Biomedical Instrumentation I

Lecture-1: The Origin of Biopotentials

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Source of Bioelectric Potentials

- Bioelectric potentials are produced as a result of electrochemical activity of a certain class of cells, known as *excitable cells*.

- The excitation cells are the main components of nervous tissue, muscular tissue, & glandular tissue.

Electrical States of Excitable Cells

There are two main states of the excitation cells;

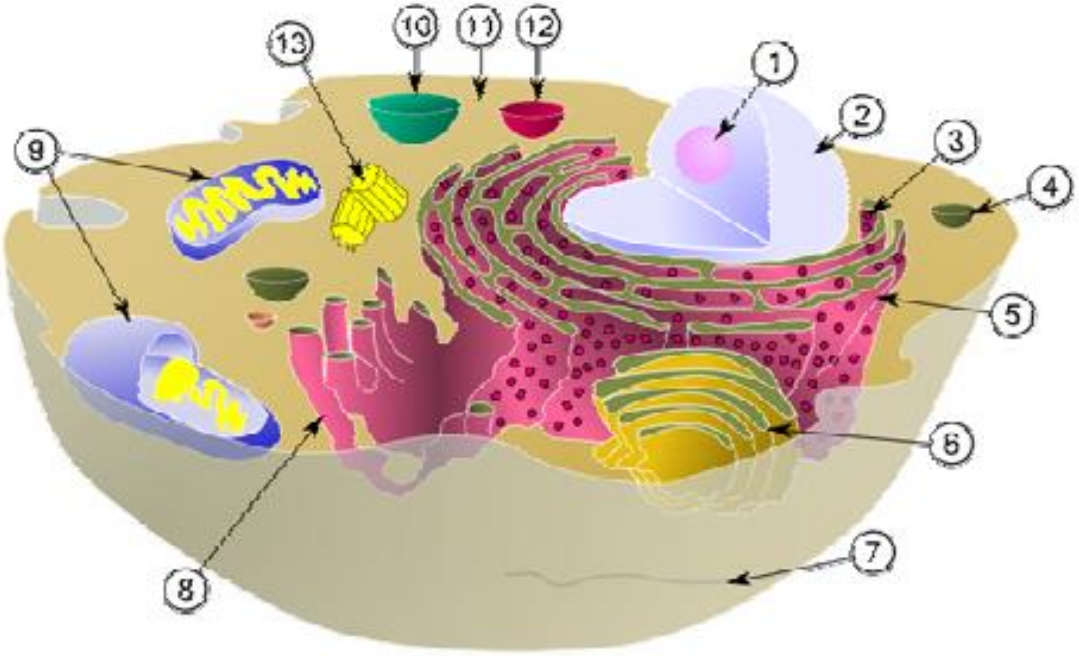
1. Resting State
2. Action State

Recordings of Bioelectric Phenomena

- Electrocardiogram (ECG or EKG)
- Electroencephalogram (EEG)
- Electroneurogram (ENG)
- Electromyogram (EMG)
- Electroretinogram (ERG)
- Electroretinography (ERG)
- Electrooculography (EOG)

Human Cell Structure

(1) Nucleolus
(2) Cell Nucleus
(3) Ribosome
(4) Vesicles
(5) Rough Endoplasmic Reticulum
(6) Golgi
(7) Cytoskeleton
(8) Smooth Endoplasmic Reticulum
(9) Mitochondria
(10) Vacuole
(11) Cytoplasm
(12) Lizosom
(13) Centrioles

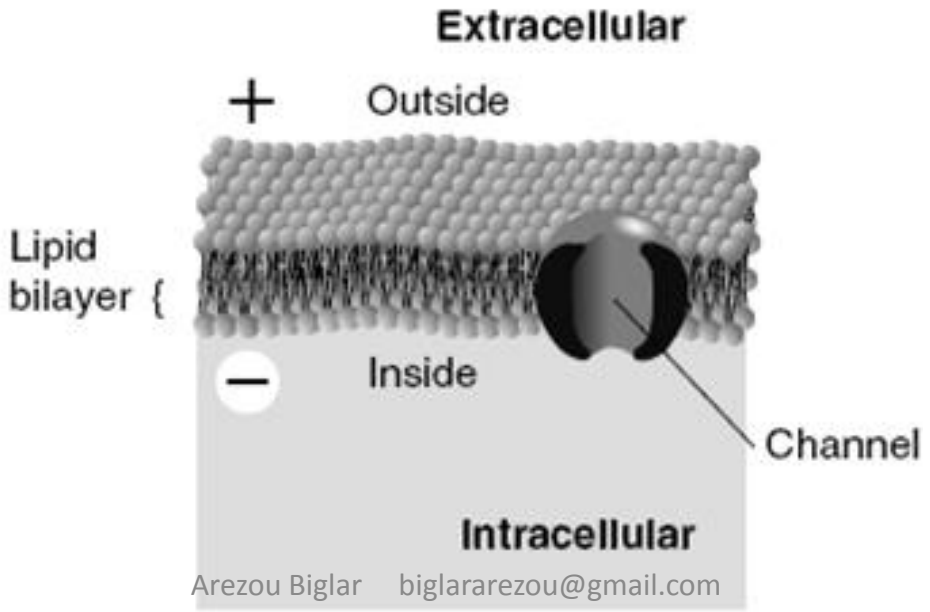


Cell Membrane

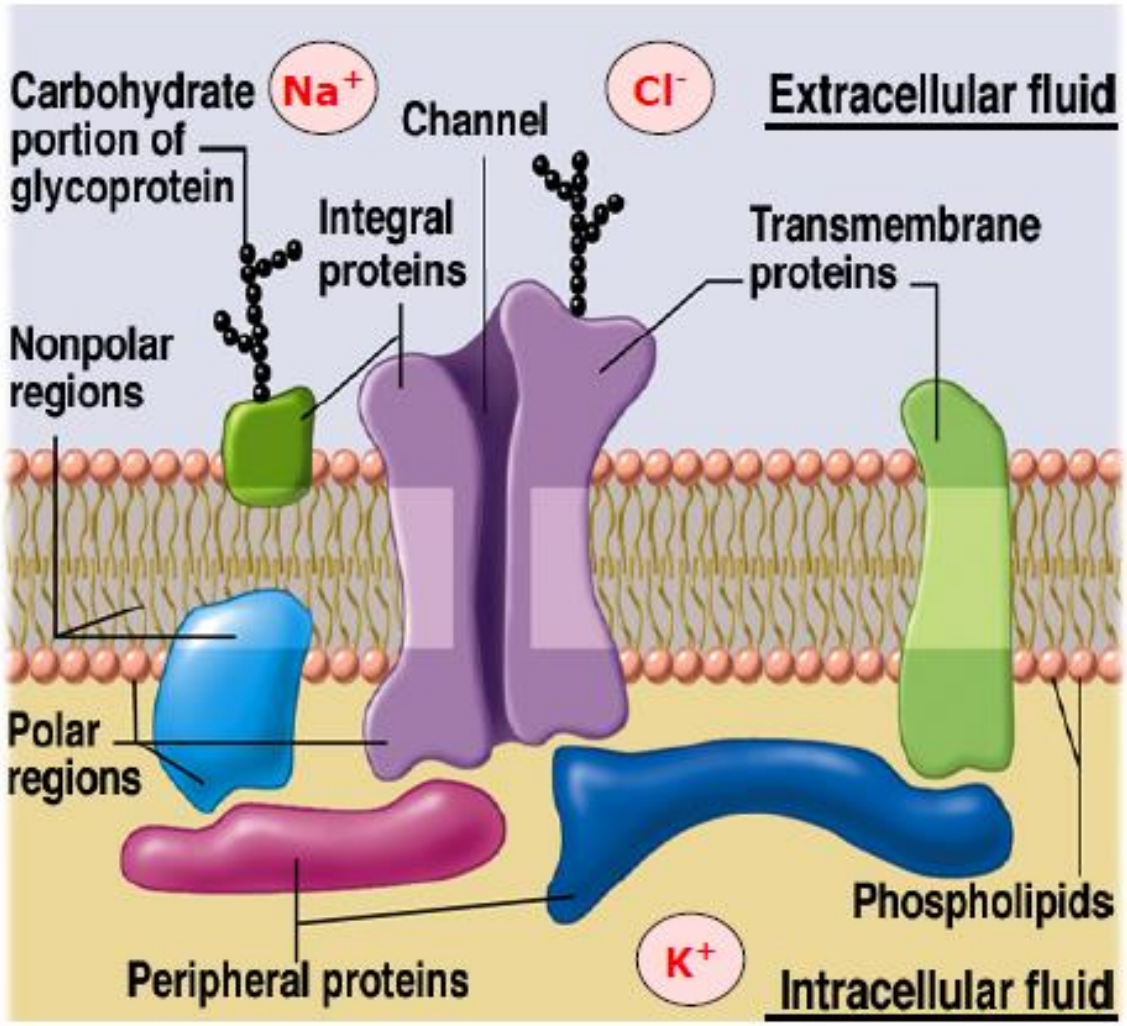
- Cell membrane is semipermeable lipid bilayer made of lipids and proteins that separates the intracellular part from the extracellular environment.

