UPII HONORS PROJECT

Electricity of the Human Heart

A Brief Overview of Electrocardiography

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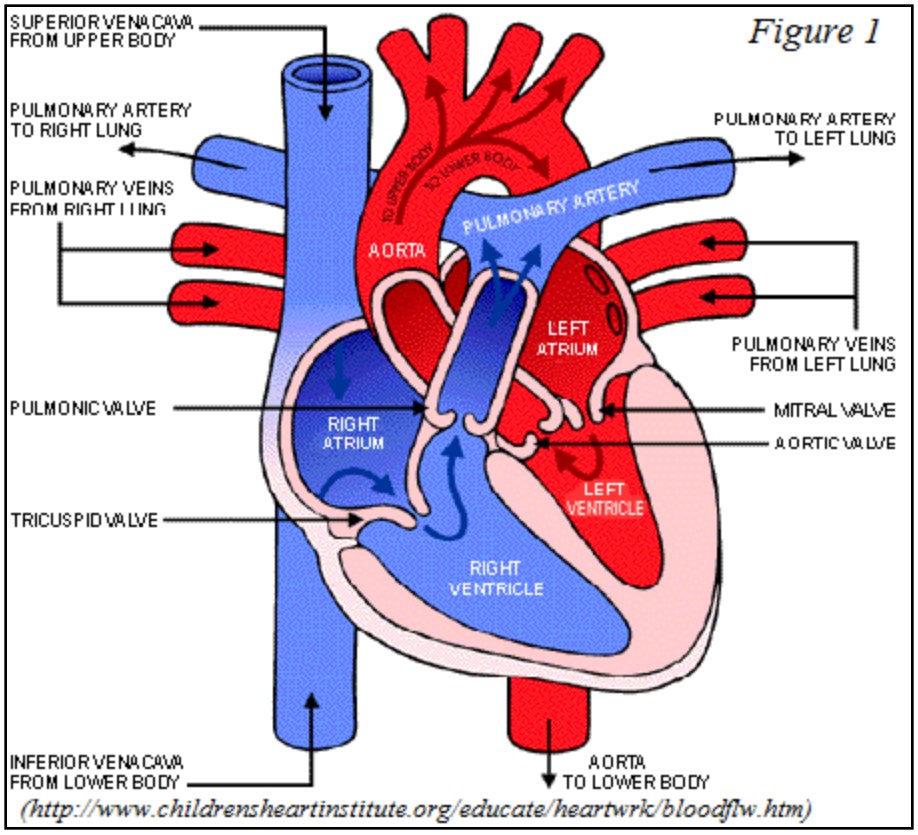
Section: H1

Physics, chemistry, and biology are considered separate fields of science, but there is no better example of how they are interconnected than the human heart. The heart consists of many different cells, a fact studied in the field of biology. These cells are able to work together through electrical impulses that are generated by specialized cells. Electricity is a subject that is studied extensively in physics. Finally, cells are able to conduct this electricity through mechanisms such as sodium-ion channels, a subject in chemistry. This is an oversimplified example, but it illustrates how these fields are interconnected. While the focus will be on the physics of the electricity of the human heart, a working knowledge of the other fields will help explain why electricity is a vital aspect to keeping the heart beating.

The heart is divided into four main areas: the left atrium, left ventricle, right atrium, and



right ventricle. Blood is received from the entire body in the right atrium. The blood is oxygen deficient, as denoted by the color blue in *Figure 1*. When the right atrium is full, it signals the

valve to open and it then enters the right ventricle. Once the right ventricle is full, the blood leaves the heart to go to the lungs to release carbon dioxide and receive oxygen. When the blood leaves the lungs, it goes back to the heart. The now oxygen rich blood, shown in red in *Figure 1*, enters the left atrium, and once it is filled, will move to the left ventricle. Once the left ventricle is full, the blood leaves the heart through the aorta and is distributed to the body. This process continuously cycles blood through the body (Abdallah).

Electricity generated by the heart regulates the speed at which blood is pumped out of the heart. The electrical impulse is initiated by the sinoatrial node, the heart's pacemaker. This impulse causes the atria and atrioventricular (AV) node to depolarize (Conover, 12). Depolarization is the process in which a cell's membrane potential either becomes less positive or less negative which is a decrease in the absolute value between the two measurements. Depolarization is caused by the movement of cations such as Na+ and Ca+ through channels in the cell ("Depolarization"). When the electrical impulse from the sinoatrial node depolarizes the resting cells of the atria and AV node, their charge switches from -90mV to +30mV. In this case, depolarization means the cells become more positive (Conover, 13). After depolarization, the cells return to their resting state through the process of repolarization, where they return to their original charge of -90mV. In this way, the electrical cardiac cycle can be described as three phases: depolarization, repolarization, and resting.

