ECG Measurement

1. ELECTROCARDIOGRAPHY

1.1. Electrical activity of the heart

The electrocardiogram (ECG) is based on the electrical activity of the heart muscle cells. In the resting stage, the inside of the cardiac cells has a negative charge compared to the outside of cells. The resulting voltage difference between the internal and external spaces of the cell membrane is called transmembrane potential (-80 to –90 mV in cardiac muscle cells). The discharging of this voltage (**depolarization**) in the heart muscle cells is presupposition to the start of the contraction in the heart muscle cell fibers. During the contraction the cell redevelops the same voltage difference (**repolarization**) over the cell membrane as before.

Electrocardiogram recorded from the skin surface does not, however, register the depolarization or repolarization of individual cells. Instead, surface ECG is created when the depolarization (activation) and the following repolarization spread in the whole heart muscle, together producing an electrical total component, which is measured at the skin surface. This cardiac electrical vector has at all times direction and amplitude specific to the activation stage. The signal registered at the skin surface originates from many simultaneously propagating activation fronts at different locations, which affects the size of the total component. Other factors affecting the total vector include the amount of activated muscle cells and the directions of activation fronts spreading simultaneously at different locations in the heart.

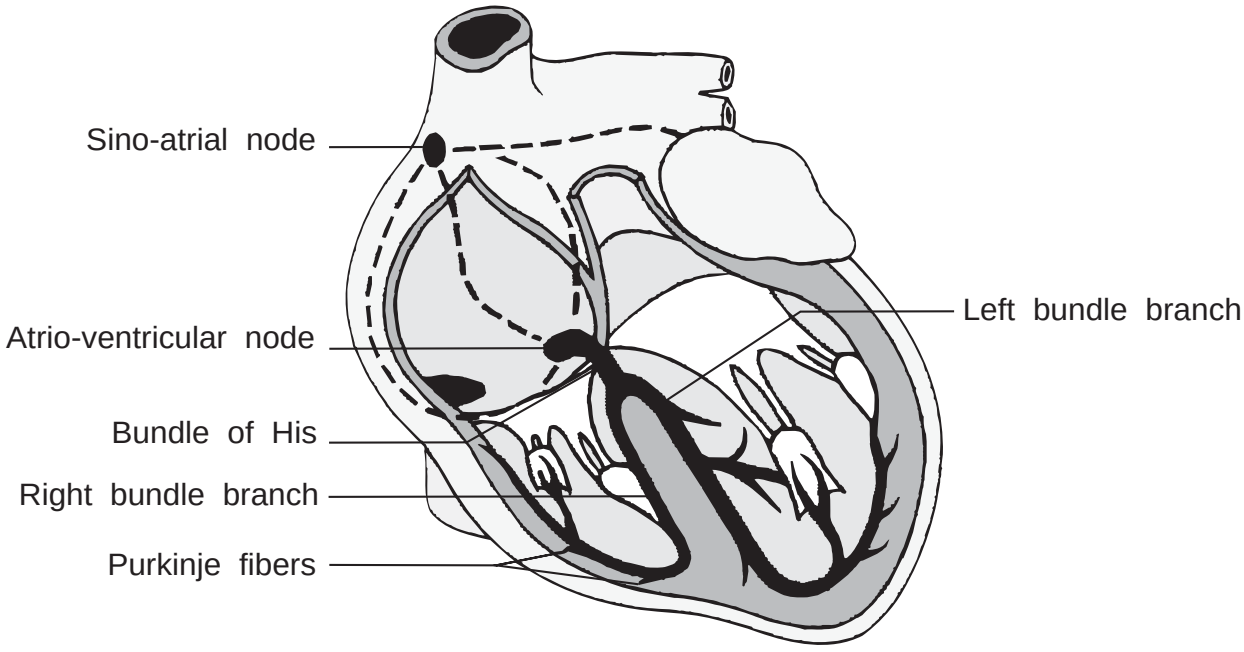


Fig 1. The anatomy of the heart.

