An electrocardiogram (ECG or EKG) is a register of the heart's electrical activity. Just like skeletal muscles, heart muscles are electrically stimulated to contract. This stimulation is also called activation or excitation. Cardiac muscles are electrically charged at rest. The inside, the cell is negatively charged relative to the outside (resting potential). If the cardiac muscle cells are electrically stimulated, they depolarize (the resting potential changes from negative to positive) and contract. The electrical activity of a single cell can be registered as the action potential. As the electrical impulse spreads through the heart, the electrical field changes continually in size and direction. The ECG is a graph of these electrical cardiac signals.

The ECG represents the sum of the action potentials of millions of cardiomyocytes. The individual action potentials of the individual cardiomyocytes are averaged. The final result, which is shown on the ECG, is actually the average of billions of microscopic electrical signals. During the depolarization, sodium ions stream into the cell. Subsequently, the calcium ions stream into the cell. These calcium ions cause the actual muscular contraction. Finally the potassium ions stream out of the cell. During repolarization the ion concentration returns to its precontraction state. On the ECG, an action potential wave coming toward the electrode is shown as a positive (upwards) signal.

Electrical activity going through the heart can be measured by external (skin) electrodes because body fluids are good conductors (indirect recording) or by internal electrodes that are applied direct on the myocardium (direct recording). A small portion of the current spreads all the way to the surface of the body. If electrodes are placed on the skin on
opposite sides of the heart, electrical potentials generated by the current can be recorded. The electrocardiogram (ECG) registers these activities from electrodes which have been attached on to different places on the body. In total, twelve leads are calculated using ten electrodes. The four extremity electrodes: LA – left arm, RA – right arm, N – neutral, on the right leg (electrical earth, or point zero, to which the electrical current is measured), F – foot, on the left leg.

**Electrocardiographic leads three bipolar limb leads (standard bipolar limb leads)**

The term “bipolar” means that the electrocardiogram is recorded from two electrodes located on different sides of the heart, in this case, on the limbs. Thus, a “lead” is not a single wire connecting from the body but a combination of two wires and their electrodes to make a complete circuit between the body and the electrocardiograph.

![Figure 2](image)

**Figure 2**

**Lead I.** In recording limb lead I, the negative terminal of the electrocardiograph is connected to the right arm and the positive terminal to the left arm. Therefore, when the point where the right arm connects to the chest is electronegative with respect to the point where the left arm connects, the electrocardiograph records positively, that is, above the zero voltage line in the electrocardiogram.

**Lead II.** To record limb lead II, the negative terminal of the electrocardiograph is connected to the right arm and the positive terminal to the left leg. Therefore, when the right arm is negative with respect to the left leg, the electrocardiograph records positively.

**Lead III.** To record limb lead III, the negative terminal of the electrocardiograph is connected to the left arm and the positive terminal to the left leg. This means that the electrocardiograph records positively when the left arm is negative with respect to the left leg.

**Einthoven’s Triangle.** In figure 3, the triangle, called Einthoven’s triangle, is drawn around the area of the heart. This illustrates that the two arms and the left leg form apices of a triangle surrounding the heart. The two apices at the upper part of the triangle represent the points at which the two arms connect electrically with the fluids around the heart, and the lower apex is the point at which the left leg connects with the fluids.
Einthoven’s Law. Einthoven’s law states that if the electrical potentials of any two of the three bipolar limb electrocardiographic leads are known at any given instant, the third one can be determined mathematically by simply summing the first two (but note that the positive and negative signs of the different leads must be observed when making this summation). An easy rule to remember: lead I + lead III = lead II. This is done with the use of the height or depth, independent of the wave (QRS, P of T). Example: if in lead I, the QRS complex is 3 mm in height and in lead III 9 mm, the height of the QRS-complex in lead II is 12 mm.

Figure 4 shows recordings of the electrocardiograms in leads I, II, and III. It is obvious that the electrocardiograms in these three leads are similar to one another because they all record positive P waves and positive T waves, and the major portion of the QRS complex is also positive in each electrocardiogram. On analysis of the three electrocardiograms, it can be shown, with careful measurements and proper observance of polarities, that at any given instant the sum of the potentials in leads I and III equals the potential in lead II, thus illustrating the validity of Einthoven’s law.

