UNIVERSITY PHYSICS II, DR. STEWART

Honors Project

Internal Cardiac Pacemaker

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Introduction

With approximately 500,000 internal cardiac pacemakers implanted in patients in the United States currently, the pacemaker is one of the most commonplace and important medical devices of the 20th century. Pacemakers are implanted into patients whose hearts are unable to provide adequate electrical impulses, either by the magnitude of the pulse or the rhythm, a problem which is encountered when the conductive cells of the heart are damaged due to disease. The rhythm of contractions which the pacemaker controls must be very precise, as a heart rate which is too fast, too slow, or irregular can lead to further medical problems [1].

Many well known heart conditions are responsible for a patient needing a pacemaker, such as coronary artery disease, heart attack, or infections of heart tissue. A precursor of atrial fibrillation, Bradycardia is another common heart condition leading to the need for a pacemaker. In this case, the patient’s heart beat is too slow, which can cause the vessels of the heart to stretch out from the stress of high pressure blood flow [1].

History of Pacemakers

The initial development of the pacemaker began in 1928 by the work of an American physician named Albert Hyman and his brother Charles, a physicist. A year later in Australia, a physician named Mark Lidwill claimed to have saved a stillborn child’s life by the application of electric stimulation. The original pacemakers were bulky, the first requiring an extra operator for transport of the device. The early Hyman models were also very limited in their functions, with impulse frequency options of only 30, 60, and 120 per minute [2].

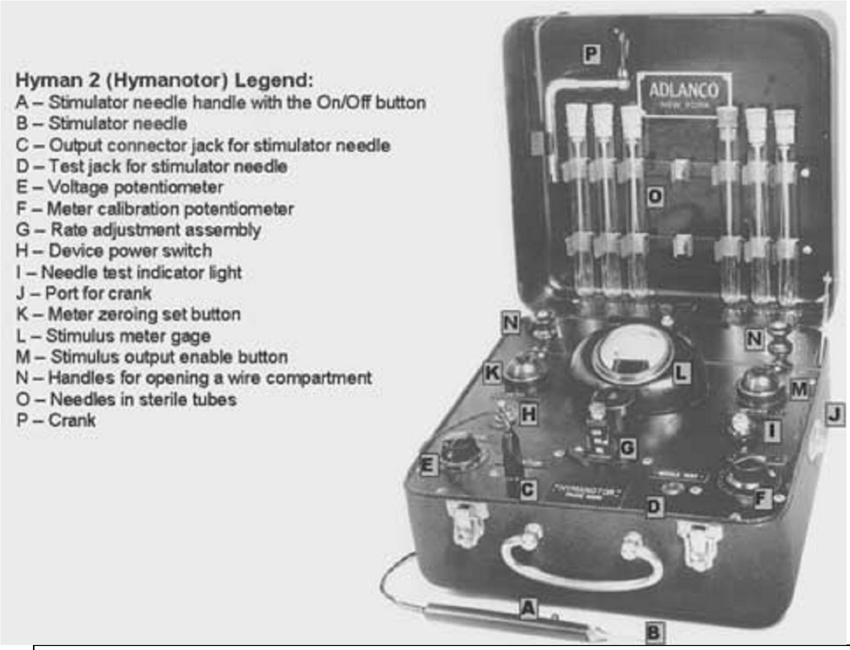


Figure 1. The Second Prototype Created by Albert Hyman with Labeled Panel Elements [2]

Widespread knowledge of the advances in electrotherapy went relatively unnoticed until 1951, when a cardiologist named Paul Zoll successfully treated a patient suffering from heart block with an external cardiac pacemaker. The pacemaker was developed by Zoll from an already available electric stimulator used in laboratory work, with two metal electrodes connected over the patient’s heart. In 1956, problems with ventricular fibrillation brought about the demand circuit device, designed by Aubrey Leatham and Geoffrey Davies. In 1957, modifications to the design made this the first commercial model, including a battery for the mobility of the patient [2].

An internal pacemaker was soon after created by Wilson Greatbatch, an electrical engineering professor, and Drs. Chardack and Gage. The first internal pacemaker was implanted in 1960 by Dr. William Chardack. Similar to many of the early surgical cases involving pacemakers, the patient was a 77-year old man suffering from complete heart block. Other designs of implantable pacemakers include the concept of inductive coupling. No internal batteries were necessary for this design, with a subcutaneous coil connecting the battery to electrodes on the epicardium. Dangers associated with removal of the device lowered the long-term impact of its development [2].