- The cell membrane is very thin with the thickness of 7-15 nm.

- Transmembrane ion channels (pores having the width of 8 nm) allow flow of ions across the membrane.



Cell Membrane



Cell Membrane

- The cell membrene is a thin dielectric material acts as a charge separator (like a leaky capacitor) with a dielectric constant of $\varepsilon = 5$, and spec. capacity of $C = 0.5$ to $1\ \mu F/cm^2$
- The cell membrane is impermeable to intracellular protein and other organic anions.
- The cell membrane is semipermeable to sodium (Na^+), potassium (K^+) and chlorine (Cl^-) ions.
- Separation of charge due to selective permeability of the membrane to ions is responsible for the membrane potential.

Cell Membrane

Transit of substances in and out of cells is regulated by:

1. Diffusion is the passive process of transfer of ions or substance from regions of higher concentration to regions of lower concentration.

2. Osmosis is the process diffusion of water through a semipermeable membrane.

3. Active transmission is the process of transfer of ions or substance from region of lower concentration to regions of higher concentration, and it requires energy.

Cell Membrane

- Ion concentration difference across membrane creates a diffusion gradient.
- Movement of ions across the membrane causes an electrical current to travel along the membrane.
- The ions flow by diffusion create a potential difference which inhibits further flow of charged ions similar to P-N junction.
- The current in electric circuits is the flow of free electrons. Similarly, the current in biological tissue is the flow of free ions.

Cell Membrane

The rules governing the ionic current are:

- Fick’s law diffusion
- Drift equation
- Einstein relation

Cell Membrane

1. Fick's Law

Diffusion through semipermeable membrane that is if there is a high concentration [C] of particles in one region that are free to move, they will flow in a direction to equalize the concentration [C] throughout the region.

$J_{diff} = -D\frac{d[C]}{dx}$ for positive ions.

J_{diff} is the current density in (A/m^2).

C is the concentration of ions as a function of distance (C/m^3)

D is the diffusion constant (m^2/s)

K^+ ions can easily leave the cell, creating an excess positive charge and the potential difference occurs - diffusion takes place until the electric field is established and it stops the process of diffusion.

Cell Membrane

2. Particle Drift

Charged particles such as ions in an electric field will move under the forces of electrical attraction and repulsion. The resulting ionic flow is called the drift current.

$J_{drift} = -\mu Z \frac{d[V]}{dx}[C]$ for positive ions.

J_{drift} is the current density in (A/m^2).

C is the concentration of ions as a function of distance (C/m^3)

Z is the number of charges on the ion.

μ is the proportionality constant, mobility $(m^2/V.s)$

V is the voltage drop, (V)

Cell Membrane

3. Einstein Relationship

Two physical constants, mobility **μ** and diffusion coefficient ***D*** are related to each other:

$$\frac{D}{\mu} = \frac{kT}{q}$$

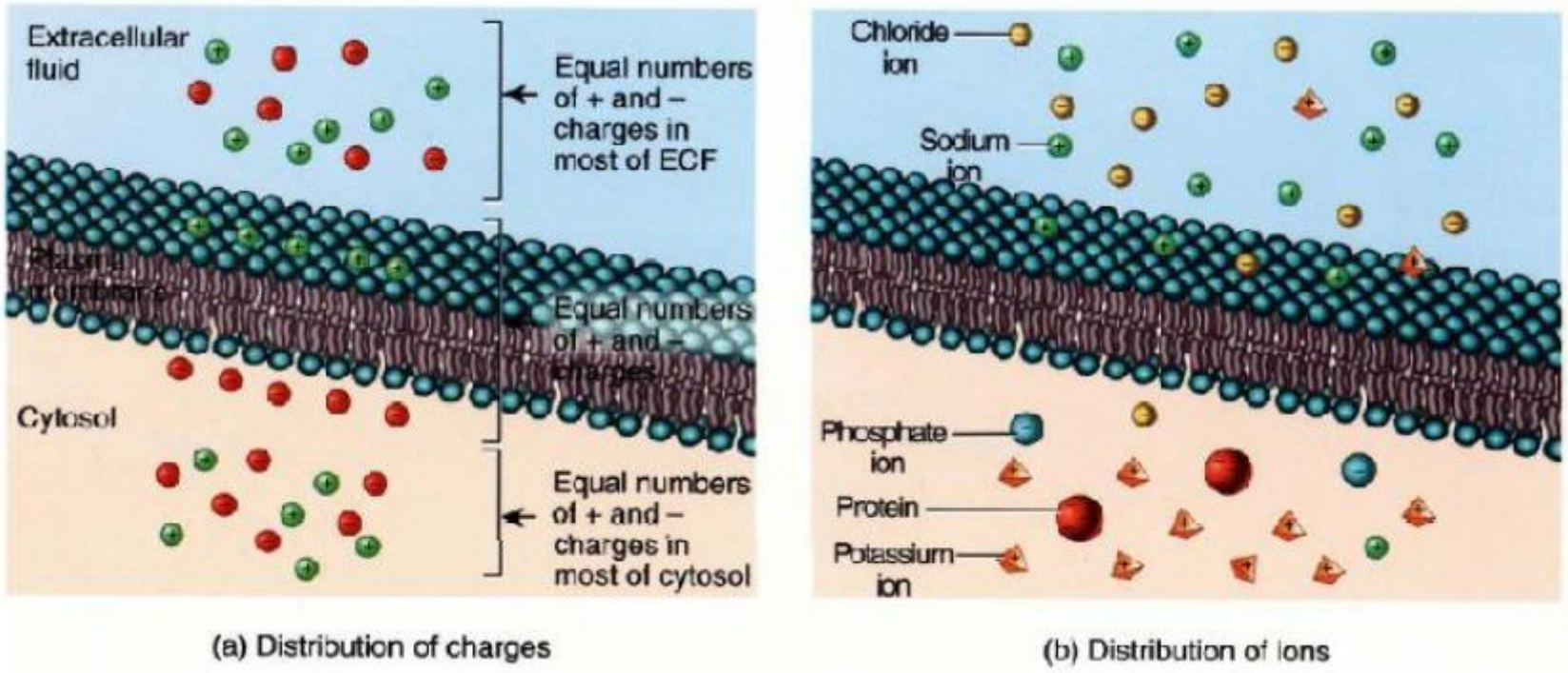
k is the Boltzmann's constant

q is the charge (C)

T is the absolute temperature (K)

Equilibrium Potential

- At equilibrium transmembrane (resting) potential, the net current through the cell membrane is zero.