If the three limbs of Einthoven's triangle (assumed to be equilateral) are broken apart, collapsed, and superimposed over the heart, then the positive electrode for lead I is said to be at zero degrees relative to the heart (along the horizontal axis) (see figure at right). Similarly, the positive electrode for lead II will be +60° relative to the heart, and the positive electrode for lead III will be +120° relative to the heart as shown to the right. This new construction of the electrical axis is called the axial reference system. With this system, a wave of depolarization traveling at +60° produces the greatest positive deflection in lead II. A wave of
depolarization oriented +90° relative to the heart produces equally positive deflections in both lead II and III.

Another system of leads in wide use is the augmented unipolar limb lead. In this type of recording, two of the limbs are connected through electrical resistances to the negative terminal of the electrocardiograph, and the third limb is connected to the positive terminal. When the positive terminal is on the right arm, the lead is known as the aVR lead; when on the left arm, the aVL lead; and when on the left leg, the aVF lead. Normal recordings of the augmented unipolar limb leads are shown in Figure 6.

They are all similar to the standard limb lead recordings, except that the recording from the aVR lead is inverted. The capital A stands for "augmented" and V for "voltage".

(aVR + aVL + aVF = 0)
Chest Leads (Precordial Leads)

Often electrocardiograms are recorded with one electrode placed on the anterior surface of the chest directly over the heart at one of some points. This electrode is connected to the positive terminal of the electrocardiograph, and the negative electrode, called the indifferent electrode, is connected through equal electrical resistances to the right arm, left arm, and left leg all at the same time, as also shown in the figure. Usually six standard chest leads are recorded, one at a time, from the anterior chest wall, the chest electrode being placed sequentially at the six points shown in the diagram.

The precordial, or chest leads, (V1, V2, V3, V4, V5 and V6) observe the depolarization wave in the frontal plane. Example: V1 is close to the right ventricle and the right atrium. Signals in these areas of the heart have the largest signal in this lead. V6 is the closest to the lateral wall of the left ventricle.

- V1 - placed in the 4th intercostal space, right of the sternum
- V2 - placed in the 4th intercostal space, left of the sternum
- V3 - placed between V2 and V4
- V4 - placed 5th intercostal space in the nipple line (place V4 under the breast in women)
- V5 - placed between V4 and V6
- V6 - placed in the midaxillary line on the same height as V4 (horizontal line from V4, so not necessarily in the 5th intercostal space)
The different recordings are known as leads V1, V2, V3, V4, V5, and V6 (Figure 8). In leads V1 and V2, the QRS recordings of the normal heart are mainly negative because, as shown in Figure 8, the chest electrode in these leads is nearer to the base of the heart than to the apex, and the base of the heart is the direction of electronegativity during most of the ventricular depolarization process. Conversely, the QRS complexes in leads V4, V5, and V6 are mainly positive because the chest electrode in these leads is nearer the heart apex, which is the direction of electropositivity during most of depolarization.

With the use of these 10 electrodes, 12 leads can be derived. There are 6 extremity leads and 6 precordial leads.

The normal electrocardiogram

The sinoatrial node (SA node) contains the fastest physiological pacemaker cells of the heart; therefore, they determine the heart rate. First the atria depolarize and contract. After that the ventricles depolarize and contract. The electrical signal between the atria and the ventricles goes from the sinus node via the atria to the AV-node (atrioventricular transition) to the His bundle and subsequently to the right and left bundle branches, which end in a dense network of Purkinje fibers. The depolarization of the heart results in an electrical force which has a direction and magnitude; an electrical vector. This vector changes every millisecond of the depolarization. In the animation vectors for atrial depolarization, ventricular depolarization and ventricular repolarization are shown.
The **P wave** is the result of the atrial depolarization. This depolarization starts in the SA (sinoatrial) node. The signal produced by pacemaker cells in the SA node is conducted to the right and left atria. Normal atrial repolarization is not visible on the ECG (but can be visible during atrial infarction and pericarditis).

