What is a Pacemaker?

The Cardiac Conduction System and the Artificial Pacemaker

Michael Kehinde
kehindem@mcmaster.ca

May 5, 2021

Contents

Abbreviations

1 Introduction

The aim of this document is to give sufficient background and information about the heart and cardiac pacemakers to begin exploring pacemaker concepts and cardiac terminology. For more in-depth information, a standard pacemaker textbook, such as the one listed in the References section, may be consulted.

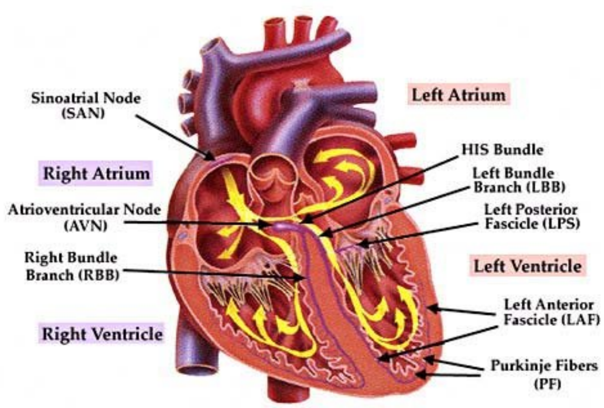
2 The Cardiac Conduction System (CCS)

The heart is a muscular organ that pumps blood throughout the body. The heart has four chambers. The two upper chambers are the left atrium and the right atrium (plural: atria). The two lower chambers are the left ventricle and the right ventricle.

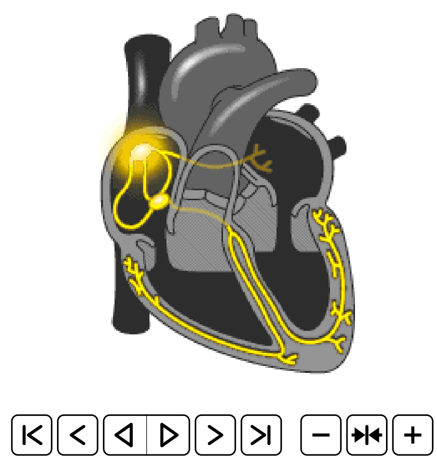
Both the atria and ventricles receive blood while relaxed. The atria contract to move blood to the ventricles. The left atrium receives oxygen-rich blood from the lungs, whereas the right atrium receives oxygen-depleted blood from the rest of the body. The left ventricle contracts to pump oxygen-rich blood throughout the body. The right ventricle contracts to pump oxygen-depleted blood to the lungs for oxygenation.

The Electrical Behaviour of the Heart

The bioelectrical network that makes your heart beat is known as the CCS. The CCS generates and conducts electric stimuli to coordinate the activation and contraction of the atria and ventricles, as is shown in Figure 1b below.



(a) Anatomy of the heart and schematic of the CCS. [IPM06]



(b) Animation — the CCS activating the mechanical function of the heart. `http://www.vascularconcepts.com/img/patients/conductionsystem.gif`

Figure 1: Illustrations of the CCS.

The sequence of events that occurs during a single heart beat is known as the **cardiac cycle**. To begin a cardiac cycle, the Sinoatrial (SA) node generates an electric stimuli that is transmitted quickly to the atria, causing the atria to contract. The signal then propagates through the Atrio-ventricular (AV) node and bundle of His. The AV node is a tissue that delays and relays the cardiac impulse to the ventricles via the Purkinje fibres. The delay typically lasts between 120-200 milliseconds. The signal spreads quickly through all the ventricular muscle via gap junctions (cell-to-cell connections) causing ventricular contraction. The muscle cells then depolarize in the opposite direction from polarization and the chambers relax to receive blood. During most of the time period that the chamber undergoes depolarization, its muscle cells cannot produce another action potential. This is known as a **refractory period**.

Nodal cells and Purkinje cells have three characteristics that allow the atria and ventricles to be synchronized: [Nek16]

1. *Automaticity*: the ability to initiate an electric impulse
2. *Excitability*: the ability to respond to an electric impulse
3. *Conductivity*: the ability to transmit an electric impulse from one cell to another

Electrocardiogram (ECG) An ECG is a graphical description of the electrical activity of the heart. Electrical activity in the heart can be depicted with the use of **surface electrodes** — conductive pads that are placed on the surface of the skin across the limbs or over the chest to enable recording of electrical currents.