Equilibrium Potential

Nernst Equation

- The Nernst equation is used for single ionic species.
- Assumes K^+ to be the main ionic species involved in the resting state that is, $P_k >> P_{na}$.

$$E_K = \frac{RT}{nF} \ln \frac{[K]_o}{[K]_i}$$

$$E_K = 0.0615 \log_{10} \frac{[K]_o}{[K]_i}$$

n is the valence of the K^+
$[K]_i$ and $[K]_o$ are the intracellular and extracellular concentrations of K^+ in moles per liter
R is the universal gas constant
T is absolute temperature in K
F is the Faraday constant

Equilibrium Potential

Example: The intracellular K+ concentration of a group of cells averages I50 x 10^{-6} moles/cm^3. The extracellular concentration of K^+ averages 6 x 10^{-6} moles/cm^3.

a)Calculate the concentration ration.

b)Calculate the diffusion potential for K^+.

Solution

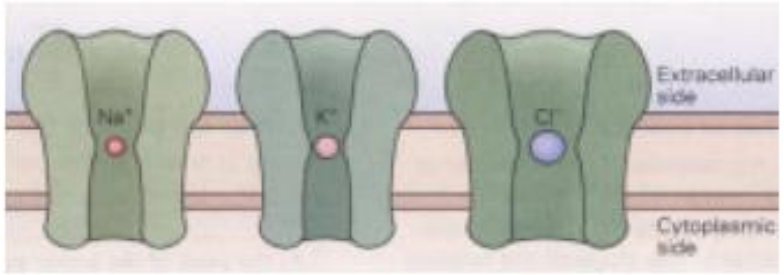
a) $$\frac{C_o}{C_i} = \frac{6 \times 10^{-6}\ \text{moles/cm}^3}{150 \times 10^{-6}\ \text{moles/cm}^3} = \frac{5}{20} = \mathbf{1/4}$$

b) $$E^{K+} = 61\ \text{Log}\ C_o/C_i = 61\ \text{Log}\ 1/25 = \mathbf{-85.3\ mV}$$

Equilibrium Potential

Goldman–Hodgkin–Katz (GHK) Equation

The Goldman equation accounts for influence of other ionic species in internal and external fluid media.



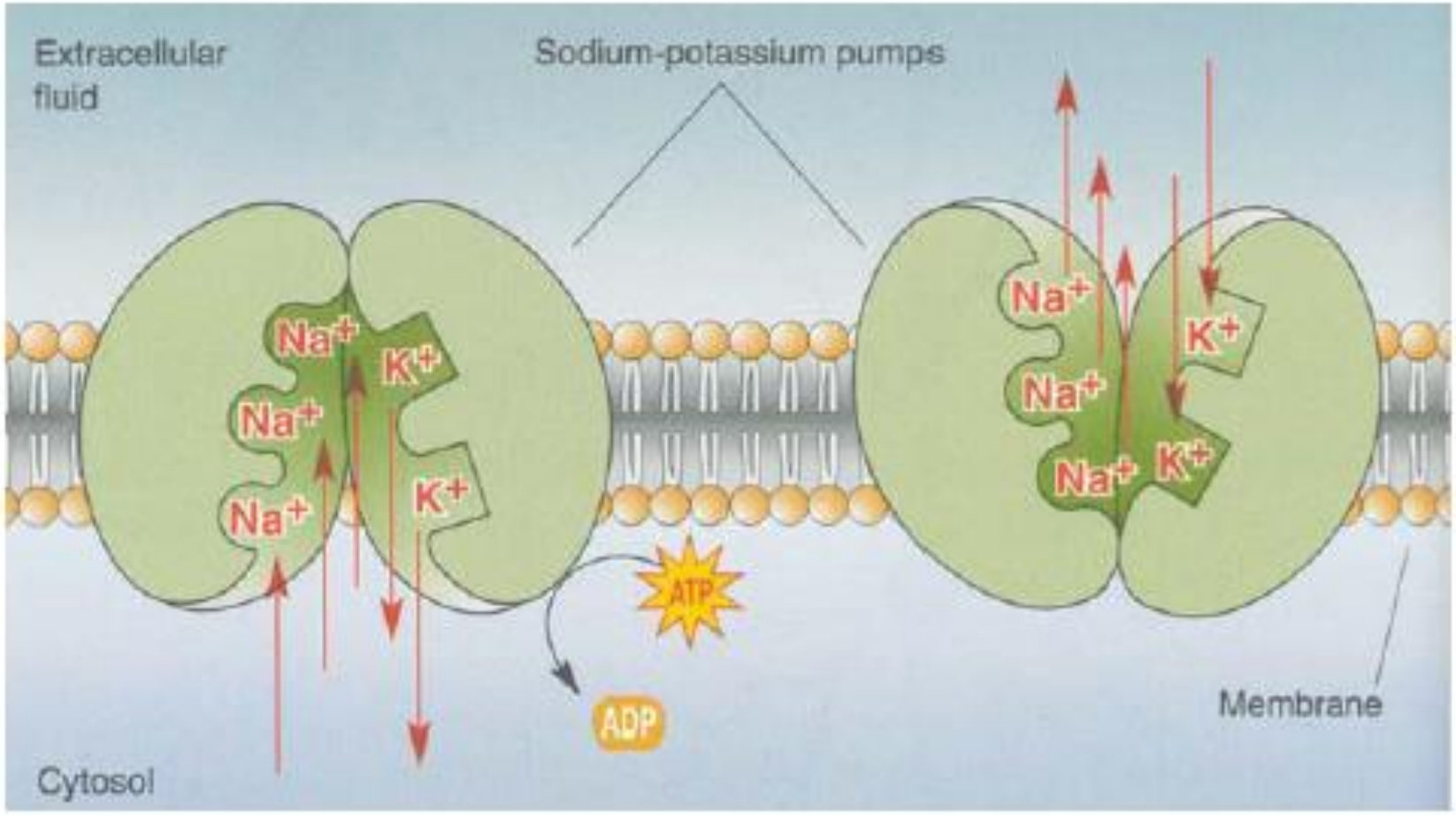
$$E = \frac{RT}{F} \ln \left\{ \frac{P_{\mathrm{K}}[\mathrm{K}]_{\mathrm{o}} + P_{\mathrm{Na}}[\mathrm{Na}]_{\mathrm{o}} + P_{\mathrm{Cl}}[\mathrm{Cl}]_{\mathrm{i}}}{P_{\mathrm{K}}[\mathrm{K}]_{\mathrm{i}} + P_{\mathrm{Na}}[\mathrm{Na}]_{\mathrm{i}} + P_{\mathrm{Cl}}[\mathrm{Cl}]_{\mathrm{o}}} \right\}$$

- **R** is the universal gas constant
- **T** is absolute temperature in K
- **F** is the Faraday constant
- **P_M** is the permeability coefficient of the membrane for a particular ionic species M (K, Na, Cl)

Active Channel: Sodium-Potassium Pump

- Maintaining steady state ionic imbalance requires continuous transport of ions against electrochemical gradients.
- Active transport mechanism located in the membrane, and is known as the ***sodium–potassium pump***.
- The sodium–potassium pump actively transports Na^+ out of cell and K^+ into cell in the ratio $3Na^+ : 2K^+$.
- Associated pump current i_{NaK} is a net outward current that tends to increase the negativity of the intracellular potential.
- The energy for the pump is provided by a common source of cellular energy, adenosine triphosphate (ATP) produced by mitochondria in the cell.

