CHAPTER 2
THE HEART AND THE ECG SIGNAL

2.1 Anatomy and Physiology of the Heart

The heart, whose sole purpose is to circulate blood through the circulatory system (the blood vessels of the body), consists of four hollow chambers as shown in figure 2.1. The upper two chambers, the right and left atria, are thin-walled; the lower two, the right and left ventricles are thick-walled and muscular. The walls of the ventricles are composed of three layers of tissue: the innermost thin layer is called the endocardium; the middle thick, muscular layer, the myocardium; and the outermost thin layer, the epicardium. The walls of the left ventricle are more muscular and about three times thicker than those of the right ventricle.

Figure 2.1. Anatomy of the heart

The atrial walls are also composed of three layers of tissue like those of the ventricles, but the middle muscular layer is much thinner. The two atria form the
base of the heart; the ventricles form the apex of the heart. The interatrial septum (a thin membranous wall) separates the two atria, and a thicker, more muscular wall, the interventricular septum, separates the two ventricles. The two septa, in effect, divide the heart into two pumping systems, the right heart and the left heart, each one consisting of an atrium and a ventricle.

The right heart pumps blood into the pulmonary circulation (the blood vessels within the lungs and those carrying blood to and from the lungs). The left heart pumps blood into the systemic circulation (the blood vessels in the rest of the body and those carrying blood to and from the body). The right atrium receives unoxygenated blood from the body via two of the body's largest veins (the superior vena cava and inferior vena cava) and from the heart itself by way of the coronary sinus. The blood is delivered to the right ventricle through the tricuspid valve. The right ventricle then pumps the unoxygenated blood through the pulmonic valve and into the lungs via the pulmonary artery. In the lungs, the blood picks up oxygen and releases excess carbon dioxide.

The left atrium receives the newly oxygenated blood from the lungs via the pulmonary veins and delivers it to the left ventricle through the mitral valve. The left ventricle then pumps the oxygenated blood out through the aortic valve and into the aorta, the largest artery in the body. From the aorta, the blood is distributed throughout the body where the blood releases oxygen to the cells and collects carbon dioxide from them. The heart performs its pumping action over and over in a rhythmic sequence. First, the atria relax (atrial diastole), allowing the blood to pour in from the body and lungs. As the atria fill with blood, the atrial pressure rises above that in the ventricles, forcing the tricuspid and mitral valves to open.
and allowing the blood to empty rapidly into the relaxed ventricles. Then the atria contract (atrial systole), filling the ventricles to capacity.

Following the contraction of the atria, the pressures in the atria and ventricles equalize, and the tricuspid and mitral valves begin to close. Then, the ventricles contract vigorously, causing the ventricular pressure to rise sharply. The tricuspid and mitral valves close completely, and the aortic and pulmonic valves snap open, allowing the blood to be ejected forcefully into the pulmonary and systemic circulations. Meanwhile, the atria are again relaxing and filling with blood. As soon as the ventricles empty of blood and begin to relax, the ventricular pressure falls, the aortic and pulmonic valves shut tightly, the tricuspid and mitral valves open, and the rhythmic cardiac sequence begins anew.

The period from the opening of the aortic and pulmonic valves to their closing, during which the ventricles contract and empty of blood, is called ventricular systole. The following period from the closure of the aortic and pulmonic valves to their reopening, during which the ventricles relax and fill with blood, is called ventricular diastole. The sequence of one ventricular systole followed by a ventricular diastole is called the cardiac cycle, commonly defined as the period from the beginning of one heart beat to the beginning of the next.

2.2 Electrical Conduction System of the Heart

The electrical conduction system of the heart shown in figure 2.2 is composed of the following structures:

- Sinoatrial (SA) node.
- Internodal atrial conduction tracts and the interatrial conduction tract (Bachmann's bundle).
- Atrioventricular (AV) junction consisting of the atrioventricular (AV) node and bundle of His.
- Right bundle branch, left bundle branch, and left anterior and posterior fascicles.
- Purkinje network.

