Basic Heart Function

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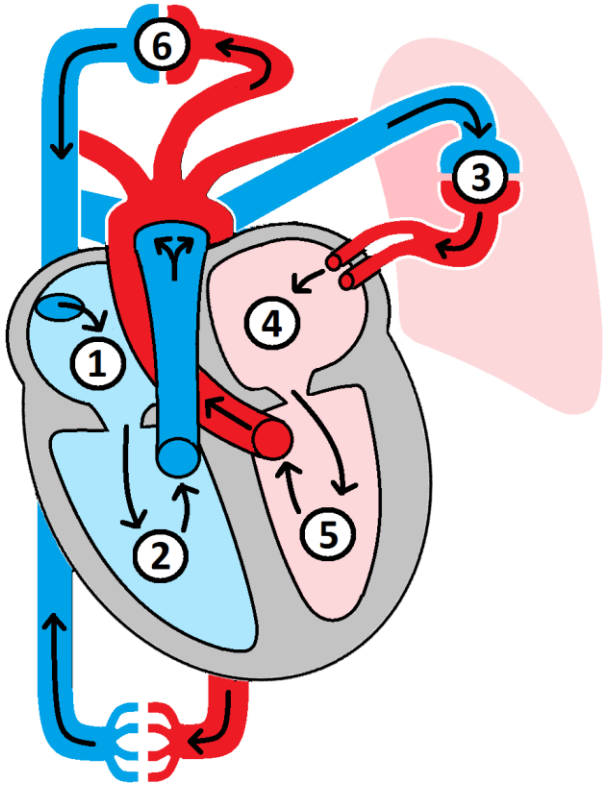
The heart is a simple pump with a very important purpose. The hearts job is to circulate blood throughout the body. Blood is a transport system for many important things in the body, including oxygen. Blood is oxygenated by the lungs and pumped by the heart through arteries in order to oxygenate tissues. After the body's tissues use up the oxygen in the blood the deoxygenated blood returns to the heart through veins. The heart then pumps the deoxygenated blood back to the lungs so the process can begin again.

The heart pumps blood by first contracting the two upper chambers (right atrium and left atrium), referred to as the atria. The purpose of atrial contraction is to load the lower two chambers (right ventricle and left ventricle) with blood. Atrial contraction makes the heart a more efficient pump but is not required to sustain life. Ventricular contraction provides the main pumping action of the heart and is required to sustain life. When the ventricles contract deoxygenated blood from the right ventricle is sent to the lungs and oxygenated blood from the left ventricle is pumped through arteries to the body. The arterial system is a high pressure system requiring the left ventricle to pump with significant force, therefore the left ventricle is the most muscular chamber of the heart.

Figure 1: Cardiac Blood Flow

1. Deoxygenated blood returns to the Right Atrium.
2. Atrial contraction forces the deoxygenated blood into the Right Ventricle.
3. Ventricular contraction forces the deoxygenated blood to the lungs.
4. Oxygenated blood returns to the Left Atrium.
5. Atrial contraction forces the oxygenated blood into the Left Ventricle.
6. Ventricular contraction forces the oxygenated blood through the arteries.



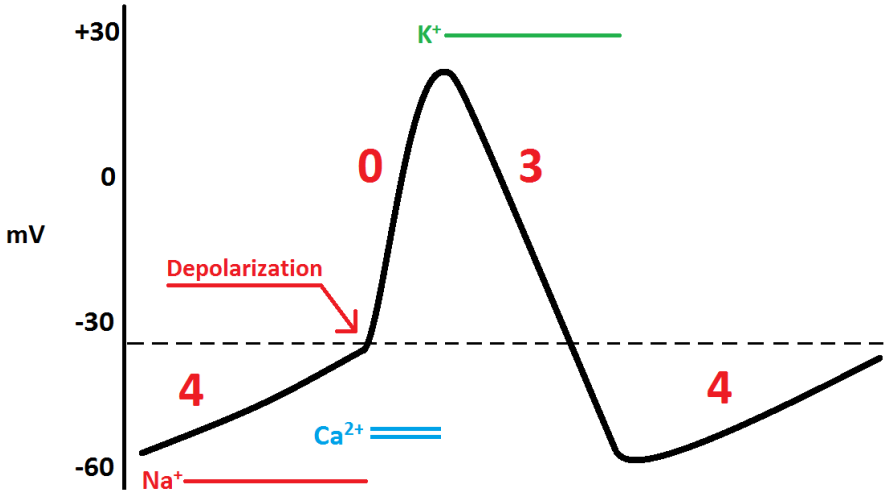
The Cardiac Electrical Conduction System

