– 27 –

Electrocardiography

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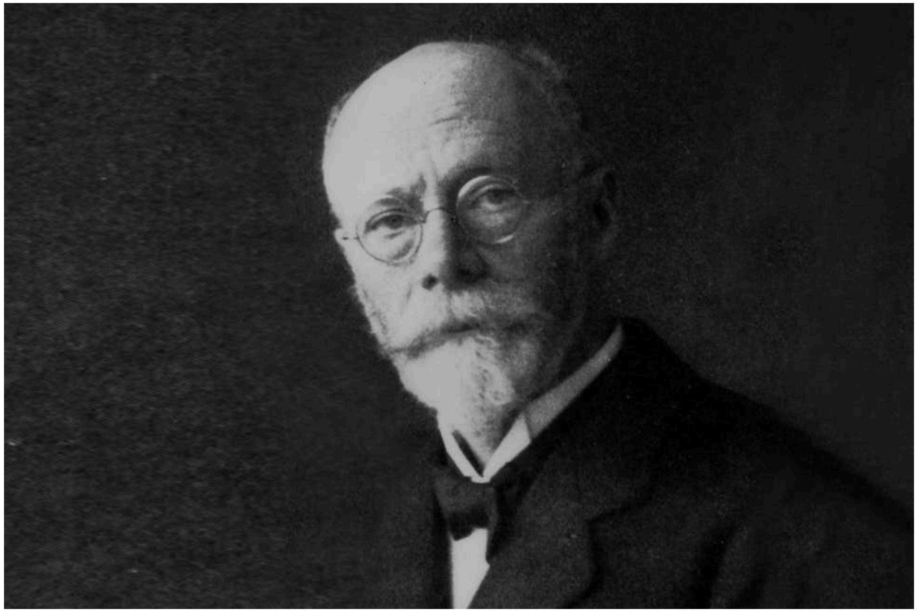
March 2020

Preface



„We should first endeavor to better understand the working of the heart in all its details, and the cause of a large variety of abnormalities. This will enable us, in a possibly still-distant future and based upon a clear insight and improved knowledge, to give relief to the suffering of our patients.”

Willem Einthoven, 1906

Introduction

Electrocardiography: A recording of the *voltage* associated with the electrical activity of the heart measured between well defined points of the body (location of electrodes) as a function of *time*.

normal sinus rhythm

atrio-ventricular block

premature ventricular contraction

ventricular fibrillation

It is a **common**, **simple** and **cheap** (≈ 1000 €/appliance) method for assessing the electrical properties of the heart.

However, its **interpretation requires experience** and **understanding** of the underlying cardiac electrophysiology and some technical details.

Timeline

1800 · 1850 · 1900 · 1950

1780s
Galvani
Discovery of „animal electricity” (in frogs)

1842
Matteucci
First evidence for electrical activity of the (frog) heart

1887
Waller
First electrical recording on human heart

1895
Einthoven
Names ECG waves

1901
Einthoven
First clinically applicable ECG

1912
Einthoven
Introduces Einthoven’s triangle

1924
Einthoven
Nobel Prize

1934-38
Wilson
Central terminal & precordial leads

1942
Goldberger
Augmented unipolar leads

1954
AHA*
Standardized 12 Lead ECG as we know it today

*American Heart Association

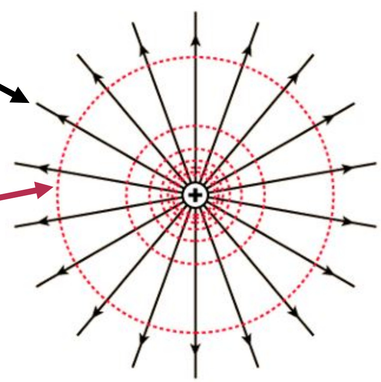
Electric Field of the Heart

Electric dipole moment: A vector quantity characterizing a dipole. Its numerical value is the product of the distance between the poles of a dipole and the magnitude of the charges. Its direction is to the positive pole. Unit: coulomb · meter = debye (D).

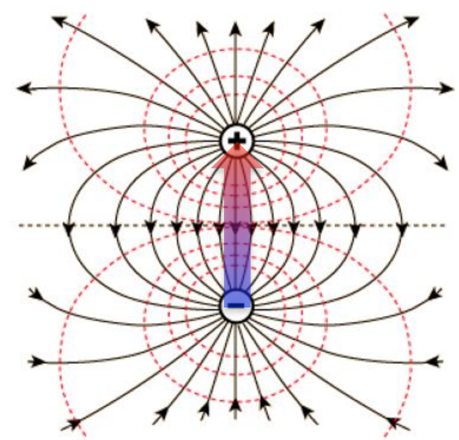
Electric field lines: Directed lines used to visualize an electric filed: lines are tangential to the electric force acting on a positive test charge

Equipotential contour lines: A set of points with equal electric potential energy

monopole

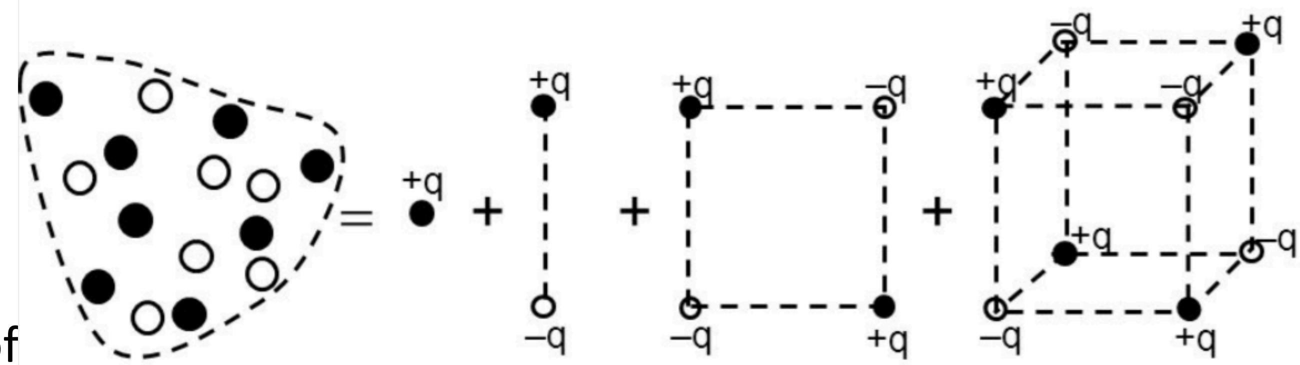


dipole



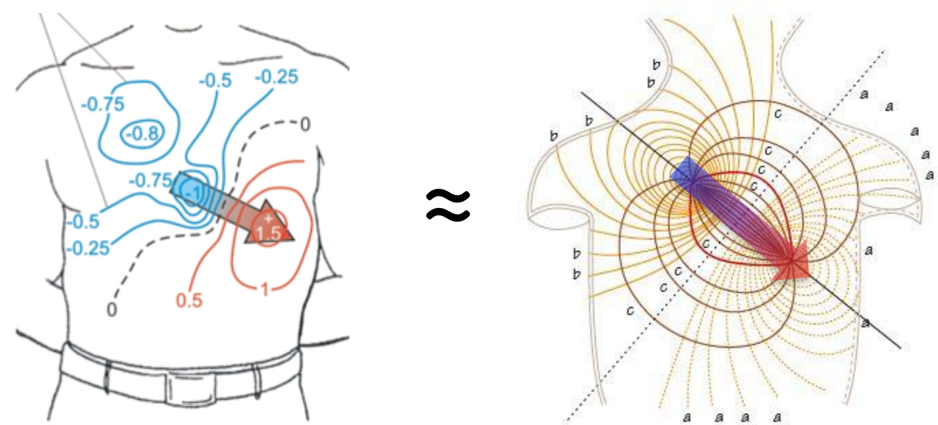
Electric Field of the Heart

Multipole expansion: A complex electric field of a set of charges written up as a weighted sum of a monopole, a dipole, a quadrupole, an octupole etc. (cf. Fourier-analysis of a signal).



monopole $U \sim 1/r$ | dipole $U \sim 1/r^2$ | quadrupole $U \sim 1/r^3$ | octupole $U \sim 1/r^4$

The electric field of the heart: A complex electric field emerging as a result of the electrical activity of the heart. In its multipole expansion:
– Terms of higher order than dipole can be neglected due to their strong inverse distance-dependence;
– The monopole term is zero because the amount of positive and negative charges in the heart are equal.

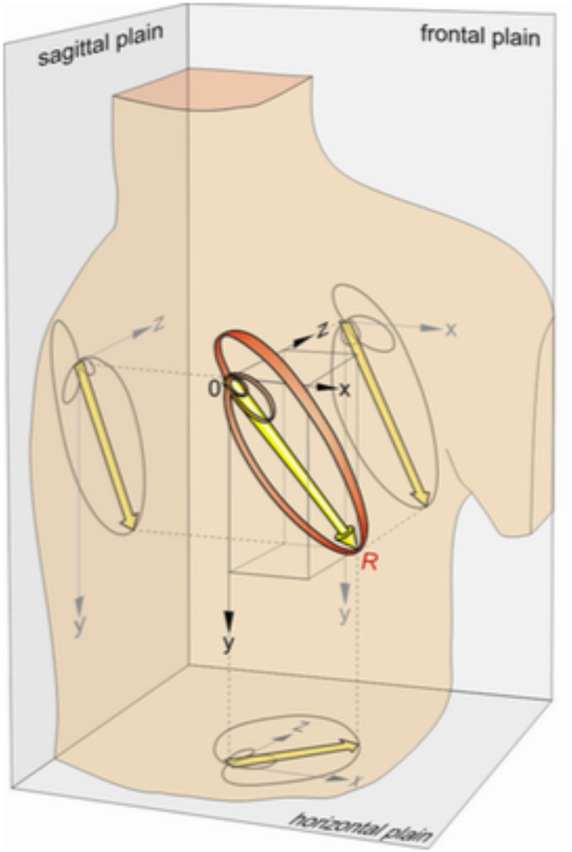


Electric Field of the Heart

The electric field of the heart: We assume that the source is a dipole in a fixed location (with a fixed negative pole, the isoelectric point) varying over time corresponding to the electrical events during the heart cycle.

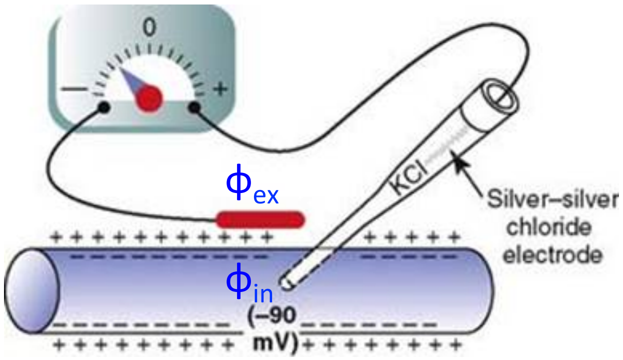
Integral vector: The integral vector is a three-dimensional vector representing the varying dipole field of the heart.

