1. Definition
The electrocardiogram (abbreviated ECG or EKG) represents the graphic recording of electrical potentials arising within the heart. Since the human body, due to its high water content, is a good electricity conductor, these electrical potentials are transmitted to the surface of the body, and can therefore be recorded by placing electrodes at the surface of the skin.

The ECG only provides information regarding the electrical activity of the heart and cannot be used to assess the mechanical phenomena of the heart. Therefore, the ECG offers the possibility to assess the heart's ability to generate electrical impulses (automaticity or chronotropy), to conduct action potentials (conductivity or dromotropy), and the ability of cardiac cells to respond to electrical impulses (excitability or bathmotropy), but offers no information about contractility (inotropy) or relaxation (lusitropy).

2. Basic concepts regarding the electrical activity of cardiac cells (see Lecture 2 - Electrical phenomena of isolated myocardial cells)
The ECG provides a general picture regarding the electrical activity of the heart, recording the electrical changes that take place at the surface of cardiac myocytes at different moments of the cardiac cycle. Because of an unequal distribution of ions between the extracellular and the intracellular spaces, the membrane of cardiac myocytes is polarized (i.e., there is an electrical potential difference between the inner and the outer sides of the membrane). In resting myocytes, the interior of the cell is more electronegative than the exterior (Figure 1), generating the resting membrane potential.

Electrical stimulation of a myocardial cell with intensity exceeding the threshold is followed by sequential changes in the concentrations of ions on the two sides of the membrane, generating an action potential. Depolarization defines a change in membrane potential making the inner side of the membrane more positive or less negative. This is usually due to an inward movement of positively charged ions (cations); however, the outward movement of negative ions (anions) would have the same effect. Repolarization defines a change in
membrane potential that returns the potential to its resting value after an initial depolarization. This is usually due to an outward movement of cations, but the inward movement of anions would have the same effect, increasing electronegativity within the cell.

3. The cardiac dipole

In the normal heart, electrical stimuli arise from pacemaker cells located in the sinus node and propagate through the heart until every myocardial cell undergoes activation. At a cellular level, electrical stimulation induces local depolarization of the membrane starting at one extremity of the fiber (Figure 2, A) and propagating longitudinally towards the other extremity (Figure 2, B), and then from one cell to the other.

![Figure 2](image)

**Figure 2.** (A) An electrical stimulus arriving from neighboring cells at one extremity of the cell (left) produces local depolarization (the inner side of the membrane becomes electropositive and the outer side electronegative) and then (B) propagates longitudinally towards the other extremity of the cell.

At a certain moment, half of the cell will be depolarized (i.e., negatively charged on the outer side of the membrane), while the other half is not yet depolarized (i.e., positively charged on the outer side of the membrane). The opposite charges on the cell surface generate an electric dipole (Figure 3).

![Figure 3](image)

**Figure 3.** Electric dipole characterizing a cardiac myocyte.

Each dipole can be represented graphically by a vector. By convention, dipole vectors point to the positive pole (orientation) of the dipole and are characterized by a length, which indicates the magnitude of potential difference. Vectors corresponding to the dipole of single myocardial fibers are called elementary vectors. As to every vector, all basic operations can also be applied to cardiac vectors (Figure 4). Thus, cardiac vectors can be added, moved (translated), measured, and projected on conventional axes.
At every given moment, the electrical status of each cardiac cell can be characterized by an elementary vector. All these elementary vectors can be moved so that their origins are all brought into a single common point – the *electrical center of the heart*. The sum of all elementary vectors arising in the heart at a certain moment will create an *instantaneous vector*, which characterizes the electrical status of the entire heart at that given moment.

Given that once a myocardial cell is stimulated depolarization will propagate in every direction throughout the heart, creating a *propagating wave of depolarization*, each of the moments of the cardiac cycle can be described by a different instantaneous vector, with different length and orientation.

During a cardiac cycle (interval of time between the beginning of one cardiac activation until the beginning of the next cardiac activation), the terminal points of instantaneous vectors describe curving lines (loops) around the electrical center of the heart. The graphic recording of this loop generates a *vectorcardiogram*. The projection of the vectorcardiogram as function of time on an axis corresponding to a *lead* represents the ECG in that particular lead.

3.1. **Graphic recording of cardiac vectors**

Graphic recording of vectors can be performed using *unipolar* or *bipolar recordings*. *Bipolar recordings* are performed by measuring the potential difference between two active (exploring) electrodes influenced by the dipole (Figure 5).

*Unipolar recordings* are also performed using two electrodes. But this time, one of the electrodes (the exploring electrode) measures the potential generated by the dipole (this is always the positive electrode), while the other electrode (the *indifferent electrode*) is not influenced by the dipole, recording a null potential (Figure 6).
Graphic recording of cardiac vectors is performed using the same principles. During rest, the membrane potential remains constant, with the inner side of the membrane being electronegative and the outer electropositive. Since there is no net ion flow no potential difference will be recorded at the cell surface. During depolarization the membrane potential is varying, with the outer side of the membrane becoming electronegative. Therefore, a potential difference will be recorded at the cell surface. Depolarization propagated towards the positive electrode generates a positive signal, while depolarization propagated away from the positive electrode generates a negative signal.

