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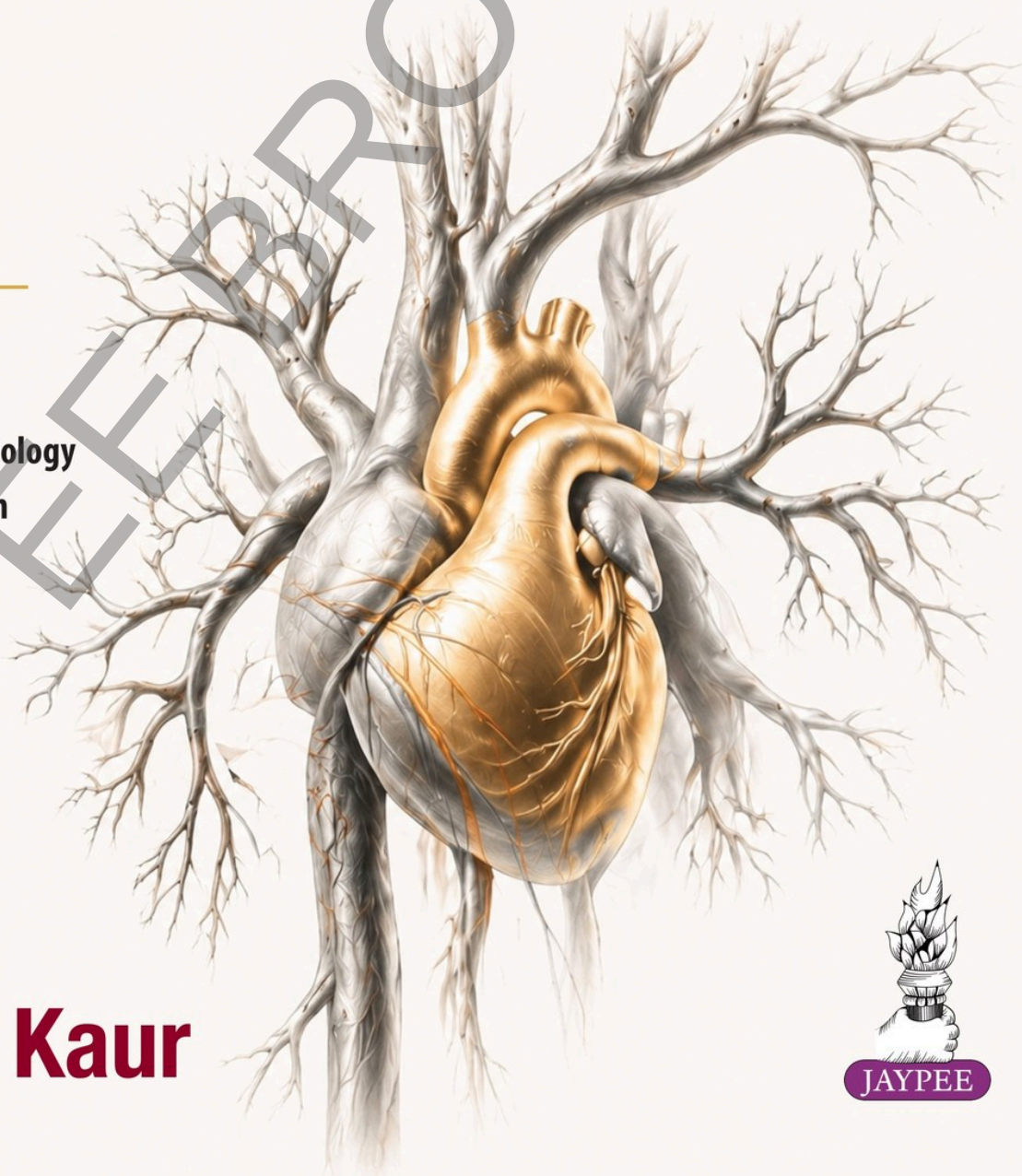
Simplified

Textbook of Physiology

Concepts With Clinical Insights

Volume **1**

- General Physiology
- Hematology
- Nerve and Muscle Physiology
- Gastrointestinal System
- Cardiovascular System
- Respiratory Physiology



Manjinder Kaur

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CHAPTER 38

Basics of Electrocardiography

Learning Objectives

At the end of reading this chapter, students will be able to:

- Describe the basic principles of electrocardiography.
- Describe the spread of cardiac impulse resulting the electrical changes in heart.
- Describe the physiological basis of various components of ECG.
- Describe the normal ECG and its physiological significance.

Myocardium is an excitable tissue which responds to electrical changes and results in myocardial contraction. The cardiac impulse generated by the SA node spreads through the entire heart through the conducting system of the heart (discussed in Chapter 5.2). While spreading from the SA node to Purkinje fibers, a dipole is created in the heart, resulting in the ***flow of current from areas of depolarization (negatively charged in ECF) to polarized/resting (positively charged in ECF) areas creating a current sink*** **(Fig. 38.1)**.

These electrical changes vary with the flow of current from one point to another, hence altering the magnitude and direction of dipole created. These changes result in variations in the instantaneous vector of current in terms of direction and magnitude of current and voltage of myocardium (discussed later). There are two main ways to record these changes, either by directly inserting the recording electrodes at various points of the myocardium ***(monophasic recording)*** or by picking up these electrical changes from the body surface ***(electrocardiography)***. The simple explanation that can be given for this procedure is that our body is mainly composed of water and electrolytes, which act as volume conductor and allows these electrical changes to be transmitted to our body surface which can be picked up by simple electrodes. Hence, electrocardiography is defined as ***surface recording of electrical changes taking place in heart from beat to beat (i.e., recording of the electrical changes during the cardiac cycle)***.

It is similar to cardiac action potential **(Fig. 38.2)**. The differences between ECG with that of cardiac action potential is shown in **Table 38.1**.

The surface recording is done using 2 electrodes, hence they yield a biphasic recording, as shown in **Figure 38.3**.