The prime function of the electrical conduction system of the heart is to transmit minute electrical impulses from the SA node (where they are normally generated) to the atria and ventricles, causing them to contract. The SA node lies in the wall of the right atrium near the inlet of the superior vena cava. It consists of pacemaker cells that generate electrical impulses automatically and regularly.

![Figure 2.2. Electrical conduction system of the heart](image)

The three internodal atrial conduction tracts, running through the walls of the right atrium between the SA node and the AV node, conduct the electrical impulses rapidly from the SA node to the AV node in about 0.03 second. The interatrial conduction tract (Bachmann’s bundle), a branch of one of the internodal atrial conduction tracts, extends across the atria, conducting the electrical impulses...
from the SA node to the left atrium. The AV node lies partly in the right side of the interatrial septum in front of the opening of the coronary sinus and partly in the upper part of the interventricular septum above the base of the tricuspid valve. The primary function of the AV node is to relay the electrical impulses from the atria into the ventricles in an orderly and timely way. A ring of fibrous tissue insulates the remainder of the atria from the ventricles, preventing electrical impulses from entering the ventricles except through the AV node.

The electrical impulses slow as they travel through the AV node, taking about 0.06 to 0.12 second to reach the bundle of His. The delay is such that the atria can contract and empty, and the ventricles fill before they are stimulated to contract. The bundle of His lies in the upper part of the interventricular septum, connecting the AV node with the two bundle branches. Once the electrical impulses enter the bundle of His, they travel more rapidly on their way to the bundle branches, taking 0.03 to 0.05 second. The left common bundle branch further divides into two major divisions: the left anterior fascicle and the left posterior fascicle. The bundle branches and their fascicles subdivide into smaller and smaller branches, the smallest ones connecting with the Purkinje network, an intricate web of tiny Purkinje fibers spread widely throughout the ventricles beneath the endocardium.

The ends of the Purkinje fibers finally terminate at the myocardial cells. The bundle of His, the right and left bundle branches, and the Purkinje network are also known as the His-Purkinje system of the ventricles. The electrical impulses travel very rapidly to the Purkinje network through the bundle branches in less than 0.01
second. All in all, it normally takes the electrical impulses less than 0.2 second to travel from the SA node to the Purkinje network in the ventricles.

2.3 Electrophysiology of the Heart

Cardiac cells are capable of generating and conducting electrical impulses that are responsible for the contraction and relaxation of myocardial cells. These electrical impulses are the result of brief but rapid flow of positively charged ions (primarily sodium and potassium ions and, to a lesser extent, calcium ions) back and forth across the cardiac cell membrane. The difference in the concentration of such ions across the cell membrane at any given instant is called the electrical potential and is measured in millivolts (mV).

When a myocardial cell, for example, is in the resting state, a high concentration of positively charged sodium ions ($\text{Na}^+$) (cations) is present outside the cell. The resting cardiac cell can be depicted as having a layer of positive ions surrounding the cell membrane and an equal number of negative ions lining the inside of the cell membrane directly opposite each positive ion. When the ions are so aligned, the resting cell is called “polarized.”

Upon stimulation by an electrical impulse, the membrane of a polarized myocardial cell, for example, becomes permeable to positively charged sodium ions, allowing sodium to flow into the cell. This causes the interior of the cell to become less negative. At the moment when the interior of the cell becomes maximally positive and the exterior maximally negative, the cell is “depolarized.” The process by which the cell’s resting, polarized state is reversed is called depolarization as shown in figure 2.3.
Depolarization and repolarization of a muscle fiber.

The fast sodium channels are typically found in the myocardial cells and the specialized cells of the electrical conduction system other than those of the SA and AV nodes. The cells of the SA and AV nodes have, instead of fast sodium channels, slow calcium-sodium channels the open when the membrane potential drops to about -50 mV. They permit the entry of positively charged calcium and sodium ions into the cells during depolarization at a slow and gradual rate. The result is a slower rate of depolarization as compared to the depolarization of cardiac cells with fast sodium channels. As soon as a cardiac cell depolarizes, positively charged potassium ions flow out of the cell, initiating a process by which the cell returns to its resting, polarized state. This process, called repolarization, involves a complex exchange of sodium, calcium, and potassium ions across the cell membrane.
Depolarization of one cardiac cell acts as an electrical impulse (or stimulus) to adjacent cells and causes them to depolarize. The propagation of the electrical impulse from cell to cell produces a wave of depolarization which can be measured as an electric current flowing in the direction of depolarization. As the cells repolarize, another electric current is produced, similar to, but opposite in direction to, the first one. The direction of flow and magnitude of the electric currents generated by the depolarization and repolarization of the myocardial cells of the atria and ventricles can be detected by surface electrodes and recorded as the electrocardiogram (ECG). Depolarization of the myocardial cells produces the P wave and QRS complex, and repolarization of the cells results in the T wave in the electrocardiogram.

