Pacemakers

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Pacemakers are small devices that are placed in the chest or abdomen to help control abnormal heart rhythms. This device uses electrical pulses to prompt the heart to beat at a normal rate. Pacemakers are used to treat arrhythmias. Arrhythmias are problems with the rate or rhythm of the heartbeat. During an arrhythmia, the heart can beat too fast, too slow, or with an irregular rhythm. In addition to helping treat arrhythmias, pacemakers help people with irregular heartbeats resume a more active lifestyle. The physics involved in the operation of pacemakers is fairly basic. The history and development of today's pacemaker is very interesting especially when applied to how a pacemaker works and what conditions it can be used to treat.

Before the pacemaker was developed, there were two generally accepted methods to regulate the rhythm of the heart (Mohee). They were mechanical stimulation of the heart, which was a direct massage of the heart muscle, and intracardial therapy. The first was used most often following accidental cardiac arrest during an operation when the patient was under general anesthesia. The second involved injecting the hormone adrenaline directly through the chest wall to stimulate the heart.

In 1932, Albert Hyman invented the first artificial pacemaker (Mohee). Intracardial therapy involved stimulating the heart multiple times to force the heart to achieve its normal rate. Hyman wanted to stimulate the myocardium with electrical impulses passed through needle electrodes. This process gave him repeated stimulation without the hazard associated with intracardial therapy. His design involved a magneto generator to produce the direct current voltage for supplying power to the electrodes. He also used two U-shaped magnets to supply the magnetic flux necessary to induce current in the generator. An interrupter disc was used to control the duration of the electrical impulses supplied to the electrodes. This design weighed 7.2 kilograms and was portable (Mohee). However, it was ineffective because of the low output of pulses generated by the generator. Use of the pacemaker was not widespread until about twenty years later.

In 1952, Dr. Paul M. Zoll initiated the first clinical application of the pacemaker (Mohee). He applied it to a 75-year old man who had been suffering from complete heart block for two years. As his condition worsened, he had also experienced episodes of ventricular asystole. Over the course of his treatments, he had been injected with adrenaline many times. Zoll applied external electrical stimulation, successfully pacing the heart for 25 minutes. He used this same procedure on a 65-year old man. That time, he kept the heart going for 5 days. This treatment was described as cardiac resuscitation via electrodes on the bare chest with 2-milli second duration pulses of 100-150 volts across the chest, consisting of about 60 stimuli per minute. (Mohee) This is the foundation upon which all future developments lie.

Dr. W. Lillehei improved on this method in 1957 by combining a pulse generator with a wire electrode attached directly to the heart. (Mohee) He first tested this theory on a dog and was successful. Many doctors had been having problems with post-operative complete heart block in open-heart surgery patients. Zoll’s method required too long of a stimulation time. Lillehei used a new technique to pace the heart of a child undergoing open-heart surgery. This time, he used impulses lasting for 2 ms at voltage ranging from 1.5-4.5 volts, much lower than that used by Zoll (Mohee). This new treatment was very effective and tolerated well by patients. Lillehei and Zoll both used a device called a particular physiological stimulator, which is a device that transforms alternating current into direct current. (Mohee) However, there was no type of battery backup for this so it often ran out and had to be replaced. Lillehei turned to a man named Earl Bakken who worked for company called Medtronic. Bakken designed a new pacemaker that was miniaturized to the size of a packet of cigarettes. When this was applied to a child with heart block, the pacemaker spontaneously restored the child's heart beat to normal and within a few days, it was removed. (Mohee)

The next step after this advancement was creating implantable pacemakers that could stay within the body for a longer period of time. This was the only way to prevent infection in the electrodes. There were two main problems that arose with trying to make implantable pacemakers. First, they were often too short-lived, causing the patients to have to undergo many procedures to receive a pacemaker for good (Mohee). Second, an industry was needed to make them at a reasonable price and to serve as a financial support for research projects. Once these were addressed, implantation was done without thoracotomy, an incision into the chest cavity, by introducing the electrode transvenously with the tip in the right ventricle (Mohee).

Programmability of pacemakers arose in the 1970s. Doctors wanted to be able to modify implantable pacemakers to work noninvasively. In 1972, Medtronic introduced a programmable pacemaker that had a gear train attached to small bar magnets inside an implanted pulse generator (Mohee). Hybrid circuitry was then developed. It drew less power from the battery because it only used power when it was undergoing actions like opening or closing a switch (Mohee). This allowed for manufacturers to downsize the generators while not compromising pacemaker longevity. In 1974, a three letter pacing code was introduced for antibradychardia pacing systems to convey functions by simple conversational means. It was later expanded to five letters to include antitachychardia functions.

