The Electrocardiogram
part I

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• **ECG** or EKG

• The **standard** clinical tool used to measure the electrical activity of the heart

• because it’s noninvasive, inexpensive and versatile

• **Used for detecting**
  - Arrhythmias
  - Conduction disturbances
  - Myocardial ischemia
  - Cardiac enlargement and hypertrophy
  - Electrolyte disturbances
  - Increased susceptibility to sudden death (QT-prolongation syndromes)
- The electrocardiogram is a graphic recording of electric potentials generated by the heart
- The heart is suspended in a conductive medium
- The signals are detected by means of metal electrodes attached to the skin, amplified and recorded by the electrocardiograph
Depolarization and Repolarization Waves

- Depolarisation (- +) moving toward positive electrode generates a **positive wave**
- Repolarisation (+ -) moving toward the positive electrode generates a **negative wave**
- No potential difference (homogenous charge, only + or only -) generates an **isoelectric line**
Characteristics of the Normal ECG

- Normal ECG consist of a number of waves, positive and negative, connected through segments of isoelectric line.
- The waves correspond to depolarization and repolarization of the heart surface during the cardiac cycle.
- **P wave** – atrial depolarization
- **PQ segment** – delayed conduction in the AV node
- **QRS complex** – ventricular activation
- **T wave** – ventricular recovery
No potential is recorded in the electrocardiogram when the ventricular muscle is either completely polarized or completely depolarized.

Monophasic action potential from a ventricular muscle fiber

ECG recorded simultaneously: QRS appears at the beginning of the AP, and T wave at the end.
• The rapid upstroke (phase 0) of the AP corresponds to the onset of QRS
  ➢ Factors that decrease the slope of phase 0 by impairing the influx of Na⁺ (flecainide, procainamide, or hyperkalemia) tend to increase QRS duration

• The plateau (phase 2) corresponds to the isoelectric ST segment
  ➢ Conditions that prolong phase 2 (amiodarone, hypocalcemia) increase the ST segment
  ➢ Shortening of phase 2 (digitalis, hypercalcemia) abbreviates the ST segment

• The active repolarization (phase 3) corresponds to the T wave
The electric currents that spread through the heart are produced by - pacemaker cells - specialized conduction system - the heart muscle itself

**The ECG records only** the extracellular currents generated by the atrial and ventricular myocardium
The cardiac depolarization and repolarization waves have direction and magnitude → they can be represented by vectors.

**ECG** records the spatial and temporal summation of electrical potentials (vectors) from multiple myocardial fibers conducted to the surface of the body.

=>

**Inherent limitations**

- In sensitivity – activity of certain regions may be canceled out or may be too weak to be recorded
- In specificity – the same vectorial sum can result from either a selective gain or a loss of forces in opposite directions
Recording the Electrical Activity of the Heart

- The electrical activity of the heart can be measured with voltmeters connected through electrodes at the surface of the body.
Electrocardiographic Lead Systems

- Recording electrodes are configured to form various types of leads.
- A lead records the fluctuation in extracellular voltage generated between its electrodes.

- The standard clinical ECG includes recordings from 12 leads:
  - 6 in the frontal plane
    - 3 bipolar leads or standard limb leads
    - 3 modified (augmented) unipolar limb leads
  - 6 in the transverse plane
    - the unipolar precordial leads
A bipolar lead
- Consists of two electrodes placed at **two different sites**
- Registers the *difference in potential* between the two sites (the actual potential at either electrode is not known)
- One electrode is designated as the **positive** input, the other as **negative**

An unipolar lead
- Measures the *absolute potential* at **one site**
- Requires a reference site
- The potential is sensed by a **single electrode** – the recording or the active electrode (considered **positive**), in relation to the reference potential
Willem Einthoven
Nobel Prize in Physiology or Medicine 1924
Bipolar Standard Leads

- **Lead I**
  - negative connection to right arm, positive connection to left arm
  - defines an axis in the frontal plane at 0°

- **Lead II**
  - negative to right arm, positive to left leg
  - defines an axis in the frontal plane at 60°

