3.3.2

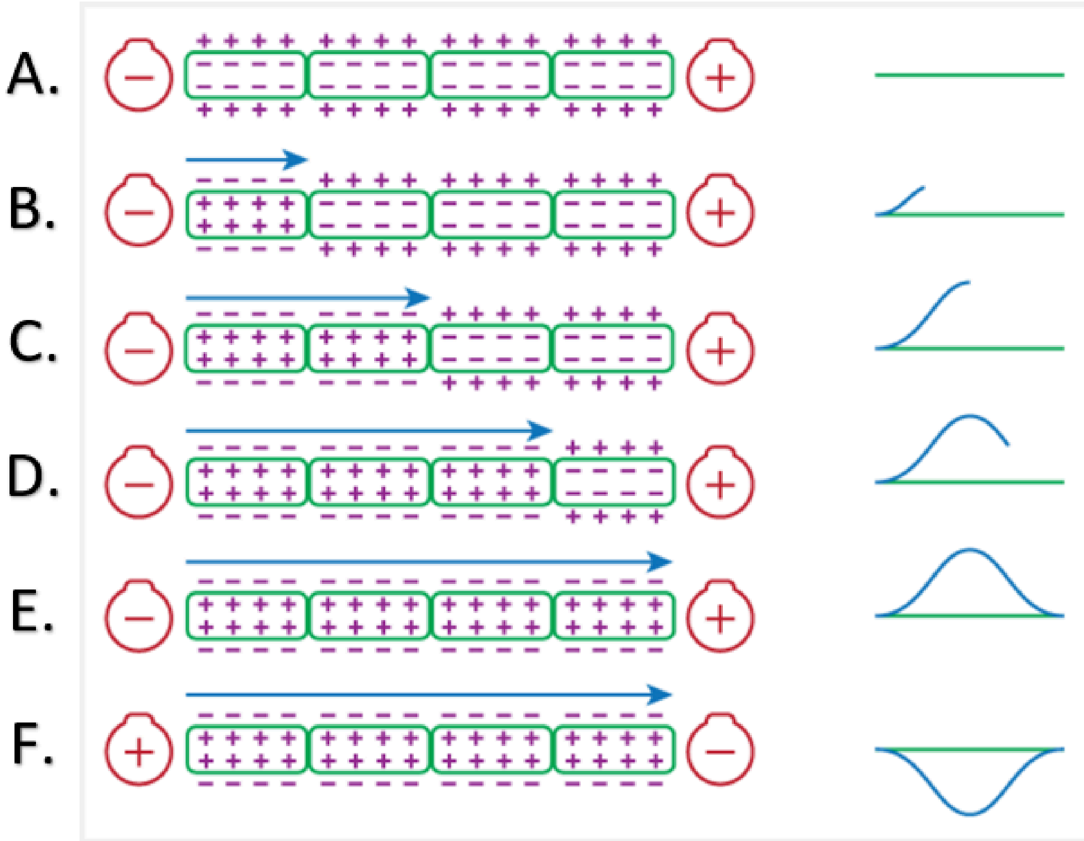
Electrocardiogram (ECG)

We have been discussing action potentials and how they are generated and conducted through the heart muscle. We have also described their role in triggering contraction of the cardiac muscle. An important technique for diagnosis of problems in the heart is to measure its electrical activity. This is accomplished using an electrocardiograph, which creates a record of the electrical activity of the heart, the **electrocardiogram** or **ECG**.

The ECG does not measure individual action potentials but instead it detects the currents flowing through the extracellular fluids, a result of all action potentials, as the charges associated with the heart muscle spread (propagation). Think what happens when you connect a wire between the opposite poles of a battery, current flows through the wire. A similar event is taking place in the extracellular fluids of the body when some of the heart cells are at rest (negative inside and positive outside) while others are depolarized (positive inside and negative outside). When this happens, an electric field is established between opposite charges on the surface of the cardiomyocytes. Sensors placed on the surface of the body can detect changes in the electric field. A tracing can be made of the events taking place during one complete cycle of the heart.

To help you understand how the ECG waves are generated, let's examine a hypothetical situation in which we have four cells connected end to end. We will explore what happens as an action potential is generated in one cell and then propagates to the other three cells.

Refer to the next figure as we explain the process.