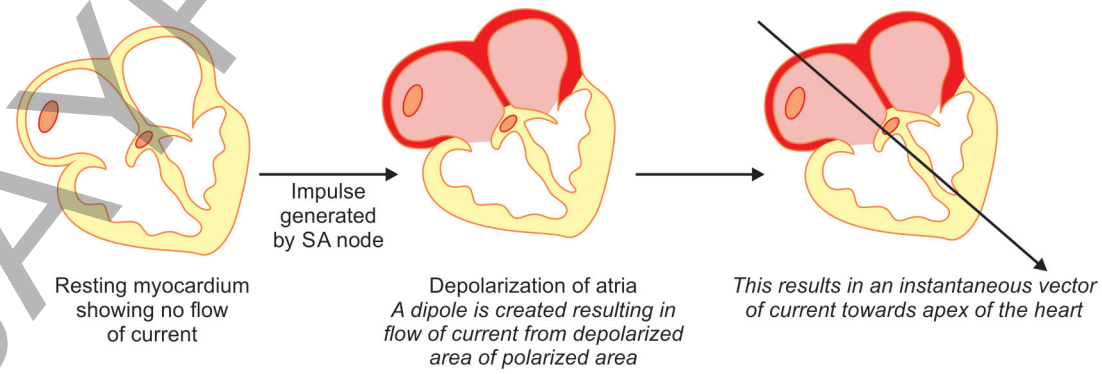


Fig. 38.1: Principle of dipole for flow of current in heart.

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Table 38.1: Features of ECG vs cardiac action potential.

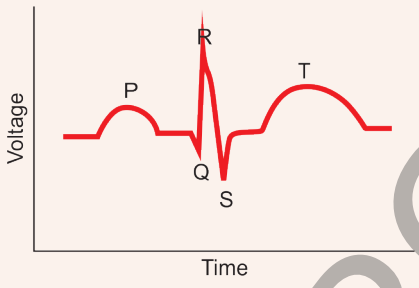
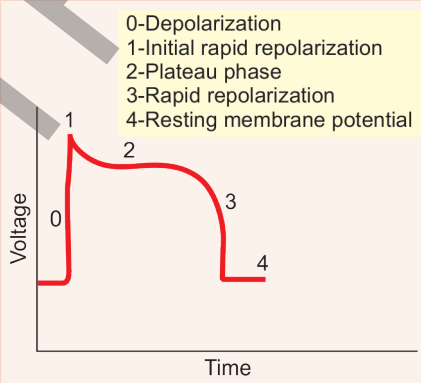
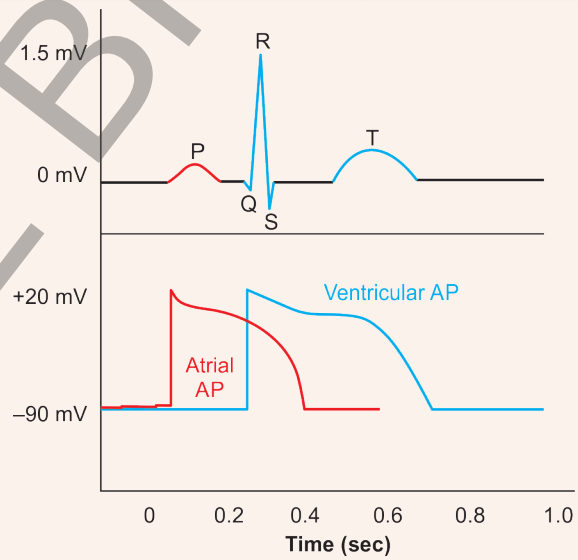
Features	ECG	Cardiac action potential
Type of event	Electrical event showing the phases of depolarization and repolarization.	Electrical event showing the phases of depolarization and repolarization
Electrode placement	On the surface of the body	One electrode on the surface of muscle and another inside the cardiac muscle
Resting membrane potential	Zero, as both the electrodes have no potential difference at rest	–90 mV, as both the electrodes measure resting potential difference across the cell membrane
Type of action potential recorded	Biphasic	Monophasic
Magnitude of maximum potential difference	2–4 mV	100–110 mV
Electrical events captured from	It shows the changes in both the atria and the ventricles	It shows the electrical changes in only one chamber, in which the electrodes are placed
Voltage time graph showing both the recordings		
Correlation between ECG and monophasic AP		

Fig. 38.2: Correlation of ECG and myocardial action potentials (AP).

Normal ECG: The record of the electrical activity of heart in terms of voltage-time graph in a normal disease free heart is called as normal ECG.

COMPONENTS OF NORMAL ECG

- **Waves:** Any deviation above and below the isoelectric line.
- **Intervals:** Intervals between 2 wave including the waves.
- **Segments:** Intervals between 2 waves excluding the waves, i.e., only on isoelectric lines. It indicates the period of no electrical activity in the heart.

Waves

Figures 38.4A and B for physiological basis of waves.

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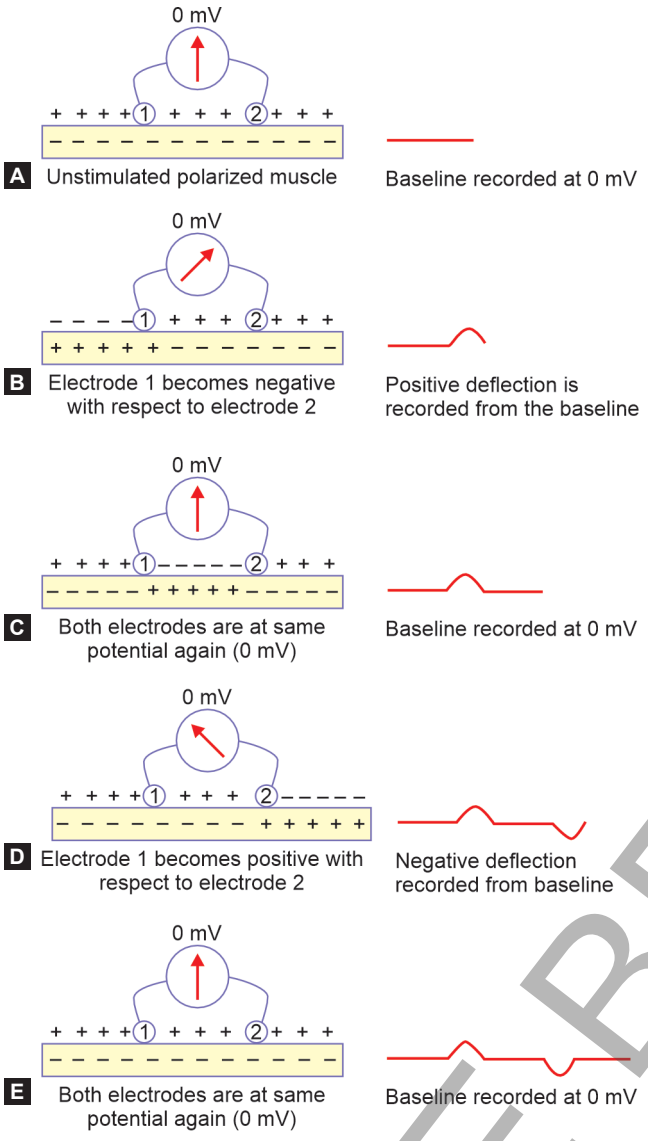


Fig. 38.3: Principle of biphasic recording.