Active Channel: Sodium-Potassium Pump



Factors Influencing the Flow of Ions Across the Cell Membrane

- Diffusion gradients
- Inwardly directed electric field
- Membrane structure (availability of pores)
- Active transport of ions against an established electrochemical gradient

The Active State

Polarization: the cell membrane is at a steady resting potential (more negative inside the cell).

Depolarization: lessening the magnitude of cell polarization by making inside the cell less negative.

Hyperpolarization: increasing the magnitude of cell polarization by making inside the cell more negative.

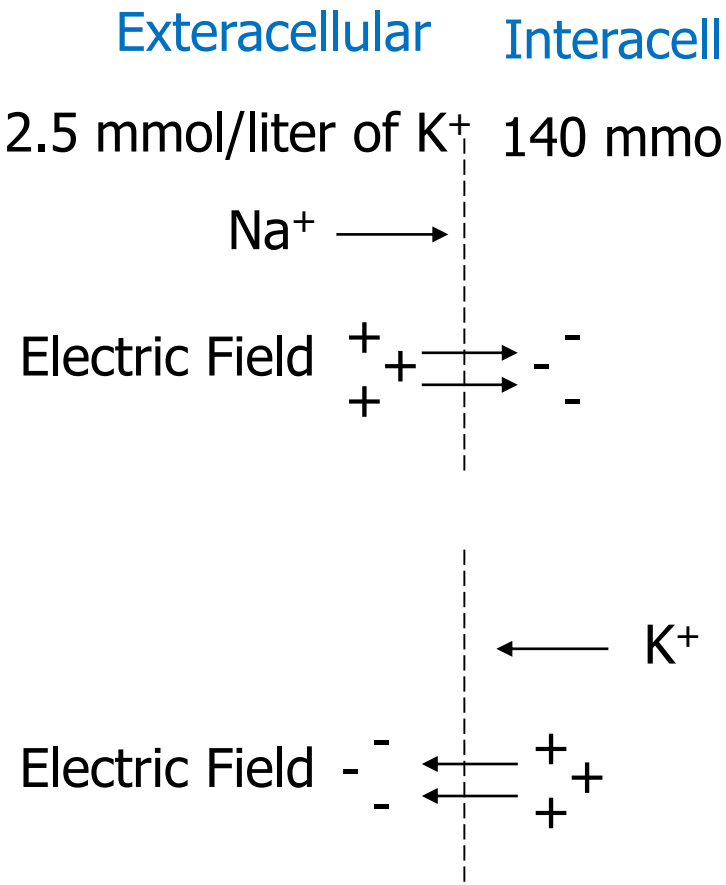
Action Potential: brief transient disturbance of membrane potential.

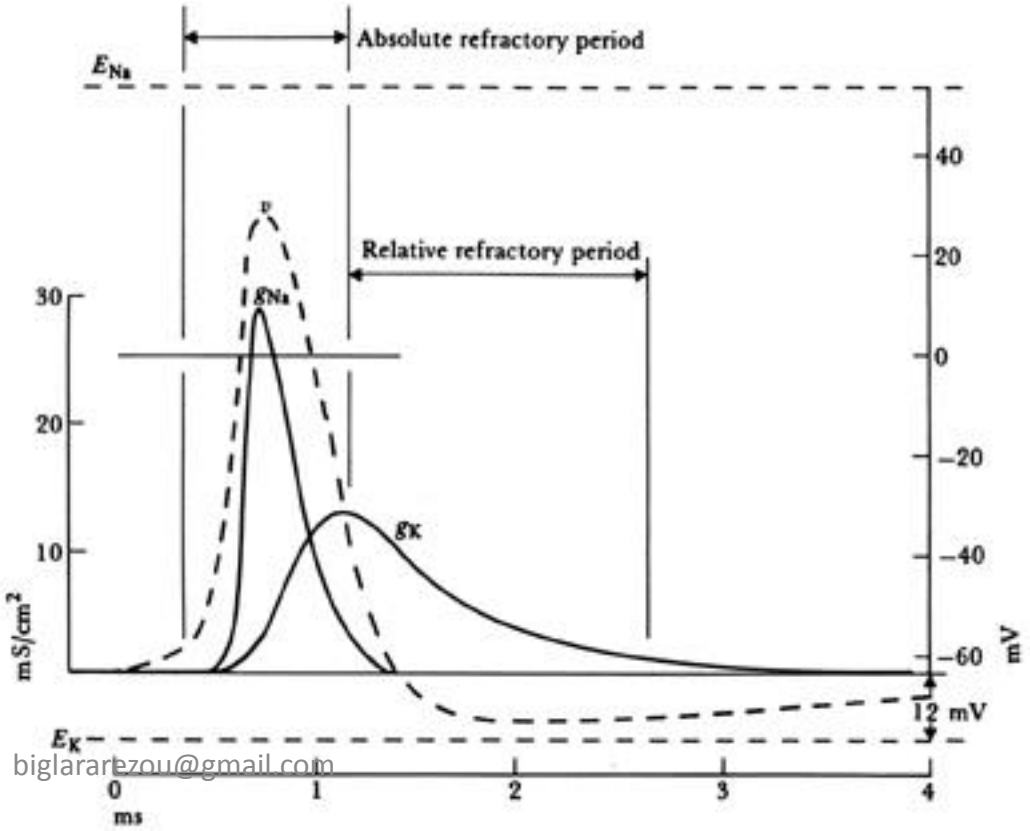
- change in membrane potential due to a stimulus adequate to bring about depolarization sufficient to exceed its threshold potential and thereby elicit an all-or-none action potential.
- change in potential from resting level.
- further increases in intensity or duration of stimulus beyond that required for exceeding the threshold level produce only the same result.

Repolarization: return to membrane equilibrium after action potential.