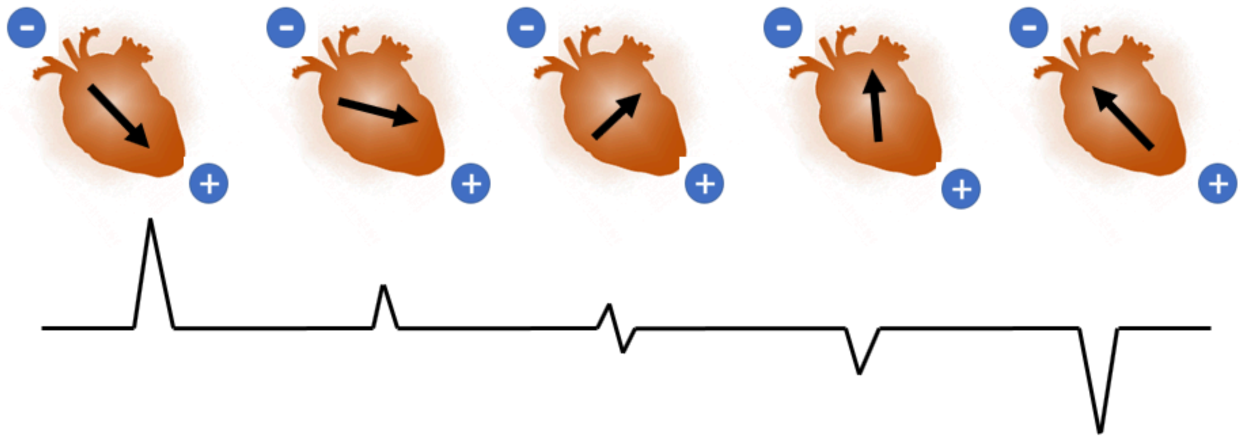


Deflection wave on ECG created as the wave of depolarization moves toward or away from the positive electrode
Drawn by BYU-Idaho student Nathan Shoemaker Fall 2016

In the figure, A-E represents the progression of an action potential beginning with the first cell of the group and then spreading to the next cells. In this example, the positive sensor is placed to the right of the cells and the negative sensor is placed to the left of the cells.

- In “A”, all of the cells are at rest. Since all of the cells have the same charge (+) on the outside of the cells, no current is flowing and the tracing would be flat as shown on the graph to the right of the cells. If there is no deflection (no current), we say that we are at the **isoelectric point**.
- As the first cell depolarizes (B), there now exists a charge difference on the outside of the cells and a dipole (+ and – poles) is established with its electric field between. At this point, we can say there is an electric force vector. The direction of this vector is determined by assessing which direction the depolarization wave is spreading. In “B”, the direction of depolarization propagation is towards the positive sensor (or to the right). The rule of thumb is that if there is a depolarization (outside of cell negative) spreading towards an opposite charge sensor, then (upward) deflection will be recorded.
- In C, the action potential has reached the midpoint, at this point we will get the maximum deflection on the ECG.
- In D, only one cell remains at rest and the tracing is returning toward the isoelectric point.
- In E, all of the cells are depolarized, all negative on the outside and the ECG has returned to the isoelectric point because there is no more dipole and so there is no more dipole electrical vector to record.
- In F, we show how the ECG tracing would look if we repeated the process but this time reversed the position of the electrodes, the positive electrode on the left and the negative on the right.

It should be apparent that where one places the electrodes affects the appearance of the ECG tracings. If a wave of depolarization is moving toward a positive electrode there should be a positive deflection. If it is moving away from a positive electrode toward a negative electrode there would be a negative deflection. If the wave is moving perpendicular to an electrode axis then there will be an equal distribution of positive and negative, thus no deflection. How large the deflection is depends both on how closely the wave is oriented to the axis of the electrodes as well as how much of the heart muscle is involved in the depolarization or repolarization. In a typical ECG the electrodes are placed at different positions to give different "looks" of what is happening in the heart.