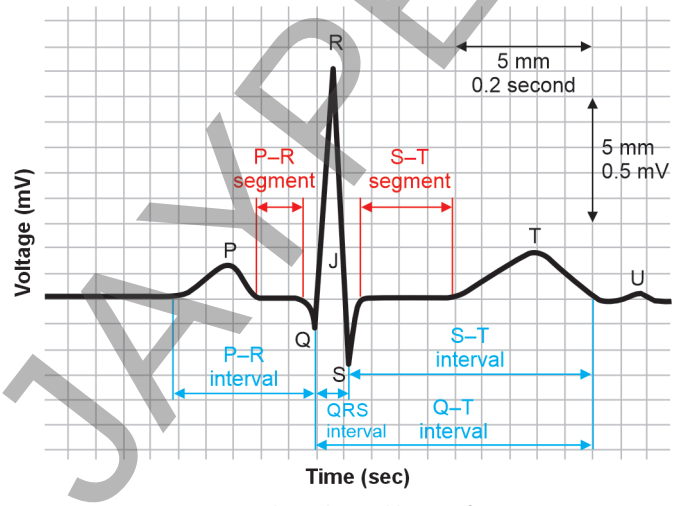


Fig. 38.4A: Physiological basis of waves.

P Wave–Depolarization of Atria

- It is a positive deflection with duration: 0.08–0.1 seconds and magnitude –0.2 mV.
- Depolarization begins in SA node and spreads in all directions.
- It is in the direction of mean cardiac vector, hence positive in all leads.

Significance of P wave: A normal P wave signifies that:

- Impulse is originating in SA node
- Spread of impulse is in usual direction (towards the apex)
- There is no defect in conduction
- Atrial musculature is normal

What is the significance of an inverted P wave?

An inverted P wave indicates that SA node fails to generate impulse and the atrial muscle is depolarizing by impulse generated in AV node.

QRS Complex–Depolarization of Ventricles

It is a positive deflection with duration: 0.08–0.12s and magnitude—0.5–2.5 mV.

- Q wave—septal depolarization
- R wave—ventricular depolarization
- S wave—depolarization of basal parts of heart

The first part of the ventricle to become depolarized is ***left endocardial surface of septum***. This is followed by depolarization of the endocardial surface of both ventricles. The ventricular mass of left ventricle is more than the right ventricle, ***posterior basal part of left ventricle*** is the last part to get depolarized.

Significance of QRS complex:

Broad QRS complexes are seen in:

- Conduction blocks especially bundle branch block
- Hypercalcemia

T Wave–Repolarization of Ventricles

It is a positive deflection with duration: 0.27 s and magnitude—0.5 mV.

Significance of T wave: T wave inversion indicates serious myocardial damage and is often associated with cardiac hypoxia.

R wave and T wave are positive

During depolarization and repolarization, the instantaneous vectors are in the direction of mean cardiac axis and hence both the waves of depolarization (QRS complex) and repolarization (T wave) are positive.

U Wave–Slow Repolarization of Papillary Muscles

It is a positive deflection with duration: 0.08 s and magnitude—0.2 mV. It is usually not visible.

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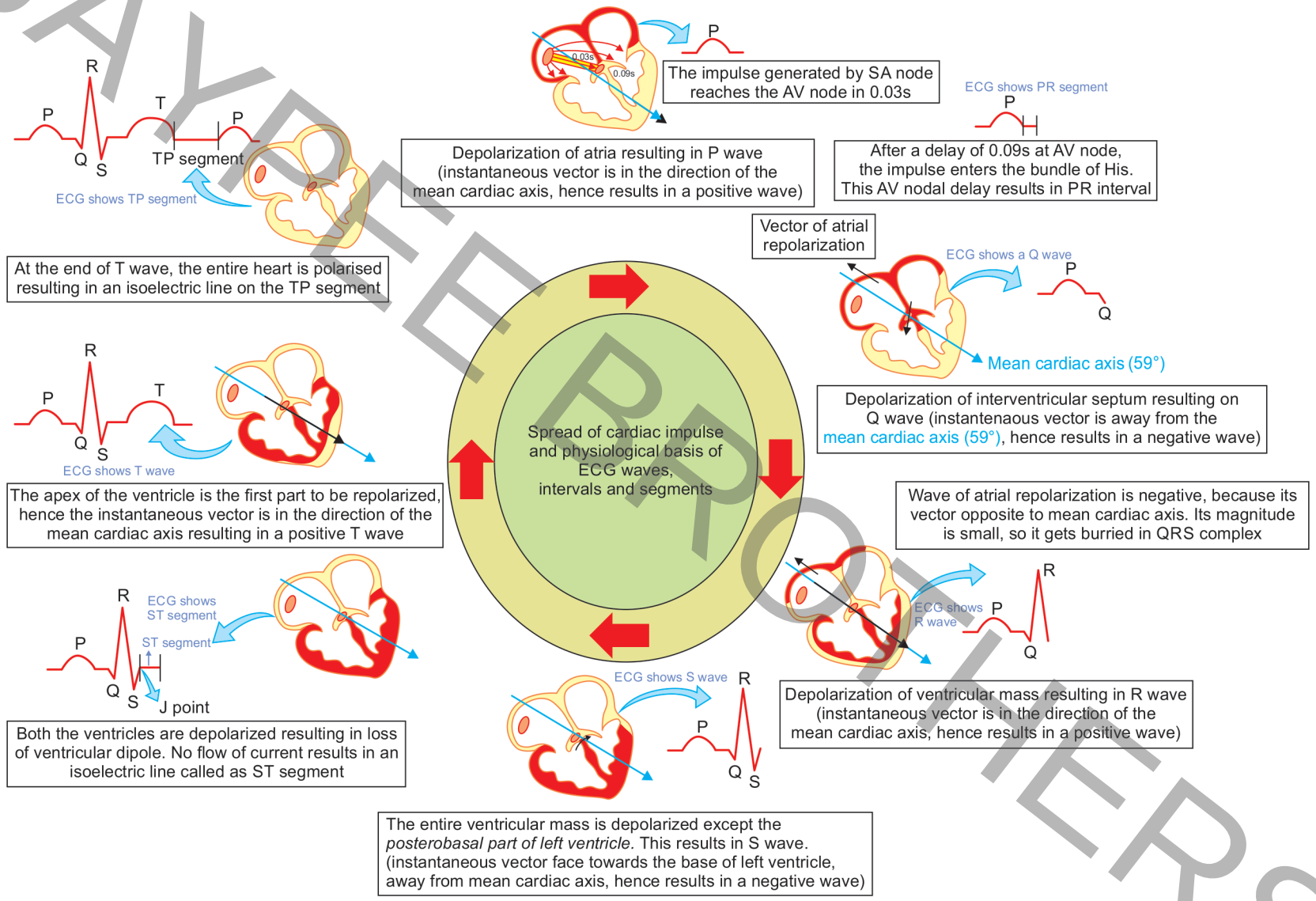