Normally, the activation of the heart is synchronized by the **sino-atrial node** formed by specialized muscular fibers locating in the upper part of the right atrium, in the base of superior vena cava. The sino-atrial node produces spontaneously the heart frequency (approximately 70 cpm), which is independent of the nervous activity, but which however the sympathic and parasympathic nervous system are able to control. The activation propagates from the sino-atrial node to the right and to the left atrium muscle tissue. The only possible path from the atria to the ventricles is through the **atrioventricular node**. Its main task is to delay the start of ventricles' activation. This delay is necessary so that there is sufficient time to fill the ventricles with blood by atrial contraction before the ventricles contract. The atrioventricular node has its independent activation frequency (approximately 50 cpm) in case the stimulation from the sino-atrial node does not come in time.

From the atrioventricular node the depolarization propagates after a delay averaging 100 ms to the ventricles through the **Bundle of His** and spreads rapidly along the conducting system to the inner sides of the ventricles and the **Purkinje fibers**. The speed of the activation in the cells of the conducting system is approximately 8 times faster than in the muscle cells, which makes it possible for the ventricles to activate simultaneously, thus producing a mechanically effective contraction.

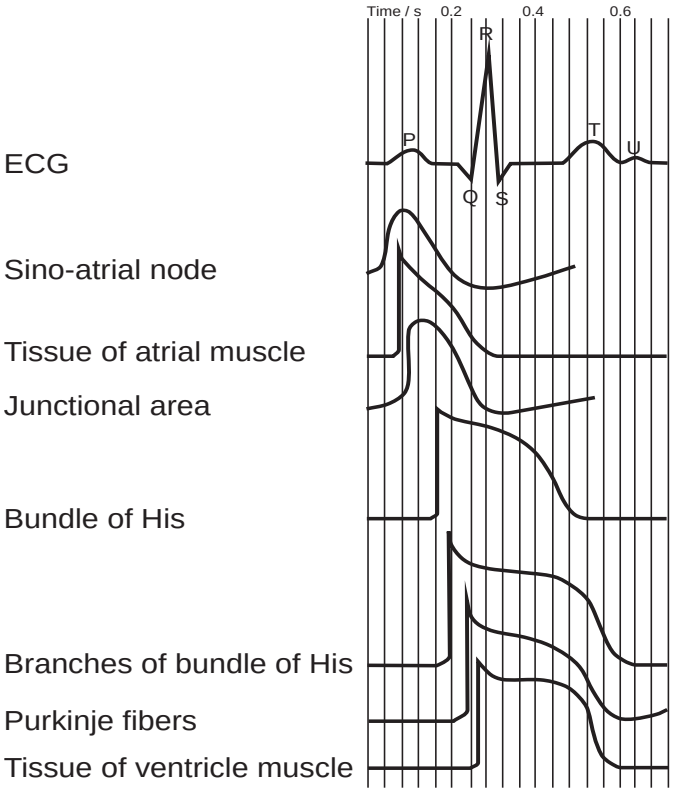


Fig. 2. Propagation of the activation in the heart fibers.

The activation of the ventricles starts simultaneously from the right and left side of the septum continuing, however, mostly from left to right. After that, the activation front propagates along the septum towards the apex of the heart. The front-, lower- and rear walls of the both ventricles are activated next so that the activation is directed from the inner to the outer part of the ventricle wall or from **endocardium** to **epicardium**. The rear-upper parts of both ventricles and septum depolarize last. The stage of repolarization starts from the outer cells and proceeds as a front towards the inner wall.

1.2. Lead vectors

Because the human body forms a volume conductor, the bioelectrical phenomena occurring inside the conductor generate a signal measurable at the skin surface. A potential change propagating (activation) in the heart muscle is counted among these types of phenomena. While the depolarization front propagates towards a positive (by definition) electrode, a positive voltage can be seen in the measuring device. Similarly, the potential difference developed by the depolarization front propagating in the opposite direction is negative. Because the potential difference over the membrane caused by the repolarization is in the opposite direction as in depolarization, also the voltages caused by 'repolarization front' show as reversed compared to the propagation direction. The repolarization occurs considerably slower than the depolarization and simultaneously in a large area, so the term repolarization front is slightly misleading.