2.4 The Electrocardiogram

2.4.1 Electrical Basis of the Electrocardiogram

The electrocardiogram (ECG) is a graphic record of the changes in magnitude and direction of the electrical activity, or, more specifically, the electric current, that is generated by the depolarization and repolarization of the atria and ventricles as shown in figure 2.4. This electrical activity is readily detected by electrodes attached to the skin. But neither the electrical activity that results from the generation and transmission of electrical impulses which are too feeble to be detected by skin electrodes nor the mechanical contractions and relaxations of the atria and ventricles (which do not generate electrical activity) appear in the electrocardiogram.
2.4.2 Components of the Electrocardiogram

After the electric current generated by depolarization and repolarization of the atria and ventricles is detected by electrodes, it is amplified, displayed on an oscilloscope, recorded on ECG paper, or stored in memory. The electric current generated by atrial depolarization is recorded as the P wave, and that generated by ventricular depolarization is recorded as the Q, R, and S waves: the QRS complex. Atrial repolarization is recorded as the atrial T wave (Ta), and ventricular repolarization, as the ventricular T wave, or simply, the T wave. Because atrial repolarization normally occurs during ventricular depolarization, the atrial T wave
is buried or hidden in the QRS complex. In a normal cardiac cycle, the P wave occurs first, followed by the QRS complex and the T wave as shown in Figure 2.5.

![ECG Components](image)

**Figure 2.5 - Components of the ECG.**

The sections of the ECG between the waves and complexes are called segments and intervals: the PR segment, the ST segment, the TP segment, the PR interval, the QT interval[40], and the R-R interval. Intervals include waves and complexes, whereas segments do not. When electrical activity of the heart is not being detected, the ECG is a straight, flat line — the isoelectric line or baseline[23],[24],[26].

### 2.4.3 ECG Leads

An ECG lead is a record (spatial sampling) of the electrical activity generated by the heart that is sensed by either one of two ways: (1) two discrete electrodes of opposite polarity or (2) one discrete positive electrode and an "indifferent," zero reference point. A lead composed of two discrete electrodes of opposite polarity is called a bipolar lead; a lead composed of a single discrete positive electrode and a zero reference point is a unipolar lead. Depending on the ECG lead being recorded, the positive electrode may be attached to the right or left
arm, the left leg, or one of several locations on the anterior chest wall. The negative electrode is usually attached to an opposite arm or leg or to a reference point made by connecting the limb electrodes together. For a detailed analysis of the heart’s electrical activity, usually in the hospital setting, an ECG recorded from 12 separate leads (the 12-lead ECG) is used. The 12-lead ECG is also used in the pre-hospital phase of emergency care in certain advanced life support services to diagnose acute myocardial infraction and to help in the identification of certain arrhythmias. A 12-lead ECG consists of three standard (bipolar) limb leads (leads I, II, and III) as shown in figure 2.6, Three augmented (unipolar) leads (leads aVR, aVL, and aVF) as shown in figure 2.7, and six pre-cordial (unipolar) leads (V₁, V₂, V₃, V₄, V₅, and V₆) as shown in figure 2.8.

Figure 2.6- The standard (bipolar) limb leads I, II, and III
When monitoring the heart solely for arrhythmias, a single ECG lead, such as the standard limb lead II, is commonly used, especially in the pre-hospital phase of emergency care[71].

Figure 2.7 - The augmented (unipolar) leads aVR, aVL, and aVF

Figure 2.8 - Pre-cordial (unipolar) leads