Fig. 38.4B: The physiological basis of generation of waves, intervals and segments of ECG.

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Note: Wave of atrial repolarization: It is a negative wave, buried in QRS complex. Hence it is not seen on ECG. But it can be seen in cases of prolonged PR interval.

INTERVALS (FIG. 38.5)

PR Interval

- Indicates atrial depolarization and conduction through AV node.
- It starts from beginning of P wave till the R wave with duration: 0.12–0.20 seconds.
- Longer PR interval indicates impaired conduction through bundle.
- Variable PR interval indicates AV dissociation.

What is the significance of PR interval?

Physiological significance: Denotes conduction delay through AV node. It allows the ventricular filling at the end of atrial systole.

Clinical significance: Longer PR interval indicates impaired conduction through bundle.
Variable PR interval indicates AV dissociation.
Heart blocks (discussed in Chapter 39)

RR Interval

It denotes the ***time taken to complete one cardiac cycle***.

It is the distance between two R waves. Its duration is 0.8 seconds.

Physiological significance: It is used to calculate the heart rate by the formula:

HR = 1500/RR interval (in mm) at paper speed of 25 mm/s.

QRS Duration

It denotes ***ventricular depolarization*** and ***atrial repolarization***.

It is measured as distance between Q wave and S wave. Its duration is 0.08 to 0.10 seconds.

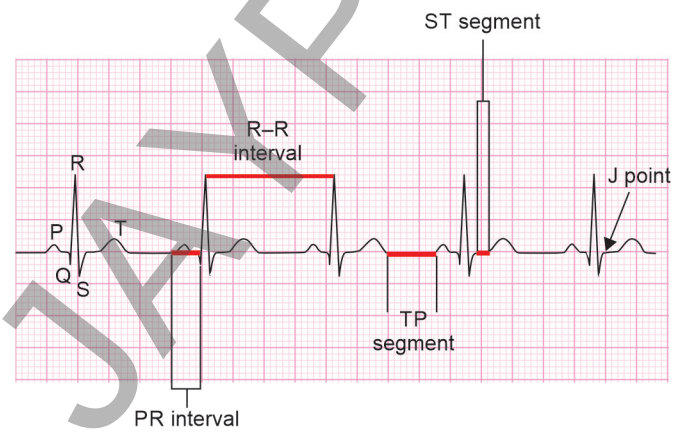


Fig. 38.5: The normal ECG trace showing intervals and segments.

QT Interval

It denotes duration of ***ventricular depolarization*** and ***repolarization***.

It is measured as distance between Q wave and the end of T wave and indicates total ventricular systolic time. Its duration is 0.40–0.43 seconds.

Clinical significance of QTc interval: QTc interval denotes QT interval corrected for the heart rate. It is measured by Bazett's formula; as the QT interval divided by square root of RR interval:

$$QTc = \frac{QT\ interval}{\sqrt{RR\ interval}}$$

A normal QTc interval should be ***0.36–0.44 s in males and 0.36–0.46 s in females. If this QTc interval is more than 0.47 seconds it acts as the predictor of cardiac disease***. But a QTc interval of more than 0.5 s predicts increased risk of life-threatening cardiac disease. It also helps in diagnosis of ***long QT syndrome***.

ST Interval

It is measured from end of QRS complex to end of T wave. Its duration is 0.32 seconds.

TP Interval

It denotes diastolic period of the heart. It is measured from end of T wave and onset of P wave.

Clinical significance of TP interval: Variable TP interval indicates AV dissociation.

SEGMENTS (FIG. 38.5)

PR Segment

- It denotes time taken by AV node to conduct the impulse.
- It is measured as the isoelectric line between end of P wave and beginning of R wave.
- Its duration is 0.04 to 0.08 seconds.

ST Segment

It denotes time gap between depolarization and repolarization of the ventricles.

It is measured as isoelectric line at the end of S wave till the beginning of T wave. Its duration is 0.04–0.08 seconds.

Physiological significance: The ST segment is the important period during the electrical changes in the ventricle, as no current flows through the ventricles at this time. It marks the period of no electrical activity in depolarized ventricle.

Clinical significance: In case of the myocardial injury occurring due to ischemia or infarction, the infarcted muscle does not get depolarized. Hence, this segment shows peculiar changes owing to the dipole so created between the healthy and infarcted myocardium. The

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current flow in this case is called the ***current of injury***. It appears as ***elevation and sagging*** of this segment indicating myocardial damage or hypoxia respectively.

The point at the beginning of ST segment, when the heart is just completely depolarized and no current flows, is called ***J point***. It is the reference point to see or diagnose the changes in ST segment.

TP Segment

It denotes the polarized or resting state of the heart. In this period, no current flows through the heart and all the chambers are polarized at rest. Its duration is 0.2 s at HR 75/min, which is inversely related to HR.

RECORDING OF ECG

After we have studied the basics of ECG, let us become familiar with certain terms and basics related to recording and analysis of ECG:

- **Electrocardiography:** It is branch of physiology related to recording and analysis of electrical activity of heart
- **Electrocardiogram:** Recording of the electrical changes in heart during the cardiac cycle
- **Electrocardiograph:** Instrument for making permanent record of small potential variations occurring in different parts of body due to electrical activity of heart.

