

Electricity and the Heart

Exploring the Electrical Properties of the Heart

Bryce Jones

11/29/2012

This paper will explain how the human heart uses electricity in order to function. In exploring the heart, the anatomy and physiology of the heart will be detailed. The nodes and the Purkinje system that separate charge and create the impulses that make the heart beat will then be described. Following this description, a section on Electrocardiograms will help explain the entire process of creating an impulse in the heart. These descriptions and processes will all be linked to the concepts of electricity-including capacitors and circuits-learned in University Physics 2.

1. Introduction

The heart, one of the most important organs of the human body, uses the electrical concepts of physics in order to operate. To function, the heart uses electricity, but explaining just how this piece of the cardiovascular system works becomes more complicated. This paper will give insight into the conduction system of the heart; therefore, it will cover not only the workings of the heart from a biological standpoint, but also take a physics perspective on how electrical forces cause the heart to beat. By approaching this question from a physicist's point of view, one will be able to appreciate the anatomy of the heart from a new mindset. This paper will first identify the anatomy and physiology of the heart in order to familiarize the reader with the different regions, tissues, and cells that compose the cardiac system. Having introduced the heart from a biological standpoint, the paper will then deal with the major physics question: how does the heart utilize electricity in order to beat? To answer this question, the specific nodes and pathways in the cardiac tissues will be examined, and the process of charge separation will be detailed. The paper will utilize a device called an Electrocardiogram in order to illustrate said process. In the end, the reader will be able to understand the link between the impulses of the heart, conductors, and circuits. Therefore, this paper will address the anatomy of the heart, examine its electric properties, and compare these properties to concepts of physics in order to illustrate how electricity exists in the heart.

2. Anatomy and Physiology

In order to understand the later explanations of how the heart functions, a basic understanding of the anatomy of the heart must be achieved. The following figures show the anatomy of the heart and some key terms.

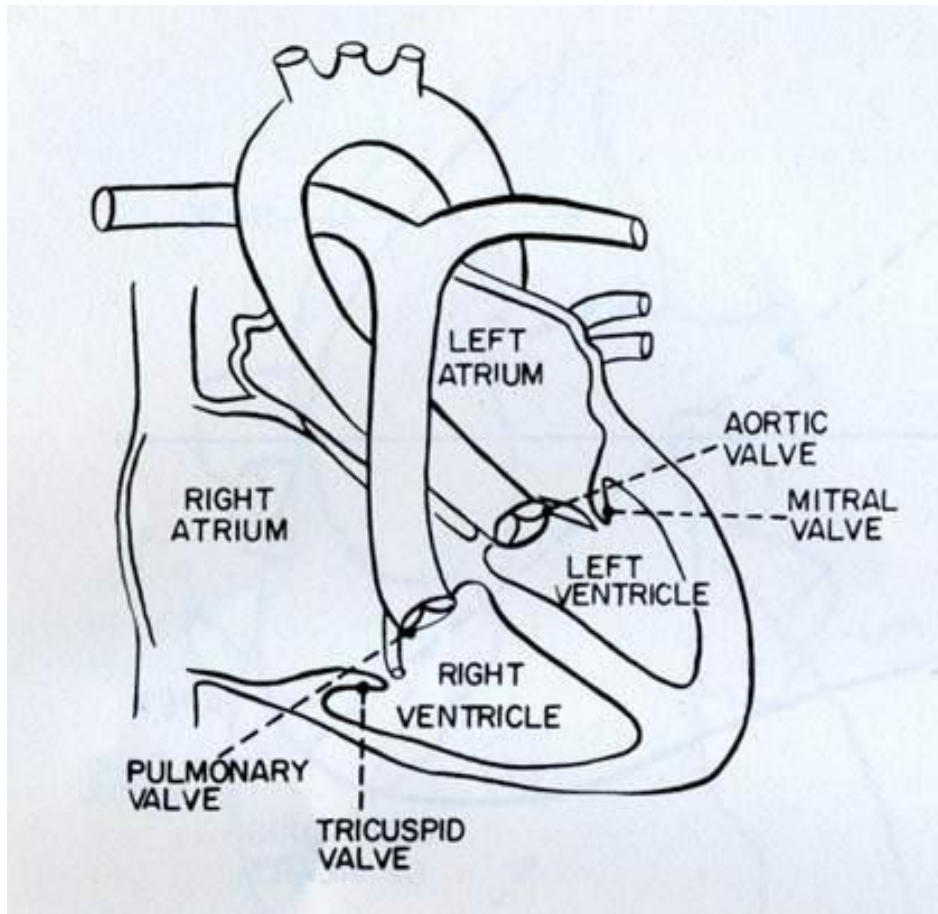


Figure 1 shows the chambers and valves of the hearts (McFarland 1975, 4)

