1 What is the electrocardiogram (ECG)?

The electrocardiogram (abbreviated as ECG or sometimes EKG) is a skin surface measurement of the electrical activity of the heart over time. It has become a routine part of any complete medical evaluation and has been used as a diagnostic test for over 70 years. An ECG detects the conduction of ions through heart muscle known as the myocardium, which changes with each heart beat (see Figure 1). Doctors use ECGs to detect and diagnose conditions such as arrhythmias (abnormal heart rhythms) and myocardial infarctions (heart attacks).

![Figure 1: An example ECG waveform.](image)

A normal resting heart rate is generally in the range of 60 to 100 beats per minute. Bandwidth requirements for an ECG measurement system vary depending on the application. Monitoring applications generally require a signal bandwidth in the range of 0.5 Hz to 50 Hz. Applications involving pacemakers can require higher bandwidths up to 1 kHz. Standard clinical applications generally have a bandwidth of 0.05 Hz to 100 Hz.
2 Basic Heart Anatomy

To understand how an ECG is generated and why it looks the way it does, let’s start by going over the basic anatomy of the heart. The heart consists of four chambers and four valves (see Figure 2). Deoxygenated blood from the body flows through the superior vena cava into the right atrium. It then is pumped down through the tricuspid valve to the right ventricle, out past the pulmonary valve to the lungs where it is oxygenated. Oxygenated blood flows back into the heart through the left atrium, down past the mitral valve to the left ventricle. Blood is pumped out of the left ventricle, through the aorta to the rest of the body.

![Figure 2: Heart Anatomy](image)

3 Electrical Conduction System

Special cells located in the sinoatrial node (S-A node), atrioventricular node (A-V node) and Purkinje Fibers have what is known as “automaticity.” This property means that they “fire” at a particular rate, which causes the surrounding muscle tissue to contract (see left half of Figure 3). Each normal heart beat starts in the S-A node, which is located in the right atrium. An electrical pathway connects the S-A node to the left atrium, such that when the S-A node fires, both the atria contract around the same time. Conduction continues down to the A-V node, where there is a slight delay before traveling down the Purkinje fibers to the ventricles. The action potentials generated by the different cells in the myocardium sum up to generate the ECG waveform that is measured at the skin surface.
4 The Dipole Model

The dipole model allows us to represent the net charge flowing through the myocardium as a vector originating from the center of a uniformly conducting sphere (vector M, see Figure 4). The projection of this vector in a particular direction is what is known as an ECG “lead.” Each ECG lead provides a different view of the heart vector. There are 12 different ECG leads, but we will focus only on the first three: leads I, II and III (see Figure 5). Leads I, II and III form a triangle when looking at the body. Lead I is the potential difference between the potential at the left arm (LA) and right arm (RA). Lead II is the difference between the left leg (LL) and RA. Lead III is the difference between the left leg (LL) and LA.

5 A Look at a Full Cardiac Cycle

Cells in the myocardium “fire” and cause muscle tissue to contract. Contraction is caused by ions flowing through the myocardium from cell to cell. As these ions enter the cell, they change the voltage potential within the cell. This process is known as depolarization. The process of restoring the cell’s original membrane potential is called repolarization. Let’s walk through a full cardiac cycle. Illustrations of each step can be found in Figures 6 and 7.

1. Atrial Depolarization - Each cardiac cycle begins with an action potential originating in the S-A node. This action potential causes the atria to begin to depolarize. The P wave begins to form.
2. **Septal Depolarization** - After a delay at the A-V node, the septum (space between the ventricles) begins to depolarize. The Q wave is visible in Leads I and II.

3. **Apical Depolarization** - The apex of the ventricles begins to depolarize. The R wave becomes more visible in all three leads.

4. **L. Ventricular Depolarization** - The depolarization vector finishes depolarizing the ventricles with the left ventricle. The R wave amplitude approaches its maximum. The S wave is visible in Lead III.

5. **Late. L. Ventricular Depolarization** - Ventricles are almost completely depolarized. Peak of S wave in Lead III.

6. **Ventricles Depolarized** - The ventricles are completely depolarized. The heart vector is zero and there is no signal.

7. **Ventricular Repolarization** - Ventricles begin to repolarize. T wave becomes visible in all leads.

8. **Ventricles Repolarized** - Cardiac cycle complete. T wave finishes.

### 6 Summary

The electrocardiogram is a skin-surface measurement of the electrical vector generated by the heart with each heart beat. Cells have “automaticity” that causes them to fire at regular intervals. Potentials generated by these cells flow through the heart muscle (myocardium) in predictable patterns to generate the ECG waveform measured on the skin.
Figure 5: The frontal leads

Figure 6: A Look at the full cardiac cycle, part 1.
Figure 7: A Look at the full cardiac cycle, part 2.