Action Potentials of Cells

The heart is a simple pump in terms of function but the mechanism responsible for heart contractions is very complex. When muscle tissue is stimulated by electricity it causes a release of Ca^{2+} within the tissue. Increased Ca^{2+} concentrations in muscle tissue allow actin and myocin to perform cross-bridging causing the muscle to contract. The control of electrical current through the heart is therefore essential to its functionality as a pump. The cells which initiate, and therefore control, this electrical stimulation are called pacemaker cells.

Pacemaker cells are cells which initiate electrical stimulation of the heart. They have what is called **automaticity** meaning they have the ability to create electrical impulses. These specialized cells maintain ion concentrations, inside and outside of the membrane, held in place by membrane gates. As the ions are allowed to move across the membrane electricity is created. This change in the voltage of the cell is called **Action Potential**. When the cell creates an electrical impulse this is referred to as **Depolarization**. After the cell depolarizes the cell must undergo **Repolarization**, meaning it must reverse the ion concentrations back to their original state, before the process can recur. The action potential of pacemaker cells are divided into 3 phases (See figure 2). As seen in phase 4 pacemaker cells have no resting membrane potential. This means they are constantly building towards a state of depolarization.

Figure 2: Pacemaker Cell Action Potential

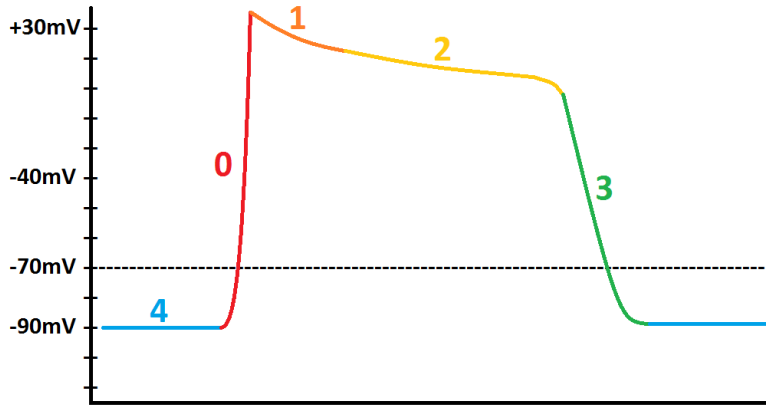


Phase 4 – Steady influx of Na^+ until the membrane potential reaches -40 to -30mV. Once the membrane reaches the voltage threshold it causes voltage regulated Ca^{2+} gates to open.
Phase 0 – Depolarization caused by rapid influx of Ca^{2+} due to the opening of voltage regulated Ca^{2+} gates.
Phase 3 – K^+ influx back into the cell causing repolarization of the cell.

Pacemaker cells initiate depolarization and make up the electrical conduction pathway which spreads this depolarization to all the cardiac myocytes of the heart. Action potentials of **cardiac myocytes** are different than those of pacemaker cells. Cardiac myocytes have a resting membrane potential,

