures 2 and 3)*

## Commercial Electrodes

A wide variety of electrodes for internal pacing are commercially available. For emergency use, trans-thoracic needles or stylets are often used. Several styles of pacing catheters are widely used because of their relative ease of placement and their versatility. A frequent technique is to insert the catheter into the external jugular vein and, under fluoroscopic control, advance it to a secure position in the right ventricle where the platinum bands will contact the lining of the ventricle (endocardium). After insertion, the catheter can be attached to an external pacemaker (also known as a pulse generator) or, for long term use, to an implantable model which is then buried in the musculature of the shoulder. For permanent pacing, the favored method is that of suturing a pair of electrodes directly to the myocardium and connecting them to an implantable pulse generator.

The pacing of patients in cardiac standstill (no ventricular beat) was first reported in the *New England Journal of Medicine* in 1962 and described the technique of external pacing. Meanwhile, intracardiac surgery was coming of age and surgically induced A-V block was a common (10%) complication of the post-operative period following closure of interventricular septal defects.

A University of Minnesota cardiac surgeon was not pleased with the alternatives available to him (external pacing and isoproterenol therapy) for the treatment of these patients and consulted a Minneapolis electronics firm which designed a battery-powered, transistorized oscillator. Variable in rate from 60 to 180 beats per minute, in amplitude from 1 to 40 milliamperes, and with a pulse duration of 2 milliseconds, it drove the heart through Teflon-coated wires attached directly to the myocardium. When the heart had sufficiently recovered, the wires could be removed by gentle traction. Both unipolar and bipolar techniques were described in the *Journal of the American Medical Association* in 1960.

### Catheter Electrodes

A different approach, that of catheter electrodes, was also being developed at this time to pace the hearts of patients with chronic Stokes-Adams syndrome but, it was felt by many, the most urgent need for this problem was a permanently implantable electrode. In Minneapolis, Norman Roth put together an experimental electrode composed of two thumb-tacks encased in a block of silicone rubber so that only the pins protruded. In 1959, the first clinical implantation of this electrode was completed on a patient in St. Paul by Dr. Samuel Hunter.

### Case Example

This man entered the hospital because of gastric problems but suddenly experienced severe Stokes-Adams attacks. Any activity triggered fainting spells frequently accompanied by cardiac arrest. The personnel in attendance brought him through these bouts by pounding on his chest to mechanically stimulate a heart beat. Since permanent pacing was a necessity, his physician asked that the electrode be implanted. Transportation of the patient to surgery proved to be the most hazardous part of the procedure. At each disturbance the patient would go into cardiac standstill.

Implantation was completed under light anesthesia and the wire from the bipolar patch was tunneled through the chest wall where it was connected to the pacemaker. This 72 year old patient made a remarkable recovery. Deterioration of the wires necessitated the use of more and more power until 1965 when it was agreed that the original electrode was not functioning all of the time.

From this time until his death in 1966, he relied on a pacing catheter. During his paced life he had undergone surgery for cancer of the bowel, weathered a severe attack of pneumonia, and survived an auto accident which left him with some paralysis.

In Rochester, New York, Dr. William Chardack, in association with W. Greatbatch, developed a pacemaker that was totally implantable within the body thus eliminating a chronic source of infection. Using the Hunter-Roth bipolar patch electrode, the wire was tunneled from the chest cavity to a subcutaneous pouch on the abdominal wall just below the belt line. The unit, which was potted in epoxy and further sealed against invasion by body fluids by a case of silicone rubber, was then connected to the electrodes and the junction sealed with silicone rubber medical adhesive. Positioned as it was, on the abdominal wall, it allowed easy access to the unit for replacement without distributing the electrodes. This was reported in the journal *Surgery* in 1960.

### Problems

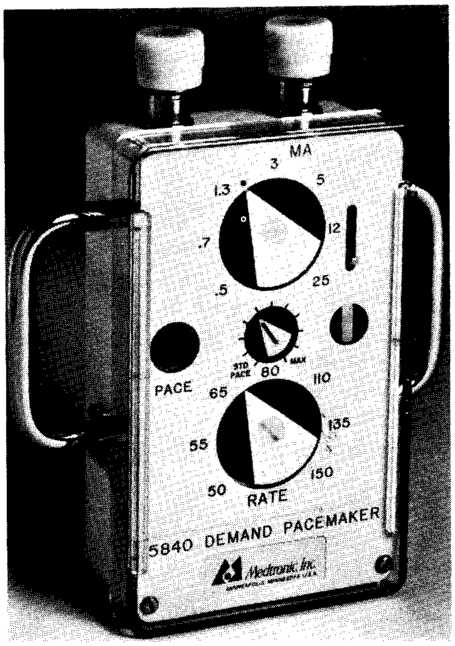
Another total implant was developed by Dr. Paul Zoll with bared wire electrodes reminiscent of the early University of Minnesota wires. Breakage due to fatigue from flexure has always been a problem with wires but the use of special alloys, finer and more numerous filaments in the braid, and platinum coatings have lessened this complication. Prior to this, many surgeons advocated placing two sets of electrodes at the initial procedure. A defect in the Hunter-Roth patch also became apparent. Since both pins were rigidly fixed to a single patch, the contractile motions of the myocardium initiated the formation of a groove around one of the pins which would cause it to frequently lose contact with the muscle.