After these early advances in electrotherapy, problems associated with batteries, fluid leaks, and the inability of the electrode to withstand the mechanical stress of repeated bending halted widespread commercialization. These problems were focused on in the 1960s and 1970s by continued research into the technology, leading to the advancement of sensory pacemakers which stimulate the heart when needed. Other advances include the ability to implant the device without the use of general anesthetic, the transition from mercury oxide-zinc batteries to lithium-iodine, and the ability to install pacemakers with passive or active fixation [2]. The use of passive or active fixation is dependent on the condition of the heart during bypass surgery. Passive fixation involves the placement of leads in the right atrial appendage, but as the right atrial appendage is often amputated during surgery, the surgeon may choose dual chamber or permanent pacing with the active fixation of the leads.

An important development in the 1970s was the ability to non-invasively program the electronic pacing device. This allowed doctors to adapt the function of the pacemaker to the changing physical needs of the patient. Another important improvement in this decade was the ability of pacemakers to sense activity and correctly coordinate the pace of the atria and ventricles, thereby preserving the heart through years of use [2].

The 1980s continued to improve on existing technology by the use of steroid-eluting leads to reduce the impact of the foreign body on the heart, doing so by decreasing inflammation from contact. Body motion detectors in the pacemaker were developed to allow the pacemaker to respond appropriately to the needs of the heart. This concept was advanced in the 1990s with the availability of microprocessors, creating a complex system of algorithms which could constantly modify the activity of electric impulses to the heart [2].

Modern advances in the longevity of the leads and in the field of rechargeable batteries brought reliability and more widespread appeal to the pacemaker industry as the primary focus shifted from the prevention of death to the improvement of the quality of life for patients.

Modern Advances in Pacemakers

Modern pacemakers are very sophisticated and advanced. The new technology that is being researched today is femtosecond laser pacemakers. These pacemakers operate by focusing near-infrared femtosecond laser irradiation on cardiomyocytes (cardiac muscle cells). This laser irradiation allows the cells to contract, thus a pulse is maintained. The laser technology is unique from other methods of pace making in the fact that it can apply a stimulus that synchronizes contractions of cardiomyocytes through significant depths of heart muscle tissue. This technology has been tested on rat cardiomyocytes and shows a pace making effect. Contractions of the cells were best when an 80 fs, 82 MHz pulse is applied with a wavelength of 780 nm. Periodic contractions were tested with 8 ms exposures at a frequency of 1 to 2 Hz. However, there is a small range in laser power or exposure that will allow the contractions to occur. This range has been determined to be 15 to 30 mW of laser power. Below 15 mW the cells will not contract because calcium levels are too low. If too much power is applied, the cardiomyocytes build up a large concentration of calcium within the cells. High levels of calcium will prevent the cardiomyocytes from relaxing after contraction. The figure below illustrates the contraction of a single cardiomyocyte at different times during laser exposure [4].

As seen in highlighted cells from Figure 2, the laser irradiation causes the

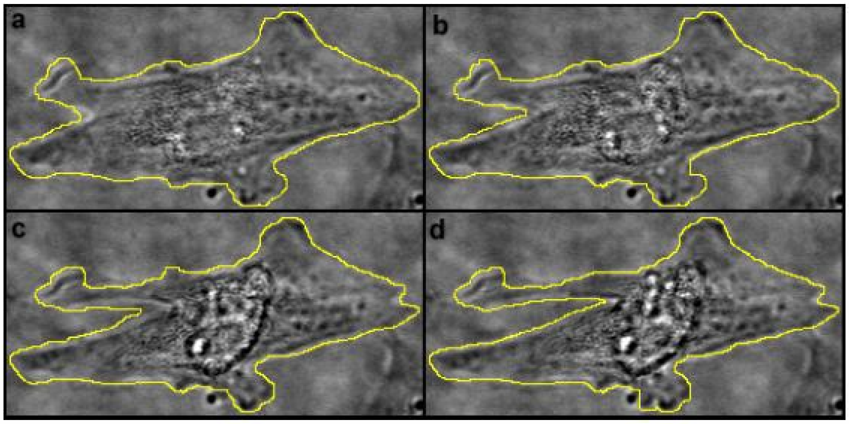


Figure 2. Effect of Femtosecond Laser Pacemaker on Cardiomyocyte Cells from Rats[4]

cardiomyocyte to contract and remain in a contracted state. The top left picture (a) is after 1 second, (b) is after 8 seconds, (c) is after 14.7 seconds, and (d) after 16.7 seconds. The laser used was running at 30 mW of average power, and 8 ms exposures happened at 1 Hz intervals [4]. Long-term exposure of femtosecond lasers can damage the heart so there is no clinical application presently being used. However, femtosecond pace-making will help in the study of heart fibrillations on the molecular level. This research could enable the invention of antifibrillation pharmaceuticals [4].