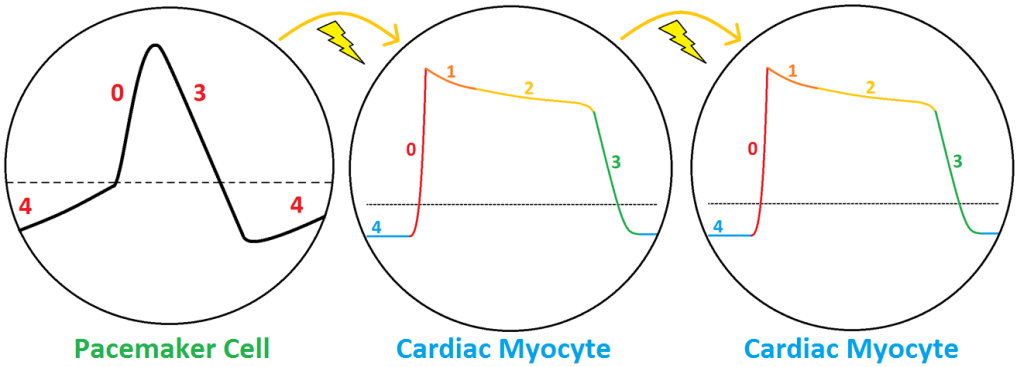
meaning they are not intended to initiate electrical impulses. These cells are essentially at rest until they are stimulated by pacemaker cells. This is illustrated by comparing phase 4 in Figure 2 with phase 4 in Figure 3. In figure 2 you can see phase 4 has an upslope because it is always building toward depolarization, whereas phase 4 in Figure 3 is flat. Cardiac myocytes will remain at rest until they are stimulated by an electrical impulse causing them to depolarize.

Figure 3: Cardiac Myocyte Action Potential



Phase 4 – Resting membrane potential at ~-90mV. During this phase sodium and calcium are at higher concentrations outside of the cell and potassium concentrations are higher inside.
Phase 0 – Initiation of depolarization. The cell has been stimulated by an electrical impulse opening its voltage regulated sodium gates allowing for the rapid influx of sodium.
Phase 1 – Voltage regulated sodium gates close and potassium gates open slowly.
Phase 2 – Plateau phase. Potassium efflux and calcium influx are ~ equal.
Phase 3 – More potassium gates open as the cells membrane potential decreases resulting in repolarization of the cell.

Figure 4: Depolarization Chain Reaction



The above figure illustrates how pacemaker cells initiate an electrical impulse causing depolarization of neighboring cardiac myocytes. This depolarization is then spread from cell to cell until all of the cardiac myocytes are depolarized.

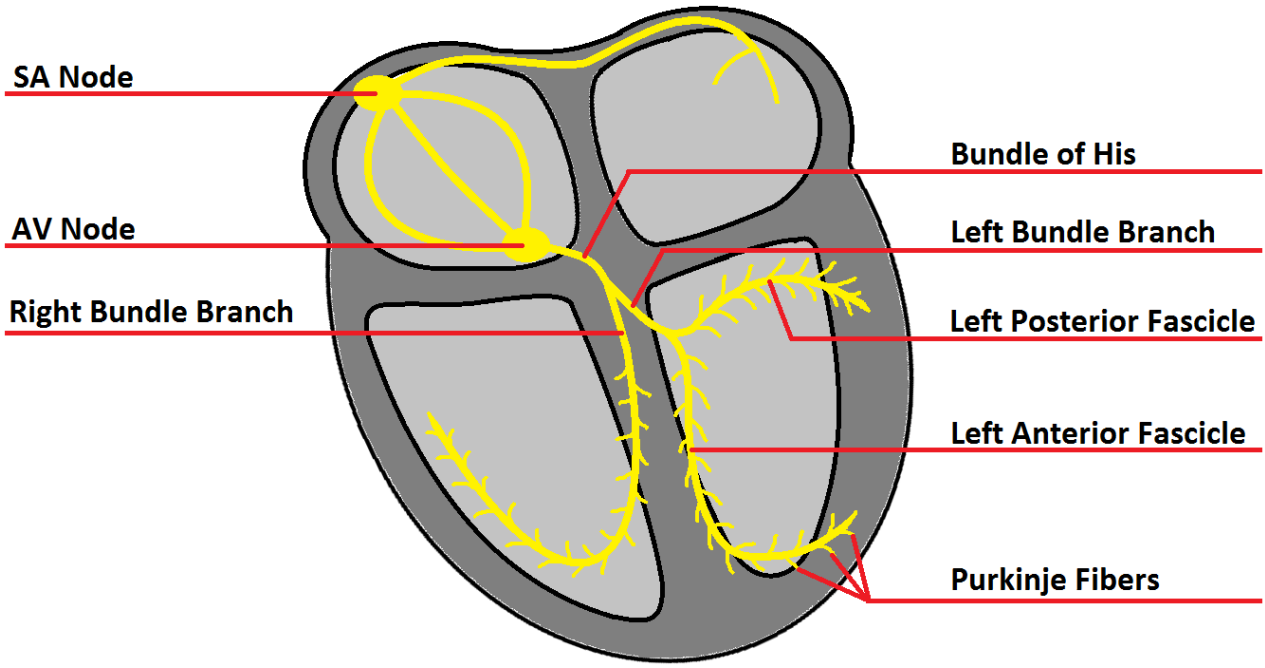
Electrical Conduction System of the Heart