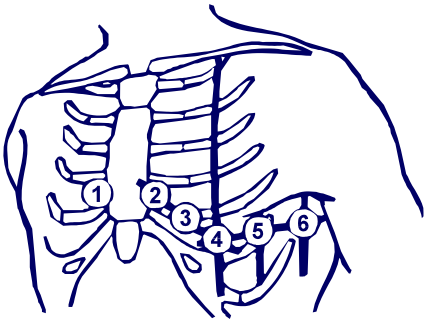
The activation front can be thought of as a vector, which indicates the direction and the strength of the front. In order to register this activation vector from the skin surface, there must be a sufficient amount of heart muscle cells forming the signal. Therefore, only the depolarization of the atria and both the depolarization and the repolarization of the ventricles can be registered effectively. The reflection of the formed whole vector between different measuring points happens by projecting the vector to the **lead vector** characteristic to these points. The properties of these lead vectors depend on the locations of the measuring points, the shape of the volume conductor and the homogeneity of the conductor. A principle representation of the propagation of the activation signal and the reflection of the electrical heart vector to lead vectors is illustrated in Appendix 1.

1.3. Lead systems

Many lead systems have been developed for research purposes, but established systems for the clinical usage are rather few due to both international agreements and historical reasons. The advantage of standardized and widely used lead systems is that they are comparable geographically and temporally.

1.3.1. The standard 12-lead ECG

The standard 12-lead ECG consists of six limb leads and six chest leads. The electrodes to be attached on the limbs are connected to the wrists and the ankles in rest ECG recording. During the exercise ECG the electrode positions are at the ends of the collarbone and the ridges of the iliac bone. The locations for the chest electrodes according to the recommendation of The American Heart Association (AHA) are as follows:



V1: Fourth intercostal space, at the right margin of the sternum.
V2: The same space, at the left margin of the sternum.
V3: Midway between V2 and V4.
V4: Intersection of left mid-clavicular line and fifth intercostal space.
V5: At the intersection of left anterior axillary line with a horizontal line through V4.
V6: At the intersection of left mid-axillary line with a horizontal line through V4 and V5.

Fig. 3. The locations of the chest leads for the standard 12-lead system

1.3.2. Unipolar leads

Unipolar leads are based on Wilson's center terminal (WCT), which is used as a reference instead of one single reference electrode. The WCT represents a 'mean electrode' calculated from the three limb electrodes. The term "unipolar" originates from Wilson's aim to develop an indifferential electrode locating at the center of heart. By removing the lead used as the measuring electrode from the Wilson's central terminal, Goldberger invented in 1942 **augmented unipolar lead system**. These augmented leads are far from Wilson's original idea, but even in spite of that they have become part of the most commonly used clinical standard. Fig. 4 illustrates that Goldberger's leads are placed 'between' the limb leads I, II ,and III.