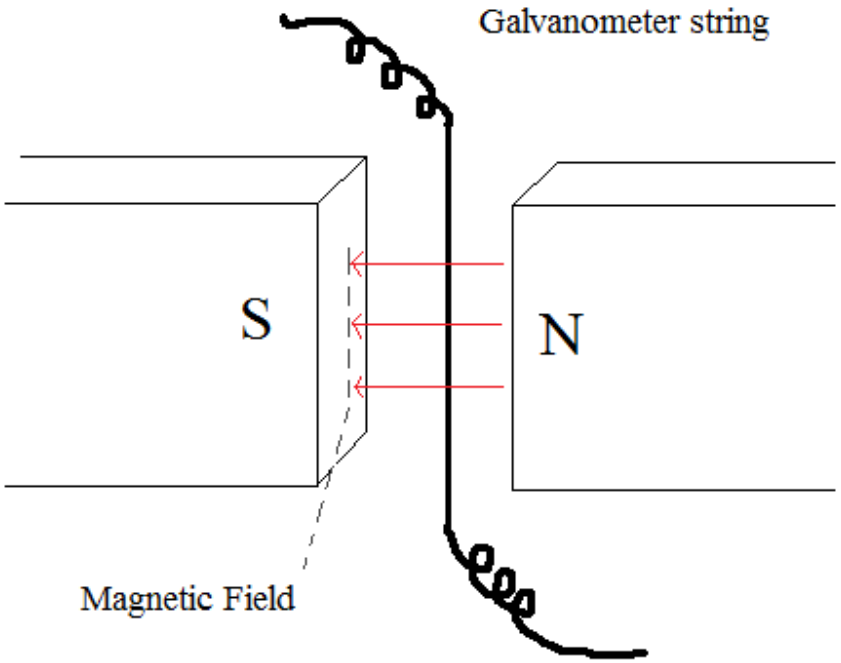
The AV node is located at the junction between the atria and ventricles. The AV node delays the electrical impulse through the heart, for if the entire heart contracted at the same time, the heart would not be able to pump blood ("The Electrocardiogram"). The atria and ventricles are basically electrically separated, and the AV node is the only point through which electrical current passes between them. The impulse generated from the sinoatrial node causes both atria

to contract, pushing the blood into both ventricles. The delay of the electrical signal in the AV node is important because it allows both atria to empty and close their valves. This keeps blood from flowing back into the atria during the next step.

After the delay in the AV node, the electrical impulse is conducted through the His-Purkinje system (Conover, 13). The first part of this system is the bundle of His. This bundle is made up of specialized heart muscle cells that conduct electricity from the AV node to the Purkinje fibers ("Bundle of His"). The Purkinje fibers are highly specialized to conduct electrical impulses quickly. Their ability to conduct these impulses quickly comes from numerous sodium ion channels and more mitochondria than surrounding cells. The Purkinje fibers are located in the ventricular walls of the heart. These fibers then transmit the electrical impulse to the surrounding cells of the ventricles. This causes the ventricles to contract and force out the blood, pumping it out of the heart. After this happens, the ventricles repolarize and the entire cycle starts again.

An electrocardiogram (ECG or EKG) is a device that displays the small voltages

Figure 2



(Burch, 17)

generated by the heart on a graph. It is useful to health providers in determining whether a heart is functioning properly. In 1787, Aloysio Luigi conducted many experiments regarding electricity, and he discovered that living tissues could conduct and generate electricity. In 1856, Willem Einthoven built on Luigi's work and invented the string galvanometer. This device is the foundation upon which an electrocardiogram works ("EKG Machine"). A string galvanometer is made from a strong electromagnet with a string suspended between the poles of the electromagnet. The string is made of a quartz glass fiber, and it is coated with platinum or silver to allow electric current to travel through the string. *Figure 2* is a diagram of a string galvanometer. The red lines in *Figure 2* represent the magnetic field produced by the electromagnet. The current from the heart runs through the string, producing a second magnetic field. Using the right hand rule for wires, the direction of the magnetic field around the string can be described as either clockwise or counterclockwise as viewed from the end of the string. This depends on whether the current is traveling up the string or down the string. The interaction between these two magnetic fields causes the string to move. This deflection can be predicted by another right hand rule. If the current is traveling upwards, the index finger points in this direction, the middle finger points in the direction of the magnetic field to the left of the page, and the deflection will be the thumb, which is out of the page. In the same respect, if the current was traveling downwards, the deflection would be into the page (Burch, 17-19). The string would be connected to the right and left arms. When the string was deflected, it would be recorded on paper. The first electrocardiogram machine was built by Einthoven in 1903 in this way ("EKG machine").