In a normal heart the pacemaker cells are the only cells initiating depolarization. Pacemaker cells can be found throughout the hearts electrical conduction system (See Figure 4). The Sinoatrial Node (SA Node) is a cluster of pacemaker cells located above the right atrium and is the main pacemaker of the heart. The SA Node does not need to be prompted to pace by the Autonomic Nervous System (ANS) as it can pace independently. Instead the ANS modifies the heart rate based on metabolic needs through sympathetic (faster) and parasympathetic (slower) stimulation. Left unmodified the SA Node is expected to pace between 60-100 bpm.

Once the SA Node initiates depolarization it travels across the heart with the help of a specialized network of pacemaker cells. Bachmann's Bundle facilitates depolarization of the left atrium as well as a number of pathways which travel across the right atrium. As the atria depolarizes it causes the heart muscles of the atria to contract forcing blood from the atria into the ventricles.

After atrial depolarization occurs the electrical impulse travels down through the **Atrioventricular Node** (AV Node) where it is delayed slightly. The delay allows time for the ventricles to fill with blood before their next contraction. Next the electrical impulse travels through the **Bundle of His** and then down through the **Bundle Branches** and **Purkinje Fibers**. The Bundle Branches are a fast track through the ventricles allowing for rapid and even depolarization of the right and left ventricles. The left main bundle further divides into the **Left Posterior Fascicle** and the **Left Anterior Fascicle**. During ventricular depolarization both ventricles contract simultaneously to pump blood throughout the body. Once the atria and ventricles have depolarized they must then repolarize before they can depolarize again.

Figure 4: The Electrical Conduction System

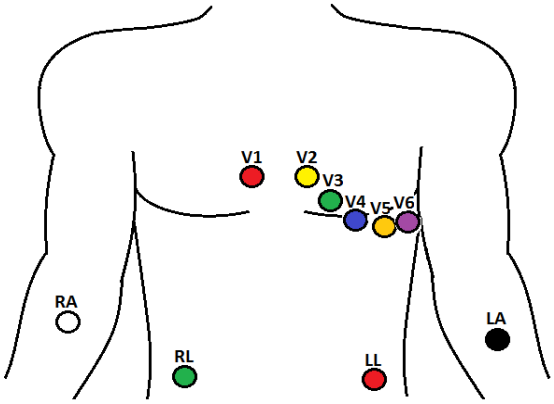


ECG Tracings and Complex Analysis

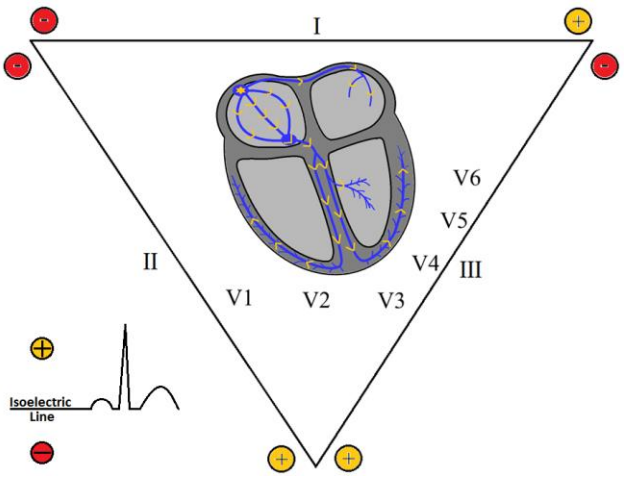
The function of the heart's electrical conduction system can be measured and interpreted by an Electrocardiogram (EKG or ECG). Electrodes are placed on the patient in very specific locations on the torso as well as the limbs. The electrodes sense electrical impulses moving toward or away from them generating a waveform. This waveform is superimposed over graphing paper so it can be measured. When the electrodes sense an electrical impulse moving toward them it registers it as a positive deflection. Conversely any electrical impulse moving away from the electrode appears negative on the graphing paper.