The heart consists of four chambers: an atrium and a ventricle located on both the left and right sides of the heart. The right atrium receives oxygenated blood from the both the superior and inferior vena cava. The blood then flows into the right ventricle, which has a muscle mass three times as thick as that of the right atrium. The right ventricle pumps the blood to the lungs, where it is oxygenated. Oxygenated blood returns from the lungs to the left atrium and from there it flows to the left ventricle, which has a muscle mass three times as much as the right ventricle. The thickness of the ventricles is necessary to pump the blood to the lungs or throughout the body. After passing through the left ventricle, the blood is pumped to the rest of the body (McFarland 1975, 4-6).

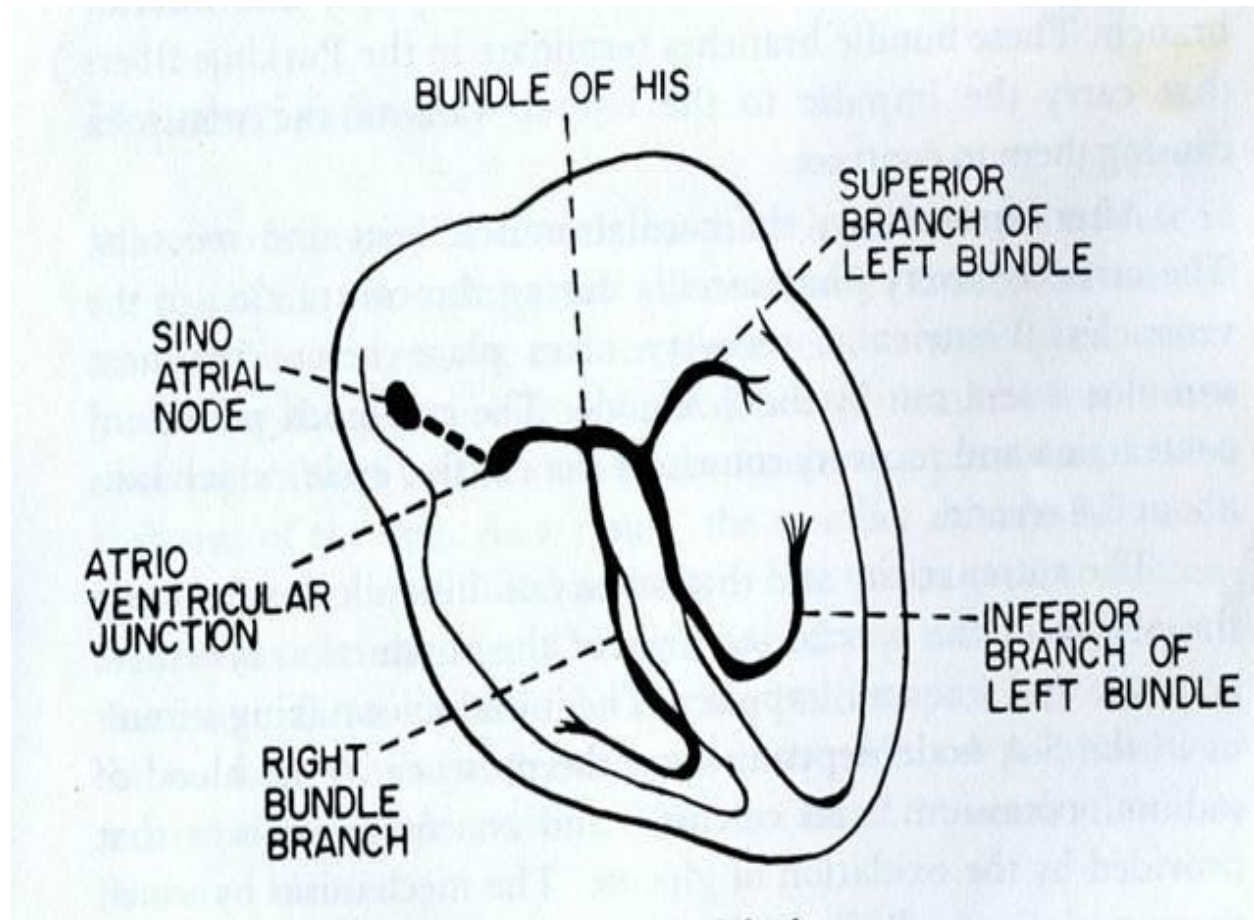


Figure 2 shows the conduction system of the heart (McFarland 1975, 9)

The conducting system of the heart consists of six major parts. The sinoatrial (SA) node is a small structure located in the right atrium near the superior vena cava (See Figure 1). The atrial syncytium is the network of cells that forms the walls of the atria. The atrioventricular (A-V) node is the structure located near the entrance to the right atrium. It is composed of Purkinje fibers; these fibers are scattered throughout the ventricles and are also connected to the Bundle of His. The Bundle of His (the atrioventricular bundle) is a continuation of the A-V node into the interventricular septum—located above the center of the heart which divides into two branches (Phibbs and Ewy 1973, 3).

3. Polarization of the Cells

Now that the basic structure of the heart has been established, the function of the heart can be analyzed. The ability of a cell to transmit electrical impulses lies in the distribution of ions along the inside and outside of that cell—otherwise known as polarization. For heart cells, the most important ions are sodium (Na^+) and potassium (K^+). Both of these ions have a positive charge (Na^+ and K^+). Sodium ions surround the cell membrane, and potassium ions are more present within the cell. Because there are more overall sodium ions outside the cell than number of potassium ions inside the cell, the outside of the cell is positively charged while the inside of the cell is negatively charged (McFarland 1975, 11).