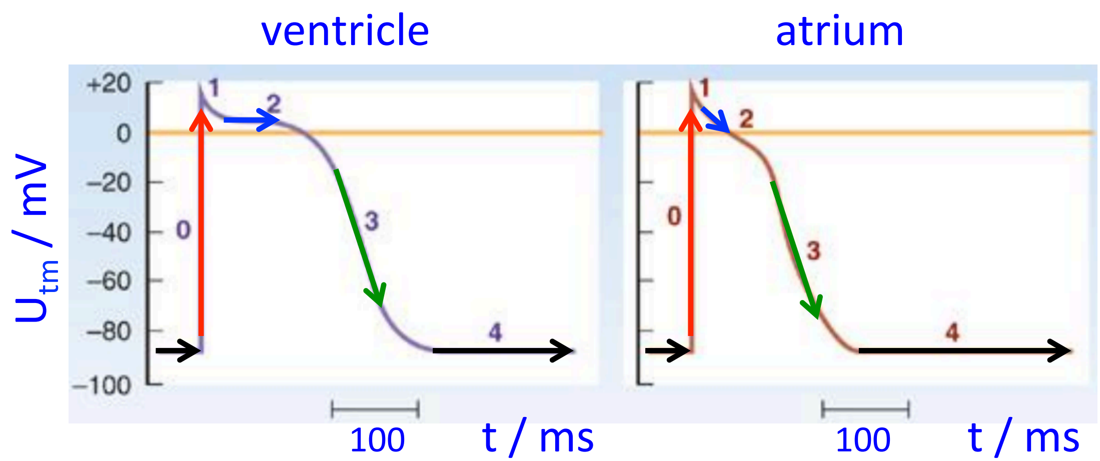
the temporal variation of the integral vector (and its planar projections) of the heart represented by loops



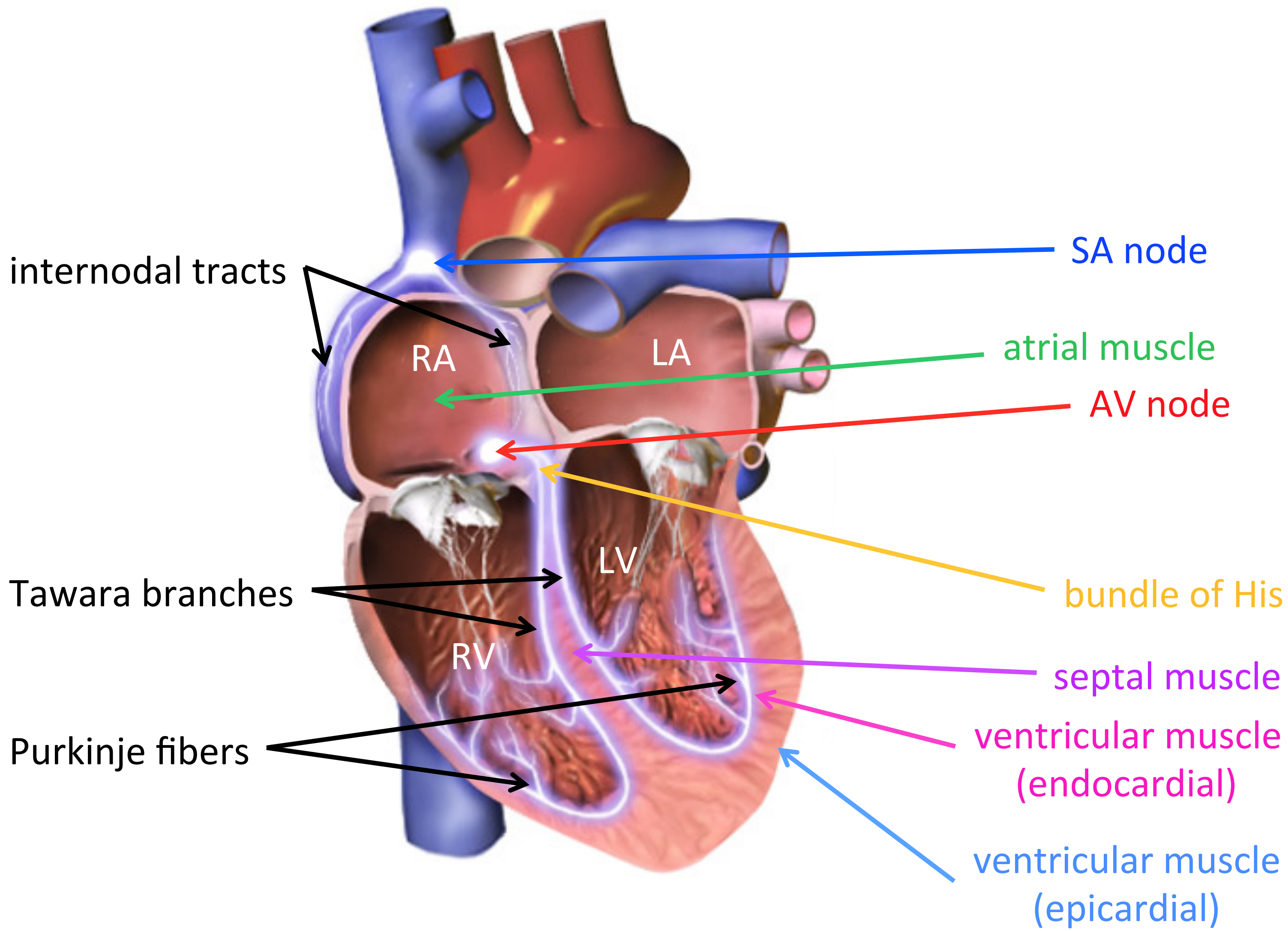
Action Potential in the Cardiac Muscle

Action potential: The transmembrane voltage (U_{tm} = intracellular potential – extra-cellular potential = $\phi_{in} - \phi_{ex}$) pattern of electrically excitable cells.
In **cardiac muscle** cells the following phases can be identified:
– **Resting potential** (4): a relatively constant **negative** voltage (≈ –90 mV) due to the balance between ion currents maintained by Na^+/K^+-pumps and Na^+/Ca^{2+}-exchangers
– **Depolarization** (0): a sharp increase in the voltage due to Na^+-influx
– **Plateau phase** (2): a relatively constant **positive** voltage (≈ +10 mV) maintained by concurrent K^+ efflux and Ca^{2+} influx
– **Repolarization** (3): the voltage decreases back to the resting level due to pronounced K^+-efflux

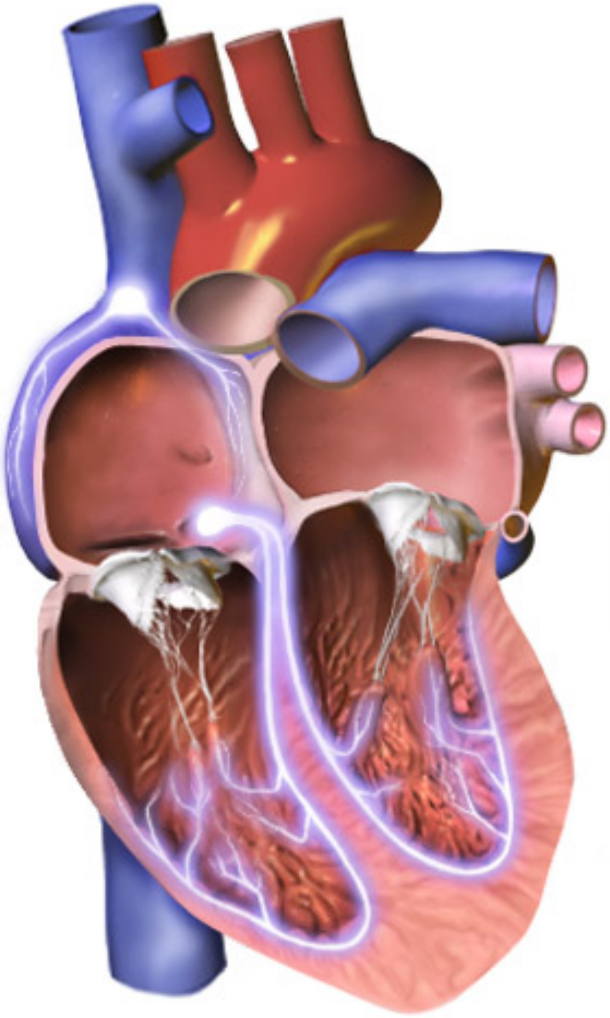




Anatomy of the Heart



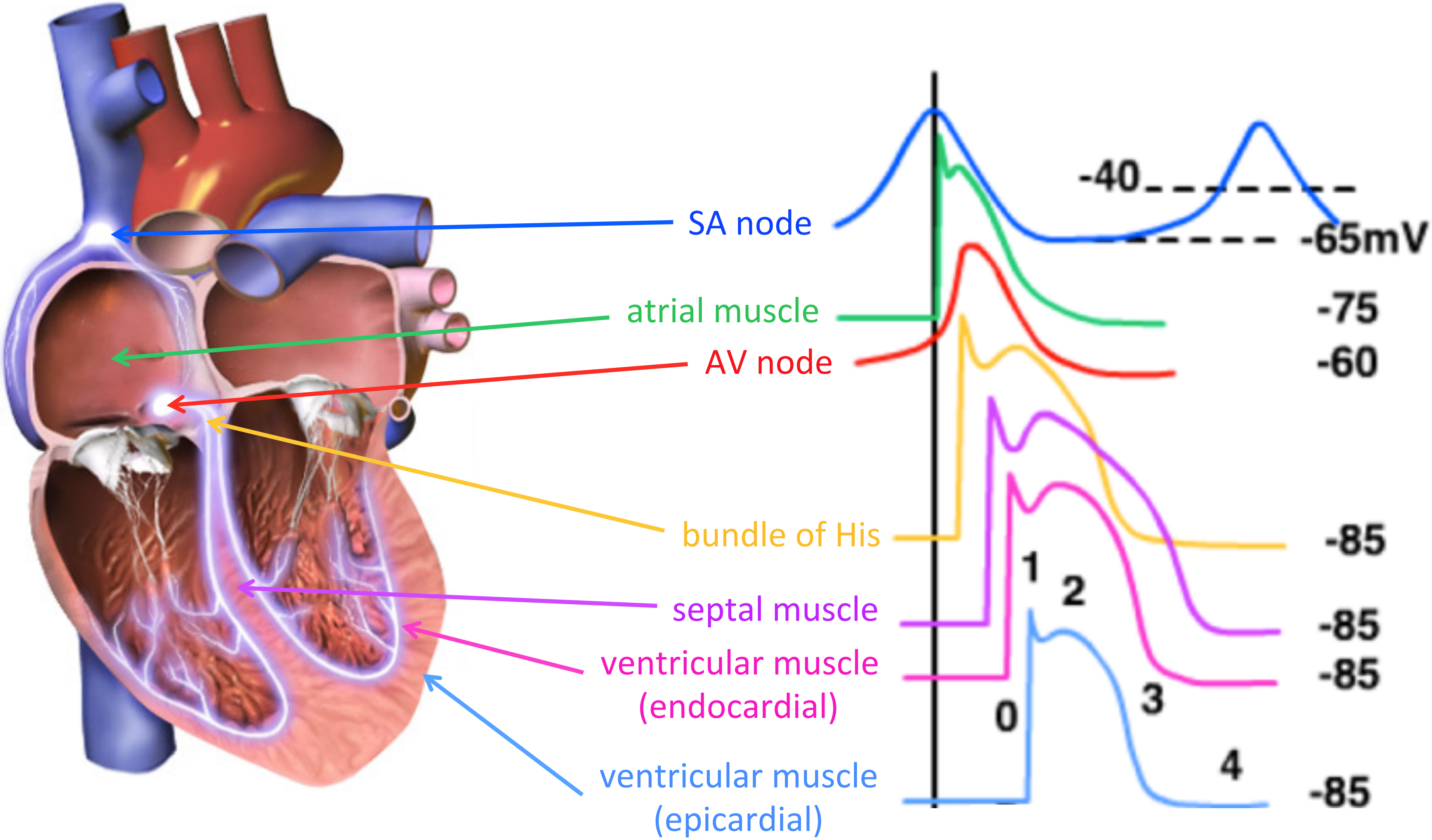
Action Potential in the Heart



– The depolarization wave is induced by the **pace-maker cells** of the sino-atrial node.
– The **depolarization** of one cell is triggered by the depolarization of a neighboring cell, therefore, the depolarization wave propagates like a chain reaction or a domino effect.
– The **repolarization**, however, occurs automatically after the plateau phase, so it is less coordinated.