Figure 5: Electrode placement

This figure shows EKG lead placements. These leads are positioned in specific locations based on the anatomy of the patient. For example, V1 is positioned at the 4th intercostal space to the right of the sternum, V4 is positioned at the 5th intercostal space on the midclavicular line, and V6 is positioned on the midaxillary line.



The figure to the right is an example of how the leads are interpreting the electrical activity of the heart. The Isoelectric line is neutral (0mV) and any electrical impulses registered by the leads will show up as a positive or negative deflection. The triangle surrounding the heart represents leads I, II, and III which is referred to as Einthoven's Triangle.



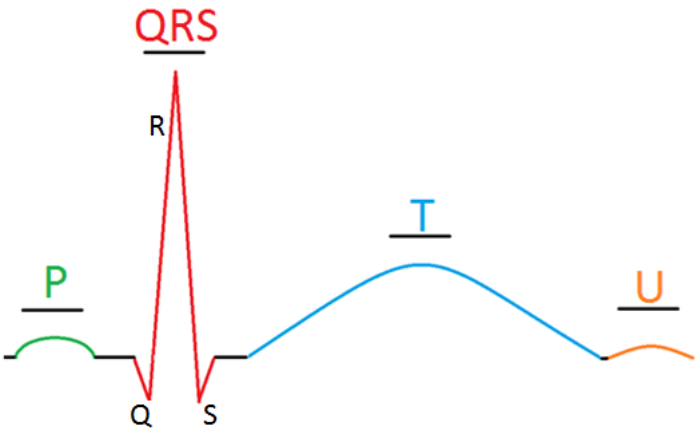
When the SA Node initiates depolarization of the atria, causing atrial contraction, it is seen as a low amplitude wave on the EKG tracing called a **P wave**. Following the P wave there is a slight delay to allow for ventricular refill. After the delay ventricular depolarization begins, causing ventricular contraction, and is seen as a higher amplitude wave called the **QRS**. After ventricular depolarization there is ventricular repolarization which is represented by the **T wave**. Occasionally a patient may have a U wave. The **U wave** can be identified by a small, low amplitude wave just after the T wave. The pathology of U waves has not been determined and can be ignored during complex analysis.

Figure 6: Complex Analysis

P wave – Atrial Depolarization

QRS – Ventricular Depolarization

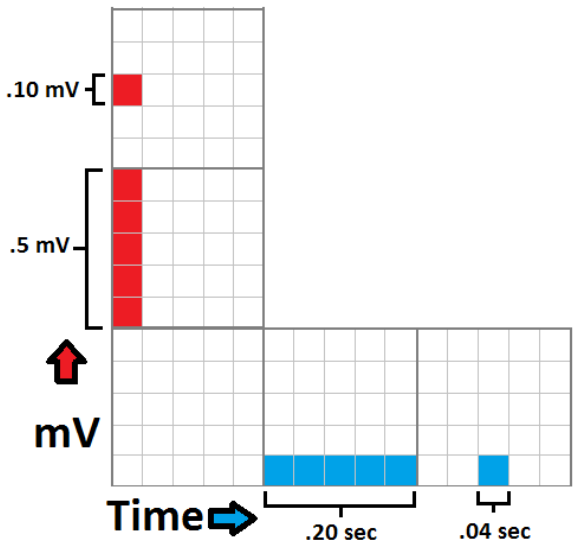
T wave – Ventricular Repolarization



When this EKG tracing is superimposed over EKG graphing paper it can be further analyzed. The height of each wave (Amplitude) can be measured vertically in millivolts (mV). Time is measured horizontally and is used to determine heart rate, distance between waveforms, duration of waveforms, etc.