Action Potential

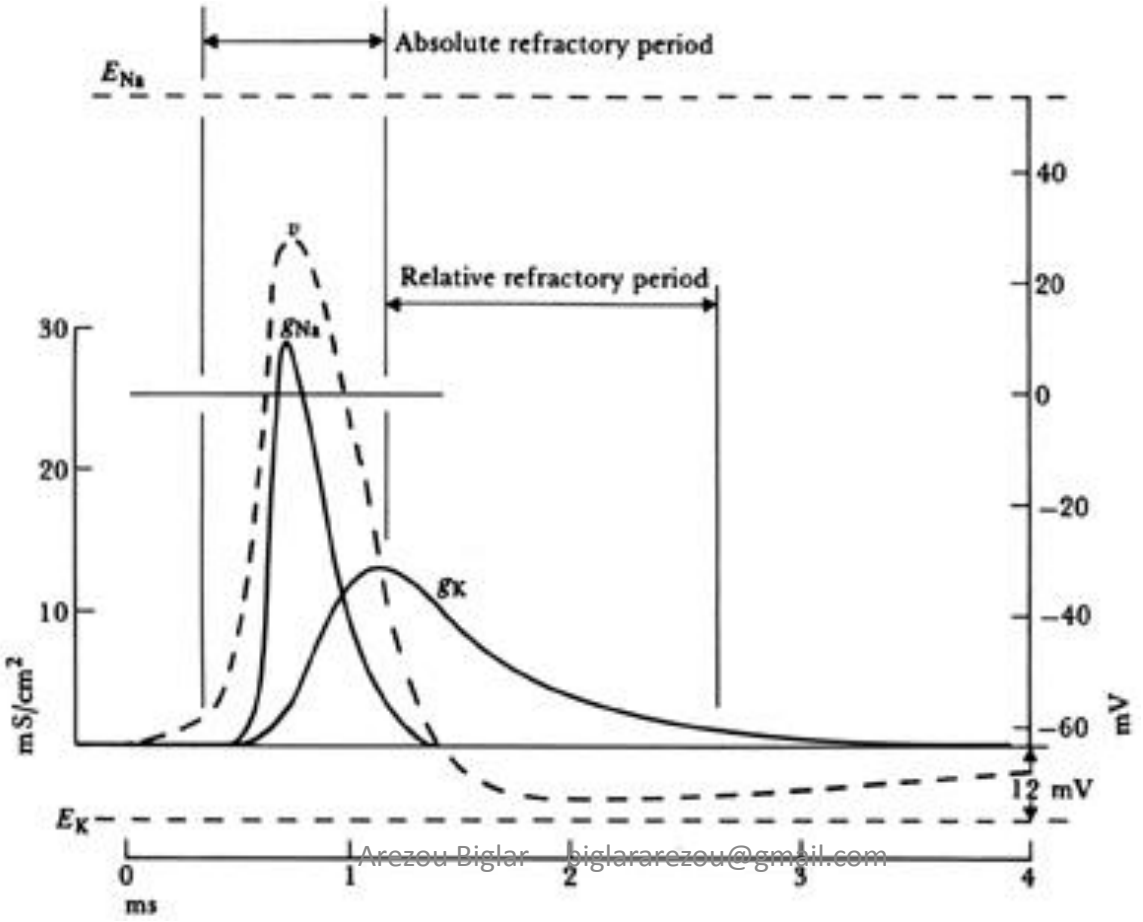
If a stimulus depolarizes the cell such that $V_{cell} > V_{threshold}$, an *action potential* is generated.





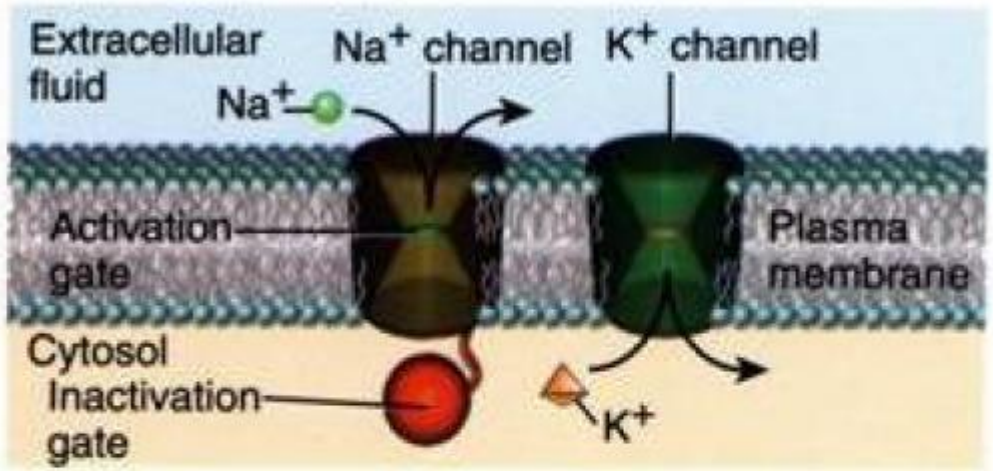
Action Potential

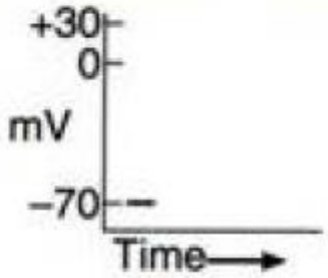
Absolute refractory period: membrane can not respond to any stimulus.
Relative refractory period: membrane can respond to an intense stimulus.



Resting Membrane Potential

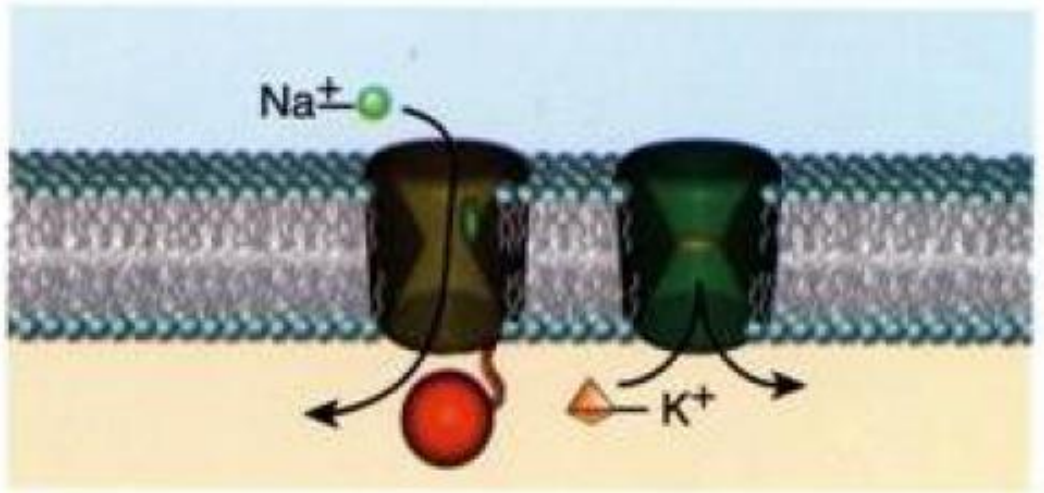
1. **Resting state:** Voltage-gated Na^+ channels are in resting state and voltage-gated K^+ channels are closed.