ECG Paper (Fig. 38.6)

It is a ***heat sensitive/thermal paper*** with a graphic pattern, on which the electrocardiograph records the electric fluctuations of heart in terms of voltage and time graph. At the paper speed of 25 mm/s, the small 25 boxes (25 mm) or 5 big boxes represent one second on the time scale, whereas 10 mm or two large boxes denote 1 mV of potential change.

ECG Jelly

It is the conducting paste, which contains very fine sand/glass particles, which produce local erythema.

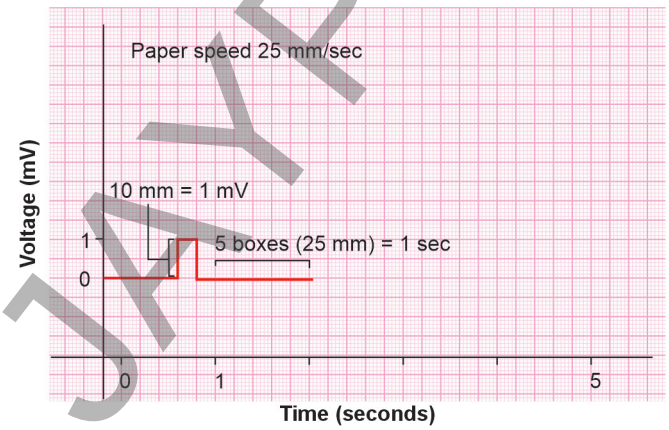


Fig. 38.6: The ECG paper showing calibration.

Electrodes and Leads (Fig. 38.7)

The rectangular flat metallic discs (7.5 × 5 cm) are called ***electrodes***, which are placed on the body surface.

In terms of physical lead, it defined as a set of two electrodes connected by a wire. However, the electrical picture of heart recorded between two electrodes on the paper is also called a lead.

Father of ECG: **William Einthoven** (1903), discovered the ECG and proposed the Einthoven's laws, which became the basis of recording ECG. He proposed the ***Einthoven's triangle*** **(Fig. 38.8)** formed by joining 2 acromion processes and the pubic symphysis with heart in the center.

Einthoven's Law: It states that "if the ECGs are recorded simultaneously with the three limb leads, the sum of the potentials recorded in leads I and III will equal the potential in lead II".

Potential of Lead I + Potential of Lead III = Potential of Lead II

This also implies that, if the electrical potential of any two of the bipolar leads are known at any given instance, the third one can be determined mathematically from first two by simply summing the first two leads.

Mean Cardiac Axis

It is the resultant vector of heart which is produced by the sum of instantaneous vectors during the series of electrical changes.

Normal Mean QRS vector is 59 degrees.
Limit of normal cardiac axis is ***–30 to +110 degrees***.

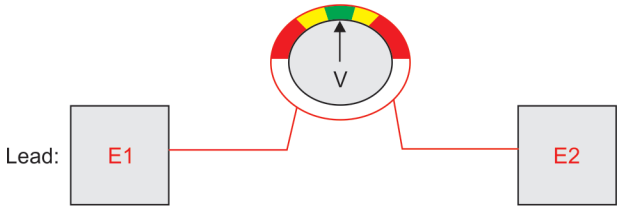


Fig. 38.7: Electrodes and leads.

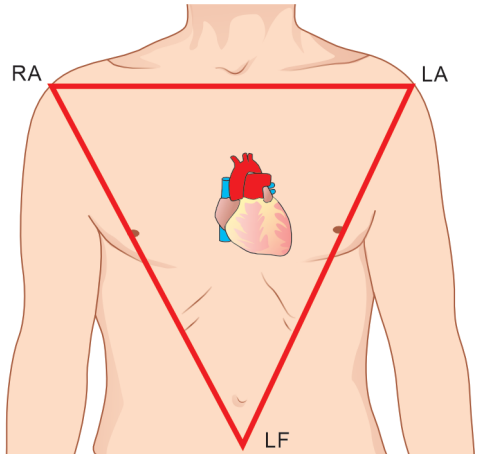


Fig. 38.8: Einthoven's triangle.

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Physiological significance: If the mean cardiac axis lies to the left of –30°, it is called ***left axis deviation***, while to the right of +110° is called ***right axis deviation***.

ECG Leads

Based on the nature of electrodes, the basic 12 ECG leads are classified as **(Flowchart 38.1)**:

1. **Bipolar leads:** It is also called as standard limb leads, having 2 active electrodes (positive and negative electrodes):
   - Lead I → between RA and LA (0°)
   - Lead II → between RA and LF (60°).
     This lead has the maximum voltage because it is in the direction of mean cardiac axis (59°)
   - Lead III → between LA and LF (120°)
2. **Unipolar leads**: These have 1 active/exploring electrode and another indifferent electrode with zero potential, hence called as unipolar leads. They are of two types:
   i. **Augmented limb leads (Figs. 38.9 and 38.10):** These are called as augmented because the signal is augmented by **50%:**
   aVR → The active electrode is at RA and reference/indifferent electrode is average of LA and LF. The ***instantaneous vector of aVR is at –150°/201° clockwise***, which is opposite to the mean cardiac axis. Hence, this lead is also called the '***inverted lead***.'
   aVL → The active electrode at LA and reference/indifferent electrode is average of RA and LF. The ***instantaneous vector of aVL is at –30°***
   aVF → The active electrode at LF and reference/indifferent electrode is average of LA and RA. The ***instantaneous vector of aVF is at 90°***.
   ii. **Chest Leads (Fig. 38.11):**
   - V1—placed in 4th intercostal space 2.5 cm to right of sternum.
   - V2—placed in 4th intercostal space 2.5 cm to left of sternum.
   - V3—placed between V2 and V4.