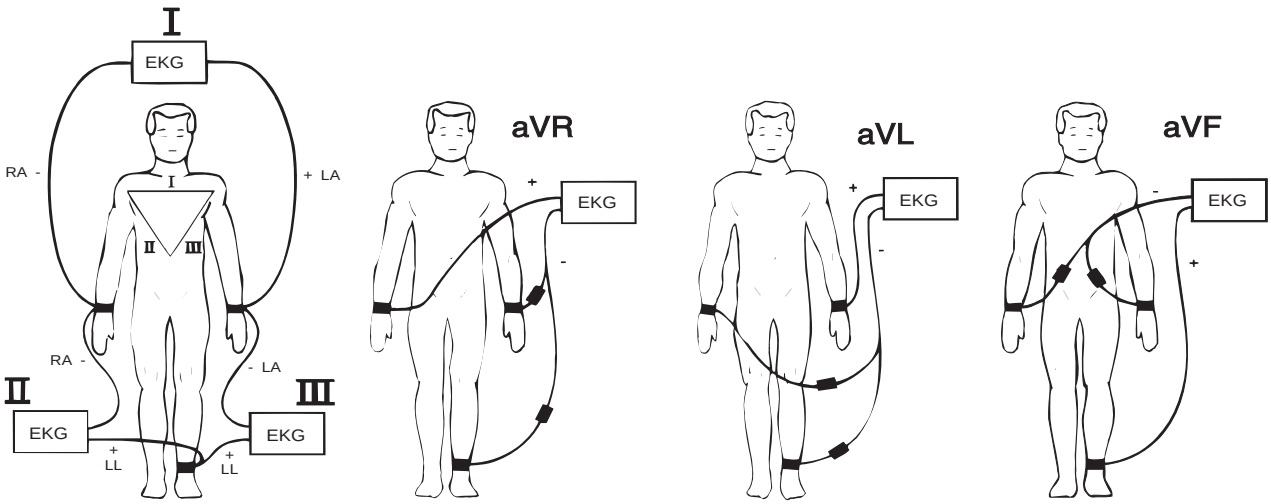


Fig. 4. The limb leads and the augmented limb leads of Goldberger.

1.3.3. Bipolar chest leads

In the bipolar chest leads, each potential recorded by a chest electrode is compared with a particular single reference electrode. Fig. 5 illustrates various reference electrode positions intended for use in different kinds of measurements. Blank circles indicate the anterior (abdomen) side and the black spots indicate the posterior (back) side. With suitable choice of the reference position, the amplitude of measuring results and the sensitivity of the connections can be affected. Also the influence of muscle activity during the different types of exercise tests affect the choice of the reference position.

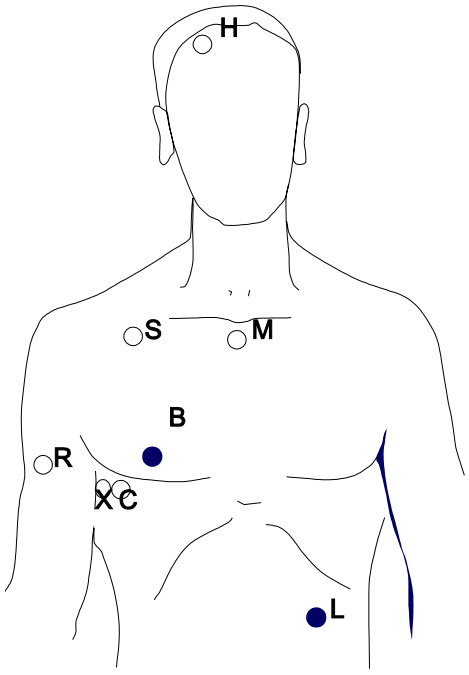


Fig. 5. The positions for reference electrode in bipolar measurements.

1.3.4. VCG leads

There is another group of leads for measuring the orthogonal lead vector. The signal measured by these leads is generally called **vectorcardiography** or **VCG,** and it is displayed in most cases in vector form with polar coordinates projected to three orthogonal planes. Also the same kind of representation as in normal ECG (time amplitude) is used for all three separate components parallel with each coordinate axis. Example of vectorcardiogram presentation is illustrated in Appendix 1.

2. BLOOD PRESSURE

The blood pressure changes during the different stages of the action of the heart. The highest or **systolic pressure** is reached during the contraction of the ventricles and lowest or **diastolic pressure** in the rest stage. The difference between the systolic and diastolic pressure is called the pulse pressure. The expression mean pressure is used to describe the average of the artery pressure, which is the (diastolic pressure + the pulse pressure) /3.