Figure 7: Graphing Paper

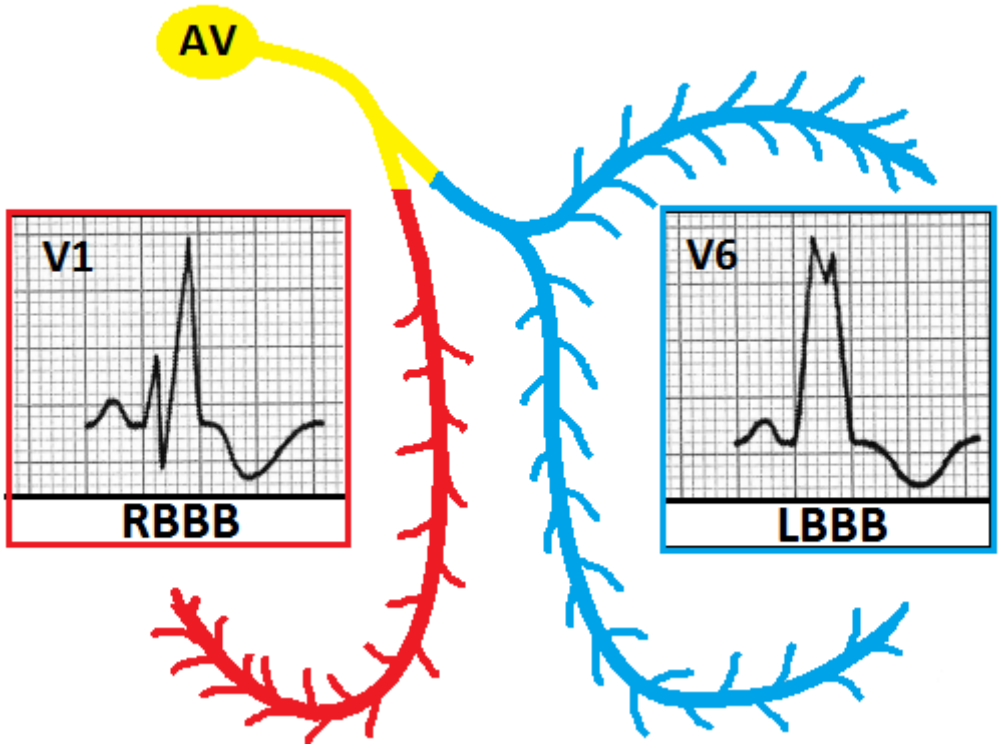
The graphing paper allows the EKG tracing to be measured. Vertically shows amplitude which is measured in millivolts (mV). Each small box represents .10 mV and each large box represents .5 mV. Looking at the graph paper horizontally is a measurement of time. Each small box represents .04 seconds and each large box represents .20 seconds.



Three common measurements of time are the PR, QRS, and QT. The **PR** interval is measured from the beginning of the P wave to the beginning of the QRS. This measures the amount of time from the beginning of atrial depolarization until the beginning of ventricular depolarization. Since the duration of atrial depolarization usually doesn't change what is really being measured is the delay through the AV node. It is expected that the PR measurement will be between .12-.20 seconds. If the PR measures >.20 second this is an indication of a delay of conduction through the AV node (AV Block).

The **QRS** represents ventricular depolarization so its measurement represents the time it took for both the right and left ventricles to completely depolarize. It is expected that the ventricles will depolarize within .06-.10 seconds. If it takes longer than .10 seconds for the ventricles to depolarize there is a delay in the conduction system. The right and left bundle branches facilitate a rapid and even depolarization of the ventricles. If ventricular depolarization is measured >.10 seconds then it is referred to as an **Interventricular Conduction Delay** (IVCD). If the QRS measures $\geq$ .12 seconds this may also be referred to as a **Bundle Branch Block** (BBB). An EKG can be used to determine if the conduction delay is present in the right bundle, left main bundle, or a fascicle (fascicular block).