Characteristics of a normal P wave:

- The maximal height of the P wave is 2.5 mm in leads II and / or III
- The p wave is positive in II and AVF, and biphasic in V1
- The p wave duration is shorter than 0.12 seconds

The P wave morphology can reveal right or left atrial hypertrophy or atrial arrhythmias and is best determined in leads II and V1 during sinus rhythm. If the p-wave is enlarged, the atria are enlarged. If the P wave is inverted, it is most likely an ectopic atrial rhythm not originating from the sinus node.
The PQ segment is the duration of time between the ending of the P wave and the beginning of the Q wave; it lasts 0.10 s.

The PQ interval starts at the beginning of the atrial contraction and ends at the beginning of the ventricular contraction. The PQ interval (sometimes referred to as the PR interval as a Q wave is not always present) indicates how fast the action potential is transmitted through the AV node (atrioventricular) from the atria to the ventricles. Measurement should start at the beginning of the P wave and end at the beginning of the QRS segment. The PQ duration depends on the conduction velocity in the atria, AV node, His bundle, bundle branches and Purkinje fibers. The normal PQ interval is between 0.12 and 0.20 seconds.

A prolonged PQ interval is a sign of a degradation of the conduction system or increased vagal tone (Bezold-Jarisch reflex), or it can be pharmacologically induced. This is called 1st, 2nd or 3rd degree AV block. A short PQ interval can be seen in the WPW syndrome in which faster-than-normal conduction exists between the atria and the ventricles.

The **QRS complex** represents the depolarization of the ventricles. The letters "Q", "R" and "S" are used to describe the QRS complex. Q: the first negative deflection after the p-wave. If the first deflection is not negative, the Q is absent; R: the positive deflection; S: the negative deflection after the R-wave; R': is used to describe a second R-wave (as in a **right bundle branch block**).

![QRS shapes](https://ecgpedia.org)

**Figure 10**

The QRS duration indicates how fast the ventricles depolarize. The normal QRS is < 0.10 seconds. The ventricles depolarize normally within 0.10 seconds. When this is longer than 110 milliseconds, this is a conduction delay. Possible causes of a QRS duration > 110 milliseconds include:

- Left bundle branch block
- Right bundle branch block
- Electrolyte Disorders
- Idioventricular rhythm and paced rhythm

For the diagnosis of LBBB or RBBB QRS duration must be >120 ms.
The ST segment represents the part on the ECG between the ending of the S wave and the beginning of the T wave and usually it is isoelectric. Duration of time is 0.10 s. The ST segment represents ventricular repolarization. Repolarization follows upon contraction and depolarization. During repolarization the cardiomyocytes elongate and prepare for the next heartbeat. This process takes much more time than the depolarization. The elongation that takes place during repolarization is not passive; it is an active process during which energy is consumed. On the ECG, the repolarization phase starts at the junction, or j point, and continues until the T wave. The ST segment is normally at or near the baseline. ST changes occur when the action potential in the ischemic area changes, resulting in an electric injury current from the healthy cardiomyocytes towards the ischemic area during the repolarization fase. Minor STT changes are not necessarily associated with cardiac ischemia. The most important cause of ST segment elevation is acute ischemia.

The T wave represents the repolarization of the ventricles. There is no cardiac muscle activity during the T wave. One heart beat consists of an atrial depolarization --> atrial contraction --> p-wave, ventricular depolarization --> ventricular contraction --> ORS-complex and the resting phase (including the repolarization during the T-wave) between two heart beats. The T wave in obligatory positive in the leads I and II, but it can be negative in the lead III. The wave is morphologically an asimetric wave having a gentle ascending limb and abrupt descending limb. It lasts 1,15-0,20 sec and its voltage is between 0,3-0,5 mV.

The T wave is usually concordant with the QRS complex. Thus if the QRS complex is positive in a certain lead (the area under the curve above the baseline is greater than the area under the curve below the baseline) than the T wave usually is positive too in that lead. Accordingly the T wave is normally upright or positive in leads I, II, AVL, AVF and V3-V6. The T wave is negative in V1 and AVR. The T wave flips around V2, but there is likely some genetic influence in this as in Blacks the T wave usually flips around V3. The T wave angle is the result of small differences in the duration of the repolarization between the endocardial and epicardial layers of the left ventricle. The endocardial myocytes need a little more time to repolarize (about 22 msec).
T waves can be peaked, normal, flat, or negative.