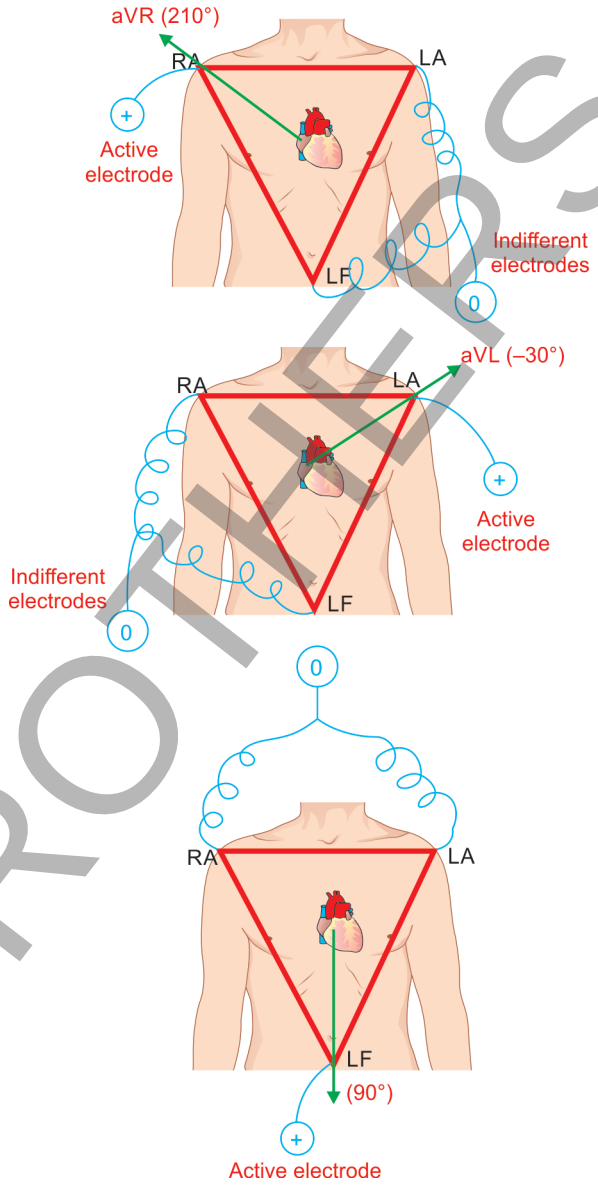
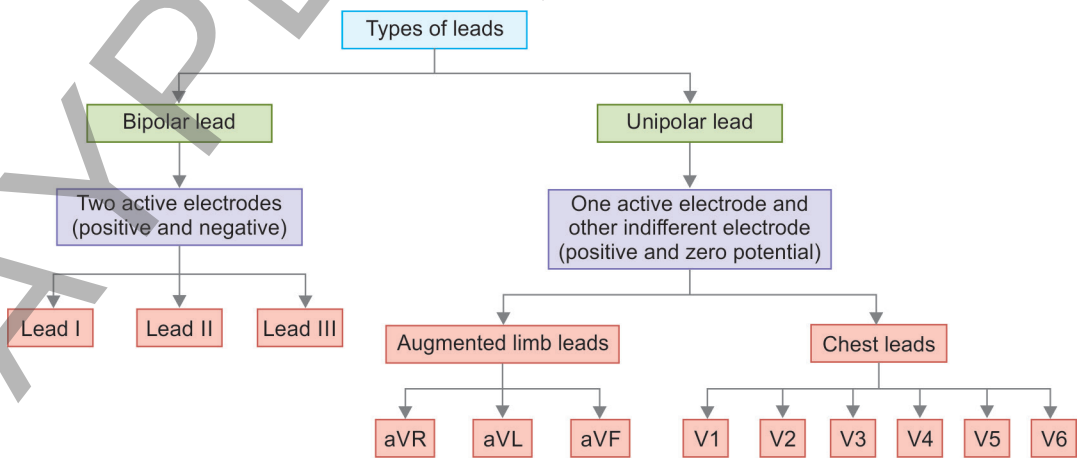


Fig. 38.9: The augmented limb leads.

Flowchart 38.1: Types of ECG leads.



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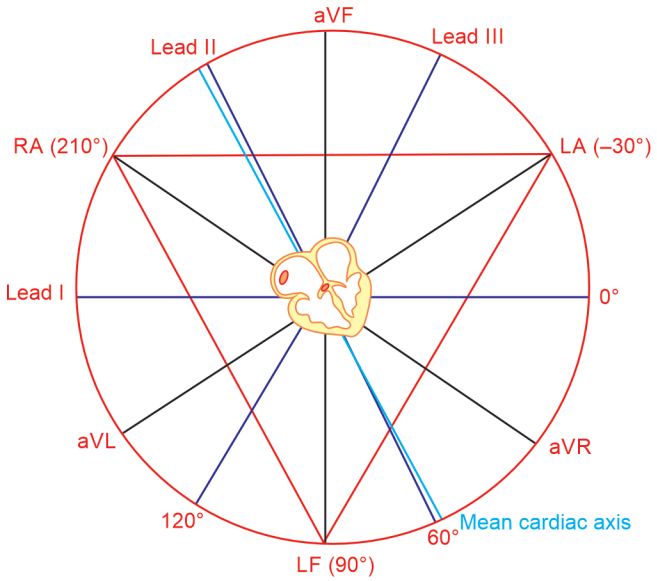


Fig. 38.10: Hexagonal arrangement showing directions of limb leads.

- V4—places in 5th intercostal space in midclavicular line.
- V5—placed in the 5th intercostal space in anterior axillary line.
- V6—placed in the 5th intercostal space in posterior axillary line.

Based on the position of these standard chest electrodes with respect to the heart, they are also called:

- Right sided chest leads (V1 V2)
- Inferior chest leads (V3 V4)
- Left sided chest leads (V5 V6)

Normal Wave Patterns in All the Standard ECG Leads (Table 38.2)

Lead I, II and III

- All characteristics are same except for voltage which is maximum in lead II
- P wave: Positive/upward

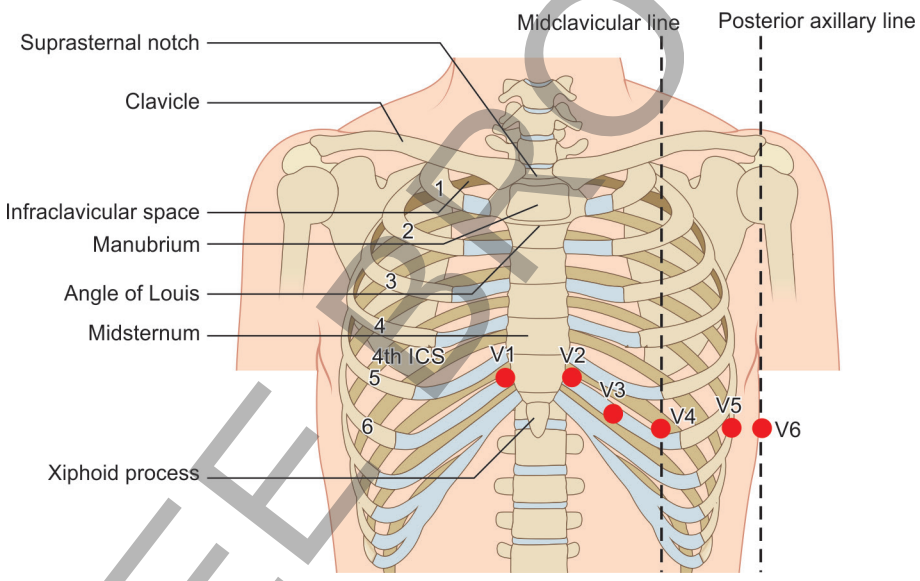


Fig. 38.11: Placement of chest leads.

