

Electrical Signaling In the Heart: Pacemakers and ICDs

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Every heartbeat is the product of electrical stimulation created and propagated within cardiac muscle tissue. A person's heart rate is subject to outside influences regulated by the autonomic nervous system, but the action potential that causes a heartbeat to occur arises from within the heart, in the sinoatrial (SA) node, located in the right atrium. From the SA node, the action potential can travel from the atria down to the ventricles, allowing all cardiac muscle cells to contract in unison. Understanding the conduction pathway of the heart is essential to understanding how a heart grows weaker and fails. If the SA node fires action potentials at irregular intervals, or if the conduction pathway from the SA node to the ventricles is obstructed, the heart cannot maintain a stable rhythm or cardiac output (Diseases and Conditions Index).

The electrical system of the heart begins in the right atrium and ends in the ventricles. Special channels called funny-type channels in the membranes of cardiac pacemaker cells allow the influx of sodium ions when the membrane potential is negative. The influx of sodium ions triggers the influx of even more sodium ions and a depolarization of the plasma membrane. A "depolarizing boost" occurs as the influx of sodium ions also triggers the opening of T-type calcium channels, allowing enough calcium to enter the cell to cause an action potential. This action potential triggers the opening of more calcium channels, called L-type calcium channels, named for how long they stay open. The influx of calcium through L-type channels balances the potassium that is exiting the cell. Normally, the exit of potassium would repolarize the cells, but depolarization is lengthened in cardiac cells due to their L-type calcium channels. The slow propagation of the action potential allows the atria to contract just before the ventricles. This is important because it allows for ventricular filling with blood from the atria. From the atria, the action potential travels down the interventricular septum through the Bundle of His. From the Bundle of His, the signal splits between the right and left bundle branches and reaches the rest of

the heart tissue via the Purkinje fibers. This spread of the action potential occurs very quickly in “a single coordinated contraction” (Widmaier et al. 2008, 367-370). After repolarization, the membrane potential is negative so the funny-type channels open and initiate the same series of events. The electrical system of the heart is shown below. This is a very complex yet efficient process just to produce a heartbeat, and throughout a person’s lifetime it is not uncommon for complications to arise in the cardiac conduction pathway. When the electrical system of the heart is in distress, a common solution is the implantation of a pacemaker.

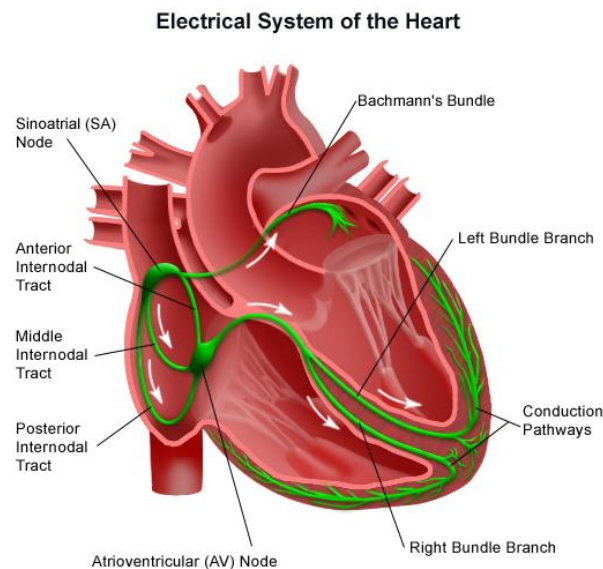


Image from <http://www.jeffersonhospital.org>

Pacemakers have been in use since the 1950’s, but their design and capabilities have changed dramatically. The original pacemakers were external pacemakers requiring an external power source and providing painful electrical shocks through the patient’s skin. Today, pacemakers are internal and battery-powered, lasting an average of seven years. They are connected to the heart via “leads,” insulated wires with electrodes on the tips. The image below shows a typical pacemaker design and placement. During the implantation procedure, which is most often done as an outpatient procedure, the leads are inserted through a vein (usually the

subclavian vein) so that they lie within the right atrium, right ventricle, or both. Then the pacemaker is inserted just under the skin in a cut made under the collarbone, and connected to the leads. The pacemaker is tested before the cut is sewn (Stewart 2009, 351-353). The placement and relative size of a pacemaker is shown below.