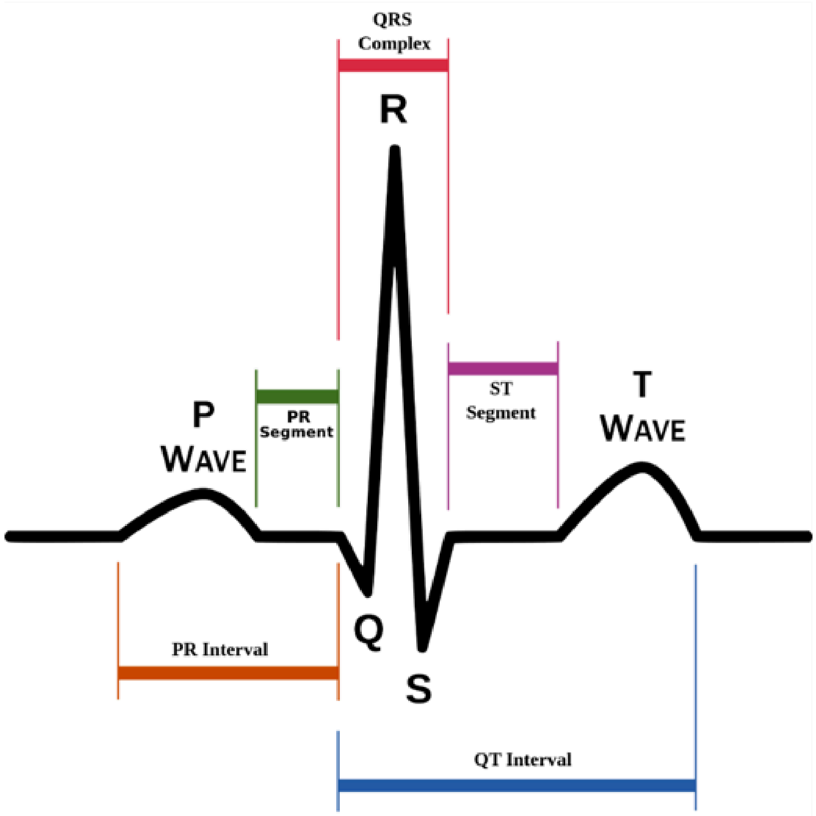
Wave Deflections based on Vector Directions

Created by BYU-Idaho instructor T. Orton Fall 2017

The difference in deflection on ECG determined by if the wave of depolarization/repolarization is traveling toward or away from the positive electrode.

Each different positioning of the electrodes is referred to as a different **lead** and there are 12 leads in a typical ECG.

When all of the electrical events for one cycle are put together we get an ECG tracing.