Scientific Principle

Pacemakers consist of a small Pulse Generator, the Device Controller-Monitor (DCM), leads, and a cardiac “donut” magnet.

- The Pulse Generator is commonly powered by a lithium battery. This generator is about the size of a half dollar and is implanted subcutaneously beneath the clavicle. The lithium batteries used today last up to 12 years and the total weight of the pacemaker is about 30 grams.
- The Device Controller-Monitor allows the doctor to manipulate the device parameters or operating state, as well as provide information such as the lead impedance and battery status. Physicians are capable of changing pulse width, pulse amplitude, or even the sensitivity of the pacemaker through the DCM [5].

- Two to three electrical wires, or leads, run from the generator to the heart through the subclavian vein. The leads are connected to the right atrium and ventricle as shown in the figure below. This is where a bundle of cells receives an electrical signal from the nervous system to contract the heart chambers in a coordinated fashion. The leads are used to monitor the natural rhythm of the heart and will transmit an electric pulse from the battery if the pacemaker finds the heart's electrical signals become deficient [6].

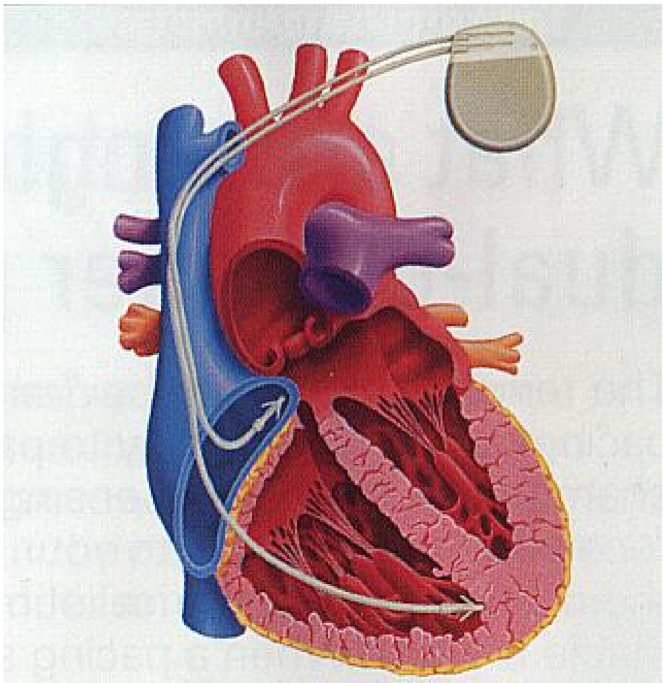


Figure 3. Location of leads for implanted cardiac pacemakers [7]

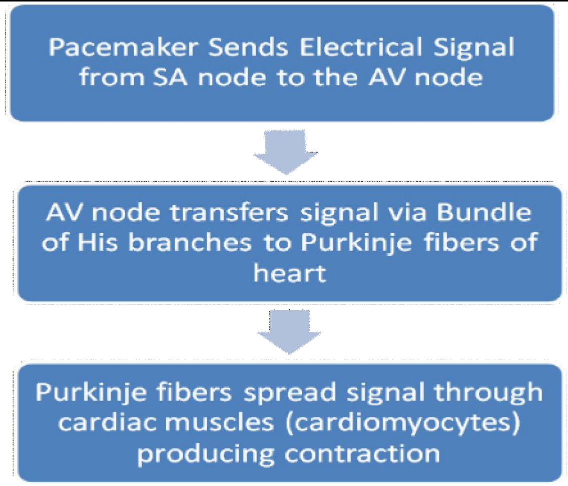
The use of passive or active fixation, concerning the placement of leads in the patient, is dependent on the condition of the heart during bypass surgery as discussed before.