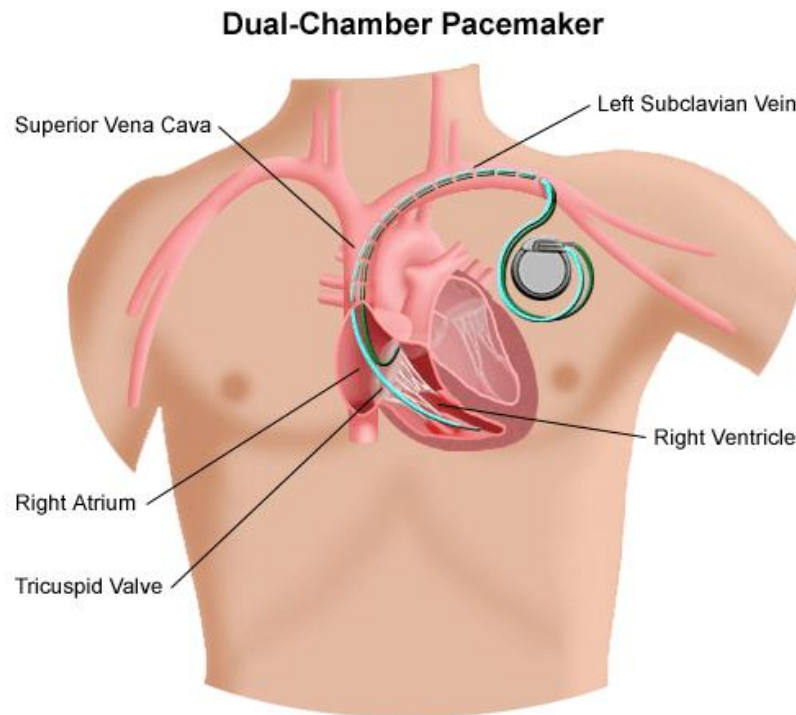


Image from <http://www.bighamandwomens.org>

Pacemakers are designed so that they can be programmed to a patient's specific needs. Pacemakers, also called pulse generators, consist of a lithium-iodine battery, electric circuitry, a small titanium case, wires, and electrodes. The number of wires and electrodes, as well as the programming that controls the voltage produced, can be altered for each patient. There are two main types of pacemakers: single chamber and dual chamber. Single chamber pacemakers contain one lead, which connects to the heart in either the right atrium or the right ventricle. Single chamber pacemakers can be used when the SA node is firing too slowly, or when atrial fibrillation causes the ventricles to contract at irregular intervals. Atrial fibrillation, the most

common type of cardiac arrhythmia, occurs when the atria quiver instead of contracting as a unit. When the atria are sending staggered impulses to the ventricles, the heart cannot beat in unison and the heartbeat becomes sporadic. Dual chamber pacemakers have an additional lead because they are connected to both the right atrium and the right ventricle. Dual chamber pacemakers can be used when the SA node is firing too slowly, or when the conduction pathway is obstructed. Dual chamber pacemakers coordinate the atrial contractions with the ventricular contractions. Both types of pacemakers can sense impulses and record information about the atria or ventricles where the electrodes are located. This information is stored in the pacemaker and can be reviewed by a physician at doctor visits to see if any changes need to be made to the pacemaker settings. Conditions that require pacemakers are bradycardia (slow heart rate), tachycardia (fast heart rate, and heart block (conduction pathway obstruction). However, some patients may experience the need for a temporary pacemaker. Sometimes after a heart attack, heart surgery, or drug overdose, a temporary pacemaker will be implanted until the heart is deemed stable (Diseases and Conditions Index).