– The **duration of the plateau phase** is "coded" into the cell:
- In the **atria** the duration is short and more or less the same in all cells
- In the **ventriculi** the duration is longer and not uniform: it is the longest in septal cells, shorter in endocardial cells and the shortest in epicardial cells

Action Potential in the Heart

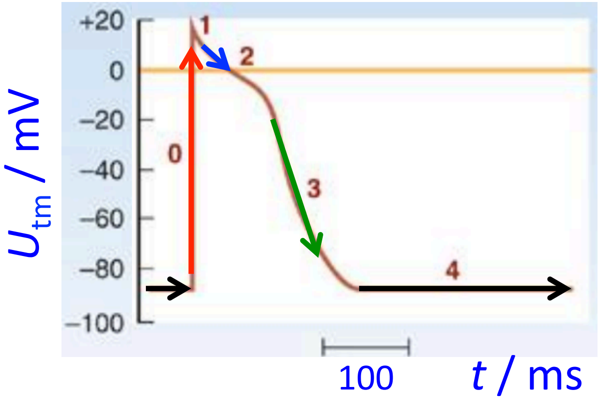


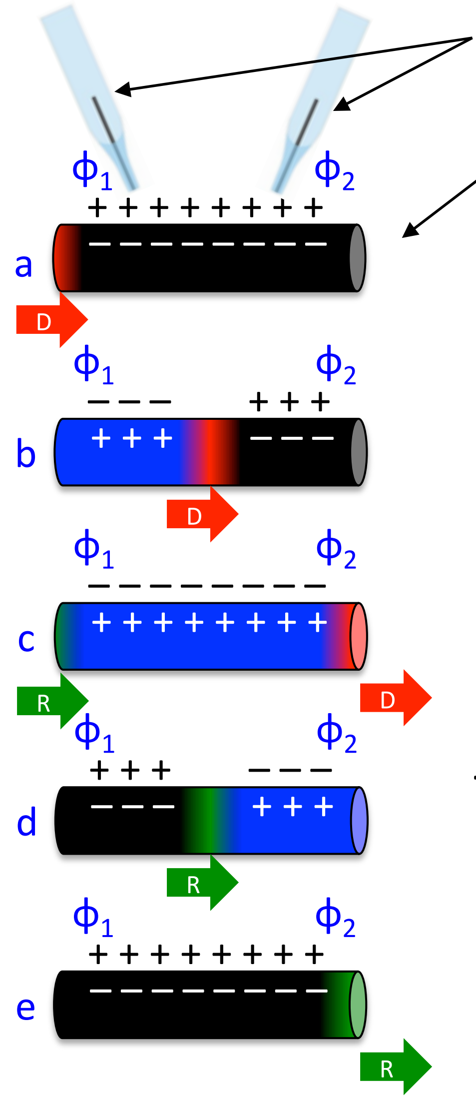
Voltage between Two External Electrodes

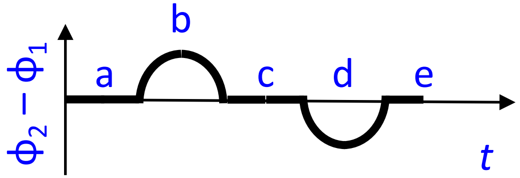
Atrial events:

– The duration of the plateau phase is short and more or less the same in all cells

– Therefore the direction of propagation of depolarization and repolarization are the same







– The depolarization (b) and repolarization (d) peaks have **opposite** polarity

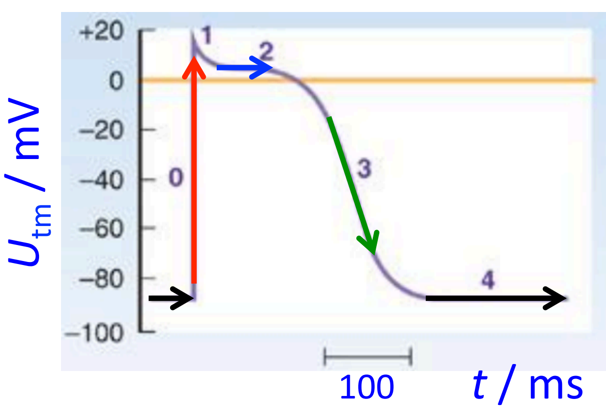
Voltage between Two External Electrodes

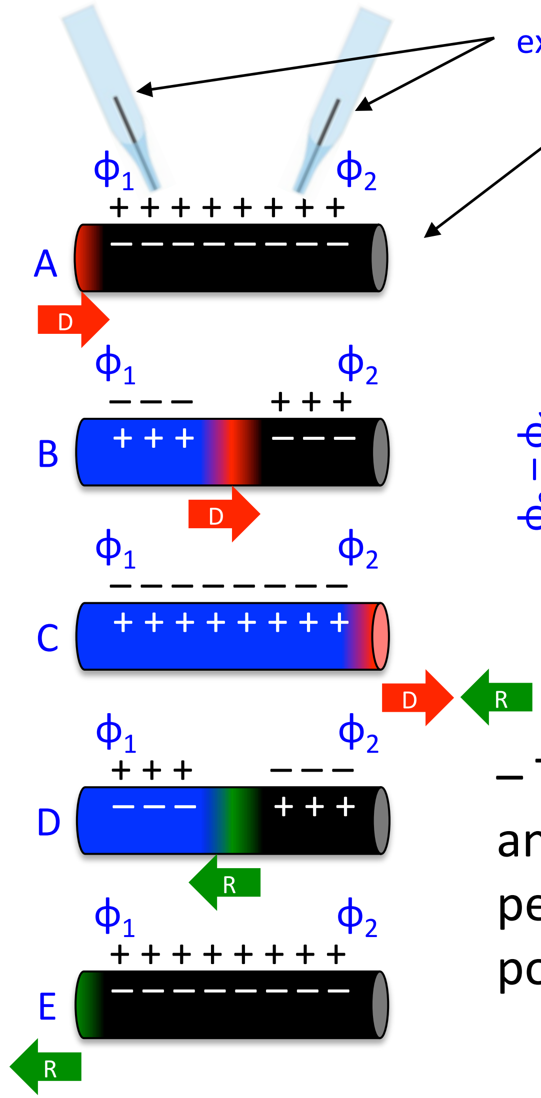
Ventricular events:

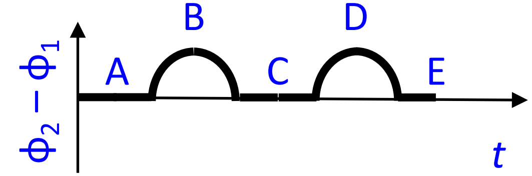
– The duration of the plateau phase is longer on the endocardial and shorter on the epicardial side

– The cells which depolarized first will repolarize last

– Therefore the direction of propagation of depolarization and repolarization are **opposite**





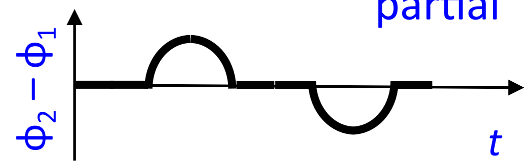


– The depolarization (B) and repolarization (D) peaks have the **same** polarity

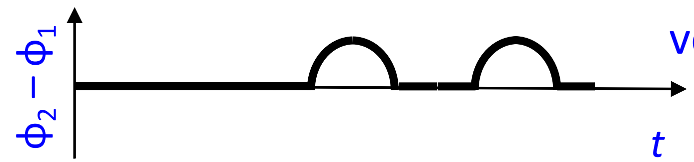
Reconstruction of a "Typical" ECG Curve

Events in the whole heart:
– Rapid **depolarization of the atria** (P-wave)
– The atria are electrically insulated from the ventricles, only connection is through the AV node
– **Depolarization continues in the ventricles** (QRS-complex): first the septal, then the endocardial, finally the epicardial muscle cells will rapidly depolarize (at the same time the atria are repolarized but this is masked by the ventricular events)
– Diffuse **repolarization of the ventricles** (T-wave): first the epicardial, then the endocardial, finally the septal cells

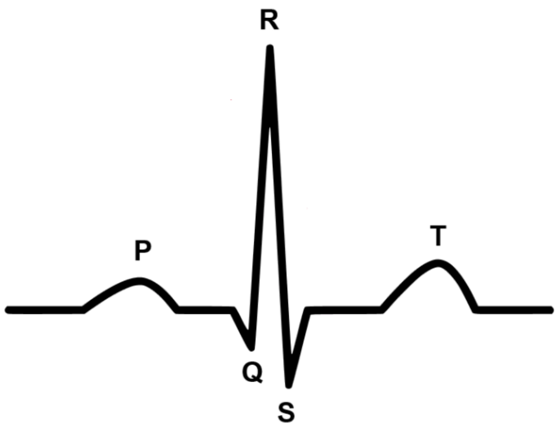
partial "ECG" of the atria



partial "ECG" of the ventricles



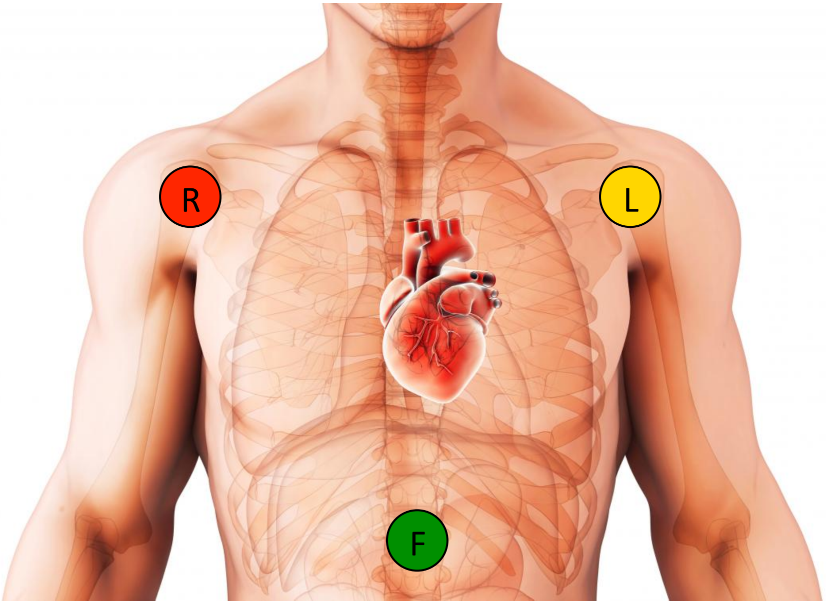
schematic of a typical ECG



The **height** of a wave is related to the maximal degree of charge separation, while its **breadth** to the duration of the underlying event.