An ECG lead represents the potential difference measured across two electrodes placed on different points of the body. In a 12-lead ECG system, there are three categories of leads: 3 bipolar limb leads, 3 augmented unipolar leads and 6 chest leads. Each lead allows physicians to view the heart from different angles and provides information about various parts of the heart. A plot of voltage over time may be constructed for one or more leads and assessed by the physician. The most commonly used lead is called Lead II and electrodes are placed on the left arm and left leg.

Figure 2 below illustrates an ECG waveform.

The resultant waveform is a summation of various action potentials across the heart. The letters PQRST are used to indicate the waves on the ECG recording or tracing. They are used as references when assessing a patient's ECG.

The P wave represents atrial depolarization and contraction of atria. The PR segment represents the AV nodal delay. The QRS complex represents ventricular depolarization and contraction. The T wave represents ventricular repolarization. The TP interval represents the time in which the ventricles are relaxed and filling.

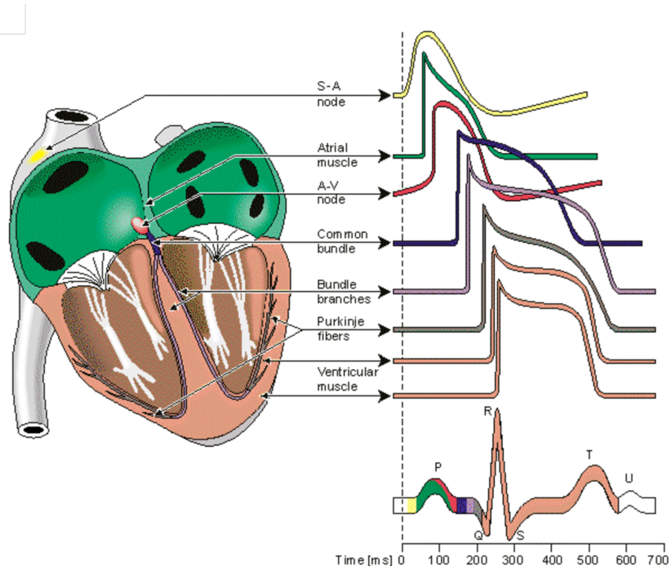


Figure 2: ECG Waveform.[Vah09]

Link between the CCS and Mechanical Events of the Cardiac Cycle

Cardiac electric events are linked with changes in mechanical properties of the heart. Wiggers diagram illustrates the pressure and volume changes in the ventricles over a cardiac cycle. The changes are presented with an ECG and a phonocardiogram, as shown in Figure 3 below.

Ventricular systole is when the ventricles contract and pump blood. Ventricular diastole is a phase of the cardiac cycle wherein the ventricles relax and the heart fills with blood. Ventricular pressure is high during systole and low during diastole.

Heart valves are cusp-like structures that control the direction of the blood flow by preventing backflow. Between the atria and ventricle chambers are the atrioventricular valves — the miltral valve and the tricuspid valve. Between the ventricles and the aorta and pulmonary artery are the aortic and pulmonary valves, respectively. The valves open or close based on the pressure differentials across the chambers.

A phonocardiogram is a graphical representation of the sounds made by the heart. Typically when one listens to the sound of a heartbeat, they are listening to the valves of the heart closing. The oscillations on the phonocardiogram in Figure 3 above represent the characteristic "lub-dub" sound one typically hears when listening to a healthy heartbeat. The first oscillation on the phonocardiogram corresponds to the reverberation of blood from the sudden closure of the miltral valve closing, whereas the second

