Pacing the Heart: The Evolution of the Pacemaker

Longpeng Jiao

WRIT 340: 66806

Instructor: Marc Aubertin

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Introduction

Is the sound “lub-Dub, lub-Dub, lub-Dub” familiar to you? Sure it is, for that’s the natural sound of our very own hearts’ valves opening and closing as they pump blood through our bodies to keep us supplied with vital oxygen. Our bodies contain about 5.6 Liters of blood, which are pumped at an average of 72 beats per minute. During an average lifetime, the human heart will beat more than 2.5 billion times to pump about 1 million barrels of blood! Remarkably though, each individual pump is precisely synchronized and timed to keep the flow of blood as smooth as possible. Heart rhythm regulation is in fact quite an amazing and complex feat that is accomplished by the heart’s natural “pacemaker” capabilities. Unfortunately, abnormalities sometimes ensue in the heart’s natural pacemaker and lead to a condition known as “Cardiac Arrhythmia,” in which the heart’s blood pumping rhythm becomes erratic. Arrhythmias can have effects that are quite detrimental to health, including blackouts, heart attacks, strokes and even death. Nevertheless, these aberrations can be treated and lives saved by Artificial Pacemakers (AP), which are born out of an intricate combination between the knowledge of cardiovascular physiology and engineering ingenuity. Nowadays, APs are ubiquitous and provide therapy which improves the quality of life of hundreds of thousands of patients suffering from Cardiac Arrhythmia, with more than 900,000 pacemaker implants taking place every year. [6]

Basic Physiology of the Heart and the Pathology of Cardiac Arrhythmia

The heart is composed of four chambers which make up two pumps, a left one and a right one. Each is composed of an ‘atrium’ and a ‘ventricle’, which act as the collection chamber and the pumping chamber of each pump respectively. The left atrium collects blood that is oxygen depleted from the rest of the body and passes it to the left ventricle, which in turn pumps that blood to the lungs where the blood gets replenished with oxygen. Once blood gets oxygenated again in the lungs, it comes back to the heart into the left atrium. From there, it is passed to the left ventricle, where it finally gets pumped to the rest of the body. Refer to Fig. 1 below to see where the atria and ventricles are located within the heart.
In a healthy heart, the contraction timing of the loading (atria) and pumping (ventricles) chambers mentioned above fall into precise coordination regulated by electrical signals that are intrinsically generated by the “pacemaker” region of the heart, the sinoatrial (SA) node. Located in the right atrium, the SA node has the ability to generate electrical discharges. The electrical impulse created is first transferred to the atria and causes them to contract and push blood into the ventricles. The electrical signal then propagates to the atroventricular (AV) node, located between the atria and the ventricles to help regulate the conduction of electrical activity to the ventricles. The AV node introduces an effective delay in the impulse propagation and allows the contraction of the atria to complete before ventricle contraction starts. This is probably the most important aspect of heart contraction regulation since it is due to this delay that an optimal ventricular filling is achieved prior to ventricular contraction. Electrical signals are conducted from the AV node through the Purkinje fibers into the ventricles and cause them to contract. [9] Refer to Fig. 1 to see how the electrical system of the heart is mapped out.

In the case of arrhythmia however, natural ventricular and atrial contractions become irregular and unsynchronized. Generally, instead of electrical discharges being regularly generated solely by the SA node, rapid and irregular discharges come from other areas of the atria. And because these other

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1 Refer to [http://www.medmovie.com/mmdatabase/MediaPlayer.aspx?ClientID=65&TopicID=768](http://www.medmovie.com/mmdatabase/MediaPlayer.aspx?ClientID=65&TopicID=768) for more information about the normal pumping of the heart and a short animation of the pumping of a healthy heart [3]
discharges often take place so irregularly, the SA node’s more regular rate is suppressed. Moreover, it is also possible for the SA node or AV node to malfunction themselves, which can lead to either faster or lower heart rates than normal, referred to in general as tachyarrhythmia, or bradyarrhythmia respectively. What follows from these aberrations is an improper filling and ejection of blood, which causes an overall inefficiency in the heart’s pumping process\(^2\) [1]. This is where artificial pacemakers are needed – to restore the normal pumping rhythm of the heart.

