# CHAPTER - 3

## THE HEART AND THE ECG SIGNAL

### Table of Contents

<table>
<thead>
<tr>
<th>S.No.</th>
<th>Name of the sub-title</th>
<th>Page No.</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.1</td>
<td>The Heart</td>
<td>24</td>
</tr>
<tr>
<td></td>
<td>3.1.1 Anatomy and Physiology of the Heart</td>
<td>24-26</td>
</tr>
<tr>
<td></td>
<td>3.1.2 Electrical conduction system of the Heart</td>
<td>27-29</td>
</tr>
<tr>
<td></td>
<td>3.1.3 Electrophysiology of the Heart</td>
<td>29-32</td>
</tr>
<tr>
<td>3.2</td>
<td>The Electrocardiogram</td>
<td>32</td>
</tr>
<tr>
<td></td>
<td>3.2.1 Electrical basis of the Electrocardiogram</td>
<td>32-33</td>
</tr>
<tr>
<td></td>
<td>3.2.2 Components of the Electrocardiogram</td>
<td>33-34</td>
</tr>
<tr>
<td></td>
<td>3.2.3 Standard ECG measurement</td>
<td>34-37</td>
</tr>
<tr>
<td></td>
<td>3.2.4 ECG Sensor requirements</td>
<td>37</td>
</tr>
<tr>
<td></td>
<td>3.2.5 ECG Electrodes</td>
<td>38-41</td>
</tr>
<tr>
<td></td>
<td>3.2.6 Noise Sources</td>
<td>42</td>
</tr>
<tr>
<td></td>
<td>3.2.7 AC Mains interface</td>
<td>43</td>
</tr>
<tr>
<td></td>
<td>3.2.8 Biological noise sources</td>
<td>43</td>
</tr>
<tr>
<td>3.3</td>
<td>Heart Beat</td>
<td>43-45</td>
</tr>
</tbody>
</table>
3. THE HEART AND THE ECG SIGNAL

3.1 The Heart

3.1.1 Anatomy and Physiology of the Heart

The heart which consists of four hollow chambers to circulate blood via circulatory system is shown in figure 3.1 [39]. The upper two chambers are thin-walled and the lower two chambers 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 endocardium. The walls of the left ventricle are most muscular and about three times thicker than those of the right ventricle.
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 bottom of the heart and the ventricles from top of the heart. The two atria’s separated by a thin membranous wall and ventricles are separated by a thick interventricular system. The heart is divided into two pumping systems by the two septa, the left and right heart, each consisting of an atrium and a ventricle.

The blood is pumped into the systematic circulation (the blood vessels in the entire body except lungs and those carrying blood to and from the body) by the left heart and the blood pumped into the pulmonary circulation (the blood vessels within the lungs and those carrying blood to and from the lungs) by the right heart. The unoxygenated is blood received by the right atrium through largest veins of the body namely superior vena cava and inferior vena cava. Inside the lungs the blood picks up oxygen and releases CO₂.

Newly oxygenated blood in the lungs is received through the pulmonary veins and this blood is transferred to the left ventricle through the mitral valve. From here the oxygenated blood pumps into aorta via aortic valve. Aorta is the largest artery in the body, which distributes the oxygenated blood into entire body. Here, the blood releases the oxygen into cell and collects the CO₂ from the cells. 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 ventricles systole is period from opening of the aortic as well as pulmonic valves. During this period, blood vacates from ventricles and this causes ventricles contraction. Ventricles diastole is the period from the closure of the aortic and pulmonic valves to their reopening. 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.

3.1.2 Electrical conduction system of the Heart
Figure 3.2 shows the electrical conduction system of the heart which is composed of the following structures:

1. Sinoatrial node.
2. Bavhmann’s bundle.
3. Atrioventricular junction consists of atrioventricular node and bundle of His.
4. Right bundle branch, left bundle branch, and left anterior and posterior fascicles.
5. Purkinje network.

**Fig.3.2: Electrical Conduction system of the heart**

The electrical conduction system of the heart transmits the small electrical impulses from the SA node to the ventricles and atria, causing them to contract. The SA node present in the wall of right atrium which is near the inlet of the superior vena cava. It includes pacemakers, which are
responsible on the generation of electrical impulses automatically and regularly.