4. Electrocardiographic leads

In order to collect the potentials generated by the electrical activity of the heart, electrodes are placed at the surface of the body. The position of electrodes at the surface of the body is standardized. The relationship between the positions of two electrodes defines an ECG lead, or, in other words, a pair of ECG electrodes defines a lead. Graphically, each lead has a corresponding axis; conventionally, each axis has an orientation. The projection of cardiac vectors as function of time on the axis corresponding to a given lead is the ECG trace recorded in that particular lead.

Vectors having the same orientation as the axis are recorded as positive, while vectors having opposite orientations than the axis are recorded as negative.

Three main lead systems are widely used in clinical practice: limb leads, augmented limb leads, and chest (thoracic or precordial) leads. In selected cases, other leads can be recorded using specific electrode locations.

4.1. The (standard) limb leads

First described by Willem Einthoven, standard limb leads are bipolar leads, exploring the activity of the heart in the frontal plane. The limb leads use three active electrodes and a grounding electrode. The three active electrodes are conventionally named with the initials of the words indicating their positions and are usually color-coded (Figure 7):
- right upper limb – R (right) – red
- left upper limb – L (left) – yellow
- left lower limb – F (foot) – green.

The grounding electrode is placed on the right lower limb and is usually black.
Limb electrodes can be placed far distally on the limbs, close to the hips/shoulders, or even on the lower abdomen/higher thorax, but they must be symmetrical. The limb lead system is represented by three leads: **lead I**, **lead II**, and **lead III** (Figure 8).

**Lead I** records the potential difference between the right arm and the left arm:

$$\text{Lead } I = VL - VR.$$  

**Lead II** records the potential difference between the right arm and the left foot:

$$\text{Lead } II = VF - VR.$$  

**Lead III** records the potential difference between the left arm and the left foot:

$$\text{Lead } III = VF - VL.$$
The axis of lead I is oriented towards the positive electrode, situated on the left arm (L); the axis of lead II is oriented towards the positive electrode, situated on the left foot (F); the axis of lead III is oriented towards the positive electrode, situated on the left foot (F). The axes of the three limb leads represent the sides of an equilateral triangle, called the Einthoven triangle (Figure 9), with the three active electrodes being located at the corners of the triangle, and the heart at the orthocenter of the triangle.

![Einthoven Triangle](image)

**Figure 9.** Einthoven's triangle. The arrows indicate the orientation of each lead's axis.

Applying Kirchhoff's second law to this electrical circuit, the fundamental law of the limb leads can be written:

\[
\text{Lead II} = \text{Lead I} + \text{Lead III}.
\]

### 4.2. The augmented limb leads (unipolar limb leads)

To obtain the augmented limb leads, the same electrodes are placed in the same positions as for the limb leads (R, L, and F). These are unipolar leads, exploring the activity of the heart in the frontal plane. The exploring electrode (considered positive) measures the potential generated by the dipole, while the indifferent electrode, obtained by Goldberger's method (connecting the two non-exploring electrodes), is not influenced by the dipole, recording a null potential (Figure 10).

![Augmented Limb Leads](image)

**Figure 10.** The augmented (unipolar) limb leads.
Potentials recorded using this method are smaller than those recorded using the bipolar method. Therefore, supplementary amplification is needed, hence the letter ‘a’ (augmented) in front of the name of these leads – aVR, aVL, and aVF. For aVR the exploring electrode is located on the right upper limb; for aVL the exploring electrode is located on the left upper limb; for aVF the exploring electrode is located on the left foot. The axes of the unipolar limb leads are perpendicular to the axes of the limb leads, pointing towards the exploring electrodes (Figure 11).

**Figure 11.** The limb leads and the augmented limb leads. The arrows indicate the orientation of each unipolar lead’s axis.

Applying Kirchhoff’s second law to this electrical circuit the fundamental law of the augmented limb leads can be written:

\[ VR + VL + VF = 0. \]

### 4.3. The hexaxial system

Both the limb leads and the augmented limb leads explore the activity of the heart in the *frontal plane*. Translating all six leads (limb leads and augmented limb leads) so that their origins are all brought into a single common point we obtain the hexaxial system (Figure 12).

**Figure 12.** The hexaxial system. The straight lines represent the axes of the leads; the arrows point to the positive sense. The dotted lines represent the negative sense. The orientation of the axes is expressed in degrees. Conventionally, the axis of lead I points to 0°. The positive direction is clockwise.
4.4. **The chest leads (precordial or thoracic leads)**

The chest leads are also **unipolar leads**. They use **six electrodes** and explore the activity of the heart in the **horizontal plane**. The exploring electrodes are placed in specific positions at the surface of the thorax, while the indifferent electrode is obtained by Wilson’s method (connecting the three exploring electrodes of the limbs - R, L, and F - in a single point, called **central terminal**). Exploring electrodes (labeled $V_1$, $V_2$, $V_3$, $V_4$, $V_5$, and $V_6$) are placed in conventional points at the surface of the chest (Figure 13):

- $V_1$ – in the 4th intercostal space, just to the right of the sternum
- $V_2$ – in the 4th intercostal space, just to the left of the sternum
- $V_3$ – between $V_2$ and $V_4$
- $V_4$ – in the 5th intercostal space, on the midclavicular line
- $V_5$ – in the 5th intercostal space, on the anterior axillary line
- $V_6$ – in the 5th intercostal space, on the midaxillary line.