Cardiac pacing technology has evolved exponentially since its humble beginnings in the late 1920’s and has culminated in the complexity and reliability of modern pacemakers, mainly due to the developments in integrated circuits technology and design. Nonetheless, despite the myriad advancements in pacemaker technology, in essence, pacemakers remain devices that deliver a controlled, rhythmic electric stimulus to the heart muscle in order to maintain an effective cardiac rhythm for long periods of time to ensure proper pumping of the heart. [5] In the simplest functionality terms, a pacemaker comprises of three basic components: an electrical pulse generator, a power source (battery), and an electrode (lead) system. Most simple modern pacemakers can be easily implanted under local anesthesia\(^3\). What follows is a historic overview of this important technology and traces the technological milestones that saw a, non-implantable, hand-wound and bulky “cardiac assist” machine, progressively turn into the reliable modern pacemaker that has saved and improved the life of thousands of patients suffering from cardiac arrhythmias.

**Beginnings of Cardiac Pacing and early pacemakers**

Most probably, the earliest attempts at cardiac pacing date back to animal experiments conducted by Marmorstein in the former Soviet Union on intact dogs in 1927. These inspired the first case of human clinical pacing which was conducted by Australian anesthesiologist, Mark C. Lidwell in 1929, who was able to revive a stillborn infant by pacing its heart for 10 minutes with an electro-stimulation device. [7]

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\(^3\) Refer to [http://www.youtube.com/watch?v=a5HI2-AVOJs&feature=results_main&playnext=1&list=PL1B3213F91CFDB3E3](http://www.youtube.com/watch?v=a5HI2-AVOJs&feature=results_main&playnext=1&list=PL1B3213F91CFDB3E3) for a quick animation on the surgery of the general pacemaker implantation [8]
The clinical benefits from these pioneering events inspired further attempts at designing a self-contained pacemaker system that could be clinically used to treat humans. Albert S. Hyman, American cardiologist, designed the first experimental heart pacemaker in 1932. [5] As it can be seen in Fig. 2 below, the bulky machine was a hand-wound, spring-driven generator, which reportedly provided six minutes of pacemaking without rewinding. Hyman was only able to perform ventricular stimulation with his device and claimed that his device restored the heartbeat of a number of animals in animal experiments. Needless to say, this first pacemaker is far removed from the implantable and programmable pacemakers that we know of today, but it served as a proof of concept of the artificial pacemaker that would inspire further developments.

Fig. 2 Hyman Pacemaker [7]

It wasn’t until 1959 that the first fully implantable pacemaker appeared, designed by engineer Wilson Greatbatch and cardiologist W.M. Chardack. [7] The device was targeted to treat patients with complete AV block, in which the conduction of electrical signals between the atria and the ventricles is blocked. It did so by delivering electrical impulses to the myocardial wall of the right ventricle through an electrode trace. Since this method only stimulates a single ventricle, it became known as single-chamber ventricular pacing. The device itself measured 6cm in diameter and 1.5cm thick with a total weight of
180g. It delivered a 1 millisecond wide current pulse to the electrodes at a repetition rate of 60 beats per minute. [5] The then popular mercury-zinc battery cell gave a continuous estimated operation life of only five years. The first patient to receive this pacemaker was a 77 years old man who had recurring syncope, or blackout episodes due to complete AV block. [7] The man actually lived for two more years after the implantation surgery and died of natural causes, proving to be the first patient whose AV block was successfully corrected, on a long term basis by an implanted pacemaker carrying its own power supply.