Table 38.2: Normal wave patterns in all the standard ECG leads.

	I	II	III	aVR	aVL	aVF	V1	V2	V3	V4	V5	V6
P wave	Positive/ upward	Positive/ upward	Positive/ upward	Negative/ Downward	May be upward/ Downward	Positive/ upward	Positive/ upward	Positive/ upward	Positive/ upward	Positive/ upward	Positive/ upward	Positive/ upward
Q wave	Absent	Absent	Absent	Absent	Absent	Absent	Absent	Absent	Absent	present	present	present
R wave	Positive	Positive	Positive	Negative	Biphasic	Positive	Positive r<<S	Positive r<S	Positive R=S	Positive R=S	Positive R>s	Positive R>s
S wave	Negative	Negative	Negative	Positive	Biphasic	Negative	Negative r<<S	Negative r<S	Negative R=S	Negative R=S	Negative R>s	Negative R>s
T wave	Upright/ positive	Upright/ positive	Upright/ positive	Inverted	Inverted	Upright/ positive	Upright/ positive	Upright/ positive	Upright/ positive	Upright/ positive	Upright/ positive	Upright/ positive

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- Q wave: Absent
- RS wave: Positive R wave
- T wave: Positive

Significance of Lead I, II and III

- For diagnosis of cardiac axis
- For diagnosis of cardiac arrhythmias
- For studying functional abnormality of heart

Augmented Limb Leads

Waves	aVR	aVL	aVF
P wave	Inverted	Biphasic	Upright
Q wave	Absent	Absent	Absent
R wave	Inverted	Positive (Biphasic RS wave)	Positive
T wave	Inverted	Inverted	Positive

Significance of augmented leads

- To find out position of heart
- Confirming ventricular damage or hypertrophy

Chest Leads

- P wave: Positive in all chest leads
- Q wave: Absent in V1, V2 and V3
- RS wave: R increases and S decreases from V1-V6
- T wave: Positive if R>S; negative if R<S ***(it is in the direction of QRS complex)***

Q Wave is Present Only in V4, V5 and V6 (Fig. 38.12)

- V1: rS pattern
- V2: rS pattern
- V3: RS pattern
- V4: qRs pattern
- V5: qRs pattern
- V6: qRs pattern

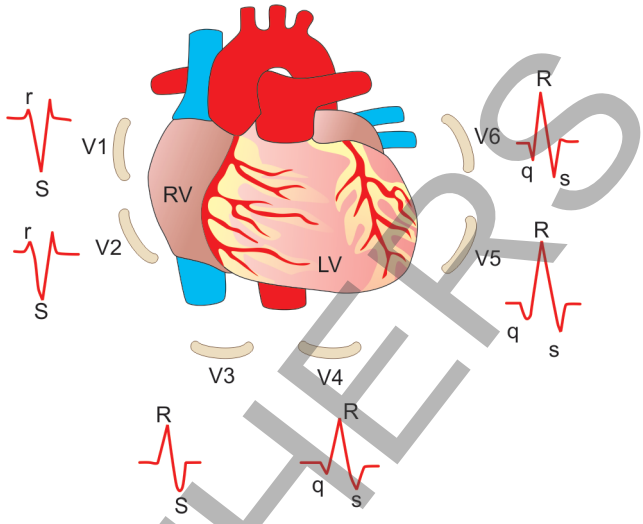


Fig. 38.12: Pattern of QRS complex in chest leads.

Significance of chest leads

- Localization of recent or old ventricular damage
- Bundle branch block
- Ventricular hypertrophy

Physio Pearls

- In this chapter, we have studied about electrocardiography (ECG), focusing on its basic principles, physiological basis, and clinical significance.
- An electrocardiogram (ECG) is a graphic representation of the electrical activity of the heart. It comprises several key components:
  a. *P wave:* Represents atrial depolarization, the contraction of the atria.
  b. *QRS complex:* Depicts ventricular depolarization, the contraction of the ventricles.
  c. *T wave:* Reflects ventricular repolarization, the recovery phase of the ventricles.
  d. *PR interval:* Indicates the time it takes for the electrical impulse to travel from the atria to the ventricles.
  e. *QT interval:* Represents the total time for ventricular depolarization and repolarization.
- **A normal electrocardiogram (ECG) consists of several segments:**
  a. *PR segment:* The flat line between the end of the P wave and the beginning of the QRS complex, representing the delay at the atrioventricular (AV) node.
  b. *ST segment:* The flat, isoelectric line between the end of the QRS complex and the beginning of the T wave, indicating the period when the ventricles are electrically depolarized but not yet repolarized.
  c. *TP segment:* The interval between the end of the T wave and the beginning of the next P wave, representing the time when the ventricles are fully repolarized.
- ECG leads are electrodes placed on the body to record the heart's electrical activity. The standard 12-lead ECG includes:
  a. *Bipolar limb leads (I, II, III):* Record electrical activity between two limbs.
  b. *Augmented voltage leads (aVR, aVL, aVF):* Measure electrical activity from a single limb and the augmented (combined) electrical activity of the other two limbs.
  c. *Precordial (chest) leads (V1-V6):* Record electrical activity across the chest, providing a comprehensive view of the heart's horizontal plane.
- Applied aspects of ECG involve utilizing electrocardiography for clinical purposes and patient care. Key applications include:
  a. *Diagnosis of heart conditions:* ECG is crucial for diagnosing various heart conditions such as arrhythmias, myocardial infarction, and conduction abnormalities by analyzing the waveform patterns and intervals.