The tri intermodal atrial conduction tracts, running along the walls of the right atrium in between SA and AV node, conducts the electrical impulses rapidly from SA node to AV node within time period of 0.03 seconds. The bavhmann’s bundle, which is a branch of the intermodal atrial conduction tracts, extends over the atria, conducts electrical impulses from the SA node to the left atrium. The AV node lies slightly in the right side of the interatrial septum in front of the opening of the coronary sinus and slightly in the upper part of the interventricular septum above the base of the tricuspid value. The important task of AV node is to switch the electrical impulses from the atria into the ventricles in timely and orderly way.

A ring of fibrous tissue insulates the reminder 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 bavhmann’s bundle of His appears in the upper part of the interventricular system, which connects the AV node with the 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 is further divided into left anterior fascicle and the left posterior fascicle. The bundle branches and their
fascicles sub divide into number of smaller branches, the smallest ones connected with 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 bahvmann’s bundle of His, left and right bundle branches, and the purkinjee network are also known as His-purkinjee system of the ventricles. The electrical impulses travel very rapidly to the Purkinje network through the bundle branches in less than 0.01 second. The electric impulses take 0.2 seconds to move from SA node to purkinje network in the ventricles.

**3.1.3 Electrophysiology of the Heart**

Cardial cells have the capability to generate and conduct the electrical impulses that are meant for the relaxation and contraction of myocardial cells. These electrical impulses are generated by the movement of positively charged ions back and forth over the cardiac cell membrane. The variation in amount of such ions across the cell membrane at any given instant is called the electrical potential and is measured in millivlots (mV).

When a myocardial cell, for example, is in the resting state, a high concentration of positively charged sodium ions (Na⁺) (cations) is present outside the cell. The resulting cardiac cell can be depicted as a cell 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 be 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 3.3.

Fast sodium channels usually found inside myocardial cells and specialized cells of the electrical conduction system apart from those of the SA as well as AV nodes. The cells of the SA and AV nodes have, instead of
fast sodium channels; slow calcium-sodium channels open, when the membrane potential drops to about -50 mV. They allow positively charged calcium and sodium ions into cells at slow along gradual rate during depolarization. The result is slower rate of the depolarization when compared to the cardiac cell depolarization with fast sodium cells. When depolarization of cardiac cell occurs, positively charged potassium ions will come out of cell, by initiating a process in which the cell returns to its resting state i.e., polarized state. This process is called as repolarization, which involves a complex exchange of sodium, calcium and potassium ions across the cell membrane.

One cardiac cell depolarization acts as an electrical impulse to adjacent cells and causes them to depolarize. An electrical impulse propagating from cell to cell causes depolarization which is the result of current flow in the direction of depolarization. In the process of repolarization, similar current is produced but in opposite direction. The electric currents which are generated by depolarization and repolarization of the myocardial cells of the atria and ventricles can be identified by surface electrodes and recorded as 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.

3.2 The Electrocardiogram

3.2.1 Electrical basis of the Electrocardiogram

A graphical record of the changes in magnitude and the direction of the electrical activity is nothing but Electrocardiogram (ECG). The electric
current is generated by the repolarization and depolarization of the ventricles and atria. This electrical activity is depicted in figure 3.4. The electrical activity is detected with the use of electrodes which are probed to the skin. But neither the electrical activity that results from the generation and transmission of electrical impulses which are feeble to be observed by skin electrodes nor the mechanical contractions and relaxations of the atria and ventricles appear in the electrocardiogram.

3.2.2 Components of the Electrocardiogram

The electrical activity detected with the help of electrodes is amplified, displayed on an oscilloscope, recorded on ECG paper or stored in memory. The P wave represents the electric current obtained by atrial depolarization. In a similar way Q, R and S waves represents the electric current produced
by the ventricular depolarization. The atrial T wave (Ta) is obtained by atrial repolarization and ventricular T wave is obtained by ventricular repolarization. Atrial T wave is hidden in the QRS complex due to the occurrence of atrial repolarization during ventricular depolarization. Figure 3.5 shows the occurrence of P wave, QRS complex and T wave in a general cardiac cycle.

![Fig.3.5: Typical ECG waveform](image)

The parts of ECG between the waves and complexes are known as intervals and segments namely the P-R interval, the R-R interval, the Q-T interval, the P-R segment, the S-T segment, and the T-P segment [27]. Segments do not have walls and complexes whereas intervals have. The ECG looks like an iso-electric line when electrical activity of the heart is not being detected [40], [41], [42].

### 3.2.3 Standard ECG measurement
The electrical impulses generated within the heart behave like a voltage source causes a flow of current in the torso and the concerned potentials on the skin. There is a possibility to model the potential distribution, if the heart is a time varying electric dipole. Figure 3.6 shows the location of electric dipole by the vector M.