Einthoven's Bipolar Limb Leads

ECG leads: Form electric circuits through which potential differences of the heart between two points (with the help of electrodes) are measured.
Active electrode: An electrode connected to a point with an electric potential varying over time. Electrodes connected to any point of the body are active.
Inactive electrode: An electrode connected to a point that has a constant electric potential over time. Such points are constructed by combining active electrodes.
Bipolar lead: An ECG lead connecting two active electrodes.
Einthoven's leads: A triaxial bipolar system of three limb leads measuring the potential difference between any two of the right shoulder (R; through the right arm), left shoulder (L; through the left arm), and the lower trunk (F; through the left leg). A fourth electrode (**N**; typically placed on the **right leg**) is used to filter out noise.
ECG recording: SEE VIDEO.



Einthoven's Bipolar Limb Leads

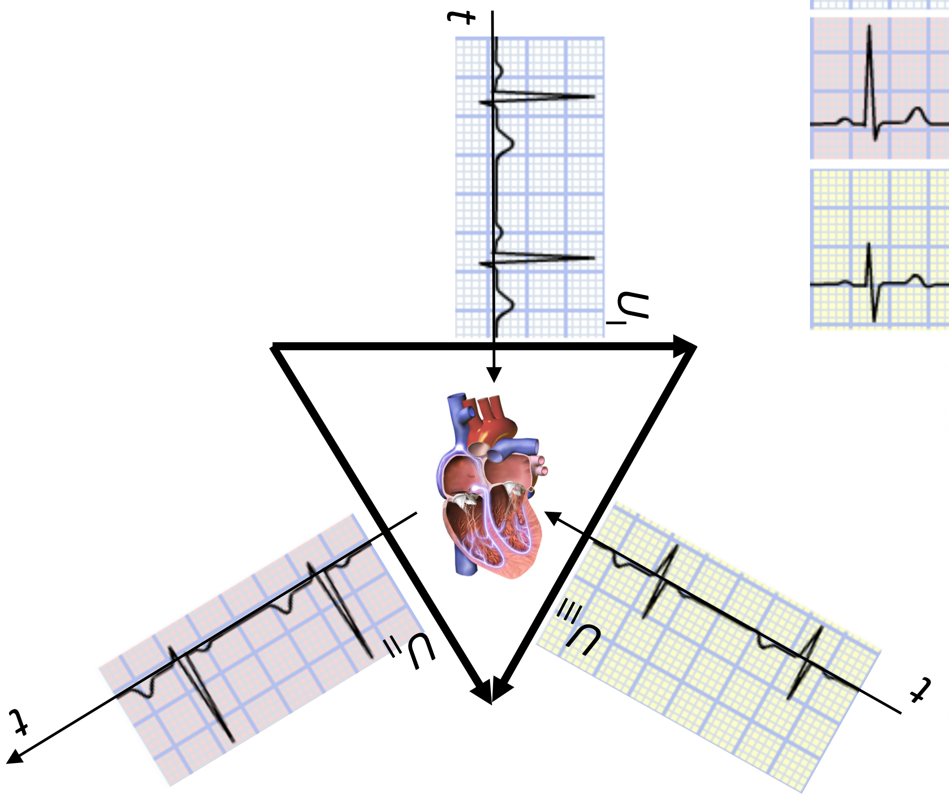
Einthoven's triangle: An imaginary equilateral triangle connecting the poles of Einthoven's limb leads. Its sides are:

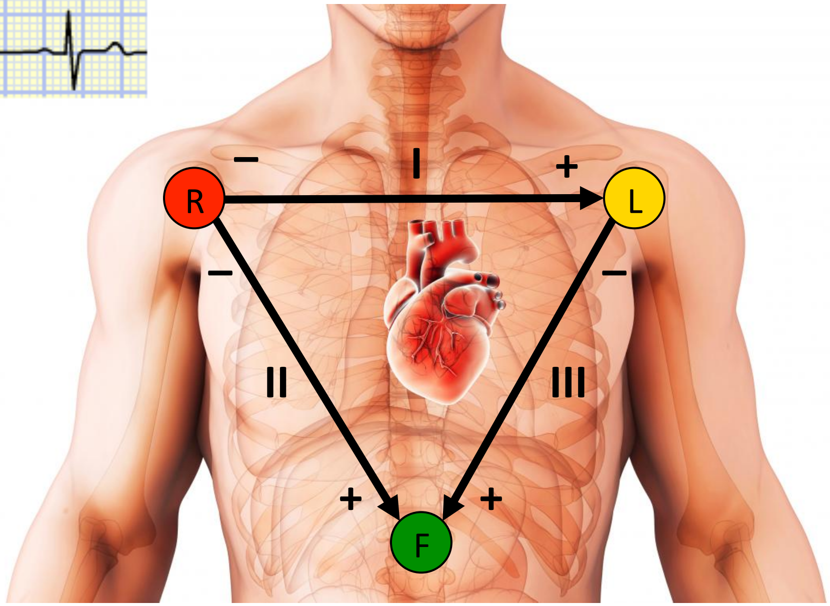
$U_I = \phi_L - \phi_R$

$U_{II} = \phi_F - \phi_R$

$U_{III} = \phi_F - \phi_L$

$$U_{II} = U_I + U_{III}$$

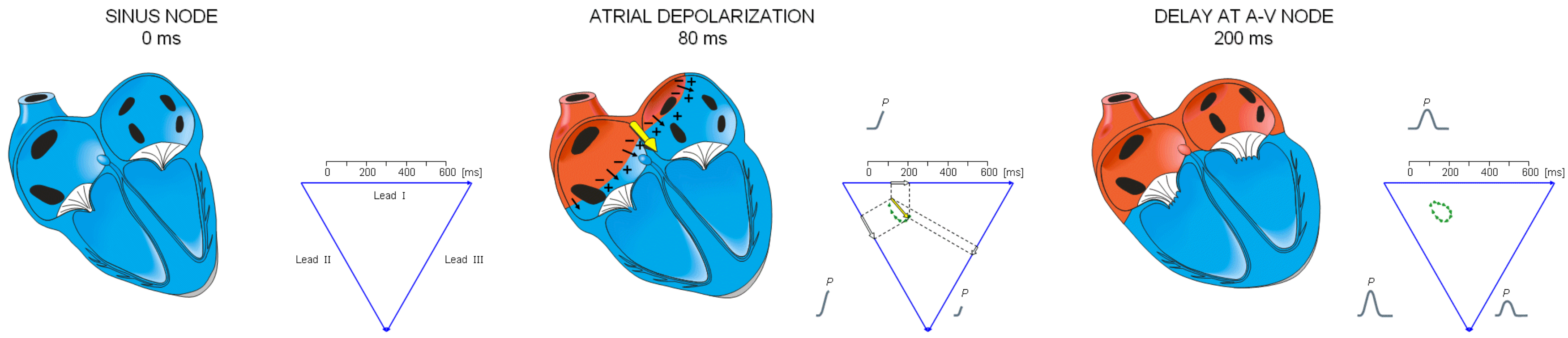




Einthoven’s Leads and the Integral Vector

Steps of atrial depolarization

P wave and P loop



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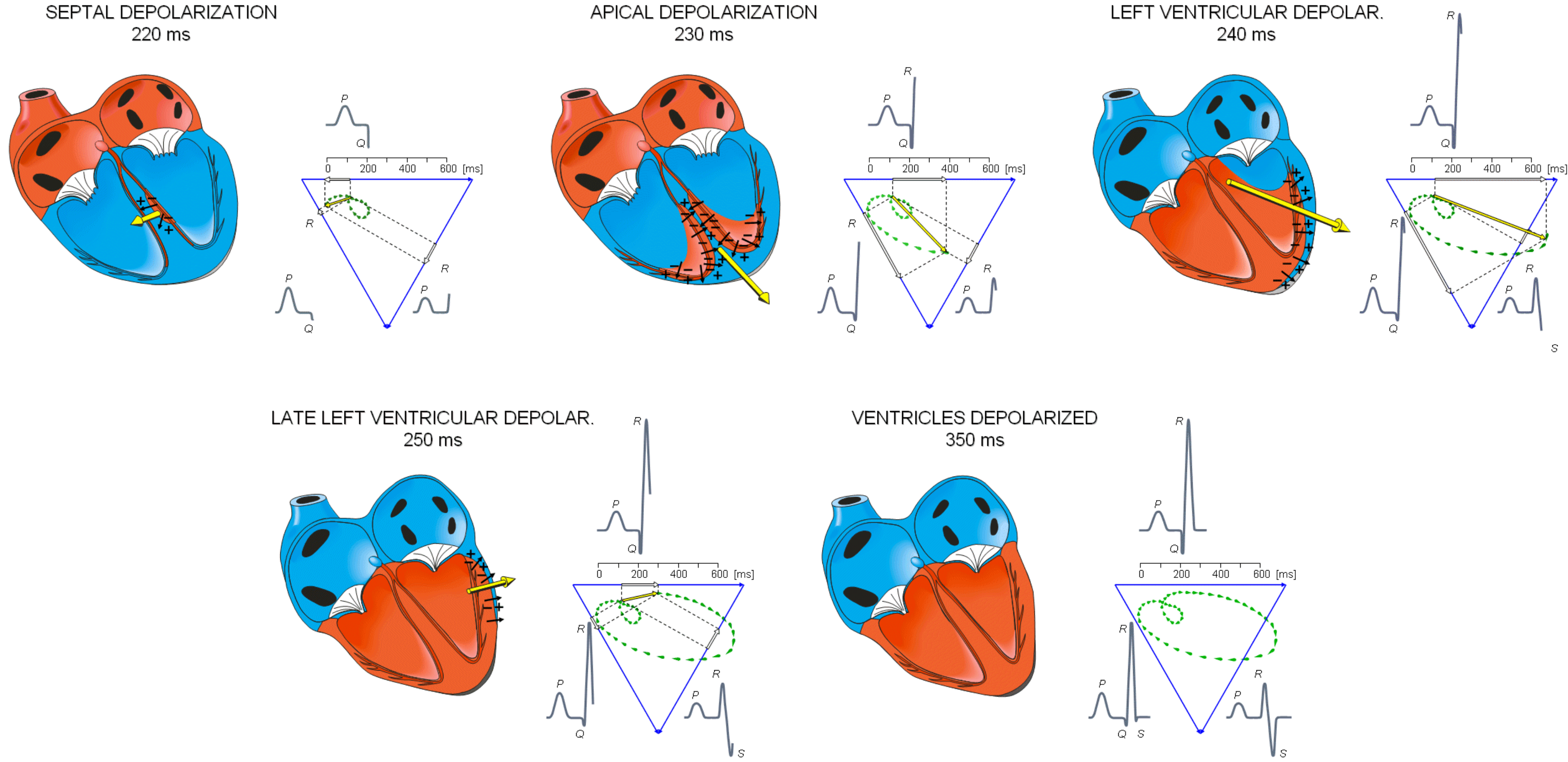
Einthoven's Leads and the Integral Vector

Steps of ventricular depolarization (and atrial repolarization)