The QT interval starts at the onset of the Q wave and ends where the tangent line for the steepest part of the T wave intersects with the baseline of the ECG. Although QT prolongation is potentially lethal, measurement of the QT interval by physicians is not standardized, since different definitions of the end of the T wave exist. Most QT experts define the end of the T wave as the intersection of the steepest tangent line from the end of the T-wave with the base line of the ECG.

1. The T wave is broad, but the tangent crosses the baseline before the T wave joins the baseline. The QT interval would be overestimated when this last definition of the end of the T wave would be used.
2. The ECG does not meet the baseline after the end of the T wave. Still, the crossing of the tangent and baseline should be used for measurements.
3. A bifasic T wave. The tangent to the 'hump' with the largest amplitude is chosen. This can change from beat to beat, making it more important to average several measurements.

The origin of the U wave is unknown. This wave possibly results from "afterdepolarizations" of the ventricles. These afterdepolarizations can be the source of
arrhythmias caused by "triggered automaticity" including torsade de pointes. The normal U wave has the same polarity as the T wave and is usually less than one-third the amplitude of the T wave. U waves are usually best seen in the right precordial leads especially V2 and V3. The duration of time is 0.16-0.25 sec and the voltage 0.4-0.5 Mv.

Figure 14

- paper speed (25 mm/s on the horizontal axis);
- calibration. At the beginning of every lead is a vertical block that shows with what amplitude a 1 mV signal is drawn. So the height and depth of these signals are a measurement for the voltage. If this is not set at 10 mm, there is something wrong with the machine setting.

Objectives of interpretation an ECG

1. **Rhythm**
2. **Frequency (heart rate) and conduction times**
3. **Heart axis (QRS axis) and morphological aspects of the waves**

1. **(Sinus Node) Rhythm**

The sinus node (SA) is located in the roof of the right atrium. It is the fastest physiological pacemaker. When the sinus node generates an electrical impulse, the surrounding cells of the right atrium depolarize. Then the cells of the left atrium, the AV (atrioventricular) node,
follow, and at last the ventricles are stimulated via the His bundle.

Criteria for normal sinus rhythm:

- A P wave morphology P wave (atrial contraction) precedes every QRS complex
- The rhythm is regular, but varies slightly during respirations
- The rate ranges between 60 and 100 beats per minute
- The P waves maximum height at 2.5 mm in II and/or III
- The P wave is positive in I and II, and biphasic in V1

2. Heart rate

To answer this question, determine the time between two QRS complexes. Previously, the ECG was printed on a paper strip transported through an ECG writer at the speed of 25 mm/second. Now, digital ECGs are common; however, the method for determining the frequency remains the same. The ECG has a grid with thick lines 5 mm apart (= 0.20 second) and thin lines 1 mm (0.04 second). There are three simple methods to determine the heart rate (HR).

The square counting method

The square counting method is ideal for regular heart rates. Use the sequence 300-150-100-75-60-50-43-37. Count from the first QRS complex, the first thick line is 300, the next thick line 150 etc. Stop the sequence at the next QRS complex. When the second QRS complex is between two lines, take the mean of the two numbers from the sequence or use the fine-tuning method listed below.
Use a calculator
Count the small (1mm) squares between two QRS complexes. The ECG paper runs at 25 mm/sec through the ECG printer; therefore:

\[
\text{Heart rate (beats/min)} = \frac{25 \text{ mm/sec} \times 60 \text{ sec/min}}{\text{number of squares}} = \frac{1500}{\text{number of squares}}
\]

The marker method
Non-regular rhythms are best determined with the "3 second marker method". Count the number of QRS complexes that fit into 3 seconds (some ECG writers print this period on the ECG paper). Multiply this number by 20 to find the number of beats/minute.

A number of factors change the heart frequency, including:

- the (para) sympathetic nervous system.
  - The **sympathetic system**, e.g. epinephrine, (=adrenalin) increases atrioventricular conduction and contractility (the **fight or flight** reaction.)
  - The parasympathic system (nervus vagus,) e.g. acetycholine, decreases the frequency and atrioventricular conduction. The parasympathic system affects mainly the atria.
- Cardiac filling increases the frequency.
- arrhythmias influence heart rate.