Despite this early success, the main inherent problem of the first fully implantable pacemaker was that it could only deliver a fixed-rate pulse to the ventricle at a preset frequency, regardless of any spontaneous activity of the heart. These became known as asynchronous pacemakers and where found to compete with the natural heart activity and sometimes even introduced further undesired arrhythmias or ventricular fibrillation. [6]

**Introduction of Demand Pacemakers**

Given the problems associated with asynchronous pacemakers, a proposed solution appeared in the form of demand pacemakers. By adding a sensing amplifier to the asynchronous pacemaker in order to detect intrinsic heart activity, and consequently avoid competition between pacemaker and natural heart activity, one obtains a demand pacemaker. As the name suggests, these are characterized by their ability to provide electrical heart-stimulation only in the absence of natural heartbeats. This breakthrough was introduced by American electrical engineer, Barough V. Berkovits, in mid-1964 and forms the basis all modern pacemakers. [5] Similar to earlier asynchronous devices, pacing is achieved by the delivery of short, intense electrical pulses to the myocardial wall where the distal end of the electrode is attached. However, that same electrode is now also used to detect the intrinsic activity of the heart, i.e. the contraction rate of the ventricle to which the electrodes is attached to. The general components of a demand pacemaker consists of a sense amplifier circuit for measuring intrinsic ventricle contraction rhythm, a timing control circuit to synchronize and time the stimulation based on the sensed electrical
activity of the heart, and an electrical pulse circuit to create the form of the stimulation. Figure 3 below shows the basic block diagram for a demand pacemaker. As it can be seen, the sense amplifier feeds data into the timing control, which in turn controls the timing of the output stimuli. The demand pacemaker model didn’t only provide more logical stimulation based on need, but the battery life of the system was prolonged because impulse generation was only activated when pacing stimuli are needed. Nonetheless, it remained a single chamber pacemaker that could only stimulate the right ventricle and several different manifestations of cardiac arrhythmia demand regulation of both atria and ventricles. Hence, just as with the previous asynchronous pacemakers, its use was still limited for treating only AV block type of arrhythmias for which ventricular contraction regulation proved enough as treatment.

Fig. 3 Basic demand pacemaker functional block diagram [5]

**Dual Chamber Pacemakers**

Dual-chamber pacemakers were first introduced in the 1970s, again, by Berkovits. [7] Obviously, the dual-chamber pacemaker requires two pacing leads: one placed in the right atrium and the other placed in the right ventricle. In accordance with the principles of the single chamber demand pacemaker, a dual-chamber pacemaker monitors electrical activity in the atrium and/or ventricle by sense amplifiers to see if pacing is needed. When it is, the pacing pulses of the atrium are timed by timing control circuits.
so that the heart’s natural way of pumping is mimicked. This mimicking implies that whenever pacing is needed, the atrial-stimulating impulse is generated first, and after a predetermined time interval, 200 milliseconds or so, the ventricular-stimulating impulse is generated. By doing so, pacemakers were able to synchronize ventricular stimuli to atrial activation, vital to normal heart contraction control. These more sophisticated dual-chamber pacemakers were developed, with their first use in late 1977. The introduction of these pacemakers broadened the spectrum of the different classes of Cardiac Arrhythmia that pacemakers could treat, not just AV block type conditions as prior single chamber pacemakers did. Mainly, pacemaker treatment could now be extended to patients suffering from sick sinus-node syndrome type conditions, in which the SA node malfunctions and monitoring and contraction regulation of the atria are needed for proper treatment.

Modern Pacemakers

Finally, after decades of adapting and improving pacemaker technology to deliver the most efficient method of heart regulation, and propelled by the technological boom that was the advent of integrated circuits, we arrive at the modern pacemaker. Modern pacemakers are characterized by their small dimensions close to the size of two silver dollar coins stacked together and incorporate reliable yet complex electronic circuitry capable of multi-programmability, and a hermetically sealed long lasting lithium-iodine battery. [5] Below is the figure of a basic dual-chamber modern implantable pacemaker (Symbios 7006, Medtronic, Inc.) shown with lead system, pulse generator and power source.