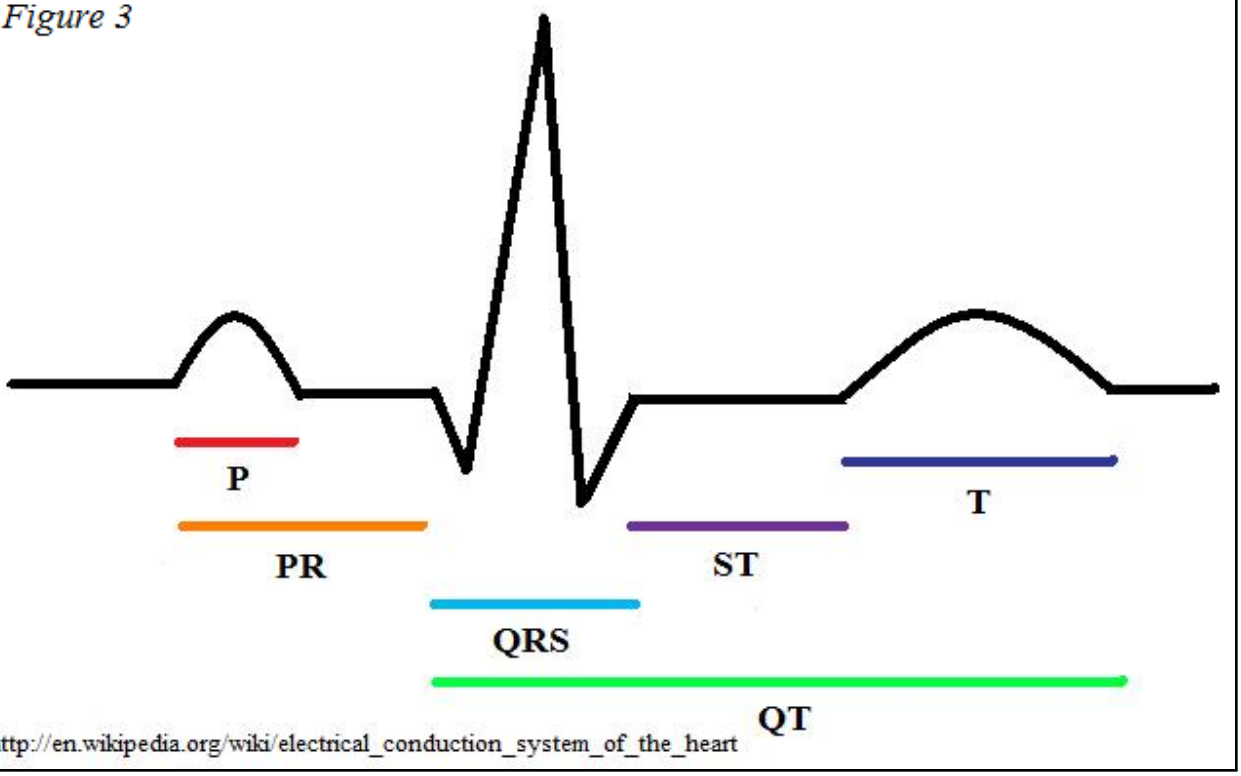
After the unveiling of the new electrocardiogram machine, many improvements were made to the device. First, the electromagnet was reduced in size, which allowed the machine to

become portable. The electrodes used to connect the body to the machine have also greatly evolved. In early models, the patient was required to submerge their hands and feet into glass electrode jars filled with salt water. Electrodes that could be connected directly to the body were then developed. These range from metal plates, to vacuum suction, to the most useful bandage-like electrodes that are not as sensitive ("EKG machine"). Today, computers are a vital aspect to healthcare, and the electrocardiogram machines now function with the help of a computer, which helps record and monitor the status of the patient.