- **Lead III**
  - negative connection to left arm, positive connection to left leg
  - defines an axis in the frontal plane at 120°

- The output – the potential difference between two limbs
The Einthoven’s Triangle

- Is delimited by the axis of the three standard limb leads
- **The Einthoven’s law**: 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 summing the first two (Kirchhoff theorem)

The positive and negative signs of the different leads must be observed when making this summation: \( I + III = II \)
Augmented Unipolar Limb Leads

- The three augmented unipolar limb leads compare one limb electrode to the average of the other two (Goldberger method).
- 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.
- **aVR** (augmented voltage right)
  - positive connection to the **right arm**
  - the axis defined in the frontal plane is -150°

- **aVL** (augmented voltage left)
  - positive connection to the **left arm**
  - the axis defined in the frontal plane is -30°

- **aVF** (augmented voltage foot)
  - positive connection to the **left leg**
  - the axis defined in the frontal plane is +90°
The Hexaxial Reference System

- The overlaid lead axes of the six frontal plane leads produce the hexaxial reference system
- The six lead axes divide the frontal plane into 12 segments, each subtending 30°
Heart Vectors Are Tridimensional
Unipolar Precordial Leads

- Usually six standard chest leads are recorded:
  - $V_1$: fourth intercostal space to the right of the sternum
  - $V_2$: fourth intercostal space to the left of the sternum
  - $V_4$: fifth intercostal space at the midclavicular line
  - $V_3$: halfway between $V_2$ and $V_4$
  - $V_6$: fifth intercostal space at the midaxillary line
  - $V_5$: halfway between $V_4$ and $V_6$. 
• Precordial (chest) leads lie in the transverse plane, perpendicular to the plane of the frontal leads

• The heart surfaces are close to the chest wall
  → each chest lead records mainly the electrical potential of the cardiac musculature immediately beneath the electrode
  → relatively minute abnormalities in the ventricles, particularly in the anterior ventricular wall, can cause marked changes in the electrocardiograms recorded from chest leads
Precordial Leads and the Wilson Central Terminal

- An **exploring electrode** is placed on each precordial site and connected to the **positive** input of the recording system.
- The **reference input** – a compound electrode = Wilson central terminal:
  - the output of the limb electrodes is combined through 5000 W resistances → each precordial lead registers the potential at the precordial site with reference to the **average potential on the three limbs**
  - the potential recorded by the reference input remains relatively **constant** during the cardiac cycle → **the output of the precordial lead is determined by the changes in the potential at the precordial site**
Wilson chest leads (unipolar)

1

2
View from above

V₁-V₆

V₁, V₂, V₃, V₄, V₅, V₆
ECG Leads - Overview

- Each lead is an axis in one of the planes (frontal, transverse, sagittal) onto which the heart projects its electrical activity.

- Each lead looks at the heart from an unique angle and plane → has its own unique point of view.

- The recording from a single lead shows how that lead views the time-dependent changes in voltage of the heart.
Views of the Heart

Some leads get a good view of the:

Anterior portion of the heart
Leads V1 – V4

Inferior portion of the heart
Leads II, III, aVF

Lateral portion of the heart
Leads I, aVL, V5, V6
Lead Vectors

- A lead can be represented as a vector = the **lead vector**
- **Directed**
  - For **bipolar leads**: from the negative towards the positive electrode
  - For **unipolar leads**: from the midpoint of the axis connecting the electrodes that make up the compound electrode, towards the active electrode (positive)
Heart Vectors

- Instantaneous cardiac activity can be approximated as a single *dipol* and represented as a vector = the *heart vector*

- The location, orientation, and intensity of a heart vector *varies* according to the pattern of cardiac activation
From Heart Vectors to ECG Waves

- The **amplitude** and **polarity** of the cardiac potentials sensed in a lead are proportional to the **size** of the **projection** of the **heart vector** on the **lead vector**
  a. The projection of the heart vector points **toward the positive pole** of the lead, → the lead records a **positive potential** → positive wave on ECG
  b. The projection is directed **away from the positive pole** of the lead → the lead records a **negative potential** → negative wave on ECG
ECG waves - fluctuations in extracellular voltage recorded by each lead