The insulation of each cell membrane is important in maintaining polarization. The membrane has molecular pores that limit the amount of ions travelling into or out of the cell. When the sodium and potassium ions are arranged in such a manner that the outside and inside of the cell are, respectively, positively and negatively charged, the cell is considered to be polarized. The end result is that there exists an electric potential difference between the inside and outside of the cell. The inside of the cell is approximately a tenth of a volt more negative than the outside. This may seem like a small value, but it amounts to roughly ten million volts per meter across the cell membrane, very close to dielectric breakdown (Winfrey 1987, 34-35).

This phenomenon of charge distribution over a surface is comparable to the concept of capacitance. Capacitance between two conductors is defined as the ratio of the charge on one of the conductors to the potential difference between them. For the capacitance of heart cells, the two sides of the cell membrane are considered to be the two conductors. The sodium and

potassium ions that are distributed on the outside and inside of the cell membrane are the “charges” that build up on each side of the capacitor.

The concept behind the depolarization of the heart cells is also comparable to capacitors. When stimulated, a resting (charged) cell increases the size of the pores along the cell membrane. Therefore, the membrane is more permeable, allowing sodium ions to rush into the cell and potassium ions to rush out of the cell. Consequently, the cell becomes depolarized and muscular contraction occurs (McFarland 1975, 11). This depolarization relates to the discharging of capacitors; the opening of the pores correlates to the touching of two oppositely charged capacitors. The end result is the identical: the charged surfaces touch and become uncharged.