Perplexed by these problems, Chardack and Greatbatch developed an electrode composed of a slender spring-like coil of platinum encased in a sheath of silicone rubber. A pair of these are stitched onto the left ventricular myocardium about a centimeter apart and, in conjunction with the implantable pacemaker, are extremely reliable when properly placed.

Because the totally implanted units have to be replaced every three to five years, efforts were made to design circuits that were permanently implantable within the chest and powered by an external source of energy. Units powered by energy waves transmitted through the chest wall were independently designed by Dr. A. Kantrowitz and by Drs. Glenn and Mauro about 1960. These units have not gained popularity because of their great complexity.

### More Sophisticated Control

But, as electronic control of the blocked heart became more sophisticated, a P wave sensing unit was developed which would trigger a ventricular stimulus after each atrial contraction. Physiologically, this would improve cardiac out-put by having the

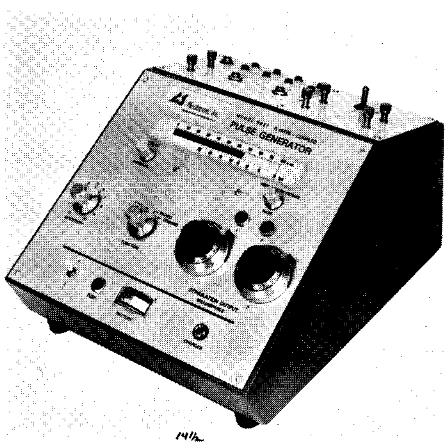



An external demand pacemaker.

ventricles properly filled by the atria and having the rate automatically adjusted to the body's changing needs.

A unique facet of this pacemaker is that it features a unipolar system. To minimize electrode destruction by electrolysis, the cathode electrode, which looks similar to Chardack's coil spring but is made of a nickel-cobalt alloy, is stitched to the heart while the anode (a plate of platinum which is highly resistant to electrolysis) is attached to the body of the pacemaker and completes the circuit when it is placed in the abdominal pouch. Again, the use of this unit is shunned by those who challenge complexity although its use proves continual increases in reliability from its fifty-four components.

To add versatility to the fixed rate, fixed amplitude models, several manufacturers have developed adjustable implantable pacemakers. Some are adjusted by the insertion of a sterile needle through the abdominal wall into ingeniously sealed potentiometers. Since this does open a new avenue for infection, other fabricators are using magnetically operated switches. Some require the taping of the magnet to the site over the pacemaker while others allow the removal of the magnet after adjustment.



An R-wave coupled pulse generator.

A new concept is "demand" pacing in which the unit measures the time lag between R-waves and delivers an impulse when the interval surpasses predetermined limits. They will pace permanently when no R-waves are present and will not pace if R-waves are normally spaced. Because of their complexity and greater power usage, they are intended primarily for patients in first or second degree block who have transient episodes of dissociation.

*(See Figure 5)*

Control of a failing heart by electronics can now be accomplished by a fantastic method. An external unit now available (and known as an R-wave coupled pulse generator) can, by proper adjustment of the timing, rate settings, and amplitude of its two built-in "pacemakers", act as a regular pacemaker, a demand pacemaker, a paired-pulse generator, and an R-wave coupled pulse generator. The last two modes of operation, of course, are the most revolutionary. With the unit adjusted to deliver a stimulus to the heart muscle just prior to the R-wave, the myocardium is depolarized into a refractory period without a muscular contraction. A recording of the ECG and arterial pressure will depict a normal ECG stimulus with no corresponding arterial pulse. This can be used to reduce the *pulse* rate to one-half of the ECG rate (with a pacing stimulus delivered prior to every other R-wave) decreasing a ventricular tachycardia by a factor of two and is known as "R-wave coupling".

*(See Figure 6)*

Also, by delivering the stimulus prior to *every* R-wave, the myocardium will be brought to a virtual standstill. Then, using the second pacemaker in the unit, a second stimulus can be delivered to the heart to yield a rate more desirable to the individual. This is known as "paired pacing".

## Summary

Reliability is of prime importance, as has been previously mentioned, and the concept of "zero defects" is held in high esteem by all manufacturers. The simpler fixed rate and amplitude pacemakers have reliability rates in excess of 99% while the more complex models are steadily increasing in dependability. Permanent electronic control of the blocked heart is one step toward technical rejuvenation of malfunctioning organs.