A – heart vector during ventricular activation

B, C, D – projections of A on leads I, II and III with the resultant waves on the ECG recording
Genesis of Normal ECG
Atrial Activation and the P Wave

Lead I vector

aVR

aVL

aVF

Frontal plane

LA

RA

biphasic P in V1

Horizontal plane
P Wave - Characteristics

- **Shape**
  - dome; sometimes biphasic (V1, V2), or discretely notched (V5, V6, aVL), due to the partial asynchrony of atrial activation

- **Polarity**
  - positive in leads I, II, aVL, aVF, V4 – V6
  - negative in aVR

- **Axis**: 0° – 75°

- **Duration**: < 0.12 s

- **Amplitude**:
  - < 0.25 mV in limb leads
  - the terminal negative deflection in V1 < 0.1 mV in depth
1 mm = 0.04 s

1 mV
Atrial Recovery and the Ta Wave

- The area in the atria that becomes repolarized first is the sinus nodal region.
  - The atrial repolarization vector is backward to the vector of depolarization.
  - Low amplitude wave with a polarity opposite to the P wave (Ta).

- In normal ECG, Ta is obscured by the QRS complex.
AV Node Conduction and the PR Segment

- **PR segment**
  - Isoelectric region between the end of the P wave and the onset of the QRS complex
  - Duration: 0.02 – 0.12 s
  - Temporal bridge between atrial activation and ventricular activation

! Activation of the **AV node**, the **bundle of His**, the **bundle branches** and the **Purkinje network** generate potentials that are too small to be detected at the body surface by a standard ECG apparatus
PR Interval

- **PR interval** = P wave + PR segment

  - Is the time between onset of atrial activation and onset of ventricular activation

  - **Duration:** 0.12 – 0.20 s, varies with **heart rate** and age
Ventricular Activation and the QRS Complex

1. Septal activation
   - $V_1, V_2, aVR = \text{right ventricular leads} \rightarrow \text{small positive wave, } r$
   - $I, aVL, V_5, V_6 = \text{left ventricular leads} \rightarrow \text{small negative wave, } q$
2. **Ventricular apex activation**
   - $V_1$, $V_2$, aVR $\rightarrow$ transition to the negative wave, $S$
   - I, aVL, $V_5$, $V_6$ $\rightarrow$ transition to the positive wave, $R$
3. **Left ventricular wall activation** - main ventricular activation vector

- $V_1$, $V_2$, aVR $\rightarrow$ negative deflection, S
- I, aVL, $V_5$, $V_6$ $\rightarrow$ positive deflection, R
4. Activation of the posterobasal areas of the left ventricle

- $V_1$, $V_2$, aVR → ends the negative deflection, $S$ (brings it back to the isoelectric line)
- $I$, aVL, $V_5$, $V_6$ → little negative deflection, $s$
QRS in the Limb Leads

Lead I vector

Lead II vector

Lead III vector

aVR

aVL

aVF

aVR

aVL

aVF

I

II

III
QRS in the Precordial Leads

rS $\rightarrow$ qRs
A vectocardiogram depicts vectorial changes at different times during the cardiac cycle.

QRS vectocardiogram
QRS Complex

- **Nomenclature**
  - **Q wave**
    - Initial downward deflection
    - Duration: \(< 0.03 – 0.04 \text{ s}; \text{ exception: in lead } V1, V2 \text{ any } Q \text{ is abnormal} \)
    - Amplitude: \(< \frac{1}{4} \text{ R wave}, < 0.2 – 0.3 \text{ mV} \)
  - **R wave**
    - First upward deflection
    - Criteria for shape or size are not absolute; high amplitude in V5, V6
    - A second upward deflection is designated R’
  - **S wave**
    - The second negative deflection if there is a Q wave, or the first downward deflection if not
    - Duration: \(< 0.04 \text{ s} \)
    - High amplitude in V1, V2
Tall waves are denoted by capital letters and smaller ones by lowercase letters.
QRS Complex - Characteristics