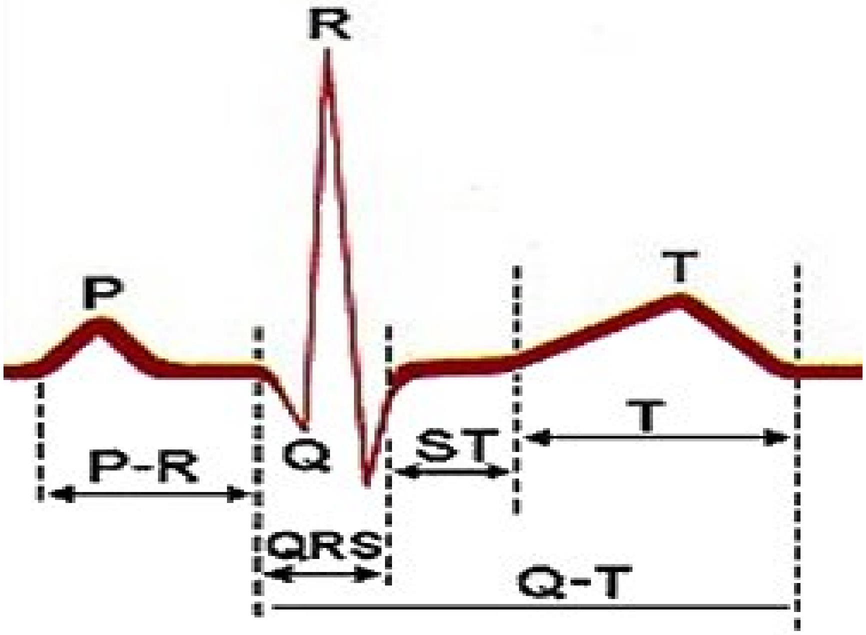
In the 1980s, Manufacturers began trying to develop a new type of pacemaker that operated under dual chamber pacing. They thought, along with many physicians, that by providing better coordination between the contractions of the atria and ventricles, these pacemakers better emulated nature and had huge benefits to the quality of life of the patient. It proved to be complicated for the doctors in the 1980s but moving into the 90s, 80% of cases involved implantation of dual chamber pacemakers (Mohee).

Current pacemaker devices include multi-chamber pacemakers, which are rate responsive units capable of pacing, cardioverison and defribrillation. Many more diseases and ailments can be treated now with pacemaker implantation. Pacemakers have witnessed dramatic technological advances over the years, yielding better results and thus higher patient acceptance, instilling an aura of hope for a healthier and prolonged life for their users.

To understand how pacemakers work, an understanding of the electrical activity of the heart must be possessed. The heart has a natural pacemaker that regulates the pace of the heart. It sits in the upper right portion of the right atrium and is a collection of specialized electrical cells known as the sino-atrial (SA) node

(Widmaier et al 2008). The SA node generates a number of electrical signals per minute that travels across a specialized electrical pathway, stimulating the muscle walls of the four chambers of the heart, causing them to contract and thus empty in a certain sequence or pattern. The normal intrinsic conduction of the heart allows electrical propagation from the SA node to the atrioventricular (AV) node (Widmaier et al 2008) Further propagation occurs allowing the myocardium to contract. The electrical impulses of the normal rhythm of the heart can be seen in the PQRST wave.

The upper chambers of the heart, the atria, are stimulated first by the SA node. This is called the P wave. Electrical activity spreads from the SA node to the AV node via intermodal tracts. There is then a short delay so the atria can empty their contents followed by the stimulation of the two ventricles (Widmaier et al. 2008). This delay is critical in the conduction system. Without it, the ventricles and atria would contract at the same time and blood would then flow ineffectively through the heart. This delay is called the PR segment of the electrocardiogram. Adrenaline causes the SA node to send more signals per minute, increasing the heart rate of the individual. The rest of the graph shows the flow of conduction through the heart to all of the heart cells, which causes them to contract. Two bundle branches in the ventricles taper out to produce the purkinje fibers that stimulate the rest of the myocardial cells to contract. This spread of electrical activity throughout the ventricular myocardium forms the QRS complex on the ECG (Widmaier et al. 2008). The final event is ventricular repolarization, where the heart returns to its resting state before contracting again. This part of the wave is influenced by the parasympathetic nervous system. A diagram of this process is below.