![Modern dual-chamber pacemaker](image)

**Fig. 4 Modern dual-chamber pacemaker [6]**

- Titanium alloy casing enclosing a pulse generator and lithium-ion battery
- Lead system (contact electrodes)
However, even though on demand pacing is considered the most efficient method of pacemaker pacing, its concept was improved even further with the introduction of complex rate-responsive pacemakers in the late 1980’s. These are characterized by their ability to regulate their pacing based on the output of a sensor system incorporated in the lead system of the pacemaker. The sensor system measures relevant parameters from the body, including respiration rate, pH, and blood pressure, amongst other parameters. [7] This development took place mainly for treating patients with sick sinus syndrome and exhibit chronotropic incompetence, which is the inability to increase heart rate to appropriate levels that satisfy body needs. An example of this deficit is not being able to reach appropriate heart rates of >100bmp during exercise. [4] To provide treatment to these conditions, modern rate-responsive pacemakers are capable of adapting to a wide range of sensor information relating to the physiological needs and/or the physical activity of the patient.

Furthermore, practically all modern pacemakers come with microprocessors and memory which allow for multi-programmability capabilities. These in turn allow the physician to adjust the pacing mode to the one best suited for the particular condition of the patient. With this feature, pacemakers are now able to treat a complete range of different arrhythmias⁴. The most important benefit of multi-programmability of modern pacemakers is that pacing parameters can be adjusted noninvasively as the patient’s pacing needs change. The fine tuning provided by multi-programmability represents an improvement in quality rather than the quantity of life. [6] Indeed, modern pacemakers don’t only have the ability to sustain life in the presence of arrhythmia, but it also provides overall comfort and well being to cardiac arrhythmia patients. Moreover, the inclusion of built-in memory in pacemakers allowed for the technologic development of telemetric systems, which is the noninvasive transmission of data from implanted pacemaker to an external receiver, placed for instance, in the physician’s office. Though

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⁴ It is important to note here that although pacemakers can be used to treat either bradyarrhythmia or tachyarrhythmia, treatment for the latter is more efficacious with cardiac defibrillators, which is another type of cardiac pacing technology. [4]
sometimes considered a luxury, it becomes a necessity with the increasing complexity of programmable pacemakers and offers major advantages to patient management. [6] Figure 5 below shows the basic block diagram of the modern pacemaker. As it can be seen from the diagram, the programmable control algorithm along, with data from the sensors feed into the logic and control section which in turn determine the overall pacing mode, which is delivered by the demand pulse generator, mentioned above.

Fig. 5 Basic block diagram of modern pacemaker [5]

The number of different pacemakers and pacing modes that were available for treatment became so complex that specialized symbols to describe pacemaker function were needed. The first effort of pacemaker categorization was the pacing mode-code proposed in 1974 by the Inter-Society Commission of Heart Disease Resources and was extremely useful for a period of time. However, as new features such as multi-programmability, telemetry, anti-tachycardia functions and sensor-driven rate variability became more prevalent, the original code needed to be revised. Currently, the pacemaker code in most common use was introduced in 1987 by the Mode Code Committee of North American Society of Pacing and Cardiac Electrophysiology (NASPE) together with the British Pacing and Electrophysiology (BPEG). [6] This last version of the code includes not only the different pacing modes available, but also the degree of programmability, anti-tachyarrhythmia functions and telemetry capabilities. Indeed, it is appreciable from
this code the complexity that pacemakers have attained and yet, this extremely powerful technology can all be packaged into the size of two silver coins stacked together.

Conclusion

Since the introduction of the first implantable pacemaker in 1932, cardiac pacing technology has changed dramatically. Around 40% of all human deaths are attributed to cardiovascular diseases, which has made the development of efficient and reliable cardiac pacing technology a must in our society. The evolution of the pacemaker went from single chamber pacemakers that could only pace ventricles asynchronously all the way to the multi-modal, fully programmable dual chambered pacemakers that can act on demand and can register and send heart rhythm information to physicians elsewhere. Moreover, pacemakers have become smaller and lighter over the years. Early devices could weigh as much as 180g, whereas today, pacemakers weigh no more than 25g and last four times as long. Indeed, the implantable pacemaker is one of modern medicine’s greatest contributions to prolonging and improving human life. Whether or not the technological plateau of pacemaker technology has been reached remains to be seen, but certainly, fine tuning of existing implantable devices will in no doubt continue to ascertain our prowess over disease.
References

<http://www.heart.org/HEARTORG/>.


<http://www.hrsonline.org/>.