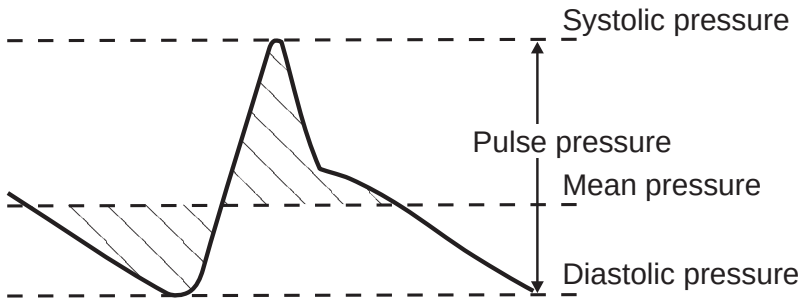


Fig. 6. Terminology of the blood pressure measurement

One of the most used indirect methods of measuring blood pressure is based on the Korotkoff sounds. In a partially compressed blood vessel, turbulent flows are induced which make the wall of the artery pulsate. When the blood pressure is measured using the usual method, the cuff is secured around the upper arm, and the Korotkoff sounds are listened with the aid of stethoscope at the inner side of elbow where the pulse of the arteria brachial is most distinctive. The pressure in the cuff is increased well in excess of the systolic pressure, e.g. up to 180-200 mmHg. Following this the cuff pressure is gradually lowered until the Korotkoff sounds are heard in the stethoscope. At this point the systolic pressure exceeds that of the pressure created by the cuff. Thus, blood flows through the compressed arteria brachial during the systolic pressure peaks. With the continued reduction of the pressure in the cuff the Korotkoff sounds become fainter, changing to a whine, and finally ceasing completely as the point of diastolic pressure is reached. In other words, the sounds cease at the point when blood flows unrestricted through the arteria brachial during the entire activation cycle of the heart and no turbulent flow is induced.

3. MEASUREMENTS

3.1. Measuring blood pressure

Measure the systolic and diastolic blood pressure of a subject (patient) in a sitting position using a sphygmomanometer (blood pressure apparatus) to be found in the laboratory.

3.2. Entering patient data

Initiate subject data entry to the ECG-analyzer (Mac-12) by pressing function key Fl (PatInfo). Type the name and date of birth (Patient's ID) of the subject. Next enter your name in answer to the question "Referred By". To the question "Location Number" type 0 and to question "Room number" type H213. The answers to the questions regarding age, height, weight, sex, and race (probable alternative being "Cauc" or "Unknown") must be obtained from the subject. The remaining questions refer to medication and the measured blood pressure values.

3.3. Placing of electrodes

Locate the positions of electrodes, remove any dead skin tissue (do this by lightly rubbing the skin with an abrasive pad), and place electrodes individually. Use the disposable electrodes, provided by the laboratory assistant, on the chest and forklike electrodes on the limbs. It is advisable to apply electrode paste to the limb electrodes.

There are four limb electrodes, which are to be placed on the wrists and ankles. Also needed are the 6 chest electrodes for the standard 12-lead connection. The four extra electrodes, which are normally used for the vector lead system (illustrated in Fig. 7), will not be used.

First attach the limb electrodes and thereafter the chest electrodes. Place the measurement module on the subject's stomach and connect the lead clips to the corresponding electrodes. Every lead clip has the name of the electrode and the limb lead is also marked with color codes according to the standard.

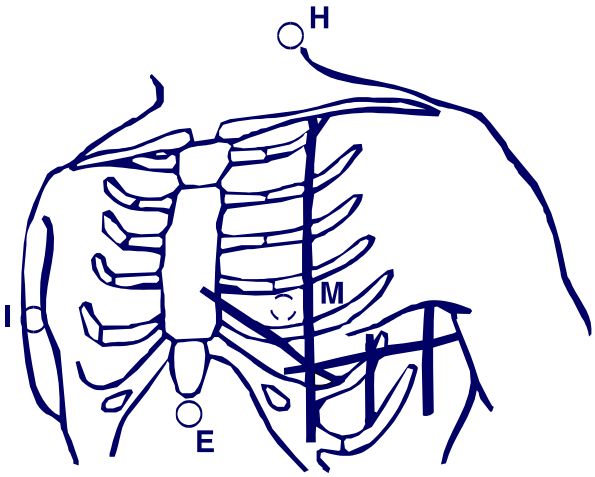


Fig. 7. The extra electrodes used for the vector lead measurement.

The pre-selected scale of the plotter channels is 10 mm/mV and the paper speed is 25 mm/s.

3.4. Standard leads

The actual measurement is taken by pressing the key "Record ECG". The device then measures a sequence of 12 sec., analyzes measuring results and prints a report. The report consists of a

2.5 sec. averaged complex of 12-lead standard leads: I, II, III, aVR, aVL, aVF, V1, V2, V3, V4, V5, V6 and a 10 sec. period of real-time measurement of vector leads (X, Y, and Z). At the top of the page you will find the patient's data, control settings of the analyzer, five different parameters calculated from the measurements and the analyzer's evaluation (diagnosis) of the measured ECG. The analyzer can also produce a long list of abnormal results with possible causes. The classification method of the analyzer is very sensitive to the locations of the electrodes.