QRS complex and QRS loop



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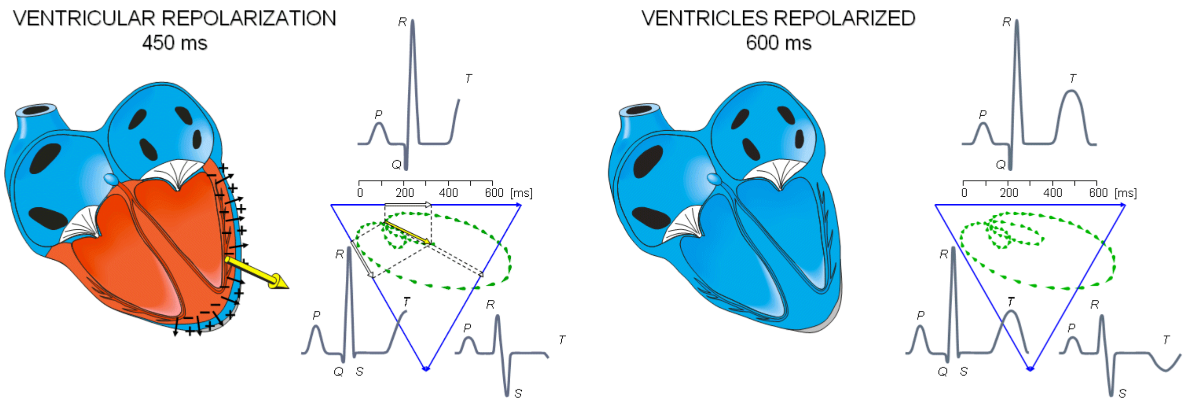
Einthoven’s Leads and the Integral Vector

Steps of ventricular repolarization

T wave and T loop



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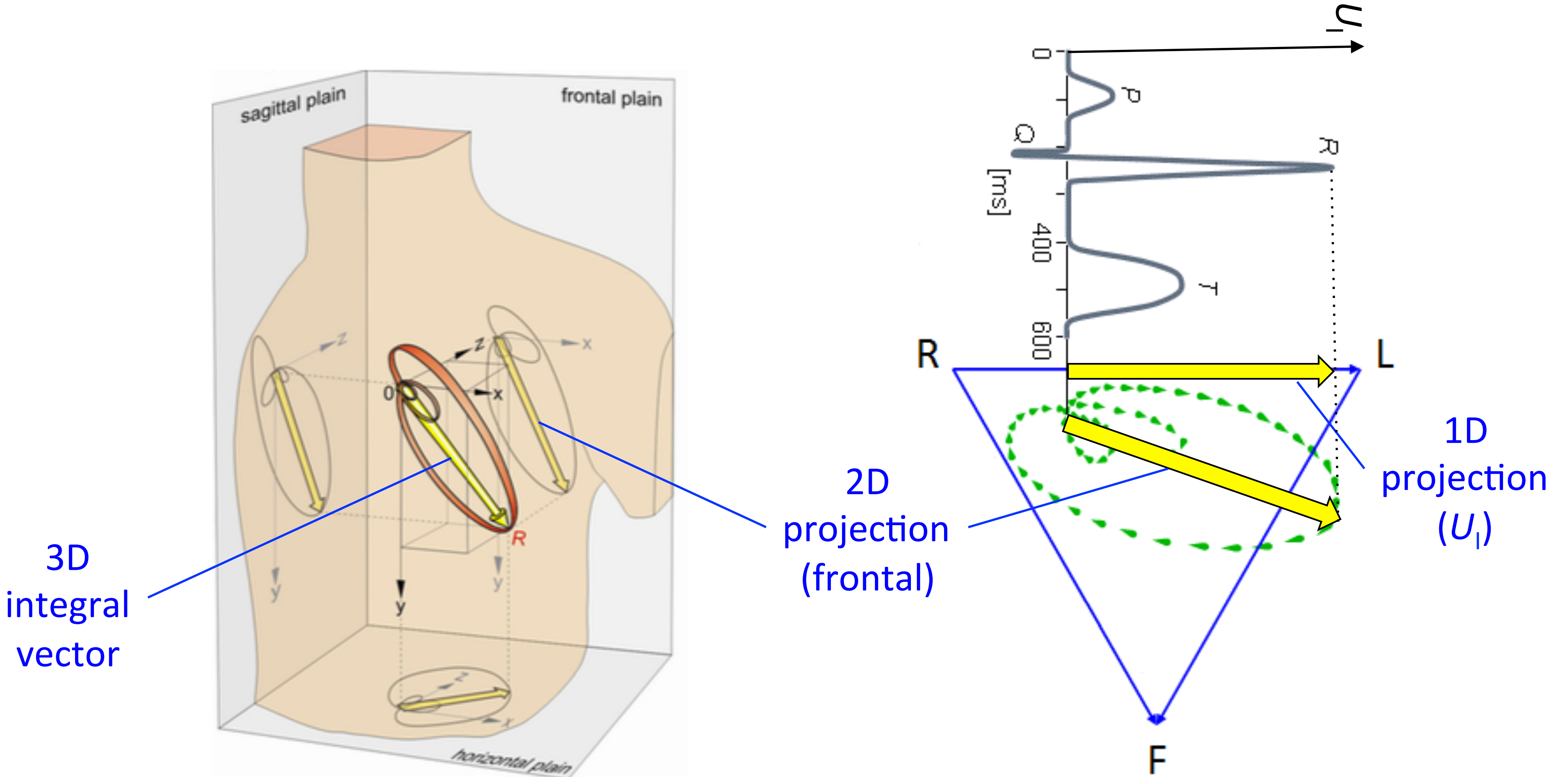
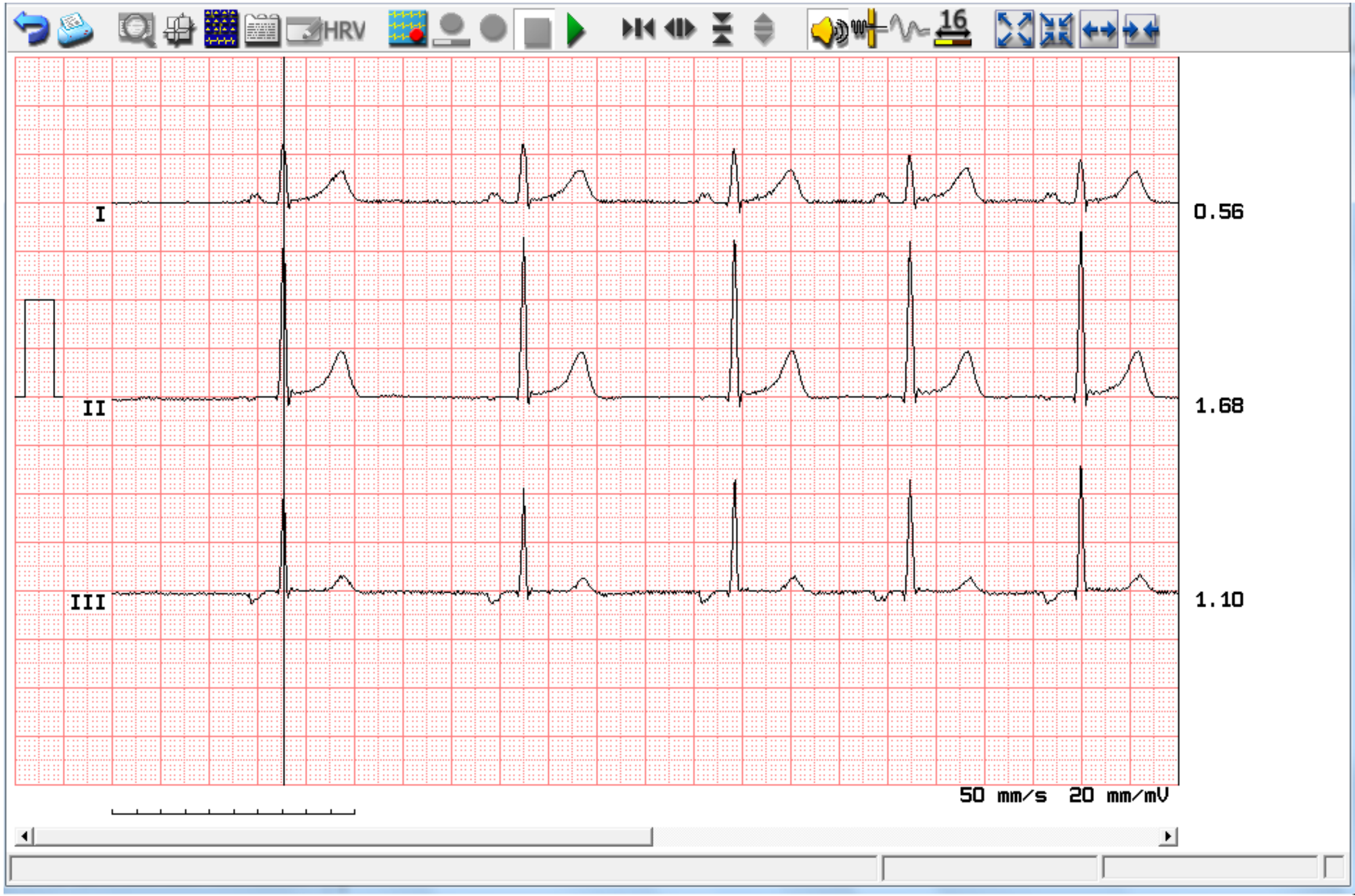
Einthoven's Leads and the Integral Vector

Different dimensional levels of projections of dipole moment vector at R-peak.



ECG Curve Recorded with a CARDIAX Appliance



Analysis of the ECG Curve

1) Determine the mean duration of heart cycles (*T*) and the heart rate (*f*).

i) Select the Einthoven recording you will analyze.

ii) Check the time scaling ("paper speed"). In our case: 50 mm/s.

iii) Read the RR-distance in mm (each small division is 1 mm). In our case: 43.5 mm.

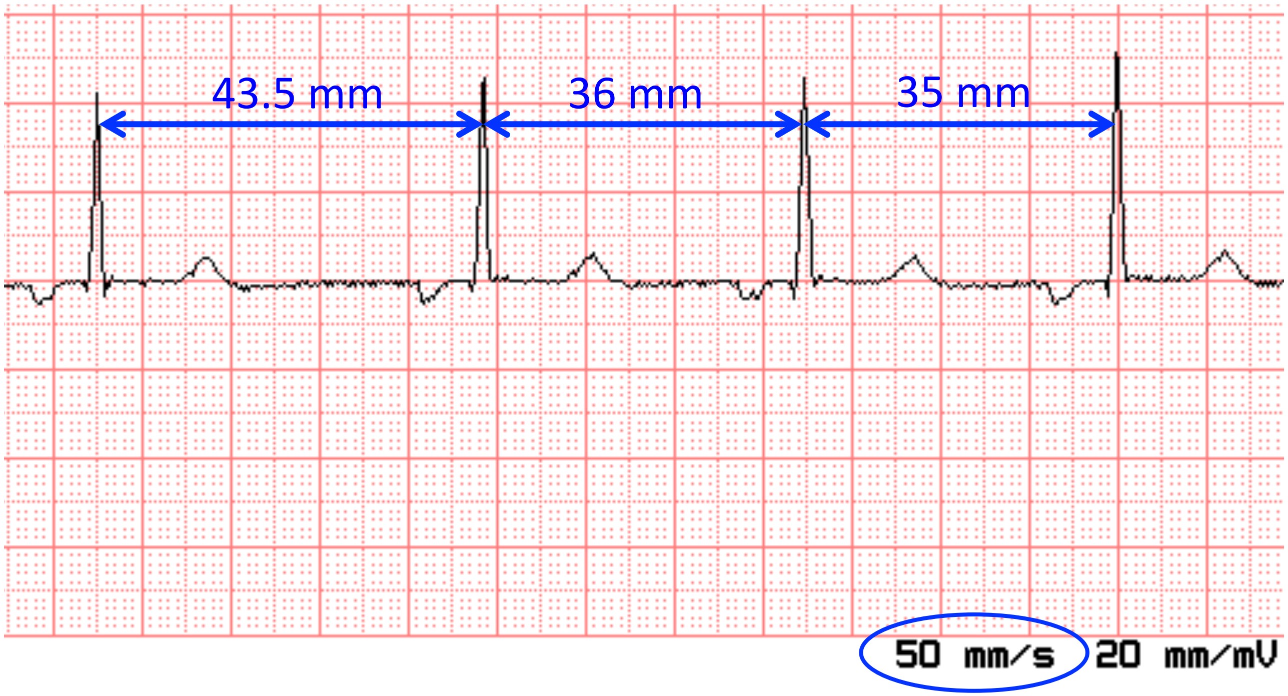
iv) Repeat the reading for another two RR-distances. 36 mm and 35 mm.

v) Calculate the mean. In our case: 38 mm.

vi) Convert it to time. In our case: (38 mm)/(50 mm/s)= 0.76 s. This is *T*.

vii) Convert this into minutes: 0.01267 min.

viii) Take the reciprocal to find *f*: 79 min^{-1}.