![Fig.3.6: Vector model of Heart and electrode interaction](image)

Electric voltage can be observed between any two points of the body by placing two leads on the two points and is a dot product of two vectors. So to obtain a full picture of cardiac vector, it is necessary to have multiple leads and continuous measurement of electric voltage. Three electrodes are required in order to provide an exact representation of the frontal projection of the cardiac vectors. These electrodes are placed on the three vertices of the Einthoven triangle. The concept of 60 degree projection allows connecting the three electrodes to the limbs [43].

Today further electrode connection points are being utilized by modern standard ECG measurement. The ECG consists of 12 leads, among
them three are bipolar limb leads, another three are augmented referenced limb leads and six are Wilson terminal referenced chest leads. Another look at the cardiac vector which is projected on the frontal plane is provided by augmented lead system but from Einthoven triangle configuration. It is rotated by 30 degrees. The cardiac vector observation is allowed on the transverse plane this is possible because of the connection of six electrodes put on to the specific positions on the chest and the used of an indifferent electrode formed by summing the three limb leads. Modern ECG is provided with a microprocessor, 12 to 16-bit ADC in addition to dedicated I/O processors.

A small pad which is in triangular shape and the perimeter of the triangle totally encircles the heart is usually placed on patients chest for ECG monitoring. This triangle is known as Einthoven triangle. The places where the leads are located on the human body are labeled as: left arm (LA), right arm (RA) and left leg (LL). Here, Right Leg is considered as reference lead. Roman numerals are used for numbering the corresponding waveforms. These small leads are connected back to a monitoring system to measure the potential difference around the heart. Based on the results obtained, the doctors diagnose the patients.

The three leads are obtained from Einthoven Triangle. They are:

Lead – I = Voltage at Left Arm – Voltage at Right arm

Lead – II = Voltage at Left Leg – Voltage at Right arm

Lead – III = Voltage at Left Leg – Voltage at Left arm
3.2.4 Sensor requirements of ECG

The ECG sensor must be capable to measure the signal which is very weak. Generally even if strongest ECG signal is considered, it will have very less magnitude of the order of 10mv. The following are the requirements for a typical ECG sensor.

1. It must be capable to sense the low amplitude signals of the order of 0.05 to 10 milli volts.
2. It should have capacity to deal with high input impedance greater than 5 ohms and low input leakage current less than one micro ampere.
3. It should have frequency response in the range of 0.05 to 100 Hz.
4. High CMRR.

3.2.5 ECG electrodes
A web of wires connected to adhesive electrodes is used for monitoring patient vital signs in medical procedures such as in surgery [44]. Cardiac monitoring in turn provides cardiac rhythm analysis and 12-lead ECG allows this analysis in more diagnostically. The electrical activity of the heart is recorded by electrocardiogram. The electrical impulses flow between two leads at one time is depicted by using cardiac monitoring, whereas 12-lead ECG gives the information about the electric impulse transmission from 12 different points of the heart, along a frontal and a horizontal plane [45]. A myocardial infarction diagnosing needs all 12 leads but only II, V1 and V6 will be typically viewed for most of cardiac monitoring situations, with the help of four electrodes limb leads. These leads include the standard and the augmented leads. The four electrodes are positioned on the right, left legs, left, right arms. These four electrodes provide six electrical views of the heart such as I, II, III, aVR, aVL and aVF. Lead I, lead II and lead III which are standard limb leads utilizes the right arm, left arm, and left leg respectively. The augmented limb leads consists of aVR, aVL and aVF utilizes all four electrodes. Augmented leads are so-named because of the need of the ECG machine to magnify the waveforms to obtain an adequate tracing. The electrical activity of the heart along a frontal plane is viewed from top of the heart to the bottom of the heart or from right to the left of the heart by limb leads. There are six additional leads namely V1, V2, V3, V4, V5, and V6 which are used to view the heart in its cross sectional view. These leads are termed as precordial leads.

**ECG Procedure:** Cardiac Monitoring
Cardiac monitoring allows the user to view patient’s electrical activity throughout 24 hours, but it doesn’t allow viewing the electrical activity at any time.

It is a cumbersome method for monitoring. To obtain an accurate data, proper placement of electrodes is necessary in cardiac monitoring or 12-lead ECG. A gel is applied on the place where the electrodes need to be placed and the skin needs to be cleaned and dried to have better conduction of electrodes. Cardiac monitoring can also be done by using 3 or 5 lead wire systems. Figure 3.8 shows the 3-lead configuration. The three leads are positive, negative and ground.