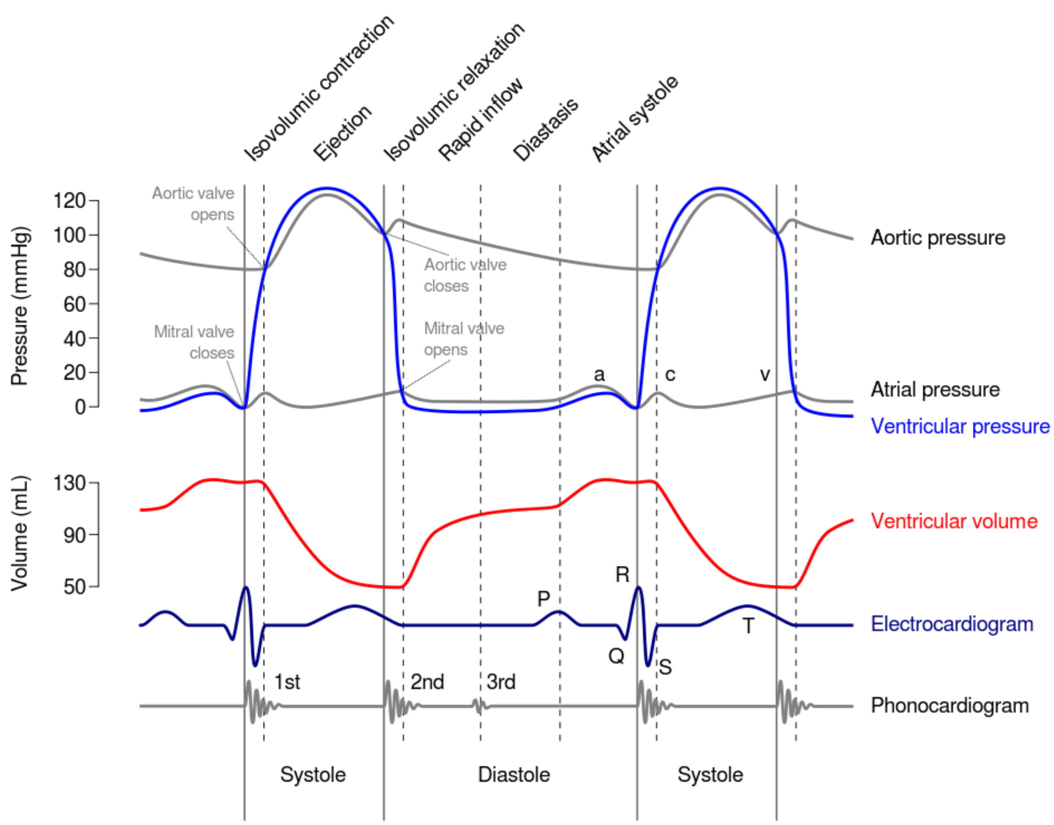
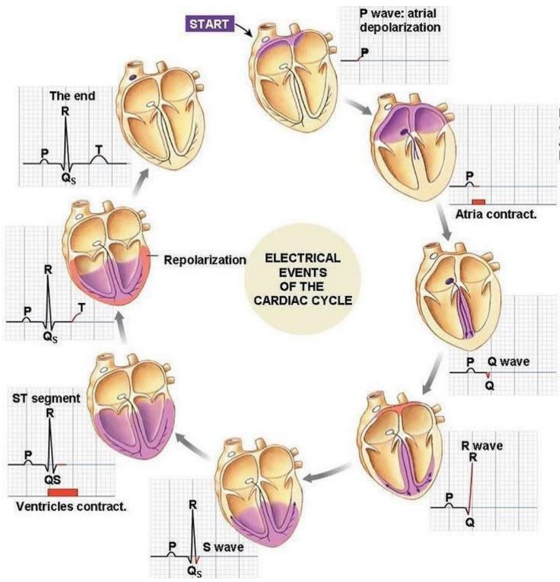
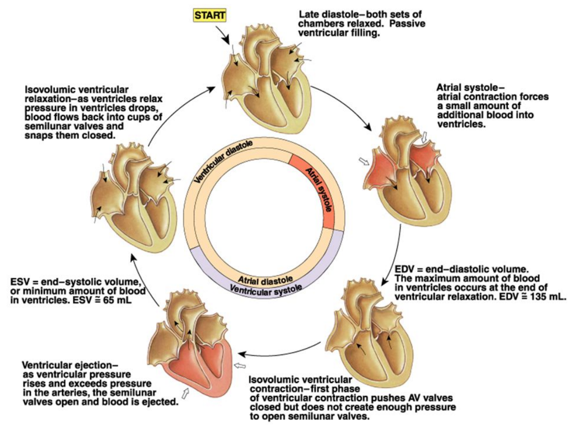


Figure 3: Wiggers diagram.[Dan12]

oscillation corresponds to the reverberation of blood from the sudden closure of aortic valve.



(a) Electrical events of the cardiac cycle. []



(b) Mechanical events of the cardiac cycle. []

Figure 4: Mechanical and electrical events of the cardiac cycle.