- The magnet is a minor component of the device, used to monitor the remaining battery life as well as other functions [5].

There are two different types of pacemakers: demand pacing and rate-responsive pacing. Demand pacing is used to send an electric shock to the heart only when the heart rate drops below a set minimum to maintain a certain heart rate depending on the patient's needs. The heart rate and pacing is determined by either an activity sensor or breathing sensor. The activity sensor monitors body movement and the breathing sensor monitors respiration. The more body movement and breathing, the faster the heart should beat. This type of pacemaker is often used with patients having high heart rates, also called tachyarrhythmia. Cardiologists determine the appropriate pacemaker for the patient [6].

The function of the pacemaker acts to mimic the natural action of electrical currents in the heart. The pacemaker acts as an artificial Sinoatrial (SA) node, where the electric signal for contraction normally originates. After the action potential is generated at the SA node, the current travels to the Atrioventricular (AV) node, through the Bundle of His' left and right branches, and to the Purkinje fibers connected with the cardiac cells found in the walls of the heart's ventricles [7].

Figure 4. Overview of Action by Pacemaker on Heart Muscle:



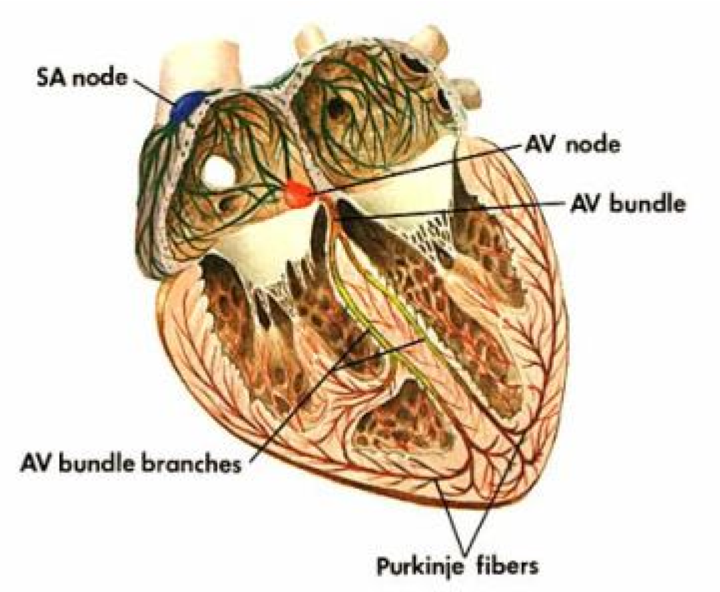


Figure 5. Overview of Heart Muscle Cells [9]

Comparable to nerve cells, cardiac cells produce an action potential during the normal beating of the heart. Initial depolarization is caused by a permeability increase in sodium ions and decrease in potassium ions. A slight hyper-polarization causes the membrane potential to approach zero as incoming calcium ions are equated by outgoing potassium ions. The calcium ion permeability then decreases as the outgoing potassium permeability remains the same, causing hyper-polarization back to the original position [8]. The Purkinje fibers of the heart, initiated by the action of a pacemaker, are used to spread the action potential from the AV node to the cardiomyocytes, whose action potential controls the contraction of the heart muscle [9].

Conclusion

The pacemaker is one of the most well known and commonly implanted medical devices worldwide. Heart disease is the leading cause of death in United

States, killing more than 850,000 people in 2005. Incorporating the knowledge and skills of several notable physicists, electrical engineers, and physicians, the pacemaker embodies an important connection between medical science and everyday life. Its most significant modern advances are seen in its ability to be non-invasively modified by physicians, by the inclusion of algorithms to control the responsiveness of the device, and in the steroid-eluting leads which reduce physiological responses of the patient. Once the major holdback to the commercial success of the pacemaker, the required battery with adequate longevity to sustain a patient without frequent modification or replacement was eventually advanced to an appropriate level for the average remaining lifetime of patients in need. Today, a pacemaker implant is considered a relatively minor surgery which can be carried out in little more than an hour. The quality of life for the hundreds of thousands of patients suffering from a variety of heart conditions is drastically improved by pacemakers, making the pacemaker among the most significant medical devices of the 20th century [10].

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Work for this project is expanded from a project done over mathematical modeling of cardiac fiber action due to pace makers using matlab in BENG 4203 taught by Dr. Kavdia of the Biological Engineering department.