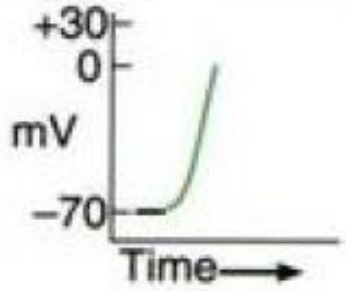




Action Potential

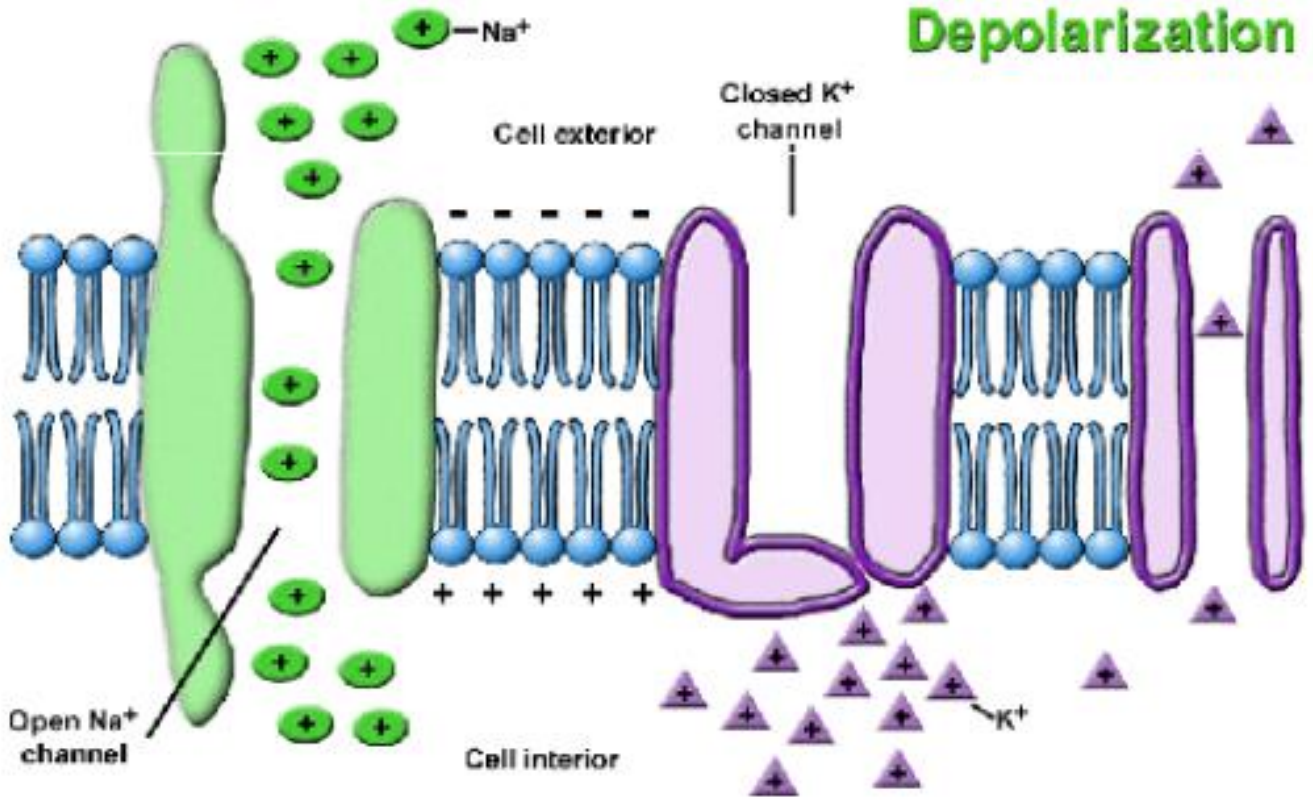
2. Depolarizing phase: Depolarization to threshold (about –55 mV) opens Na^+ channel activation gates. The inflow of Na^+ further depolarizes the membrane until its polarity is reversed.





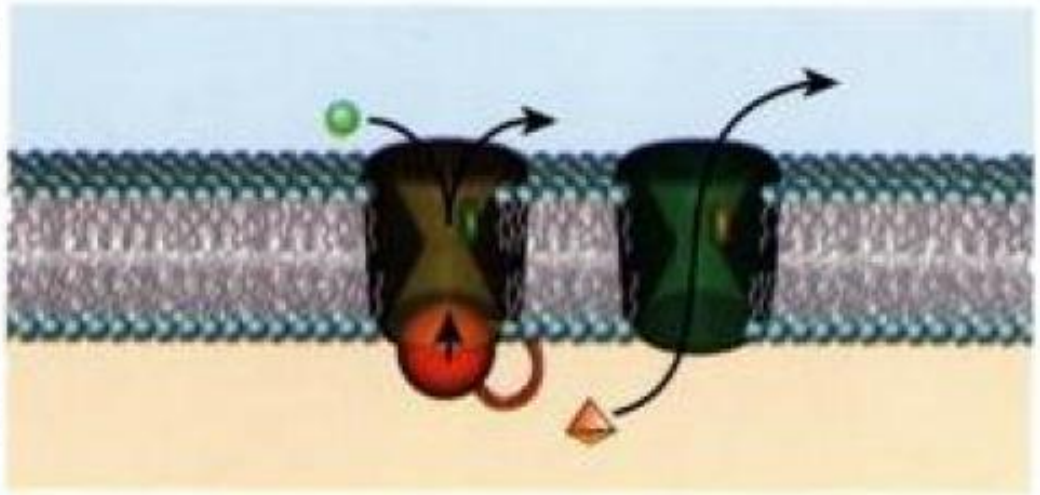
Action Potential

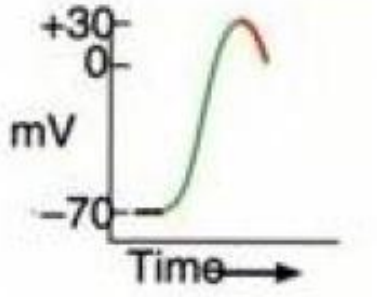
As a result of stimulus, the permeability of membrane to Na+ increases up to 1000 times folds. Therefore, the Na+ rush into the cell carrying enough positive charges to change the membrane potential. This is called “Depolarization”.



Action Potential

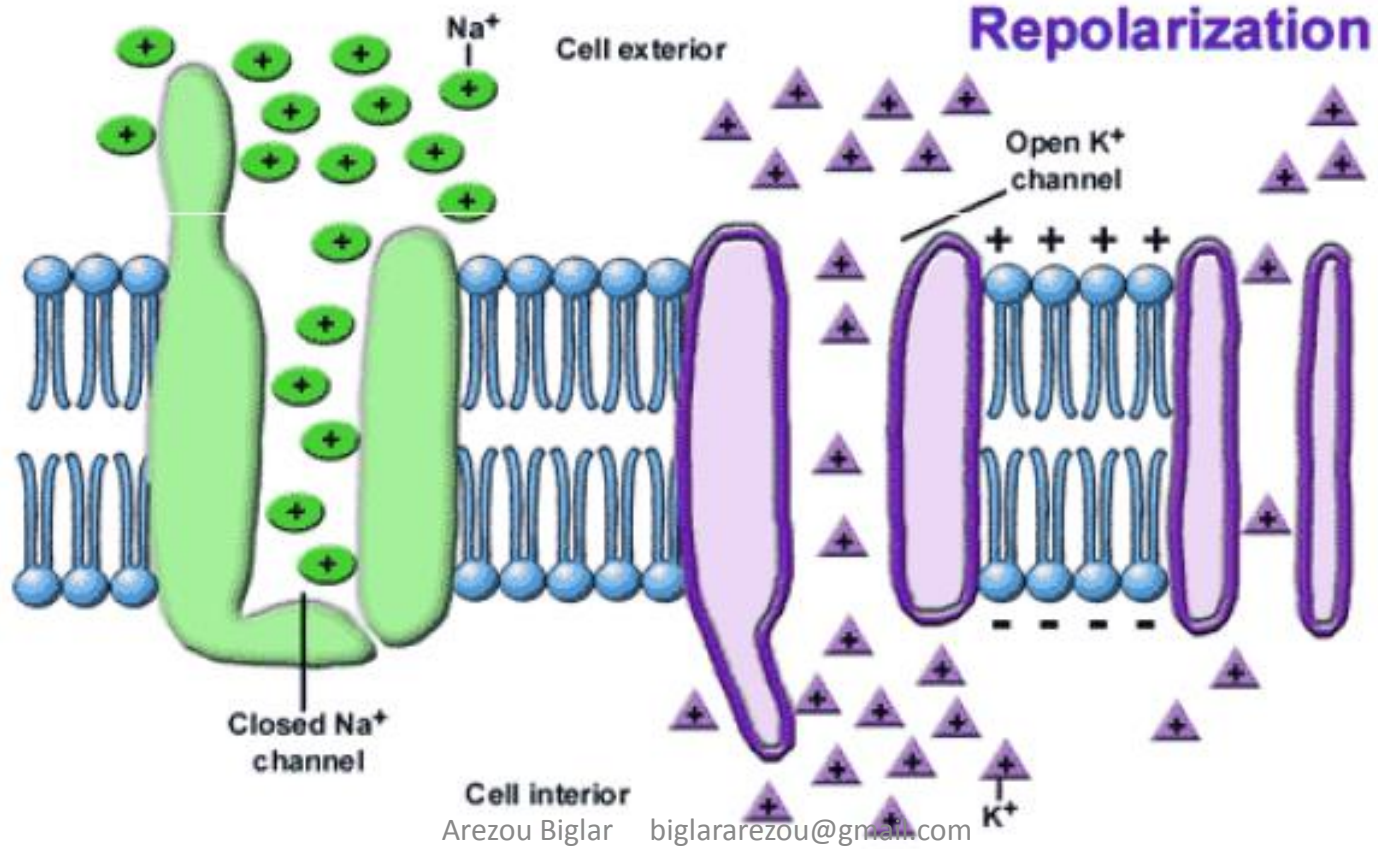
3. Repolarizing phase: More slowly, depolarization also opens voltage-gated K^+ channels, which permit outflow of K^+. At the same time Na^+ channel inactivation gates are closing.