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b. *Monitoring cardiac health:* ECG monitoring is used in hospitals and ambulatory settings to continuously track and assess a patient's cardiac activity, providing real-time information about rhythm changes and potential issues.
c. *Risk stratification:* ECG findings contribute to assessing the risk of cardiovascular events, aiding healthcare professionals in determining appropriate interventions and treatments.
d. *Exercise stress testing:* ECG is commonly employed during exercise stress tests to evaluate the heart's response to physical activity, helping diagnose coronary artery disease and assess cardiovascular fitness.
e. *Electrolyte imbalance detection:* ECG can reveal abnormalities associated with electrolyte imbalances, such as potassium or calcium, which can impact cardiac function.

Let us see, how much you have learnt?

Review Questions

Long/Short Answer Questions

Q1. Define electrocardiogram. Describe the physiological basis of the genesis of ECG waves and intervals.
Q2. Draw a well labeled diagram of normal electrocardiogram.
Q3. Describe the physiological basis of PR interval. Describe the clinical significance of PR interval.
Q4. What is relationship of ECG waves with cardiac action potential?
Q5. Name the inverted lead, why it is called inverted?

Explain Why? (Reasoning Questions)

Q1. P wave on an ECG represents atrial depolarization.
Q2. QRS complex on an ECG is larger in amplitude than the P wave.
Q3. PR interval on an ECG is important for assessing atrioventricular (AV) conduction.
Q4. ST segment should be isoelectric (flat) in a normal ECG.

Critical Thinking Case-Based Questions

Q1. A 25-year-old healthy male, came for a routine physical examination. His physician suggested an electrocardiogram (ECG) as part of the examination due to a family history of heart disease. The ECG showed a normal sinus rhythm with no abnormalities. Depending upon given scenario, answer the following question:

a. Describe the physiological basis of a normal electrocardiogram (ECG) tracing.
b. How does the ECG reflect the different phases of the cardiac cycle?
c. What are the physiological significance of ECG leads?

Multiple Choice Questions

Q1. Vagal stimulation of the heart causes:
a. Increased heart rate
b. Increased R-R interval in ECG
c. Increased force of heart contraction
d. Increased cardiac output.

Q2. Einthoven's triangle, what is the value of Lead III when Lead I = 2 mV and Lead II = 1 mV?
a. 1 b. 2
c. 3 d. 4

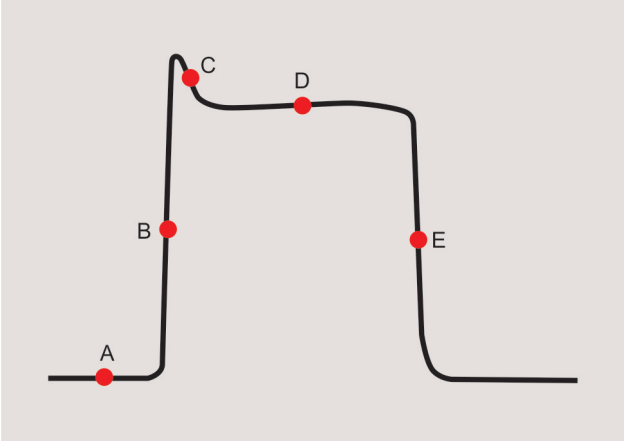
Q3. In a standard electrocardiogram, an augmented limb lead measures the electrical potential difference between:
a. Two limbs
b. One limb and two other limbs
c. One limb and neutral (zero)
d. Two limbs and two other limbs

Q4. QRS complex indicates:
a. Atrial repolarization
b. Atrial depolarization
c. Ventricular repolarization
d. Ventricular depolarization

Q5. The ECG of a 40-year-old male was recorded using standard bipolar limb leads. The sum of voltage of the three standard leads was found to be 5 millivolts. This indicates:
a. A normal heart
b. Right ventricular hypertrophy
c. Left ventricular hypertrophy.
d. Increased cardiac muscle mass.

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Q6. The phases of the ventricular muscle action potential is given below:



At which point on the above ventricular action potential is membrane potential most dependent on calcium permeability?

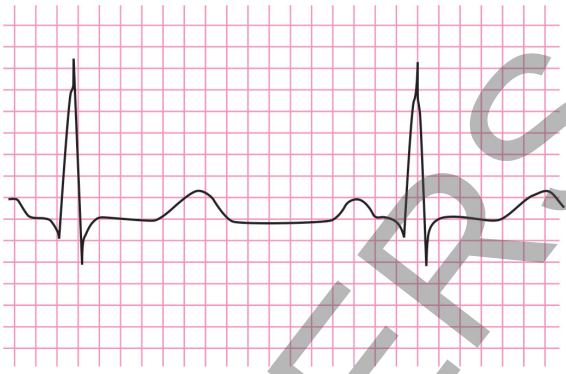
a. Point B
b. Point C
c. Point D
d. Point E

Q7. The 58 -year-old male is brought to cardiac emergency unit with chest pain. From his symptoms and lab diagnosis, he is diagnosed with inferior wall myocardial infarction. His ECG shows ST segment elevation and T wave inversion. Which phase of cardiac cycle is affected in this patient?

a. Atrial depolarization and repolarization
b. Ventricular depolarization and repolarization
c. Ventricular repolarization
d. Ventricular depolarization

Q8. How is the heart rate, calculated in the given ECG strip, recorded at 25 mm/sec?

a. 25 × 60/RR interval (in mm)
b. 1500/RR interval (in cm)
c. 25/RR interval (in cm)
d. 150/RR interval (in mm)



Q9. ECG (electrocardiogram) was developed first by:

a. Wilhelm His
b. Steward
c. Hubert Mann
d. Willem Einthoven

Q10. A normal ECG report must consist of the following information:

a. Rhythm, cardiac axis
b. Conduction intervals
c. Description of the ST segments, QRS complexes, T-waves
d. All of these

Q11. For the normal heartbeat, depolarization stimulus originates in:

a. His-bundle areas
b. Epicardium
c. Sinoatrial (SA) node
d. Atrioventricular (AV) node

Q12. P wave indicates:

a. Depolarization of right ventricle
b. Depolarization of left ventricle
c. Depolarization of both atria
d. Atria to ventricular conduction time

Q13. Ventricular muscle depolarization is indicated by:

a. PR interval
b. P wave
c. U wave
d. The QRS complex

ANSWERS

1. a **2.** c **3.** c **4.** d **5.** d **6.** c **7.** b **8.** a **9.** d **10.** d **11.** c **12.** c **13.** d

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