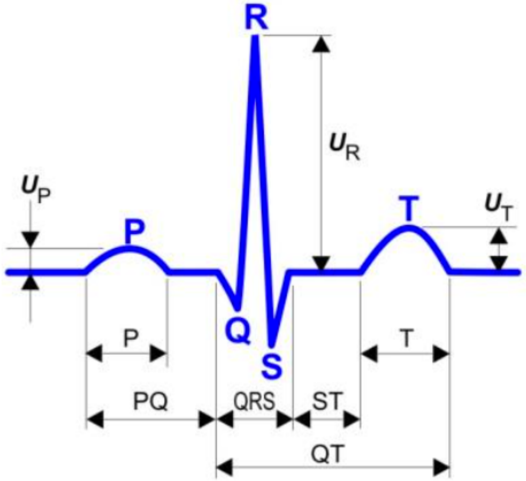
Analysis of the ECG Curve

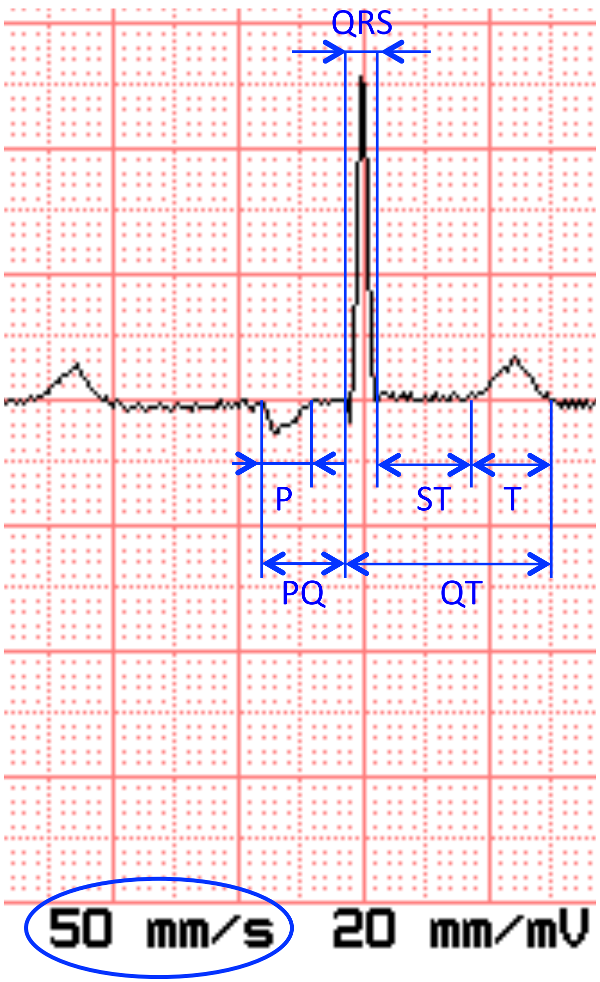
2) Determine the characteristic time and voltage values of an ECG cycle.

i) First, select the ECG lead and period you will analyze

ii) Then read the durations in mm and convert them to time using the time scale (here: 50 mm/s):

P:	4 mm	–>	0.08 s = 80 ms
PQ:	6.5 mm	–>	0.13 s = 130 ms
QRS:	2.5 mm	–>	0.05 s = 50 ms
ST:	7.5 mm	–>	0.15 s = 150 ms
QT:	16.5 mm	–>	0.33 s = 330 ms
T:	6.5 mm	–>	0.13 s = 130 ms



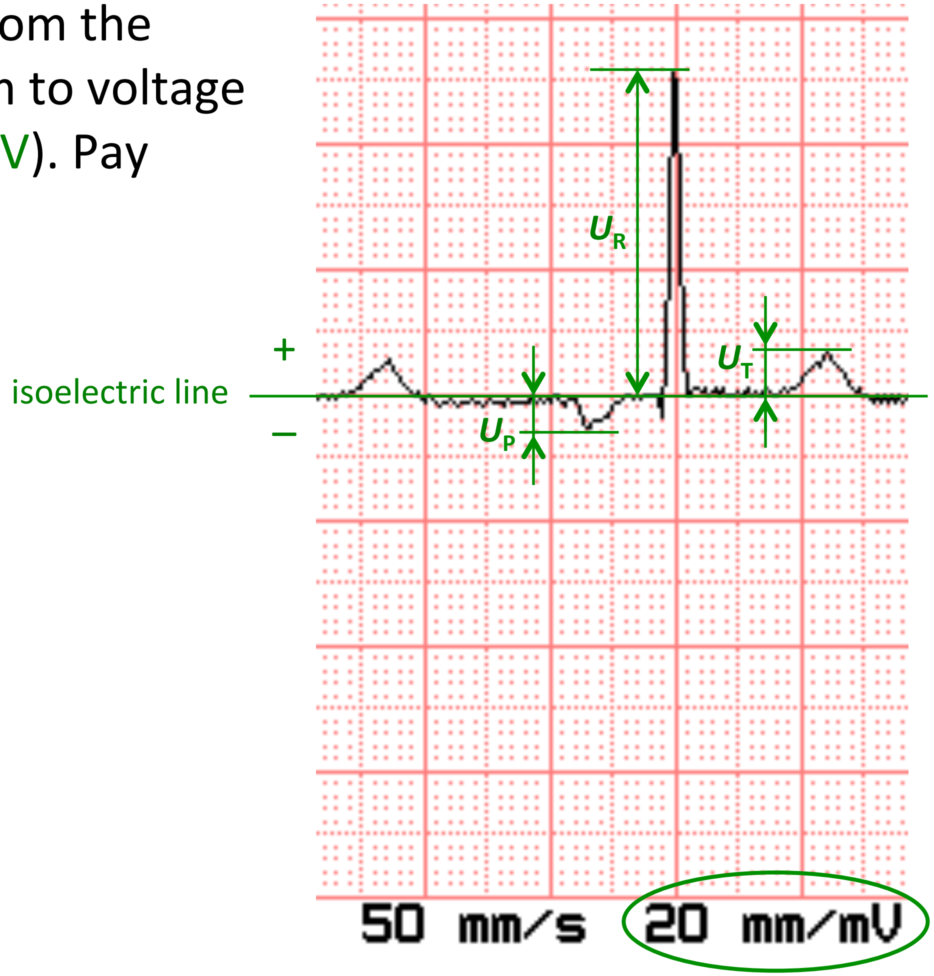


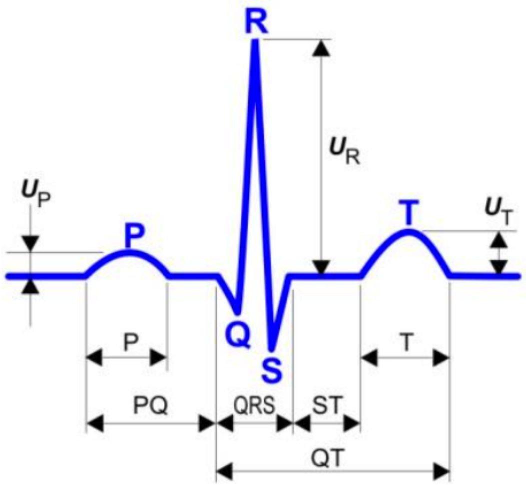
Analysis of the ECG Curve

2) Cont.

iii) Next, read the amplitudes (measured from the isoelectric line) in mm and convert them to voltage using the voltage scale (here: 20 mm/mV). Pay attention to polarity.

U_P: –3 mm –> –0.15 mV
U_R: 26 mm –> 1.30 mV
U_T: 3.5 mm –> 0.18 mV





Analysis of the ECG Curve

3) Construction of the frontal projection of the integral vector (SEE VIDEO):

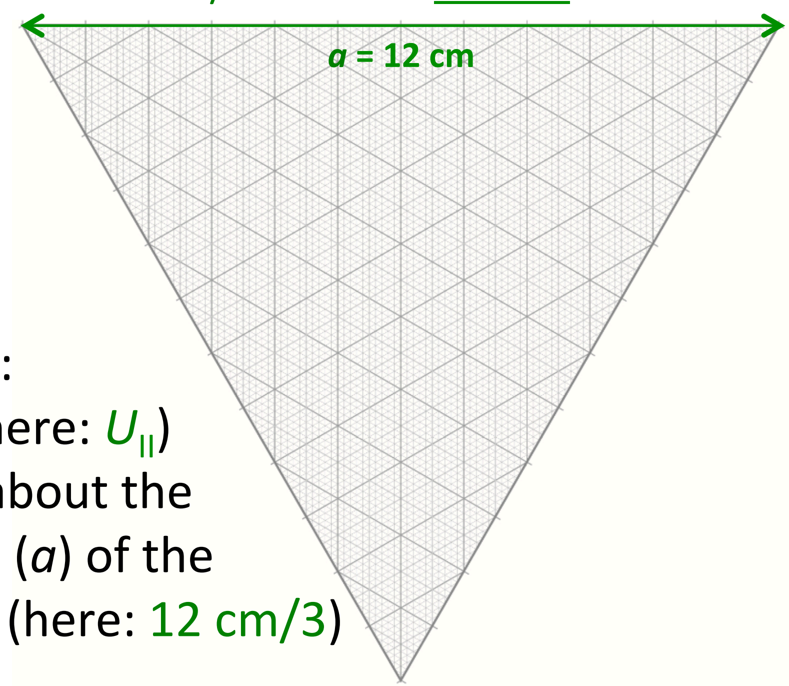
i) Read the voltages around the R-peaks of all Einthoven leads at the same time. In our case:

	recording	voltage	calculated length used in graph
U_I:	9 mm	–> 0.45 mV	–> 0.45/1.7* 4 cm = 1.06 cm
U_{II}:	34 mm	–> 1.70 mV	–> 4 cm
U_{III}:	25 mm	–> 1.25 mV	–> 1.25/1.7* 4 cm = 2.94 cm