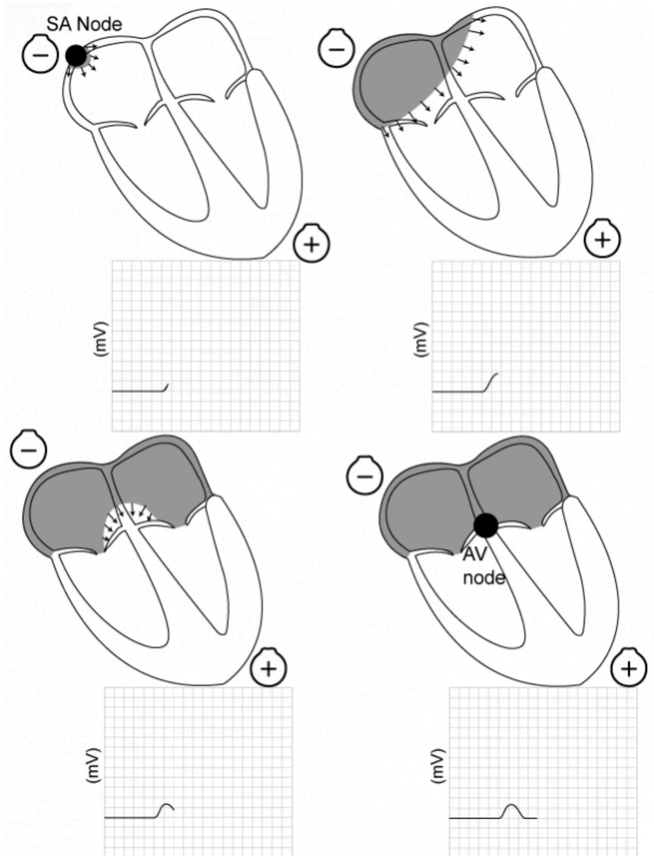


ECG Tracing

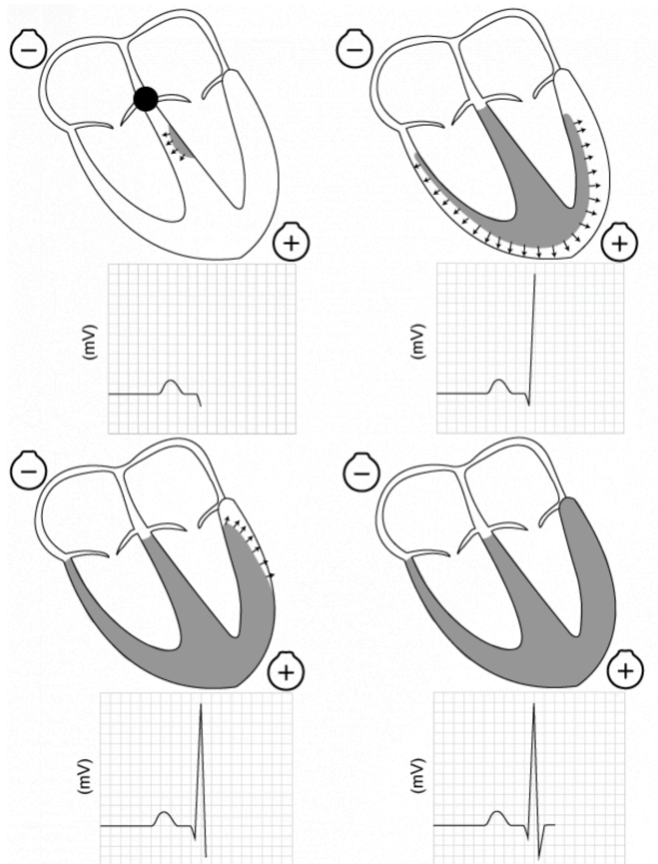
The image above shows a typical ECG. Notice that there are several deflections (some up and some down) that occur during the cycle. Each deflection is referred as a wave and each wave is labeled with a letter. A typical ECG has five waves, P, Q, R, S and T. The **P wave** is generated during depolarization of the atria which causes the atria to contract pushing the blood to the ventricles below. The next three waves (Q, R, S) are generated during depolarization of the ventricles which causes the ventricles to contract forcing the blood out of the heart to the lungs and the rest of the body. Since all are generated during ventricular depolarization we typically refer to these three waves collectively as the **QRS complex**. The Q wave is the first downward deflection and then back to isoelectric, the R is the large upward deflection and then back to isoelectric, and the S is the second downward deflection and back to isoelectric. The final wave, the **T wave**, is generated during repolarization of the ventricles. You may be asking yourself where the wave representing repolarization of the atria is. We typically do not observe a repolarization wave for the atria because it is occurring at the same time the ventricles are depolarizing. Since the muscle mass of the ventricles is so much larger than that of the atria, ventricular depolarization probably masks any waves associated with atrial repolarization. Now let's see if you are getting it. What would the tracing shown in the ECG figure look like if the positive and negative leads were switched?

Hopefully, it is becoming apparent that any change in the heart that affects how the action potential's spread through the tissues can be detected on the ECG. For example, if a section of heart muscle were damaged by a heart attack the tracing would be altered, usually in a predictable manner. With practice, the physician can diagnose many abnormalities based on the shape and timing of the various waves.