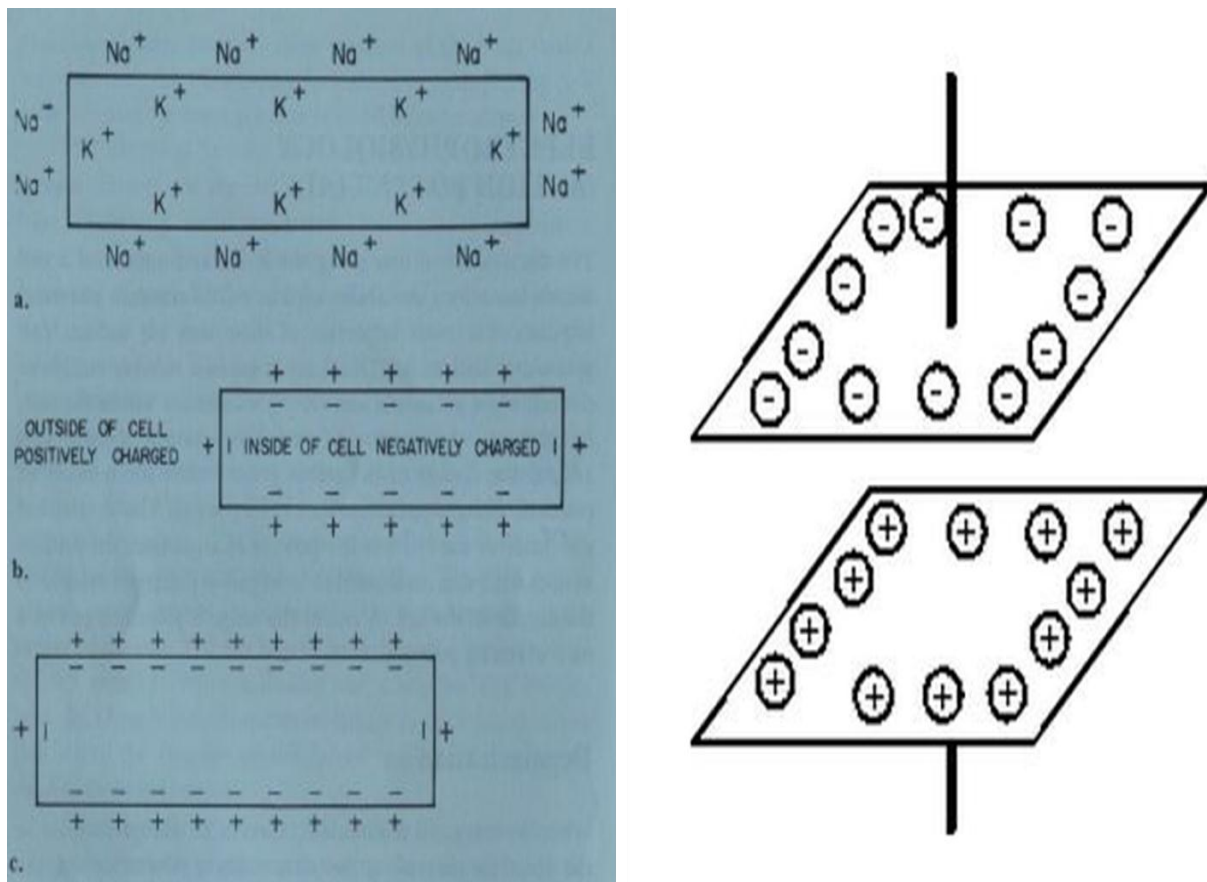


Figure 3: (right) the polarization of heart cells. (left) a typical capacitor (McFarland 1975, 12)

4. Node Functions

The fibers in the SA node are considered to be the pacemaker of the heart for two reasons. The cells in the SA node are capable of self-excitation (the ability to become polarized) because of their high permeability for ions, which means that more sodium and potassium ions are able to move through the cell membrane during depolarization. The cells also contain more sodium and less potassium compared to other cardiac fibers, making them more polarized (the ratio of sodium ions to potassium ions will be greater than other cardiac cells). The fibers in the SA node usually have an electric potential of 15-25 mV (Verlag and Heidelberg 1976, 5-7). Due to these unique features of the SA node cells, the cells are capable of generating impulses more rapidly than any other cardiac cells.

As the pacemaker of the heart, the SA node sends out an electric impulse wave that travels through the conducting tissues of the heart. The electric impulse is the result of the depolarization of the cardiac cells in the SA node. A depolarization beyond a certain limit (a large enough separation of charge) causes changes in the cell membranes that allow an ion current to pass (Winfree 1987, 35). This ion current triggers the depolarization of the conducting tissues, producing the muscular contraction and expansion of the heart. Following the depolarization of the cells surrounding the SA node, the impulse travels to the A-V node. The A-V node postpones the impulse, creating a delay of around 0.2 seconds before the impulse moves on. The impulse is then sent through the Purkinje fibers and divided between the two branches of the Bundle of His. The fibers in these branches are close to the ventricles: the most muscular cavities of the heart. Because of their large muscle mass, the ventricles provide 2 of the 2.5 watts used by the heart (Winfree 1987, 33-34).