![Three-lead wire electrode placement](image)

**Fig.3.8: Three-lead wire electrode placement**

Another method of cardiac monitoring is a five lead wire system. The placement of five lead electrodes is displayed in figure 3.9
Fig.3.9: Five-lead wire electrode placement

The five lead wires are generally color coded to provide accuracy of placement on the patient’s chest as designated below.

They are:

1. Right Arm – White
2. Left Arm - Black
3. Right Leg - Green
4. Left Leg - Red
5. Ground - Brown leafy

The electrical activity of the heart can be interpreted by using a 12-lead ECG system. It requires placing of electrodes on lower leg and upper arm for monitoring standard and augmented leads along with frontal plane. In addition to this, the electrical activity of horizontal plane can be measured by using additional chest leads through assessment of V1 to V6. Fig.3.10 shows the 12-lead wire electrode placement.
Fig. 3.10: 12-Lead Electrode Placement

3.2.6 Noise Sources
There are four types of noise coupling mechanisms. They are noise capacitive, inductive, conductive and radio-active coupling mechanisms. Capacitive coupling is due to changing electric fields in the vicinity of signal path with respect to time. Inductive coupling is due to the changing magnetic fields in the area encircled by the signal circuit. The result of sharing current from different circuits in common impedance is known as conductive coupling. If the separation between an electromagnetic field and the signal circuit is too large, the coupling of magnetic and electric fields is called as radioactive coupling. The noise is of two types: One is thermal noise and the other one is crosstalk. The noise sources with coupling mechanisms are shown in figure 3.11.

**Fig.3.11: Typical noise sources and coupling mechanisms**

### 3.2.7 AC Mains Interference
In bio medicine signaling, the interference is commonly due to the 50 Hz mains power line frequency and their components. The coupling of AC interference into the system is due to fluorescent lamps. The commonly used coupling mechanisms are magnetic or capacitive. The most efficient coupling mechanism is capacitive coupling.

### 3.2.8 Biological Noise Sources

When an electrode is placed on the skin, a slow changing voltage (up to ± 300 mV) will be displayed. If the electrodes are not properly connected, the voltage can change and causes to noise interference with ECG signal. A movement in the human body disturbs the electrode connections and causes unnecessary effects in the measured signal. When the human body is at rest or relaxed state, the best ECG signal will be obtained. The preparation of the skin to remove poorly conducting dead skin and effective electrode attachment plays a vital role in obtaining a good ECG signal.

### 3.3 Heart Beat

**Physiology of the Heart:**

The number of heart beats per minute is referred as heart rate. It is regulated by the sympathetic fibers to the heart, middle and inferior cardiac nerves etc. To maintain a good circulation of the blood during an activity, the heart beats should be very fast. For adults the normal resting heart rate is about 60-80 beats/min, depending upon physical fitness of a person. If the heart rate is about 80-85 beats/min, it is considered to be normal state. A heart rate above 100 beats/min is considered to be high. A person is under stress; too much caffeine heart rate is elevated. For physically active
people, their resting heart rate can be 60 beats/min or below. During a normal daily routine (and not having consumed too much caffeine) a heart rate of 80-84 beats/min is normal.

The cardiac cycle:

Cardiac cycle is defined as the number of events that will occur in one heart beat. Average heart beat rate will be around 72 beats/min and each beat will come to end by 0.8 sec. Stroke volume is defined as the pumping of 70 cc of blood in one stroke. During physical activity of a person, five liters of blood tend to be pumped per minute.

Action potentials of cardiac cells:

- Rapid Depolarization:

  The rapid depolarization is caused due to sodium channels are opened and the membrane suddenly becomes permeable to sodium.

- The Plateau:

  The sodium and calcium channels are called slow channels and when the sodium channels become closed, the calcium channels will open.

- Repolarization:

  As the plateau continues, calcium channels begin to close while slow potassium channels begin to open.

Refractory Period:
- The membrane will not respond in the interval for which an active potential starts. This interval is known as Refractory Period.
- Absolute Refractory Period – In this period, the membrane will not respond at all.
- Relative Refractory Period – In this period, Sodium channels are closed and have the ability to open.
- Heart beat depends on sodium, potassium and calcium to cause a heartbeat.

Conducting system:

- In the absence of neural or hormonal simulation, cardiac muscle contacts on its own. This process is termed as automaticity.
- The system which is conducting is a network with special cardiac cells, which initiate and distribute electric impulses.