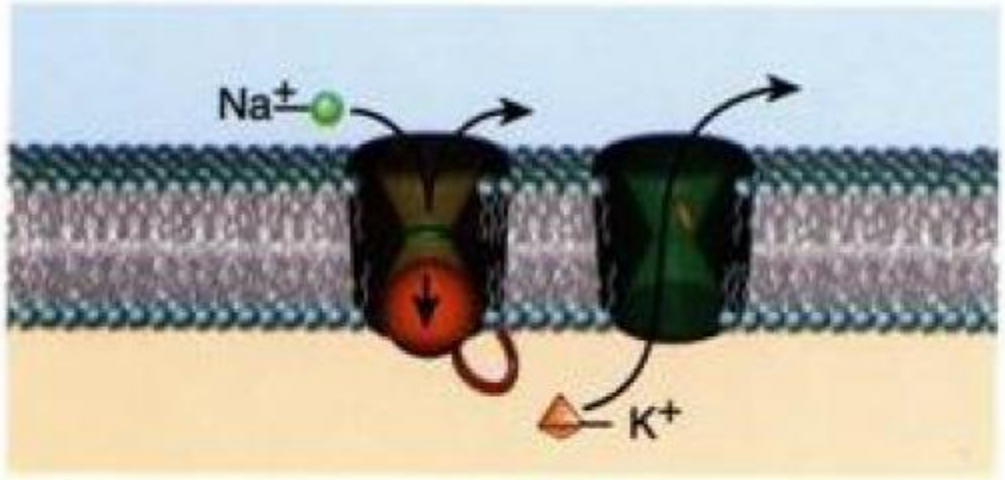
Action Potential

Almost immediately after depolarization, the pores of membrane again become almost impermeable to Na+ and the membrane potential goes back to its resting state. This is called “Repolarization”.

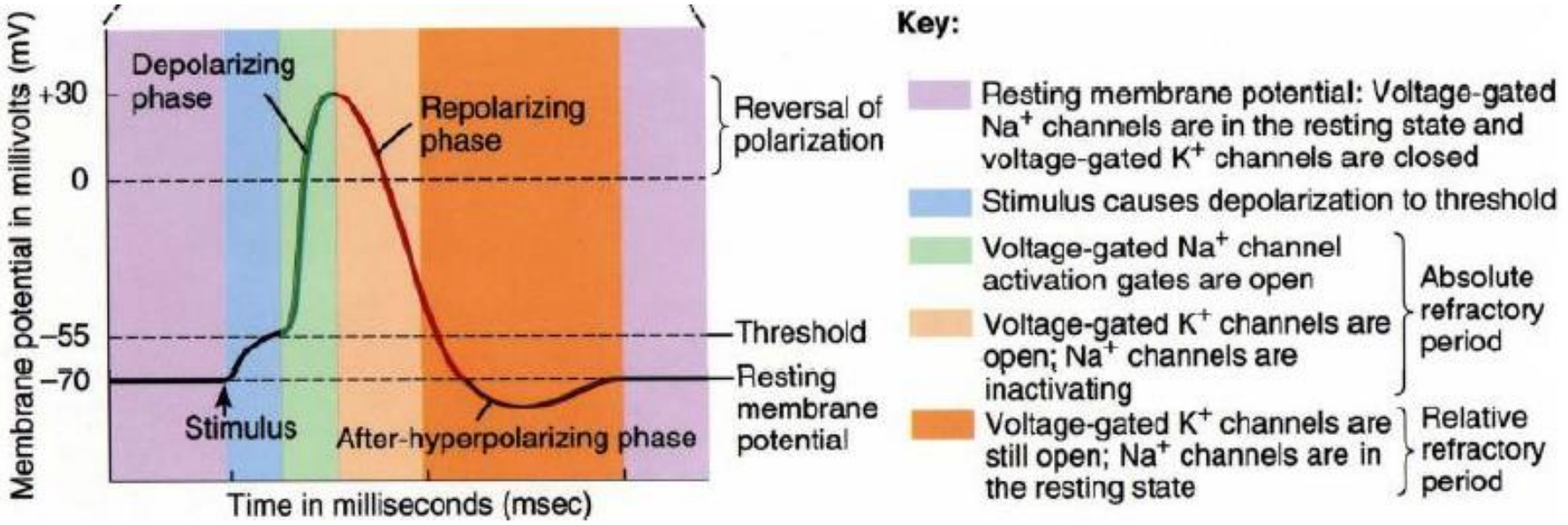


Action Potential

4. Repolarization continues:
Outflow of K^+ restores the resting membrane potential, Na^+ channel inactivation gates are opening and K^+ channels are closing.