The pacemaker settings can be described in a three or four-letter code. The first letter tells which chamber(s) is being paced. The second letter tells which chamber(s) is being sensed. The third letter tells how the pacemaker responds to sensed events. The fourth letter tells of any other features of the pacemaker. The options for the first two letters are A (atrium), V (ventricle), or D (dual, for both atrium and ventricle). The options for the third letter are I (pacemaker is inhibited after sensing an impulse), T (pacemaker is triggered after sensing an impulse), or D (dual, for both inhibition and trigger). Pacemakers can be inhibited if the sensed impulse is at an appropriate interval, or triggered if no impulse is sensed. If the pacemaker is rate-responsive, then the fourth letter can be R. Rate-responsive pacemakers monitor other signals, such as

respiration rate, body temperature, vibrations, and acceleration, to determine if the body will need an increased cardiac output (Stewart 2009, 353-355). An example of a pacemaker code is VVIO. This pacemaker paces the ventricle, senses impulses from the ventricle, is inhibited when it senses an adequate impulse, and is not rate-responsive. A very common pacemaker mode is DDD0, meaning that it paces and senses both the atrium and ventricle. The third D implies that if a heartbeat is sensed, the pacing output of the pulse generator will be inhibited, but if an atrial beat is sensed without being followed by a ventricular beat, then the pulse generator will deliver current to the ventricle (Kirk 2006, 11).

The physics of a pacemaker can be understood by studying the common complications that arise with pacemakers. Pacemaker longevity varies from patient to patient, and is often a direct result of how often the pacemaker has to work; for example, rate-responsive pacemakers that are monitoring the body's level of physical activity lose battery power much faster than non rate-responsive pacemakers. The battery most often used in pacemakers, the lithium iodine battery, was selected because of its long life span. In a lithium iodine battery, lithium acts as the anode. Lithium atoms lose electrons and become lithium ions. Iodine atoms accept electrons to become iodine ions. Lithium and iodine will react with each other, forming lithium-iodide. Electrons flow from the anode (lithium) to the cathode (iodine) (Barold et al, 2004, 291). As the amount of lithium-iodide increases in a battery, its resistance increases as well. Eventually, this resistance will be low enough to indicate the elective replacement time and the battery can be replaced (Mallela 2004, 206).

To form the battery, lithium sheets are cut into specific sizes to form the anode shape. Then the anode is covered in polyvinylpyridine (PVP). A mixture of iodine and poly-2-vinyl pyridine (P2VP) is poured around the anode and allowed to cool into a conducting solid. When

this solid makes contact with the lithium, it reacts to form a crystalline lithium iodine layer that allows for the flow of lithium ions but not iodine, establishing the current flow (Mallela 2004, 206). The current is delivered to the heart by the leads, and reaches the heart between two electrodes. Some leads have two actual electrodes: a negative electrode at the tips and a positive electrode ring underneath it. These are called bipolar leads. Current reaches the heart in a very small region and then spreads. Unipolar leads contain only one electrode at their tip, using the metal pacemaker case as the other “electrode.” Since current reaches the heart between the two electrodes, unipolar leads deliver current to a very large area (Kirk 2004, 6). Both types of leads relay impulse signals back to the pacemaker for data storage. Again, unipolar leads detect impulses over a larger area, and therefore pose the risk of relaying large signals from other parts of the body to the pacemaker, causing an inappropriate response (Kirk 2004, 8). Unipolar and bipolar electrodes are shown below.

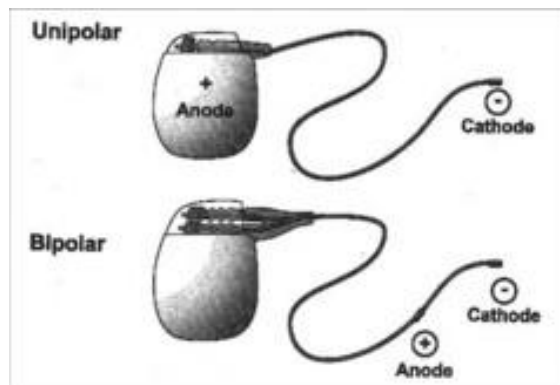


Image from <http://i.quizlet.net>

The battery composes about half of the weight and volume of the pacemaker. The rest is composed of various circuits: some for pulse generation, some for monitoring time, and some for sensing the presence or absence of impulses. Many pacemakers will also include special mechanisms for programming as well as memory for recording data. Surrounding the battery and circuitry is a titanium case that is hermetically sealed. Titanium is preferable because it serves as