3. Heart axis (QRS axis)

![Figure 17](image)

The electrical heart axis is an average of all depolarizations in the heart. The depolarization wave begins in the right atrium and proceeds to the left and right ventricle. Because the left ventricle wall is thicker than the right wall, the arrow indicating the direction of the depolarization wave is directed to the left. A change of the heart axis or an extreme deviation can be an indication of pathology.

To determine the heart axis you look at the extremity leads only (not V1-V6). If you focus especially on leads I, II, and AVF you can make a good estimate of the heart axis. An important concept in determining the heart axis is the fact that electricity going towards a lead yields a positive deflection in the electric recording of that lead. Imagen the leads as cameras looking at the heart. Lead I looks horizontally from the left side. Lead II looks from the left leg. Lead III from the right leg and lead AVF from below towards the heart. A positive
deflection here is defined as the QRS having a larger 'area under the curve' above the baseline than below the baseline. With these basics in mind, one can easily estimate the heart axis by looking at leads I and AVF:

- Positive (the average of the QRS surface above the baseline) QRS deflection in lead I: the electrical activity is directed to the left (of the patient)
- Positive QRS deflection in lead AVF: the electrical activity is directed down.

![Figure 18](image)

This indicates a normal heart axis. Usually, these two leads are enough to diagnose a normal heart axis! A normal heart axis is between -30 and +90 degrees.

- A left heart axis is present when the QRS in lead I is positive and negative in II and AVF. (between -30 and -90 degrees)
- A right heart axis is present when lead I is negative and AVF positive. (between +90 and +
- An extreme heart axis is present when both I and AVF are negative. This is a rare finding.

The largest vector in the heart is from the AV-node in the direction of ventricular depolarization. Under normal circumstances, this is directed left and down.(towards leads I and AVF). The position of the QRS vector is given in degrees. See the figure. A horizontal line towards the left arm is defined as 0 degrees. An iso-electric lead can help estimate the heart axis more precisely. When the depolarization is perpendicular on the lead, this is called iso-electric. The QRS is neither positive nor negative.

Undetermined axis. When all extremity leads are biphasic, the axis is directed to the front or back, in a transverse plane. The axis is then undetermined.
Abnormal heart axis

Heart axis deviation to the left in case of an inferior infarct. Left anterior hemiblock is a common cause. A left axis is between -30 and -90 degrees. The axis is -30 degrees.

Heart axis deviation to the right in right ventricular load, as in COPD or pulmonary embolism. A right axis is between +90 and +180 degrees.

The direction of the vector can changes under different circumstances:

1. When the heart itself is rotated (right ventricular overload), obviously the axis turns with it.
2. In case of ventricular hypertrophy, the axis will deviate toward the greater electrical activity and the vector will turn toward the hypertrophied tissue.
3. Infarcted tissue is electrically dead. No electrical activity is registered and the QRS vector turns away from the infarcted tissue
4. In conduction problems, the axis deviates too. When the right ventricle depolarizes later than the left ventricle, the axis will turn to the right (RBBB). This is because the right ventricle will begin the contraction later and therefore will also finish later. In a normal situation the vector is influenced by the left ventricle, but in RBBB only the right ventricle determines it.

Causes of left axis deviation include:

- Normal variation (physiologic, often with age)
- Mechanical shifts, such as expiration, high diaphragm (pregnancy, ascites, abdominal tumor)
- Left ventricular hypertrophy
- Left bundle branch block
- Left anterior fascicular block
- Congenital heart disease (e.g. atrial septal defect)
- Emphysema
- Hyperkalemia
- Ventricular ectopic rhythms
- Preexcitation syndromes
- Inferior myocardial infarction
- Pacemaker rhythm

Causes of right axis deviation include:

- Normal variation (vertical heart with an axis of 90°)
- Mechanical shifts, such as inspiration and emphysema
- Right ventricular hypertrophy
- Right bundle branch block
- Left posterior fascicular block
- Dextrocardia
- Ventricular ectopic rhythms
- Preexcitation syndromes
- Lateral wall myocardial infarction
- Right ventricular load, for example Pulmonary Embolism or Cor Pulmonale (as in COPD)