![Figure 13. The chest (precordial or thoracic) leads.](image)

The origin of the chest leads’ axes is the electrical center of the heart, and the axes are oriented towards the exploring electrodes.

The standard electrocardiogram contains these **twelve leads** (three limb leads, three augmented lead leads and six chest leads), hence the name of **standard 12-lead ECG**. If needed, other leads can be recorded by placing electrodes on the posterior chest wall ($V_7$, $V_8$, $V_9$), on the right side of the thorax ($V_{3R}$ to $V_{6R}$), or using esophageal or intra-cardiac electrodes.

Leads $V_1$ and $V_2$ view the heart mainly from its right side; thus, they are also called **right precordial leads**. Leads $V_5$ and $V_6$ view the heart mainly from its left side; thus, they are also called **left precordial leads**.

Each of the twelve leads records the electrical activity of the heart from different perspectives, which also correlate to different anatomical areas of the heart:

- anterior wall of the left ventricle: $V_1$-$V_6$
- lateral wall of the left ventricle: leads I, aVL, $V_5$-$V_6$
- inferior wall of the left ventricle: leads II, III, aVF.
The posterior wall of the left ventricle is not seen directly by any of the leads, but a ‘mirror image’ appears in leads V₁-V₂.

5. Recording of the electrocardiogram
5.1. The electrocardiograph
The device used for recording the ECG is called electrocardiograph. The main components of an electrocardiograph are:
- the signal acquisition system – includes the electrodes and the cables. The electrodes are electrical conductors used to collect the electrical potentials generated by the heart. Four electrodes, encoded by colors (See above), are used to record the limb leads and the augmented limb leads, and six additional electrodes, labeled V₁ to V₆ (See above), are used to record the chest leads. The electrodes are placed on the body surface in a standardized way (See Figures 7 and 13). The cables connect the electrodes to the amplifying system and are usually marked in the same way as the electrodes.
- the amplification and signal filtering system – is used to amplify the relatively small potentials collected by the electrodes (in the order of mV) and to limit the artifacts. To evaluate calibration, a rectangular ± mV reference curve is recorded at the beginning of the trace (Figure 14).

![Figure 14](image)

**Figure 14.** Different types of reference curves used to evaluate the calibration of the electrocardiograph.: (A) normal reference curve; (B) over-amplification – small artifact waves may appear and wave amplitudes are higher than real; (C) under-amplification – small waves may disappear and wave amplitudes are lower than real.

- the signal charting system – displays the ECG trace either on millimeter paper (Figure 15) or on a screen. One or more leads can be recorded simultaneously depending on the type of electrocardiograph used.

![Figure 15](image)

**Figure 15.** Electrocardiographic (millimeter) paper. On the y-axis 1 mV is represented as 10 mm. On the x-axis, at a standard paper speed of 25 mm/sec, 1 sec is represented as 25 mm. The y-axis is used for measuring the amplitudes of various electrocardiographic elements. The x-axis is used for measuring the durations of various electrocardiographic elements.
5.2. The recording procedure
For recording the ECG, the patient is laying back, relaxed, and is advised not to move or speak. Occasionally, ECG is performed with the patient sitting, but this may cause some changes in the normal ECG tracing. The recording should be performed at a room temperature between 18°C and 22°C. At lower room temperature shivering may occur, leading to motion artifacts.

The four limb and the six chest electrodes are placed and fixed on the skin as described above. To facilitate the collection of electrical potentials by the electrodes conductor gel can be used. This step is not required if single-use electrodes are used, as they are already coated with conducting gel. If necessary, the cables are attached to the corresponding electrodes and then the recording can start.
TEST YOUR KNOWLEDGE

1. The ECG allows you to assess:
   a. myocardial conductivity
   b. myocardial contractility
   c. blood flow through the heart valves
   d. myocardial automaticity
   e. myocardial lusitropy

2. Which of the following ECG leads are unipolar?
   a. lead I, aVR, V₁, V₄
   b. V₂, V₃, V₄
   c. V₄, V₅, V₆
   d. leads I, II, and III
   e. aVR, aVL, and aVF

3. Which of the following leads describes a 60° angle with lead II?
   a. aVR
   b. aVF
   c. lead I
   d. aVL
   e. lead III

4. Which of the following leads explore the activity of the heart in the frontal plane?
   a. V₁-V₃
   b. aVL, aVF, and aVR
   c. only aVL and aVR
   d. V₄-V₆
   e. leads I, II, and III