5. Refractory and Nonrefractory Periods

Sending an electric impulse and creating an electric potential requires work on behalf of cardiac cells. After an impulse is sent and the cell becomes depolarized, it becomes fatigued, meaning that the cell is unable to transmit another impulse until it has recovered. The period of time in which the cell is unable to send any kind of electric impulse is called the absolute refractory period. Normally, the amount of time that it takes a cell to recover is a finite, measurable amount. A cell is fully recovered when it is able to transmit another impulse normally. If the cell is only partially restored, it is still able to transmit an electric impulse, but it does so slowly. The period of time where the cell slowly transmits an impulse is called the relative refractory period (Phibbs and Ewy 1973, 6-7). A nonrefractory period exists when a cell is fully capable of polarization and depolarization again. At any given time, there exist cardiac cells that are in a refractory period and other cells that are in a nonrefractory period. As a result, the conduction of impulses in the heart occurs in a wave-like manner (McFarland 1975, 14).

6. Nervous Control

Nerve fibers connected to the heart are able to control the rate at which electrical impulses are transmitted. Two types of nerve fibers influence the conduction system: sympathetic and parasympathetic nerve fibers. Based on which type of fiber stimulates the heart, the conduction system will either increase or decrease the rate of the heartbeat. Sympathetic fibers are cardioacceleratory, meaning that stimulation through these fibers accelerates the rate of conduction, leading to an increase in the firing rate of the SA node. In this fashion, sympathetic fibers impel the rate of the heartbeat. Parasympathetic fibers, also known as vagal fibers, are

inhibitory: these fibers cause depression of pacemakers and slowing of conduction. For this reason, the SA node will reduce its rate of discharge (Phibbs and Ewy 1973, 6).

7. Using an Electrocardiogram to detect electric impulses

An electrocardiogram (ECG) is a way of measuring the electrical activity of the heart. By using electrodes attached to specific positions on the human body, an electrocardiograph machine can create a graphic representation of changes in electrical impulses in the heart. These electrodes are customarily placed on the right and left arm, the left leg, and one of six different positions on the chest. A final electrode is attached to the right leg to act as a ground. The positioning of these electrodes allows detection of the electrical forces at each of the specified points. Accordingly, the electrical impulses of the conduction system of the heart can be detected. Much like a seismometer for earthquakes, the ECG will record the deflections caused by the electric forces in the body as waves on the ECG paper (McFarland 1975, 16).

The different waves of the electrocardiogram correspond to the different electric forces exerted by the cardiac fibers. The first wave, called the P wave, represents the discharging of the SV node. The initial upstroke of the wave indicates the beginning of depolarization of the node. Return of the wave to the baseline corresponds to the completion of SV node activation. What follows the P wave is known as the P-R interval: the period of time it takes the impulse to travel from the SV node to the A-V node where it is delayed. No electrical activity is documented during this time, and therefore this interval is recorded as remaining at baseline (Phibbs and Ewy 1973, 4-6).

The largest electric force caused by depolarization is felt during the time segment known as the QRS complex. The depolarization of the ventricles occurs at this time. Three different waves

occur in the QRS complex: the Q wave, the R wave, and the S wave. The Q wave represents the beginning of ventricular depolarization. This is followed by the R wave, which records the largest deflection and most of the depolarization of the ventricles. The final wave of the QRS complex, the S wave, represents the depolarization of the most remote part of the Purkinje network (Phibbs and Ewy 1973, 4-6). Overall, the QRS complex represents the biggest deflection that the ECG records. The large deflection correlates to a large electric force, confirming the fact that the ventricles are the most powerful sections of the heart. Knowing that the ventricles consume 2 of the 2.5 watts produced by the conduction system, it is no surprise that such a large force is produced with their depolarization.

The S-T segment, which follows the QRS complex, corresponds with the resting (refractory) period between depolarization and repolarization. No electric force is indicated in this interval, and, therefore, it remains baseline on the ECG. The T and U waves that follow the S-T segment represent the repolarization of the conduction system. At the terminus of these waves, the entire process repeats itself beginning with a P wave (McFarland 1975, 21-22).