(Widmaier et al 2008)

There are three conditions most commonly treated with pacemakers. They are tachycardia, bradychardia and an AV block. Tachycardia is an excessively rapid heart rate. It results from action potentials from the SA node that yield heart rates greater than 100 beats per minute (bpm). Bradychardia is the opposite, an extremely low heart rate, caused by SA node impulses at a rate less than 60 beats per minute (Epstein 2008). AV blocks occur when the conduction between the atria and ventricles are impaired, causing less blood flow. When the pacemaker is installed in these cases, it can replace the lost electrical signal that is lost when it comes to the block and stimulate the ventricles to contract and thus empty their blood to the rest of the body. This stimulation is what is imitated by the use of a pacemaker.

A pacemaker consists of a battery, a computerized generator, and wires with electrodes at their tips (NHLBI 2009). The generator is powered by the battery and both are surrounded by a thin metal box. The wires are what connect the generator to the heart. The overall purpose of a pacemaker is to control and monitor a person's heartbeat. The heart's electrical activity is detected by the electrodes, which then send data to the computer. If the rhythm of the heart is abnormal, the generator will send electrical pulses to the heart, stimulating more normal rhythms. Doctors can program pacemakers from external devices. There is no need now for any type of direct contact with the pacemaker or stimulation from needles.

Pacemakers function just as any other generator. By definition, a generator is any device that converts mechanical energy into electrical energy by spinning a coil of wire in a magnetic field (Stewart 2011). The electrical energy produced is measured in volts. The equation for magnetic flux with a uniformly spinning coil is,

$$\Phi_m = NBA\cos\theta,$$

where N is the number of turns of the coil, B is the magnitude of the magnetic field, and A is the area over which the coil is turning. The electromotive force is defined as the work per unit charge done by an electric or magnetic field on a charge particle. It can be found by Faraday's Law, which basically shows how the magnetic flux varies with time (Stewart 2011).

$$emf = -\frac{d\Phi_m}{dt}$$

Because the coils inside the generator of a pacemaker spin uniformly, the angular frequency can be substituted into the flux equation for theta. If the coil turns are a constant rate, $\theta(t) = \omega t$, but only if the normal to the loop is parallel to the field at t=0. ω is called the angular frequency.