a great shield for its contents, allowing patients to use a wider range of electronic appliances. The casing can be hermetically sealed because lithium iodine batteries, unlike some of their predecessors, do not release hydrogen gas. Past batteries could not be hermetically sealed because the gas needed to be able to diffuse out of the pacemaker. This severely shortened the battery's longevity because fluid would gradually enter the pacemaker and destroy it. A diagram of a lithium-iodine battery is shown below. Almost all pacemakers implanted today are lithium iodine pacemakers, although a variety exists among patients who have had their pacemaker for several years. For example, nuclear batteries using plutonium are no longer sold due to their toxicity risks and traveling inconvenience, yet several patients will keep their nuclear pacemakers until there is a legitimate reason for them to have a replacement. (Mallela 2004, 205-206).

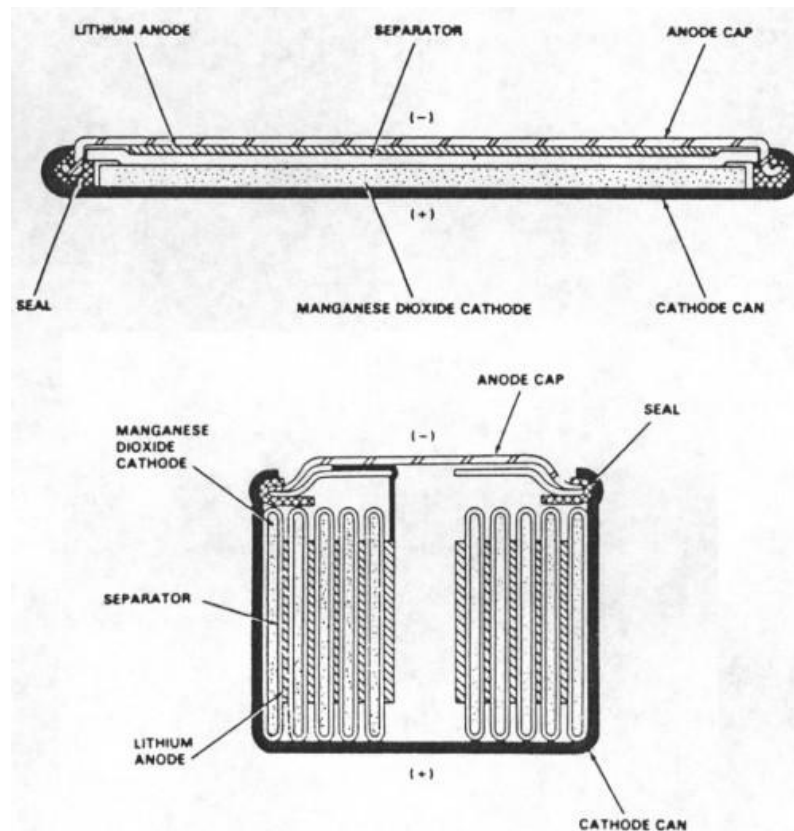


Image from <http://www.sahha.gov.mt>



The current delivered to the heart from the pacemaker leads depolarizes the cardiac tissue to cause contraction, making up for the irregular, obstructed, or damaged conduction of the action potential. The smallest amount of energy needed to stimulate a contraction is called the pacing threshold. The actual output of a pacemaker is typically double the pacing threshold to allow for a safety margin. The output cannot be too high because that will drain the battery faster (Kirk 2004, 13). To determine a pacemaker's longevity it is important to know a battery's capacitance and current drain. Current drain is a function of the electrode type and the circuitry of the pacemaker. Increasing circuitry for additional physiological regulations and data storage ("housekeeping tasks") will increase the current drain. Lithium batteries tend to have a relatively low current drain, adding to their usefulness. As resistance, or impedance, increases over time with the formation of LiI, the current released will drop. This is inevitable according to Ohm's Law ( $\text{current} = \text{voltage}/\text{resistance}$ ) since the voltage output is programmed to be constant, but it is manageable if resistance increases gradually. Lithium iodine batteries are well known for having stable voltage decay, making elective replacement time easy to predict. (Mallela 2004, 206-208). While the average pacemaker lasts seven years, battery depletion is considered normal if it occurs more than three years after implantation, as long as the depletion appears gradually and pacemaker is still functioning at the detection of depletion. Premature battery depletion occurs when the elective replacement time is less than three years after implantation. Premature depletion can be caused by an unusually high, programmed output voltage, software complication, or other events resulting in a sharp decline in output voltage (Hauser 2007, 154). It is very common for pacemaker studies to emphasize the importance of advancements in battery longevity. This can be accomplished through innovations in lowering pacing threshold, lowering current drain, and increasing battery capacity (Hauser 2007,158).