- **Morphology:**
  - R/S < 1 in V1 – V3; any Q wave is abnormal in these leads
  - R/S > 1 in V5 – V6

- **QRS axis** = the resultant vector of ventricular activation
  - normal limits: -30° - +90°
  - left axis deviation -30° - -90 °
  - right axis deviation 90° - 180°
• **QRS duration**: $< 0.11 \text{ s}$ measured in the lead with the widest complex

- **Intrinsecoid deflection:**
  - measures the duration of transmural activation under the recording electrode of a precordial lead (V1, V2, V5, V6)
  - measured from the peak of the last R of the complex until the onset of the QRS complex
  - Normal values: $< 0.035 \text{ s}$ in V1, V2 and $< 0.045 \text{ s}$ in V5, V6
• **QRS amplitude** = algebraic sum of the amplitudes of the component waves
  - > 1 mV in one preordial lead, > 0.5 mV in a standard lead

- The amplitude of R and S waves it is used for the diagnosis of **left ventricular hypertrophy**:
  - Sokolow-Lyon index: $Sv_1 + (Rv_5 \text{ or } Rv_6) > 3.5 \text{ mV}$
  - Cornell voltage criteria: $Sv_3 + S_{aVL} \geq 2.8 \text{ mV}$ for men, $\geq 2.0$ for women

  or of **right ventricular hypertrophy**:
  - $Rv_1 > 0.7 \text{ mV}$, $Sv_5 \text{ or } v_6 > 0.7 \text{ mV}$ etc.
Ventricular Recovery

- **ST segment**
  - Isoelectric, the ventricles are fully depolarized
  - Variations of <1mm (< 2 mm in V1,2) are admitted

- **T wave**
  - The *epicardial* areas of the ventricular muscle and the apex are repolarizing first
  - The repolarizing vector of the ventricles is oriented towards the apex
  - The T wave has the same polarity as the net polarity of the preceding QRS complex
T Wave Characteristics

- **Morphology**
  - Asymmetric, with mild ascending slope, abrupt descending slope, and round peak

- **Polarity**
  - Positive in I, II, aVL, aVF, V5, V6
  - Negative in aVR
  - Variable in III, V1 - V3

- **Axis**
  - 0° - 90°
  - Makes a < 60° angle with the QRS axis = QRST angle

- **Duration**
  - Indeterminable, the onset of T wave cannot be accurately established

- **Amplitude**
  - 1/3 of the amplitude of the preceding R wave
The U Wave

- Sometimes follows the T wave
- Has the same polarity as the T wave and less than 0.1 mV in amplitude
- Its electrophysiological basis is uncertain; could be caused by delayed repolarization of midmyocardial cells (with long AP) or of myocytes in areas that undergo late mechanical relaxation
QT interval

- Lasts from the beginning of the QRS complex to the end of the T wave
- Covers the duration of ventricular activation and recovery (corresponds to the duration of ventricular AP)
- Should be measured in the lead with the longest QT interval and without U waves
- It is defined by duration
• QT duration
  ➢ **Varies with the heart rate** (decreases as HR increases)
    Bazzet equation:
    \[ QTc = \frac{QT}{\sqrt{RR}}, \]
    where QTc is corrected QT and RR is the duration between to consecutive R waves (one cardiac cycle)
    *Why?* AP duration decreases as the rate increases
  ➢ **It is lead dependent** = QT dispersion; normal variations < 0.05 s, longest in V2, V3; increased QT dispersion is a mark for increased variability of repolarization and risk for arrhythmias
  ➢ Normal values: QTc < 0.44 s; may be slightly longer in women
ECG Elements – Evaluation Criteria

- **Waves**
  - Morphology
  - Polarity
  - Axis
  - Amplitude (mV)
  - Duration (s)

- **Segments**
  - On the isoelectric line or not?
  - Duration

- **Intervals**
  - Duration