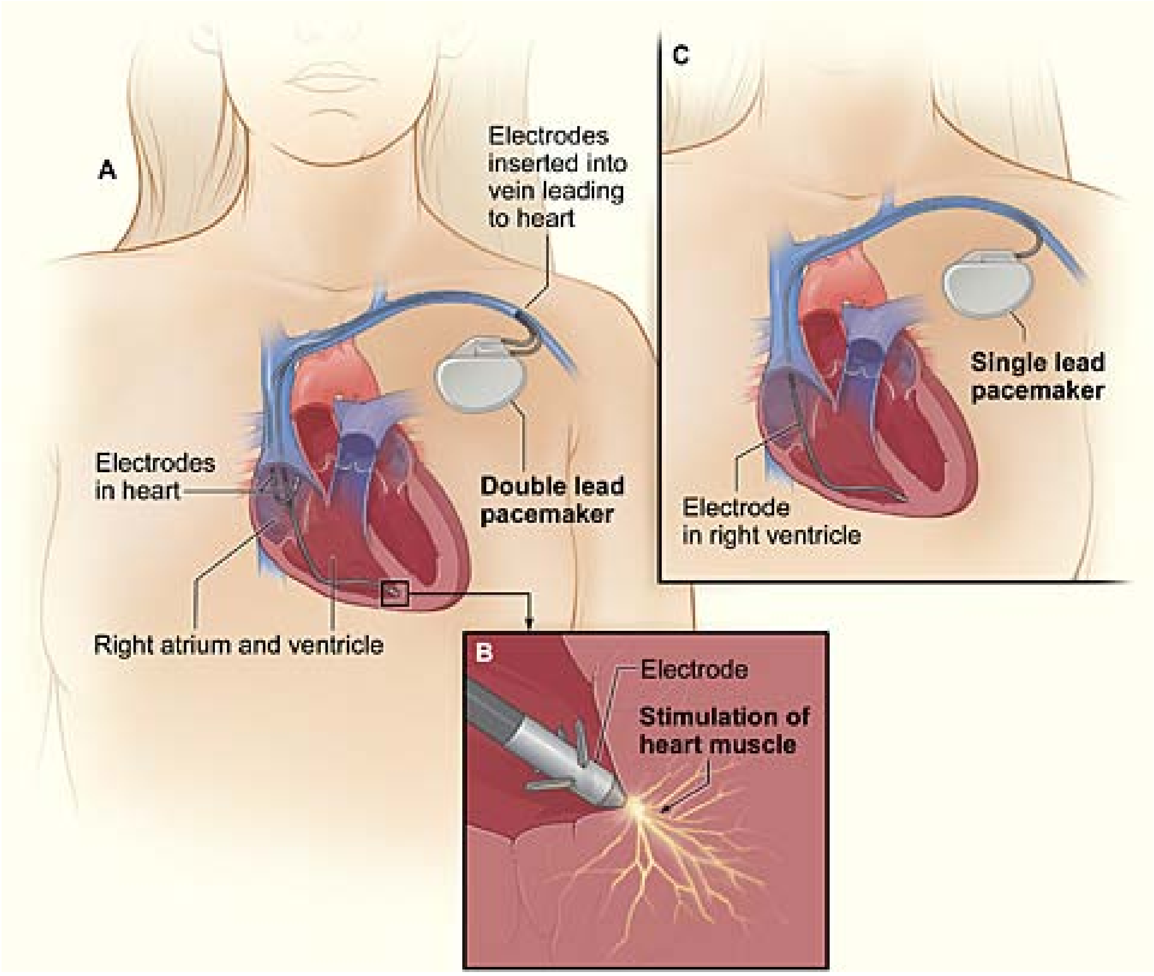
$$\Phi_m = NBA = NBA\cos\omega t$$

By taking the derivative according to Faraday's Law, an equation for the electromotive force can be created.

$$emf = -\frac{d\Phi_m}{dt} = -\frac{d}{dt}NBA\cos\omega t = NBA\omega\sin\omega t$$

It is these volts that are sent to the atria and ventricles of the heart to stimulate the heart's usual electrical activity. The amount of voltage needed varies with the differing conditions present that require the installment of a pacemaker.

Pacemakers have one to three wires that are each placed in different chambers of the heart (NHLBI 2009). In a single-chamber pacemaker, the wires usually carry pulses from the generator to the right ventricle of the heart. Dual-chamber pacemakers utilize their wires by sending the pulses from the generator to the right atrium and the right ventricle. The pulses help coordinate the timing of these two chambers' contractions (NHLBI 2009). The wires in a biventricular pacemaker carry pulses from the generator to an atrium and both ventricles (NHLBI 2009) Electrical signaling is coordinated by the pulses between the two ventricles. This is also called a cardiac resynchronization device. A diagram of these types of pacemakers is shown below.



(NHLBI 2009)

The image shows a cross-section of a chest with a pacemaker. Figure A shows the location and general size of a double-lead, or dual-chamber, pacemaker in the upper chest. The wires with electrodes are inserted into the heart's right atrium and ventricle through a vein in the upper chest. Figure B shows an electrode electrically stimulating the heart muscle. Figure C shows the location and general size of a single-lead, or single-chamber, pacemaker in the upper chest (NHLBI 2009).

There are two types of programming for the pacemakers of today. They are called demand pacing and rate-responsive pacing (NHLBI 2009). A demand pacemaker monitors the rhythm of the heart. The only times electrical pulses are sent out from the generator are when the heart is beating too slow or misses a beat. A rate responsive pacemaker will speed up or slow down the heart depending on the person's level of activity at specific moments. The device monitors a person's sinus node rate, breathing, blood pressure and other factors to determine the activity level.

Once a person has a pacemaker installed, it is imperative that he or she avoid prolonged contact with electrical devices or devices with strong magnetic fields. This includes cell phones, household appliances, high-tension wires, metal detectors, and electrical generators as well as many other devices (NHLBI 2009). The Law of Linear Superposition for magnetic fields states that the total field at any point P is the sum of all fields acting on that point (Stewart 2011)

$$\vec{B} = \sum \vec{B}_i$$

The magnetic fields of these types of devices can greatly interfere with the magnetic field of the pacemaker. They can add to it or cancel it out. Either way, that type of interaction would cause a change in magnetic field, thus affecting the flux of the pacemaker's generator, which would then in turn affect the electromotive force produced by the generator. The voltage that would usually be produced by the pacemaker could be changed, causing detrimental effects to the person's heart. Another way other magnetic fields could affect the pacemaker is that by increasing or decreasing the total field, changing the flux, a new current could be induced to oppose the change in flux. This is called Lenz' Law (Stewart 2011). Any of these types of interactions would greatly affect the pacemaker and could cause great harm to the individual.

In conclusion, the pacemaker has been an astounding advancement in the field of medicine. It can be seen by looking at the history of the pacemaker that without it, people today would be subject to some fairly painful procedures that would have limited effectiveness. The simplicity of how it works is also amazing in that something that can extend the life of a person so well is basically a generator producing an electromotive force. If future advancements in this field follow suit with the trend of advancements that the world has seen so far, people with heart conditions requiring a pacemaker will have nothing to worry about and will be able to lead long and happy lives.

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