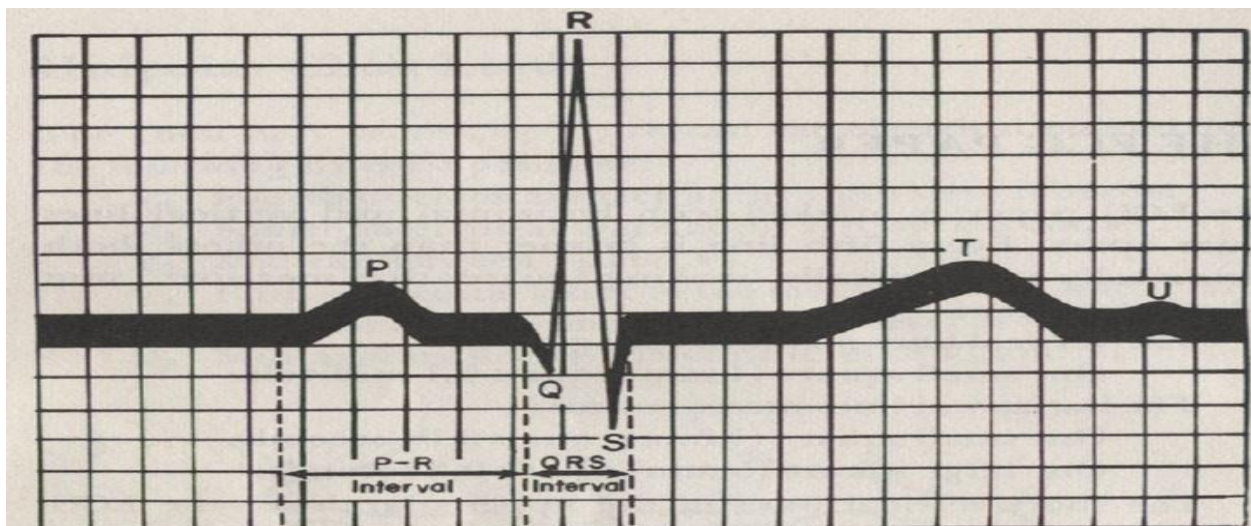


Figure 4 shows a normal interval of waves recorded on an ECG (McFarland 1975, 20)

8. Conclusion

Through this paper's examination of the heart, a better understanding of the physics behind the heartbeat has been attained. Comprehending the anatomy and physiology of the heart leads to the revelation of the simple construction of the conduction system of the heart. The analysis of the pathways from the SV node to the A-V node and the Purkinje fibers serves to delineate the flow of electric impulses.

Analyzing how a cell created an electric impulse led to many interesting finds. The first discovery whereby physics applied to the heart was made in the polarization of cardiac cell membranes; this is a revolutionary discovery because the separation of sodium and potassium ions creates a capacitor system across the cell membrane is crucial in the overall process of making the heart beat. The parallel between cell polarization and physics capacitors is clearly shown in these findings. Numbers, such as the potential difference between the cell membrane, some 10 million volts, illustrate the immense power that the heart is able to generate through polarization.

Defining the pathways of the conduction system also demonstrated how electric impulse travels as current through the heart. The SA node, the pacemaker of the heart, possesses cells which display high permeability and are capable of self-polarization. By investigating the manner in which the electric impulse traveled from the SA node to the A-V node and other branches of the conduction system, a better understanding of how the heart beat occurs was achieved. Using the electrocardiogram to detect these electrical impulses also confirmed how the conduction system works. These findings illustrate the fundamental reliance of the function of the heart on electric forces and electric systems of physics.

Bibliography

McFarland, Mary Brambilla. 1975. *Interpreting Cardiac Arrhythmias*. New York: Springer Publishing Company, Inc.

Phibbs, Brendan, and Ewy, Gordon A. 1973. *The Cardiac Arrhythmias*. United States: C. V. Mosby Company.

Verlag, Springer, and Heidelberg, Berlin. 1976. *Cardiac Pacing*. Germany: Konrad Triltsch.

Winfrey, Arthur T. 1987. *When Time Breaks Down*. New Jersey: Princeton University Press.