3.5. Unipolar limb leads

Measure a few second period raw data by choosing with the key F2 (Rhythm) leads aVR+aVL+aVF. Measurement is started by pressing the key "Record Rhythm" and stopped by pressing the key "Stop". Based on the Wilson's unipolar center terminal, define the way to measure the limb leads VR, VL and VF, which are not found among the preprogrammed leads. As a hint to solve this problem, basic knowledge of the leads in question is required. The answer will not be found in the measuring device or in the manuals. When the problem has been solved, you can measure the leads VR+VL+VF for a few seconds.

3.6. Bipolar chest leads

Measure from the bipolar chest leads CS1-CS3 and CH1-CH3 a sample of both, approximately the length of three complexes. Also the measuring of these leads requires the knowledge of their basic principle and a slightly unusual measurement method. **Clarify the basics of the latter and the Wilson's leads preferably before you come to do the measurements!**

4. PROJECT REPORT

4.1. Blood pressure

Explain the principle for measuring blood pressure using Korotkoff sounds. Give the results of your measurement. Do they fall into normal range of blood pressure values? What possible error sources can you think of and how could they be prevented?

4.2. The unipolar and Goldberger's limb leads

Explain the difference between the unipolar and bipolar ECG-measurement. Prove that the amplitude of Goldberger's augmented limb leads is 1½ times greater compared to the amplitude of Wilson's unipolar signals (show also the intermediate phases when deriving the formula).

4.3. Interference elimination

Present at least five possible error sources causing distortion of the ECG signal (preferably also others than the ones simulated in the laboratory). Clarify the character of these errors (e.g. electrically or magnetically induced, patient induced etc.) and how they may affect the recorded signal. Suggest ways to eliminate them.

4.4. Vectorcardiogram

Explain the VCG measurement and the orthogonal lead system by using the Frank's lead system as an example. Discuss especially, what is measured by VCG and how the orthogonal lead system is constructed. Consider also the information content of the VCG methods compared to the traditional 12-lead system. Which of the standard 12-lead system electrodes can be used in the Frank's VCG measurement with the four extra electrodes?

4.5. Measurement result analysis

4.5.1. Comparison of limb leads

Explain the arrangement used in the laboratory for measuring the unipolar limb leads VR, VL, and VF. Present your measurement results of the unipolar limb leads (e.g. R-peak amplitudes) and compare those with the corresponding results of the augmented limb leads. Do the results support the proven theory in section 4.2?

4.5.2. Basic parameters of the ECG

Define shortly the following parameters. Calculate the QT-duration and the corrected QT-duration (use Bazett's formula) and the electric axis of the heart. Also mark all the corresponding spots on the ECG printout.

a. the R-amplitude
b. the T-amplitude
c. the QT-duration
d. the corrected QT-duration
e. the electric axis of the heart (the mean vector)