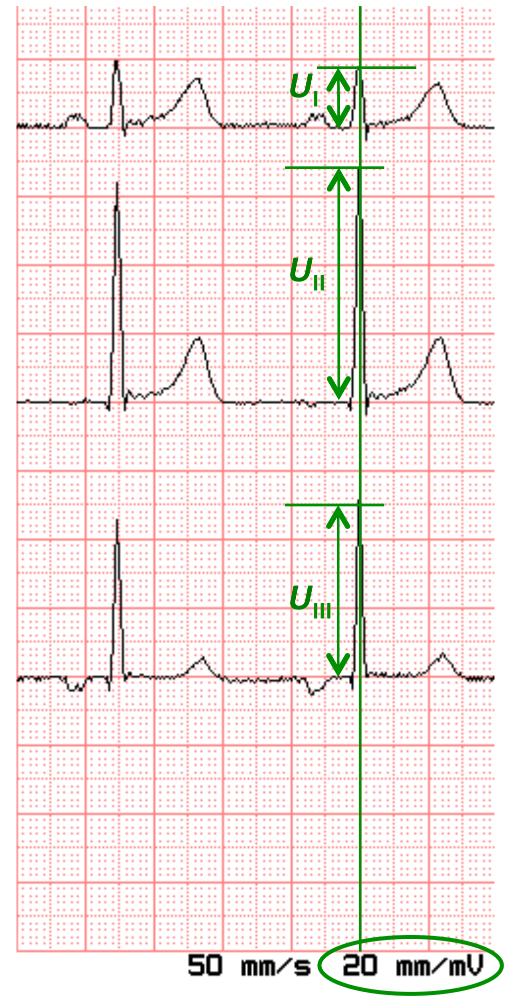
Important! Check if:

$U_{II} = U_I + U_{III}$

(R-peaks are often not coincident).



ii) Convert voltages into lengths. Rule of thumb: The greatest voltage (here: U_{II}) should correspond to about the third of the side length (*a*) of the triangular graph paper (here: 12 cm/3)



Analysis of the ECG Curve

3) Cont.

iii) Set the starting point of the integral vector.

iv) Construct its normal projections on all three sides.

v) Use these as starting points to draw the calculated lengths. Pay attention to the direction (polarity).

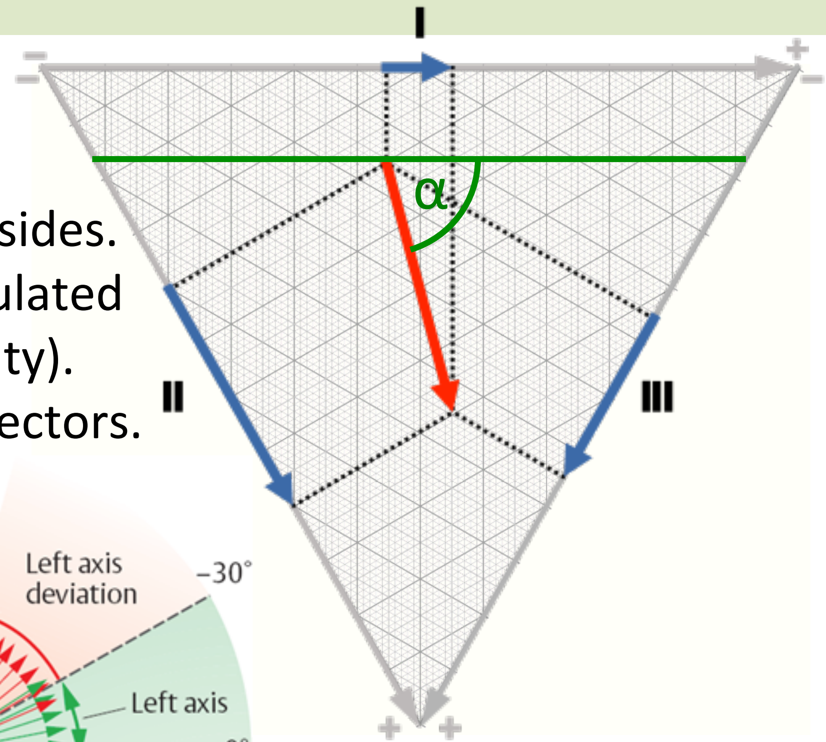
vi) Draw normals in the end points of all three vectors.

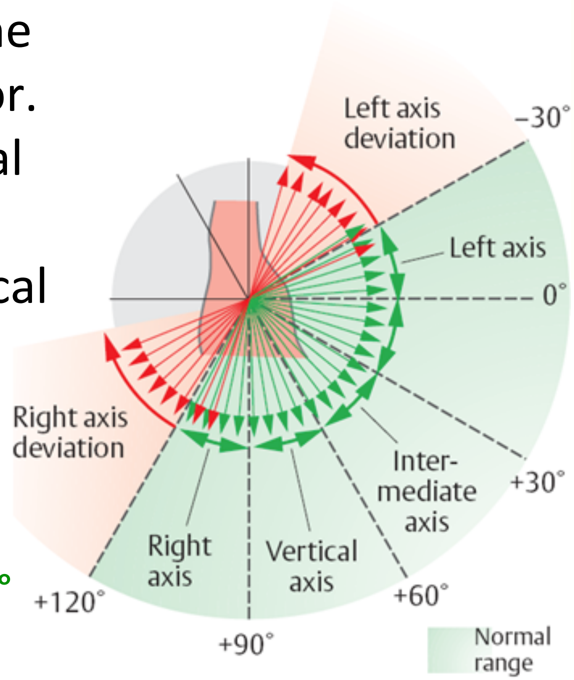
vii) The common intersection is the end point of the integral vector.

viii) The angle between the integral vector and the axis of the first lead is the angle of the electrical axis of the heart (α).

ix) The angle (if $-90° < \alpha < +90°$) can also be calculated:

$$\alpha = \arctan\left(\left(\frac{U_{II}}{U_{I}} - \frac{1}{2}\right)\cdot\frac{2}{\sqrt{3}}\right) = 75.2°$$



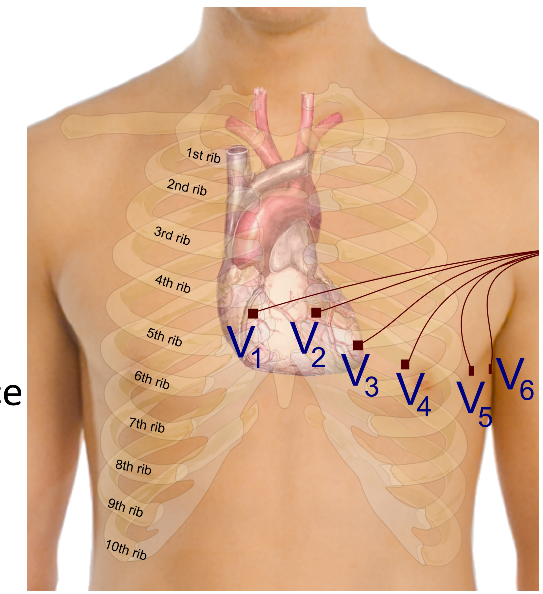


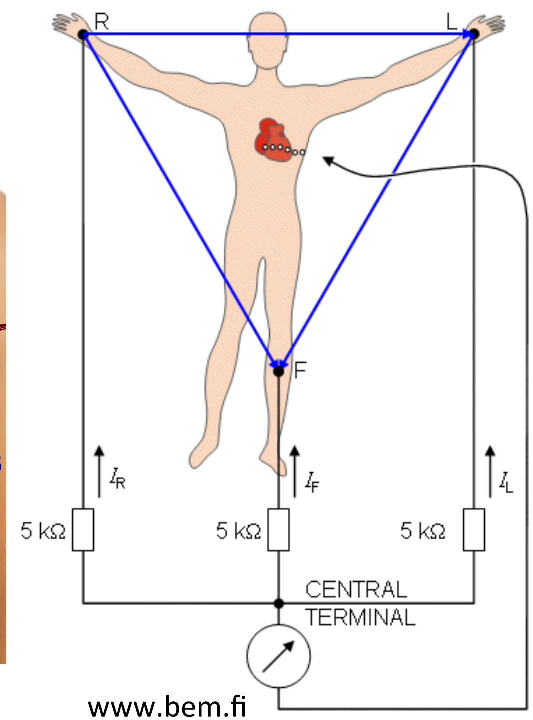
Wilson's Unipolar Precordial (Chest) Leads

Unipolar lead: An ECG lead with an active and an inactive electrode.
Wilson's central terminal (CT): An inactive „virtual" electrode created by connecting the three limb electrodes through resistors. Its potential is the average of the potentials of these electrodes.
Wilson's leads: A set of six unipolar leads (V_1 ... V_6) measuring the potential difference between one of six points of the chest against the Wilson CT.

The positions of active electrodes for the precordial leads are:

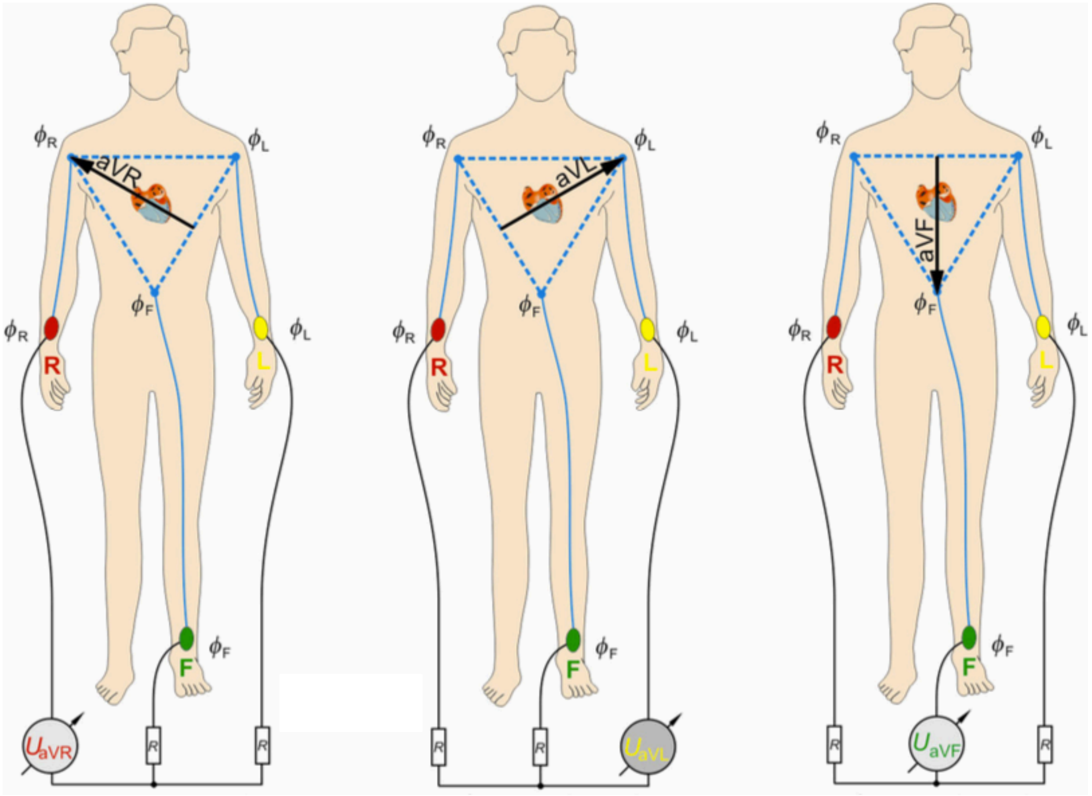
V_1: right parasternal line, 4^{th} intercostal space
V_2: left parasternal line, 4^{th} intercostal space
V_3: between V_2 and V_4
V_4: left mid-clavicular line, 5^{th} intercostal space
V_5: left anterior axillary line, 5^{th} intercostal space
V_6: left mid-axillary line, 5^{th} intercostal space





Goldberger’s Augmented Unipolar Limb Leads

Goldberger’s leads: A set of three pseudo-unipolar leads connecting one limb with an „imperfect” Wilson CT formed from the other two limbs. Here the Wilson CT is not perfectly inactive, but the leads – with a certain tolerance – can be considered unipolar.