Figure 3 is a diagram of the output of generated by an electrocardiogram machine. Each part of the wave represents one of the steps in the electrical cycle of the heartbeat. When there is a negative deflection, the graph moves below the baseline, and positive deflections move above the baseline ("The Electrocardiogram"). The first wave, known as the P wave, represents the depolarization wave through the atria, and it shows the relative time it takes for this event to occur (Conover, 20). Both the left and right atria are activated during the P wave, which is normally a smooth curve (Conover, 18). If the P wave is not smooth, then there might be problems with the atria in the heart. The next part is the P-R interval, which is a delay of the electrical impulse to the AV node (Burch, 19). This interval encompasses the P wave. During the segment between the end of the P wave and the start of the QRS complex, the His-Purkinje system is activated, even though this is not explicitly shown on the electrocardiogram. The QRS complex represents the activation of the two ventricles (Conover, 19). The beginning and end of the QRS complex represents the span of ventricular depolarization. The duration of this complex can indicate heart problems if they are abnormal. For example, a duration of longer than 0.10 second usually indicates cardiac disease (Burch, 81). The shape of the QRS complex can assume many shapes. The S-T interval represents the time from the end of depolarization to the

beginning of repolarization in the ventricles (Burch, 23). This interval is usually flat on the

Figure 3



http://en.wikipedia.org/wiki/electrical_conduction_system_of_the_heart

electrocardiogram. The T wave is ventricular repolarization. This wave is important in diagnosing cardiac disease (Burch, 108). Many shapes can be seen in the T wave, and can be caused by a number of reasons unrelated to cardiac diseases. For this reason, it is important to eliminate these factors when using an electrocardiogram to diagnose abnormal T waves (Burch, 108-109). The Q-T interval encompasses the QRS complex, S-T segment, and T wave. It is the overall time for depolarization and repolarization to occur in the ventricles.

Many heart diseases can be detected by the use of an electrocardiogram. Any type of interruption in the heart's electrical system will affect the heartbeat and the heart's ability to pump blood. One example is an arrhythmia, an abnormal rhythm of the heart. There are two types of arrhythmias: abnormalities of conduction and impulse initiation (Conover, 53). Conduction refers the path through which an electrical pulse is transmitted, which can be

blocked or affected in other ways. Impulse initiation concerns the cells that generate the electrical impulse. Another disorder of the heart is cardiac infarction. This is where some of the heart cells die, which interrupts the electrical conduction through that area. One example is myocardial infarction, more commonly known as a heart attack. Usually because of a blocked artery, part of the heart dies, and it prevents conduction causing irregular heart rhythms. This in turn affects the amount of oxygen available to the rest of the body. A final example of disorder of the heart is Wolff-Parkinson White Syndrome. The heart uses one main pathway to conduct the electric signal from the sinoatrial node to the AV node to the ventricles. In Wolff-Parkinson White Syndrome, the heart uses an accessory pathway to conduct electrical signals, which causes the ventricles to contract too soon. The main symptom of this syndrome is tachycardia, or a rapid heartbeat. About 1 to 3 people in 1,000 have this disorder, which is caused by a mutated gene.

An automated external defibrillator, or AED, is a portable device that is connected to a patient and assesses their heart rate and electricity. If the machine finds something wrong, it will use electricity to defibrillate the heart to get it to work properly. The machine focuses on recognizing arrhythmias of the ventricles. Due to an irregular pattern, the AED uses electricity to restore a normal pattern to the patient's heartbeat ("Automated External Defibrillator"). AEDs are specifically designed to get a patient sooner medical attention, rather than waiting on an ambulance or a trip to the hospital. People are often certified in their use in conjunction with CPR training. The machines also contain instructions in word form, and they may also have audible instructions from the AED. The automated part of the name AED refers to its ability to assess the patient's condition without the user having any knowledge. This is important because it means more people can potentially use one, getting help to a patient faster if they are not near a