3 CCS Conduction Disorders

A conduction disorder is a problem with the CCS that exists when one or both of the following situations occur:

- the CCS signal is not generated properly
- the CCS signal does not travel through the heart properly

Conduction disorders may be attributed to several reasons, including:

- heart disease
- congenital heart defects
- side effects from medications
- damage from cardiac surgery

Conduction disorders are classified based on where they originate and the effect they have on the heart rate (the number of heart beats or contractions in a minute). Classifications of conduction disorders include: atrial fibrillation, atrial flutter, supraventricular tachycardia, Wolff-Parkinson-White syndrome, ventricular tachycardia, ventricular fibrillation, long QT syndrome, sick sinus syndrome, conduction/heart block and premature contractions.[] []

3.1 Origins of a Conduction Disorder

SA Node Malfunction

The SA node is often called the heart's natural pacemaker because it generates the signal that begins a cardiac cycle and establishes the heart rate. Problems with the CCS arise when the SA node malfunctions, causing the heart to beat too slowly, too quickly or erratically. SA node malfunction can also be a cause of **chronotropic incompetence**, a condition where the heart rate does not change sufficiently to meet the metabolic demands of the body during exercise.

Abnormal Firing of Heart Chambers

The cells in the heart's atria or ventricles may fire abnormally and interfere with the signal coming from the SA node (fibrillation and flutter). The atria and ventricles contract out of coordination with each other and the heart rate increases.

Conduction Defects

Conduction defects occur when there is a malfunction in the electrical pathways. In some cases, muscle fibre blockages can impair or prevent the conduction of electric stimuli from the atria to the ventricles — a problem known as AV block or **heart block**. Heart block may be classified as first degree, second degree (Wenckebach) or third degree depending on the level of severity. Heart block typically disturbs the heart rhythm by delaying ventricular contraction.

In some cases, there may be an additional electrical pathway between the atria and ventricles that effectively acts as a short-circuit and causes the CCS signal to travels prematurely or to bounce back towards the chamber that the signal was traveling from (Wolff-Parkinson-White syndrome).

3.2 Types of Arrhythmias

Arrhythmia is a condition wherein the heart beats irregularly or abnormally.

Bradycardia arrhythmia is a condition wherein one has a Resting Heart Rate (RHR) that is abnormally slow. The question of "how slow is abnormally slow?" may differ from individual to individual because the heart's RHR tends to decrease with age and among individuals with higher fitness levels. For most adults, a slow RHR is less than 50 or 60 Beats per Minute (BPM). Symptoms of bradycardia may include fatigue, dizziness, fainting, heart palpitations and breathing problems.

Tachycardia arrhythmia is a condition wherein one has a RHR that is abnormally fast. For most adults, a fast RHR is above 100 BPM.

Arrhythmia becomes a serious problem when heart does not supply the body with enough oxygen-rich blood. In some cases, conduction disorders can be fatal and also lead to heart attack.

3.3 The Role of the Cardiac Pacemaker

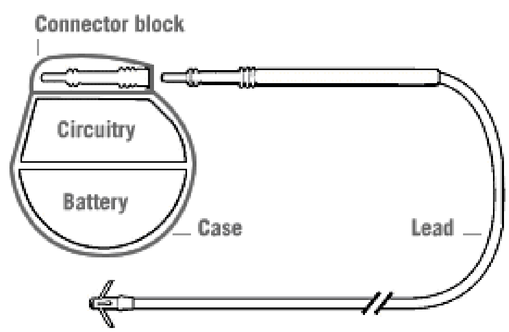
A physician would implant a pacemaker in a patient's body when the cardiac conduction system is not working properly. A cardiac pacemaker (also known as an artificial pacemaker) is a medical device that monitors and regulates a patient's heart rate by stimulating the chambers of the heart synthetically. Most pacemakers are implanted in the body and assist the CCS by sensing the heart's electric signals and generating electrical pulses at specified intervals to precisely determine when the atria and ventricles contract. Pacemakers are often used as a standard treatment for arrhythmia.

4 Parts of the Pacemaker System

A pacemaker system consists of a pacemaker device (which consists of a pulse generator and one or more pacing leads), and a device controller-monitor.