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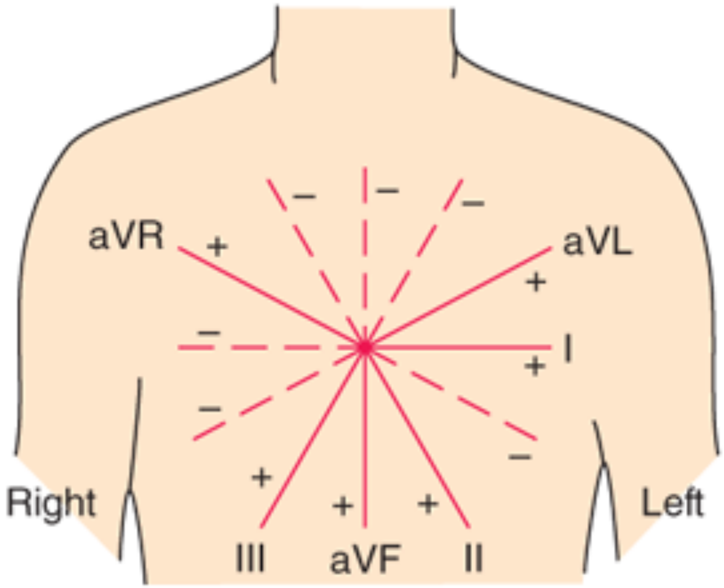
Standard 12-Lead ECG System

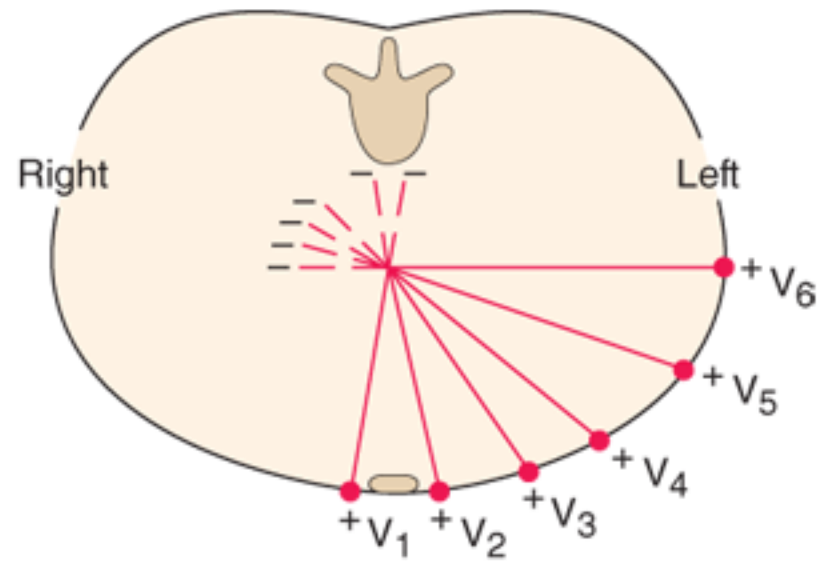
Each lead represents a certain projection of the integral vector of the heart dipole.

Superior



Inferior

Posterior



Anterior

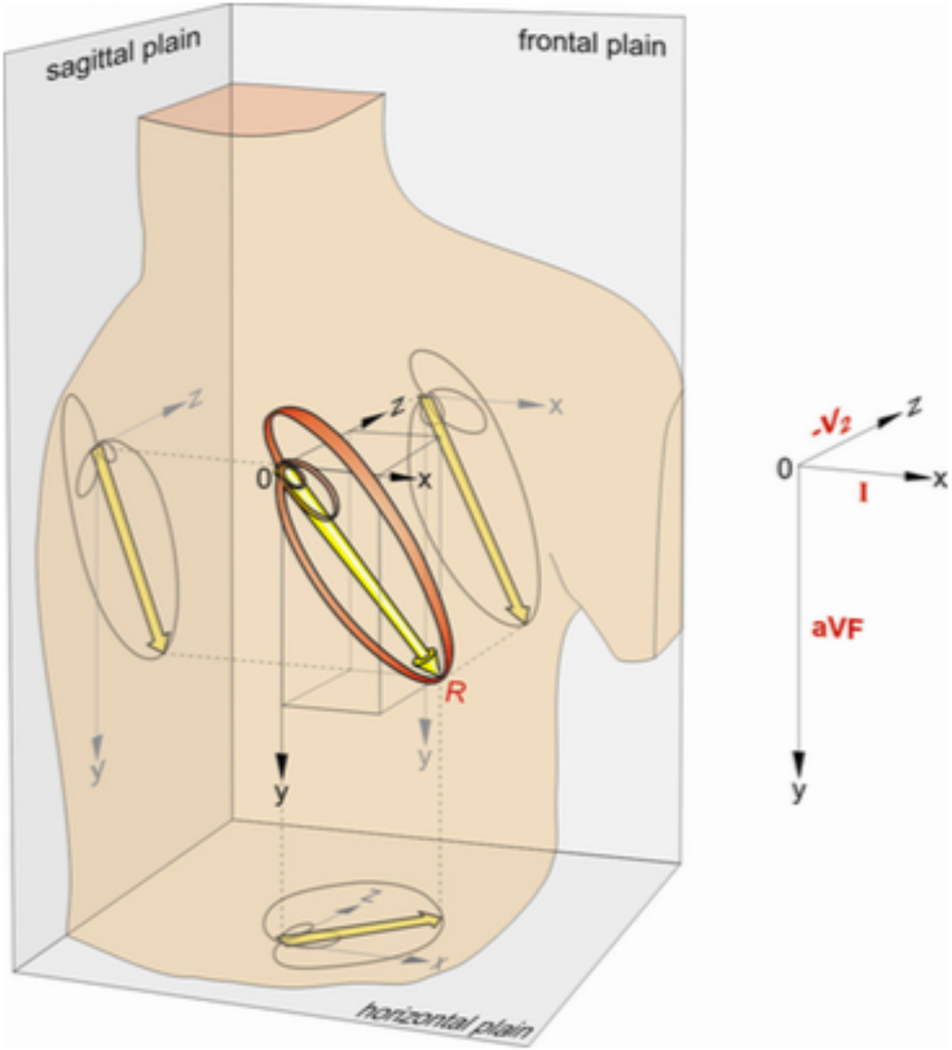
The **Einthoven** and **Goldberger** leads are roughly in the frontal plane (creating Cabrera's hexaxial system)

The **Wilson** leads are roughly in the horizontal plane

Vectorcardiography

Vectorcardiography creates recordings of the planar (frontal, sagittal or horizontal) projections of the 3D integral vector of the heart.

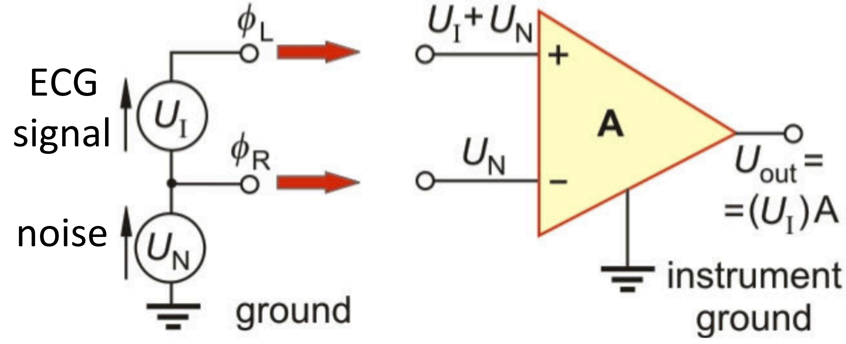
The used leads are:
x-axis: Einthoven's **I lead**
y-axis: Wilson's **$-V_2$ lead**
z-axis: Goldberger's **aVF lead**



Amplification & Filtering

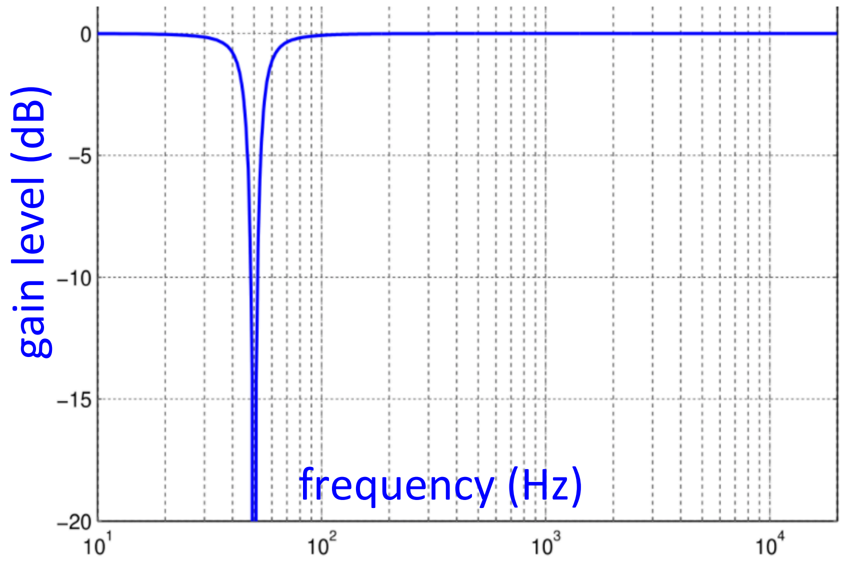
Differential amplifier: A special amplifier which amplifies the difference of two input voltages. In case of ECG, the two input voltages come from the pair of electrodes of the actual lead, while an extra electrode (N) is connected to the ground of the amplifier.

schematic of a differential amplifier



50 Hz noise and its overtones (100 Hz, 200 Hz etc.) are a result of capacitive coupling of the body with the mains network electricity. These may be removed using a notch filter

frequency response of 50 Hz notch filter



Noise > 35 Hz comes from the activity of skeletal muscles. It can be removed by a low pass / high cut filter.

Sources & Literature

– The 12-Lead ECG System (*http://www.bem.fi/book/15/15.htm*)
– Kollai M: Az elektrokardiogram (Semmelweis Egyetem, 2001)
– CARDIAX computerized ECG system (*http://www.imed.hu*)
– Matteucci C: Sur un phenomene physiologique produit par les muscles en contraction (Ann Chim Phys, 1842)
– Waller AD: A demonstration on man of electromotive changes accompanying the heart's beat (J Physiol, 1887)
– Einthoven W: Galvanometrische registratie van het menschelijk electrocardiogram (Leiden, 1902)
– Einthoven W: Le telecardiogramme (Arch Int de Physiol, 1906)
– Wilson FN et al: Electrocardiograms that represent the potential variations of a single electrode (Am. Heart J. 1934)
– Wilson FN et al: The precordial electrocardiogram (Am Heart J, 1944)
– Goldberger E: The aVL, aVR, and aVF leads [...] (Am Heart J, 1942)
– AlGhatrif M, Lindsay J: A brief review: history to understand fundamentals of electrocardiography (J Community Hosp Intern Med Perspect, 2012)