4.5.3. Bipolar chest lead signal detection

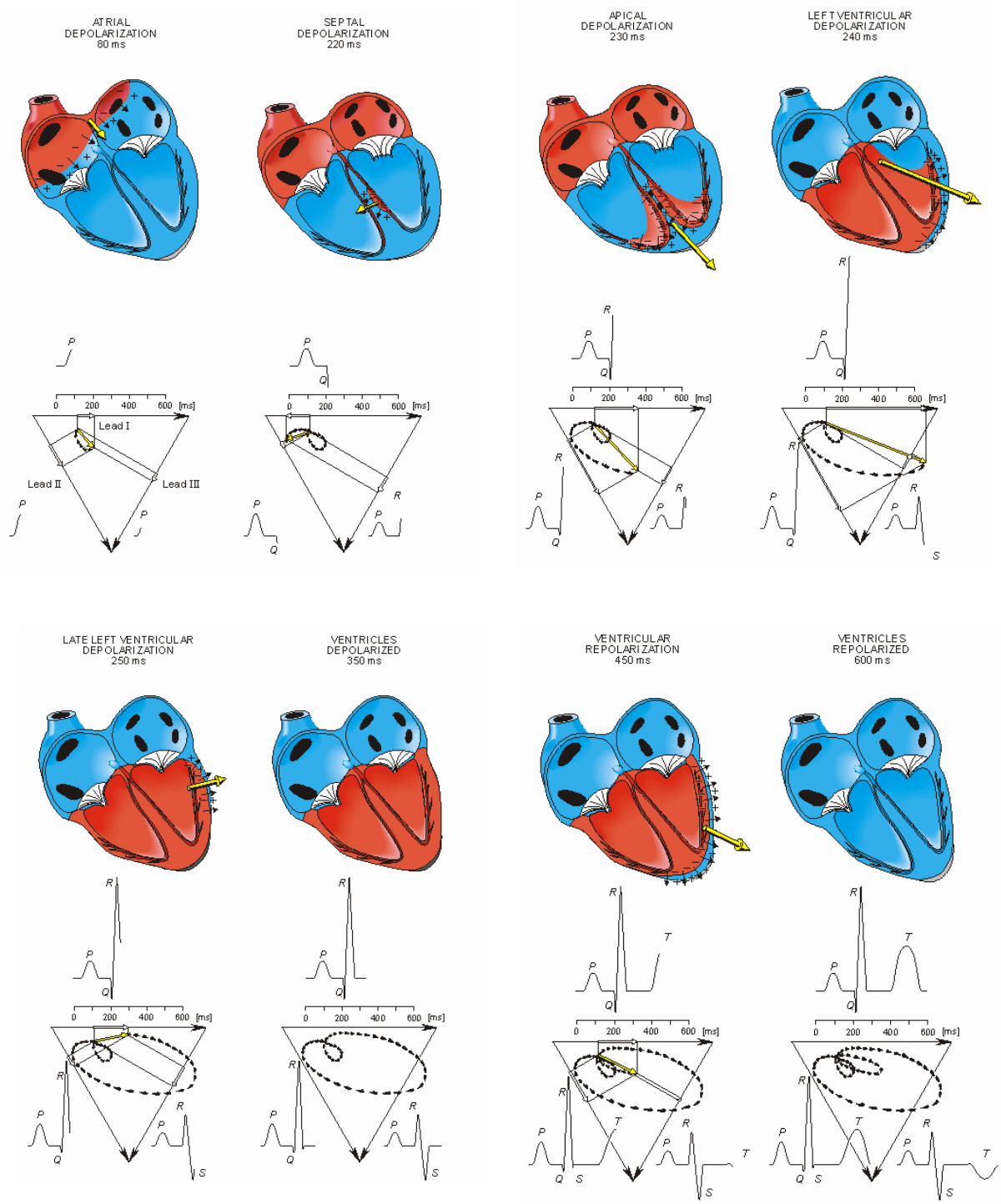
Explain the arrangement used in the laboratory for measuring bipolar chest leads CS1-CS3 and CH1-CH3. Compare the signals from the bipolar chest leads to those measured by unipolar chest leads. Consider the advantages and disadvantages of the other reference points given previously in Fig. 5. In what circumstances would they be preferable?

4.5.4. Interference: causes and elimination

Analyze the error sources simulated in the laboratory. Explain shortly how the errors were induced and how they affect the recorded ECG signal, i.e., compare the sensitivity of the leads to the signals originating from the heart with their sensitivity to signals originating from interference sources. In a clinical situation, how could these errors be eliminated?

4.6. Recommended references

- Heikkilä, Juhani. EKG – Perusteet ja tulkinta.
- Horacek, Milan. Comprehensive electrocardiology, Lead theory.
- MacFarlane, P. Comprehensive electrocardiology, Lead systems.
- Kalliomäki, K. Sähköiset häiriölähteet, niiden vaikutukset ja mittaussysteemin suojaus
- Malmivuo, J. & Plonsey, R. Bioelectromagnetism
- Nousiainen, J. Lääketieteellinen laitetekniikka (pruju)
- Rowlands, D.J. Understanding the Electrocardiogram. Section 1.
- etc…



Appendix 1. Propagation of the activation and projection to the limb leads