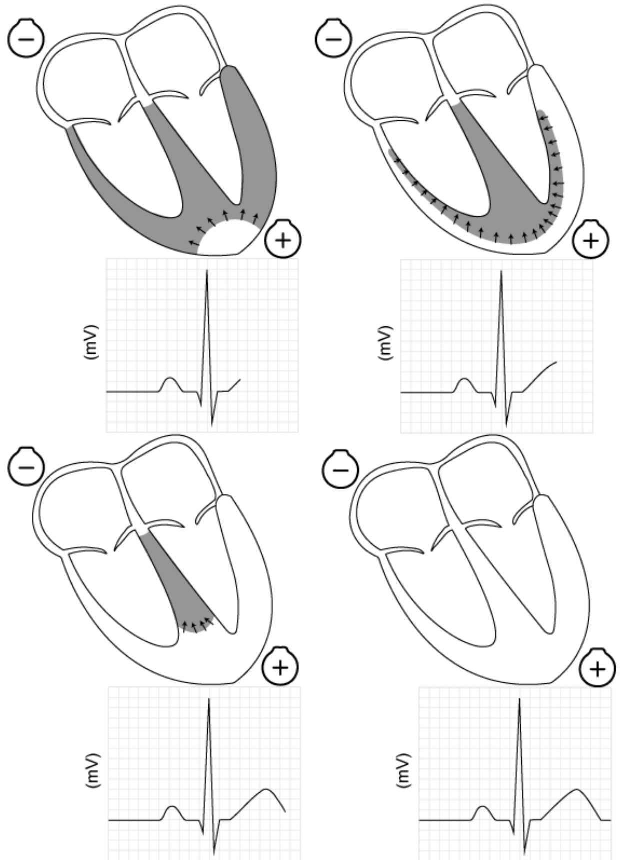
It is important to note that the ECG measures one main thing – the electrical signal as it travels through the heart. It can show if the signal is getting through the conduction fibers as it should or how quickly the heart is beating. In order to measure the strength of the heart you would have to look at several other factors such as: the pressure inside the ventricles at each beat, the resistance of the vessels and/or the volume of blood being ejected with each beat. The figures below illustrate the spread of the action potential across the heart and its associated deflections.



The image above depicts the generation of the P-wave. Notice that depolarization of heart cells begin in the SA node and propogates out in all directions from that point, but the "average" or resultant vector spreading from the SA node is in the general direction of the apex or inferior border of the heart. We see a sensor with positive polarity located below the heart. This depolarization and direction of propogation sends a negative tail vector towards a positive polarity sensor which makes the ECG deflect up.



In the image above we see that the action potential propogation has come from the AV node and has descended down the Bundle of His and into the bundle branches. The propogation descends more quickly down the left bundle branch and creates an opportunity for the left bundle branch to propogate to the right and even in a sligh upward direction in an attempt to depolarize the right bundle branch cells which are propogating more slowly. There will be a temporary depolarizing vector (negative tail) moving in a direction that is more upward (or towards the negative sensor) than downward. At this moment the deflection will be down and makes a Q wave. This is temporary though, and soon the bundle branch cells are all depolarized and continue to descend down the septum. Also, the purkinje fibers will depolarize and propogate the actiton potential to the endocardial surface of the left and right ventricles. This will create a propogation vector that moves from endocardium to epicardium. All of these vectors (down the septum and endocardium to epicardium) form a resultant vector that points to the positive sensor below the heart and this creates a large delfection up (or R wave). The left side of the heart is thicker and has more muscle tissue. This creates a situation where the propogating action potential will finish depolarizing the right ventricle before the left is completed. So, the last portion of tissue to be depolarized will be the superior left ventricle. As this area is depolarized, we will have another small and temporary vector that will point up more than down. This means we will have a depolarizing vector pointing towards the negative sensor on top for just a moment and this caues a small deflection down (or S wave). After the superior portion of the left ventricle is depolarized, we see that the entire ventricular surface is depolarized and all the cells will have a negative charge on the outside of the cell. This means there is not a dipole or separation of charge across the surface of the heart. The ECG will not deflect up or down at this moment but would return to baseline.



Images by JS BYU-Idaho F17

ECG tracing waves explained

Finally, the cells of the apex begin to repolarize. As the cells repolarize in this area, the cells gain positive charges on the outsides of the membrane and a dipole or separation of charge across the heart surface can be measured again. Because we are repolarizing we have a vector that expands the positve charge towards a negative sensor. The reason that the vector is propogating up to the negative sensor instead of down to the positive sensor is because the apex repolarizes first and then the epicardium of the ventricles begins to repolarize and the endocardium of the ventricles is the last to repolarize. There is some belief that after the endocardium repolarizes the papillary muscle inside the ventricles becomes the last tissue to repolarize. It may be that this last repolarization of papillary muscle can create a kind of second bump on the T wave. When this happens it is called a "U-wave". However, we will not explore U waves and we will not ask about them in this course quizzes or exams. Some have asked how it is possible that the endocardium repolarizes so late, given that it depolarized before the epicardium so how does it "know" to wait and repolarize after the epicardium. The answer is that the plateua phases are longer in the endocardium and purkinje fibers and so it takes longer before the repolarization can occur.