Example: Right and Left Bundle Branch Blocks

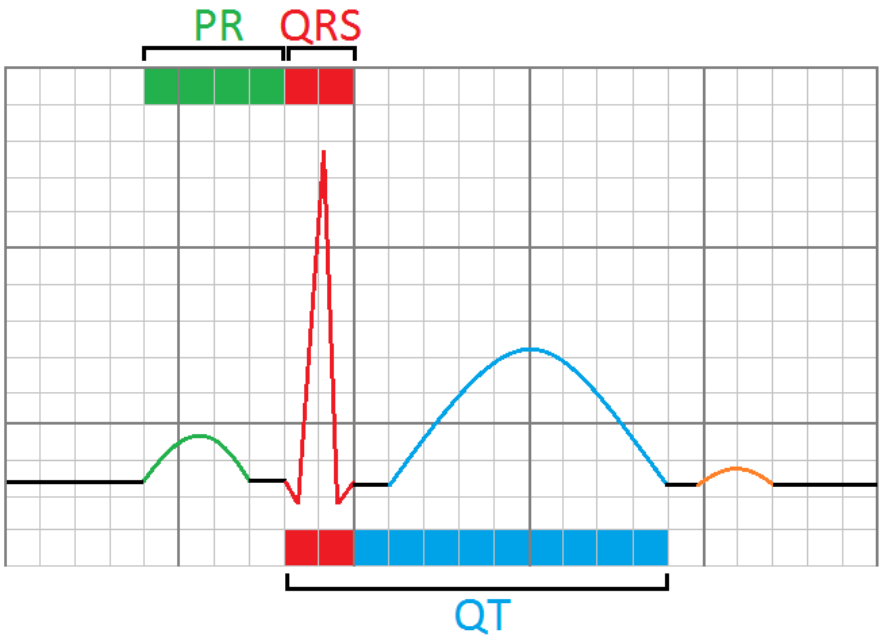


Right Bundle Branch Block (RBBB) illustrated above in red indicates electrical impulses are blocked through the right bundle. The EKG findings show "rabbit ears" in V1.

Left Bundle Branch Block (LBBB) illustrated above in blue indicates the entire main left bundle is blocked, including both anterior and posterior fascicles. The EKG findings show "rabbit ears" in V6.

The **QT** represents the duration of ventricular depolarization and repolarization. This is measured from the beginning of the QRS to the end of the T wave and is expected to be between .36-.44 seconds. This measurement can be influenced by a BBB however usually what is being evaluated is the duration of ventricular repolarization. The QT can also be influenced by the overall heart rate, shortening with increased HR and elongating with slowing HR. In order to accurately compare a patient's QT measurement the EKG software has the ability to adjust the QT based on rate. This adjusted or corrected QT is referred to as a QTc.

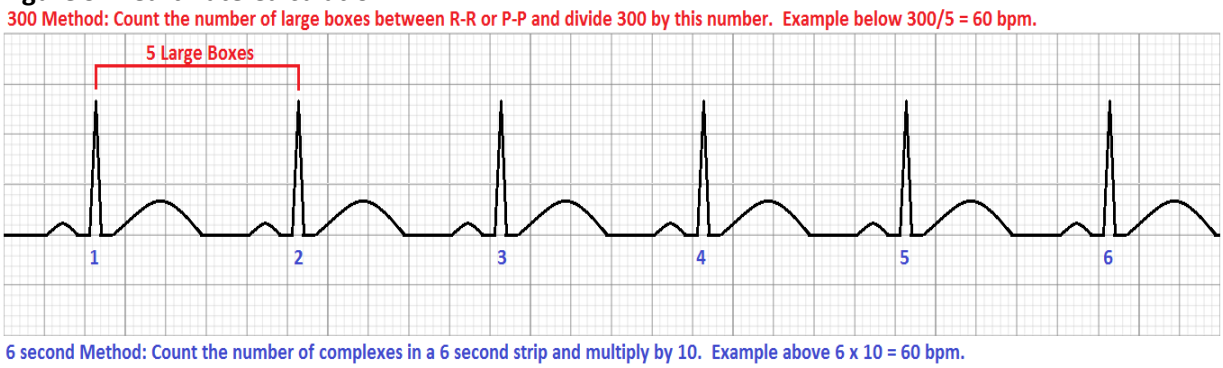
Figure 8: Complex Measurements



Expected Values: PR .12 - .20 sec QRS .06 - .10 sec QT .36 - .44 sec

The EKG graphing paper can be used to determine the atrial rate and the ventricular rate of a rhythm. Two common methods are the 6 second method or the 300 method. The 6 second method uses a 6 second strip, which is exactly 30 large boxes long (30x.20 sec = 6 sec), as seen in Figure 9. Count the number of complexes within the six second strip and multiply by 10. Another way to calculate rate is by using the 300 method. Count the number of large boxes between R-R or P-P and divide 300 by that number.

Figure 9: Heart Rate Calculation



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