4.1 Pulse Generator

(a) Pacemaker pulse generator. []



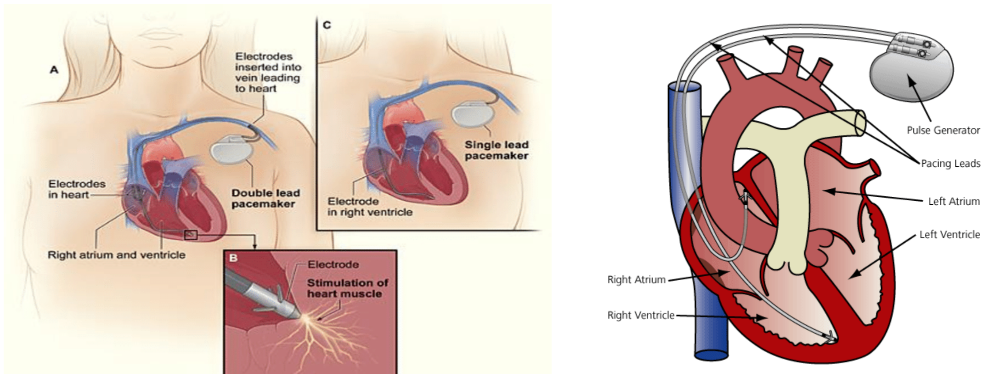
(b) Pacemaker device. []

Figure 5: Pulse generator diagrams.

The pulse generator (also known as the "can") contains the battery of the pacemaker and the circuits that deliver the pacing stimuli. The metal case provides electrical isolation between the internal pacemaker circuit and the CCS. The lead connector block is physical interface for the can and the pacemaker leads. Separate channels are assigned to each heart chamber being paced. Pacemakers usually have a telemetry antenna or magnet built in that allows pacemaker to be re-programmed wirelessly. During a surgical implant, the pulse generator is placed in a pouch underneath the skin below the collarbone.

4.2 Leads

Leads are insulted wires that carry electrical stimuli from the pulse generator to the heart, and carry information about the heart's natural activity back to the pulse generator. They are the first component of the pacemaker system that is implanted in the



(a) Pacemaker placed in body. []

(b) Pacemaker leads. []

Figure 6: Pacemaker leads placement.

body during surgery and are usually inserted through the subclavian vein. The electrodes on the end of the lead are then attached to the heart. The leads may be poked into heart tissue (if the leads are passive fixated leads) or hooked or screwed into heart tissue (if the leads are active fixated leads). Note that the tip electrode on the active fixation lead in Figure 7 is a small screw-like mechanism designed to screw into the heart tissue at the electrode-myocardium interface. Lead connections are typically tested by taking electrical measurements of the heart, before the pulse generator is connected and inserted under the skin.

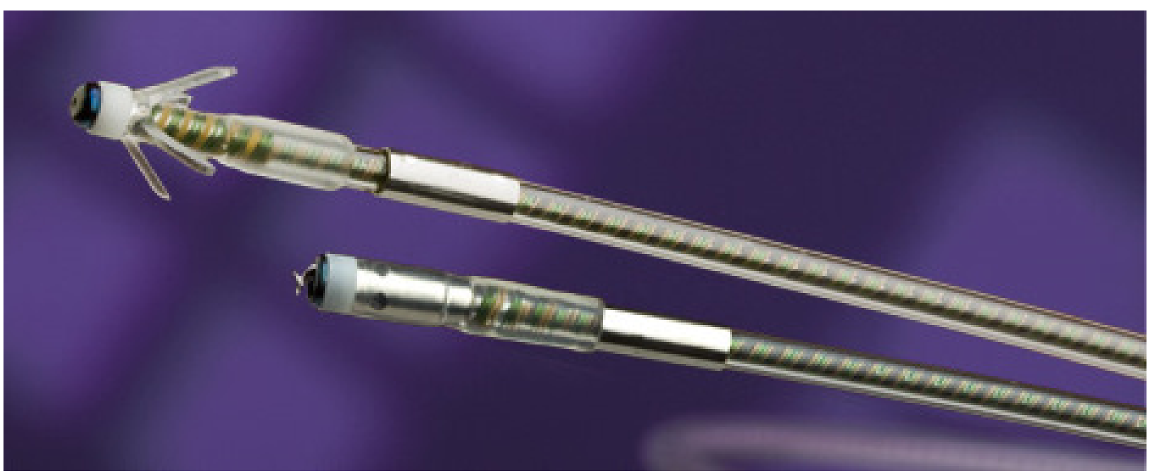


Figure 7: Passive (top) and Active (bottom) Fixation Pacemaker Bipolar Leads.[]

Leads may be bipolar or unipolar. With bipolar leads, the electric stimuli is transmitted across two electrodes: the ring electrode and the tip electrode. Both electrodes are embedded inside the heart. With unipolar leads, one electrode is embedded inside the heart and the other is the pacemaker can.