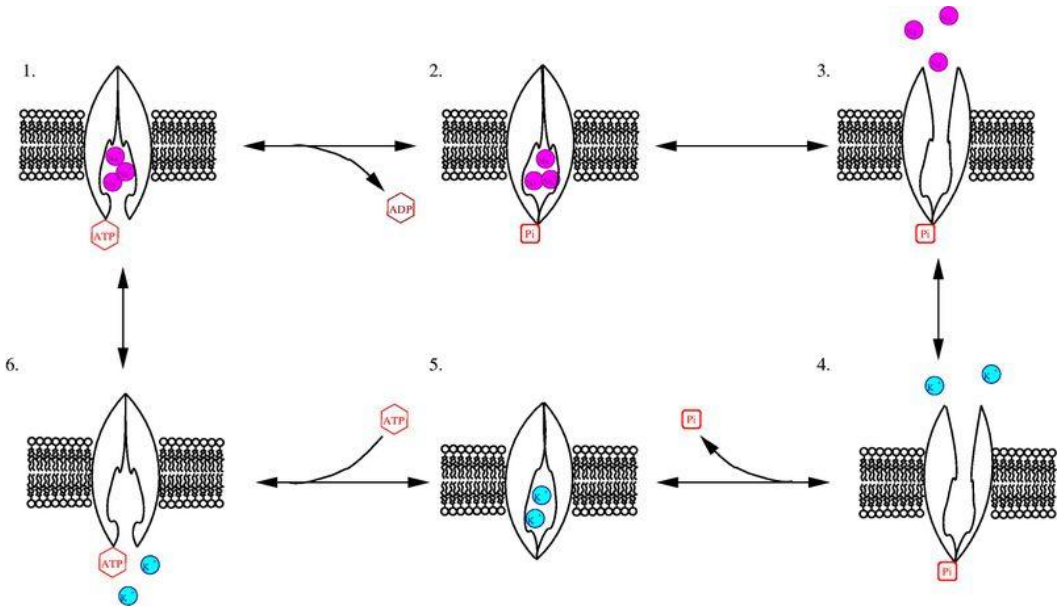
hospital. The external part of AED refers to its external placement. The electrodes are stuck to the patient's abdomen, where the electrical charge is delivered. Other forms of defibrillators are inside the chest and placed near the heart. As mentioned before, the defibrillation part of the name means restoring a normal beat back to the heart. AEDs are only designed to treat arrhythmias, where the heart is beating at an irregular pace, and cannot cause a heart to start beating. In the instances of defibrillating the heart, the aim is to prevent cardiac arrest. If the heart has altogether stopped beating, then CPR is the only option. After only three to five minutes of heart fibrillation, a person can experience irreversible heart and brain damage. The AED machines have introduced faster response times to combat this problem.

The electrical impulses in the sinoatrial node, or pacemaker, keep the heart beating in a regular pattern, but how is this electricity generated? The answer lies in ion channels. Ion channels are proteins that control the voltage on either side of a cell's membrane ("Ion Channel"). There are many types of ion channels, but the channel used in the sinoatrial node is a voltage-gated ion channel. The term voltage-gated describes how the ion channel is opened. In this case, the voltage gradient across the cell membrane can trigger the ion channel to open. A voltage gradient is the difference between the voltage on one side of the plasma membrane versus the other side. A big difference between the two voltages would create a strong voltage gradient.

The ion channels that produce electricity in the sinoatrial node are hyperpolarization-activated cyclic nucleotide-gated channels. These channels are one of the types of the voltage-gated channels. Hyperpolarization is a change in the cell membrane's potential that makes it more polarized, which would mean a stronger voltage gradient. This is in contrast to depolarization, which would be a reduction in the potential across the membrane. The cyclic

nucleotides cAMP and cGMP alter the channel opening's sensitivity to voltage. The nucleotide cAMP stands for cyclic adenosine monophosphate, and cGMP stands for cyclic guanosine monophosphate. These nucleotides are derived from adenosine triphosphate (ATP) and guanosine triphosphate (GTP). Both sodium and potassium ions are able to travel through these channels. There are four different types of hyperpolarization-activated cyclic nucleotide-gated channels, and the fourth type, abbreviated HCN4, plays the most prominent role in the regulation of the rhythm of the heart ("Ion Channels").

In the other cells of the heart, the sodium-potassium adenosine triphosphatase (ATPase) pump is an energy driven mechanism in the sarcolemma, the cell membrane of a muscle cell. In the sodium-potassium ATPase pump, three sodium ions are pumped out for every two potassium ions pumped in (Conover, 13). This exchange is powered through one ATP molecule. In this way, the resting potential, or resting voltage, can be maintained in the cell. The mechanism starts with an ATP bound to the pump, and it binds three sodium ions. ATP is then hydrolyzed



and released as ADP. The pump is phosphorylated, and the three sodium ions are released when the pump undergoes a conformational change. While in this conformation, and after releasing

the three sodium ions, it binds two potassium ions. This causes dephosphorylation of the pump, and the pump changes conformation back to its original form, bringing the potassium ions into the cell. The unphosphorylated form of the pump has a higher affinity for sodium ions, so it will bind two more sodium ions. The pump will also bind another ATP, and the process starts over again ("Sodium-potassium Pump").

The heart is an organ that works in a detailed and highly orchestrated way. Focusing on its electrical system gives insight into how it maintains a steady beat, and is able to supply the body with blood. The electrical impulses generated in the pacemaker are transmitted throughout the heart, which leads to the concerted actions that pump blood. The actions of the heart can be monitored with an electrocardiogram machine, and diseases can also be diagnosed. The various ion channels of the heart maintain voltage potentials and create the electrical impulses needed to regulate the heart. Overall, physics is an important tool for studying the heart, and a thorough understanding of how the heart works includes this field.

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