Because pacemakers rely on the accuracy of electric signaling, patients must be aware of how closely they interact with electromagnetic devices. Common precautions that patients take are keeping MP3 players and high-frequency cell phones in pockets away from the implantation area, avoiding metal detectors, and informing dentists and new doctors about their device. There are several medical procedures known to interfere with pacemaker signaling and it is best for both physicians and dentists to know as soon as possible about a pacemaker (Oregon Health). Pacemaker patients must be extra cautious about MRI scanning. Several studies have been done that show there are increased risks to having an MRI with a pacemaker. The static magnetic field of an MRI machine is thought to interfere with the reed switch of pacemakers. The normal use of the reed switch is to create a magnetic field when activated to help physicians test the pacemaker; however, MRI scans are expected to inhibit reed switch function (Dewinder 2000, 202). Also, MRI contains changing magnetic fields, which are expected to create an induced current in the electrodes. The leads, which form closed loops within the pacemaker, act as antennas for the electromagnetic field; flux through the electrode is increased and the induced currents causes a sharp rise in temperature. In a study done in Germany in the 1990's, 7 out of 25 patients had electrode temperature increases of greater than 15°C when exposed to 90 seconds of MRI. This effect of MRI is especially dangerous because it goes undetected by the patient during the procedure, and tissue necrosis at the electrode site can cause serious long-term complications such as an increased pacing threshold, cardiac perforation, or arrhythmias (Achenbach 1997, 472).

Single and double chamber pacemakers are not the only defibrillators available to treat cardiac arrhythmias. Some pacemakers contain three leads and are used to treat patients with advanced heart failure using a method called biventricular pacing, or cardiac resynchronization

therapy (CRT) (Widmaier 2008, 352). The third electrode is connected to the left ventricle to improve the timing of their contractions, which should be simultaneous. (Diseases and Conditions Index). Pacemakers can improve a variety of arrhythmias using low energy impulses, but they are most often used for bradycardia and atrial fibrillation. Tachycardia usually requires an implantable cardioverter defibrillator (ICD) because this type of defibrillator can create high-energy electrical pulses to bring the heart rate down, but it is still capable of producing the low energy pulses characteristic of most pacemakers (Oregon Health).

The technology behind pacemakers is similar for all defibrillators and is the product of decades of research and clinical trials. Pacemakers are estimated to exist in over 3 million people worldwide, with a growing implantation rate of 600,000 pacemakers per year (Mallela 2004, 201). While lithium iodine batteries have served as a successful energy sources since the 1970's, research is being done on alternative power sources with the hope of increased longevity to improve both the reliability of the device and the quality of life for the patient. This technology extends into other treatments as well, providing implantable drug-delivering systems and potential advancements for conditions such as cancer, multiple sclerosis, cerebral palsy, and diabetes (Holmes 1999, 34).

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