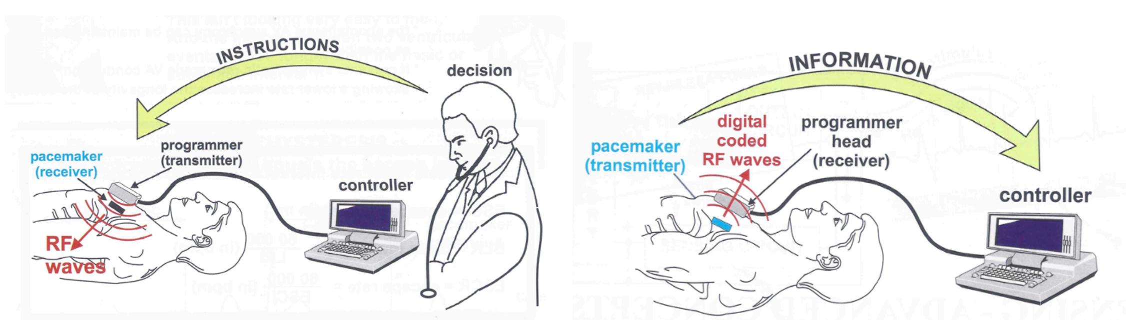
Lead Construction Unipolar leads consist of a single helical conductor coil connecting the lead connector to the tip electrode. Bipolar leads have an additional coaxial outer coil connecting the lead connector to the ring electrode and separated from the inner coil with insulation. [CB08]

Pacemakers can have anywhere between 1-3 leads depending which chamber of the heart requires pacing stimuli, and the degree of synchronization that is required between the chambers. Most pacemakers are dual chambered pacing systems, having one lead connected to the right atria and another connected to the right ventricle.

4.3 Device Controller-Monitor (DCM)

The Device Controller-Monitor (DCM) is a device used by the physician to test, interrogate and alter the behaviour of the pacemaker device. The DCM provides a means of remotely transmitting instructions to the pacemaker (**programming**) and receiving information from the pacemaker (**telemetry**). The DCM is used to configure the pacemaker immediately after the pacemaker implant procedure and every 3-6 months during scheduled follow-up appointments with the patient.

The following figure illustrates the concepts of programmability and telemetry.



(a) Concept of Programmability. [BSS08] (b) Concept of Telemetry. [BSS08]

Figure 8: Concepts of Programmability and Telemetry.

Programmability means the system is capable of accepting a new set of instructions that alter its behaviour. Instructions are sent to the pacemaker to modify any of its programmable parameters, which in turn alter the behavior of the pacemaker. Programmable parameters include, and are not limited to:

- pulse rate (the frequency of the pacing pulse)
- pulse width (the duration of the pacing pulse)
- pulse amplitude (the strength of the pulse)
- sensitivity of the sensing circuit
- mode of pacing
- refractory period
- hysteresis on/off

Telemetry is the process of measuring the readings from the pacemaker remotely. Data obtainable by telemetry include:

- Administrative Data (model, serial number, patient's name, date of implantation, indication for implantation)
- Programmed Data (mode, rate, refractory period, hysteresis on/off, pulse amplitude & width, sensitivity)
- Measured Data (rate, pulse amplitude, pulse current, pulse energy, pulse charge, lead impedance, battery impedance, battery voltage, battery current drain)
- Stored Data (Holter function, rhythm histogram)
- Marker Signals (for ECG interpretation)
- Intracardiac Electrogram (potential difference between the two electrodes used for pacing)

Pacemaker telemetry and programming are both performed without removing the pacemaker, as shown in Figure 8. Physicians try to limit the number of times subsequent surgical operations are required to maintain the pacemaker device. Additional surgical operations may increase the patient's risk of further heart complications or infections. However, sometimes a surgical operation cannot be avoided. It is necessary to extract or replace the leads in the event of complications such as lead fractures, formation of scar tissue at the electrode-myocardium interface expediting battery depletion, onset of infections at the site of the pulse generator or leads, and blockage in the subclavian vein. Lead extraction can be especially challenging when leads become surrounded by fibrous tissue and tethered to the heart and veins. Moreover, when the pacemaker battery is low, a surgical operation is required to replace the pacemaker device. The lithium iodine battery is currently the gold standard for pacemaker batteries due to its long life. However, improving power efficiency and the battery life for pacemakers continues to be an advancing area of research with modern pacemakers.

Revision History

Version	Date	Modification	Modified by
1.0	Sept. 13, 2020	Initial Document Creation	Kehinde, Michael

List of Figures

References

[IPM06] Blagoy Iliev, Gheorghe Pop, and Gerard Meijer. "In-vivo Blood Characterization System". In: May 2006, pp. 1781–1785. DOI: 10.1109/IMTC.2006.328249.

[BSS08] S.S. Barold, R.X. Stroobandt, and A.F. Sinnaeve. *Cardiac Pacemakers Step-by-Step: An Illustrated Guide*. Wiley, 2008. ISBN: 978-1-4051-4065-2. URL: https://books.google.ca/books?id=1CsOHpKsby4C.

[CB08] A.W.C. Chow and A.E. Buxton. *Implantable Cardiac Pacemakers and Defibrillators: All You Wanted to Know*. Wiley, 2008. ISBN: 9780470790427. URL: https://books.google.ca/books?id=jECAnTGBBoUC.

[Vah09] Anwar Vahed. "3-Lead Wireless ECG". In: 2009.

[Nek16] Paula Nekic. *Pacemaker learning package*. 2016. URL: https://www.aci.health.nsw.gov.au/__data/assets/pdf_file/0003/306588/Pacemaker_Learning_Package.pdf.

[] *Conduction Disorders*. [Online; accessed September 7, 2020]. URL: https://www.heart.org/en/health-topics/arrhythmia/about-arrhythmia/conduction-disorders.

[] *Heart arrhythmia*. [Online; accessed September 7, 2020]. URL: https://www.mayoclinic.org/diseases-conditions/heart-arrhythmia/symptoms-causes/syc-20350668.

Images

[Dan12] DanielChangMD revised original work of DestinyQx; Redrawn as SVG by xavax / CC BY-SA (https://creativecommons.org/licenses/by-sa/2.5). *Wiggers Diagram*. [Online; accessed September 6, 2020]. 2012. URL: https://commons.wikimedia.org/wiki/File:Wiggers_Diagram.svg.

[] *Boston Scientific Essentio MRI Pacemaker*. [Online; accessed September 8, 2020]. URL: https://www.bostonscientific.com/content/dam/bostonscientific/Rhythm%5C%20Management/portfolio-group/Pacemakers/ESSENTIO/Essentio-MRI_960x960.png.

[] *Cardiac Cycle Diagram*. [Online; accessed September 7, 2020]. URL: http://3.bp.blogspot.com/-k6Y7KP050mc/TZSLwLmUY2I/AAAAAAAAACg/US6WL80aqWA/s1600/cardiac%5C%2Bcycle%5C%2Bdiagram.JPG.

[] *Electrical Events of the Cardiac Cycle*. [Online; accessed September 7, 2020]. URL: https://i.pinimg.com/originals/e0/02/1b/e0021b%5C%20f51ff8da59cc04e80fd027ef19.jpg.

[] *Pacemaker Leads Placement*. [Online; accessed September 8, 2020]. URL: http://3.bp.blogspot.com/_ZWqgYBROGHw/TR5GMQLw7sI/AAAAAAAACFo/IbDLiixIUNg/s1600/Pacemaker+Leads+Placement.gif.

[] *Pacemaker Placed In Body*. [Online; accessed September 8, 2020]. URL: https://www.researchgate.net/publication/317153404/figure/fig1/AS:761433004466176@1558551183953/Pacemaker-placed-in-body.png.

[] *Photoheader Implantable*. [Online; accessed September 8, 2020]. URL: https://3.bp.blogspot.com/_jQ-v-9IkLys/TUJ3G0_6ihI/AAAAAAAAAWU/JiHFh0EzV-0/s1600/photoheader-implantable.jpg.

[] *Tekening Pacemaker*. [Online; accessed September 8, 2020]. URL: http://www.vitatron.com/images/tekening_pacemaker.gif.