Action Potential



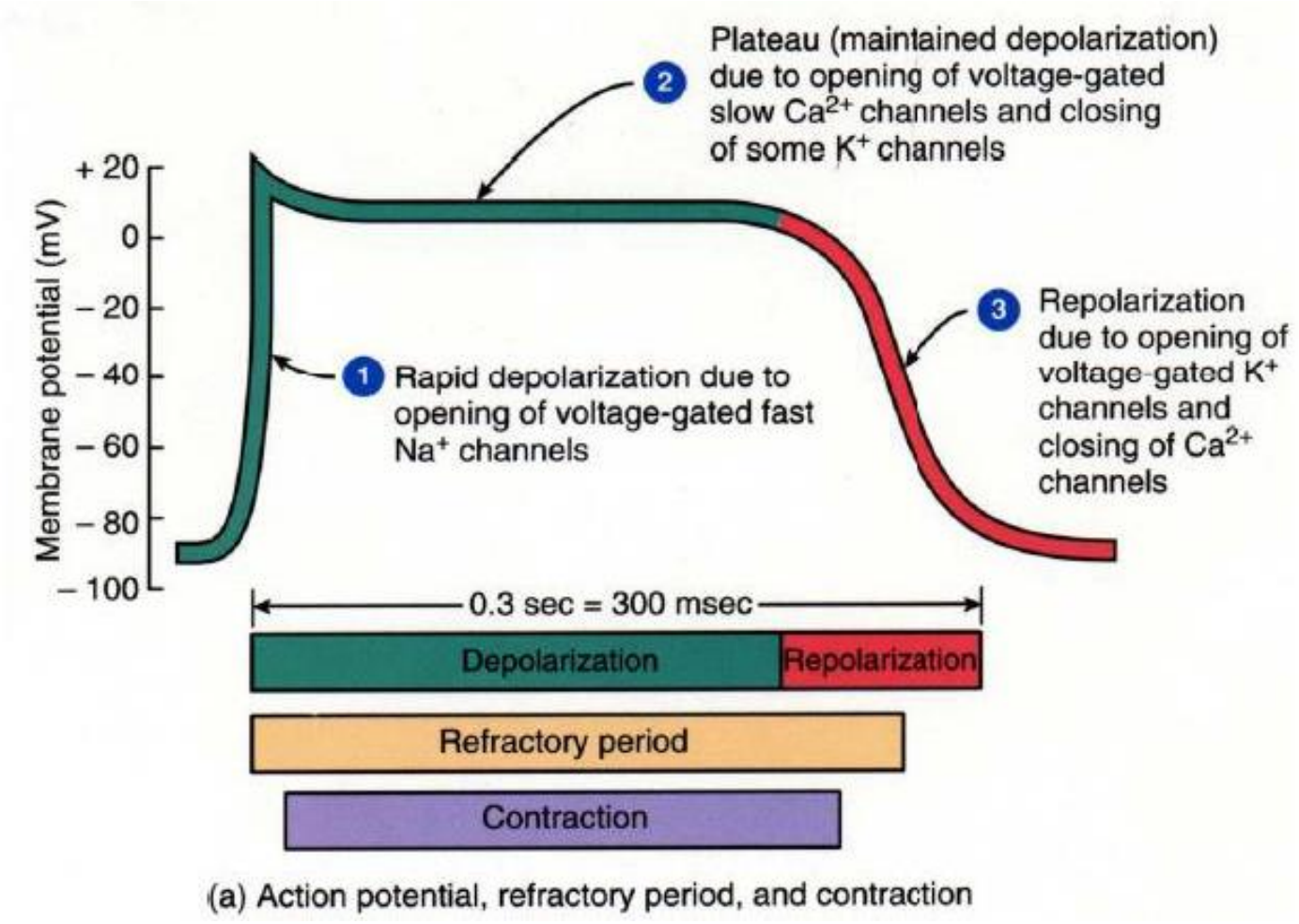
Action Potential

- An action potential elicited at any point on a membrane, usually excites adjacent portions of the membrane, resulting propagation of the action potential in any direction.

- The action potential moves and depolarizes through the entire membrane or it fails to travel at all.

- This is called “all-or-none law”.

The ECG: Cardiac Action Potential



(a) Action potential, refractory period, and contraction

Biomedical Instrumentation I

Lecture-2: The Heat & Electrocardiogram (ECG)

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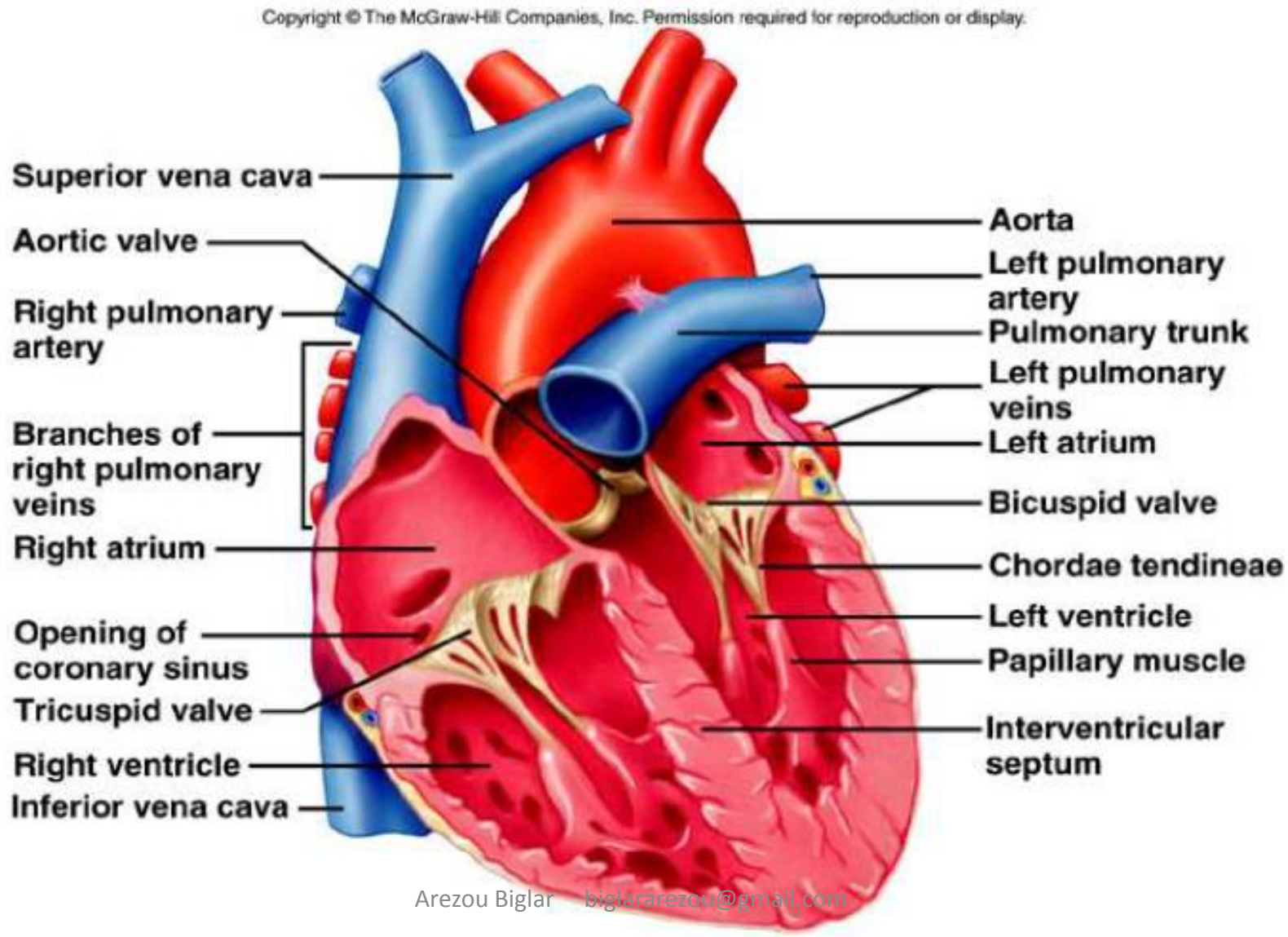
Lecture Outline

- **The Heart**
- **The Heart as a Pump**
- **Blood Flow Cycle**
- **Electrical System of the Heart**
- **Heart Dipole**
- **Einthoven Triangle**
- **The Electrocardiogram (ECG)**
- **The standard 12 Lead ECG System**
- **Electrocardiography**
- **Types of ECG Recorders**
- **Cardiac Rhythms - Normal & Abnormal**
- **Block Diagram of ECG System**
- **Frequent Problems in ECG System**
- **ECG Artefacts**
- **Cardio Tachometer**
- **ECG Telemetry System**

The Heart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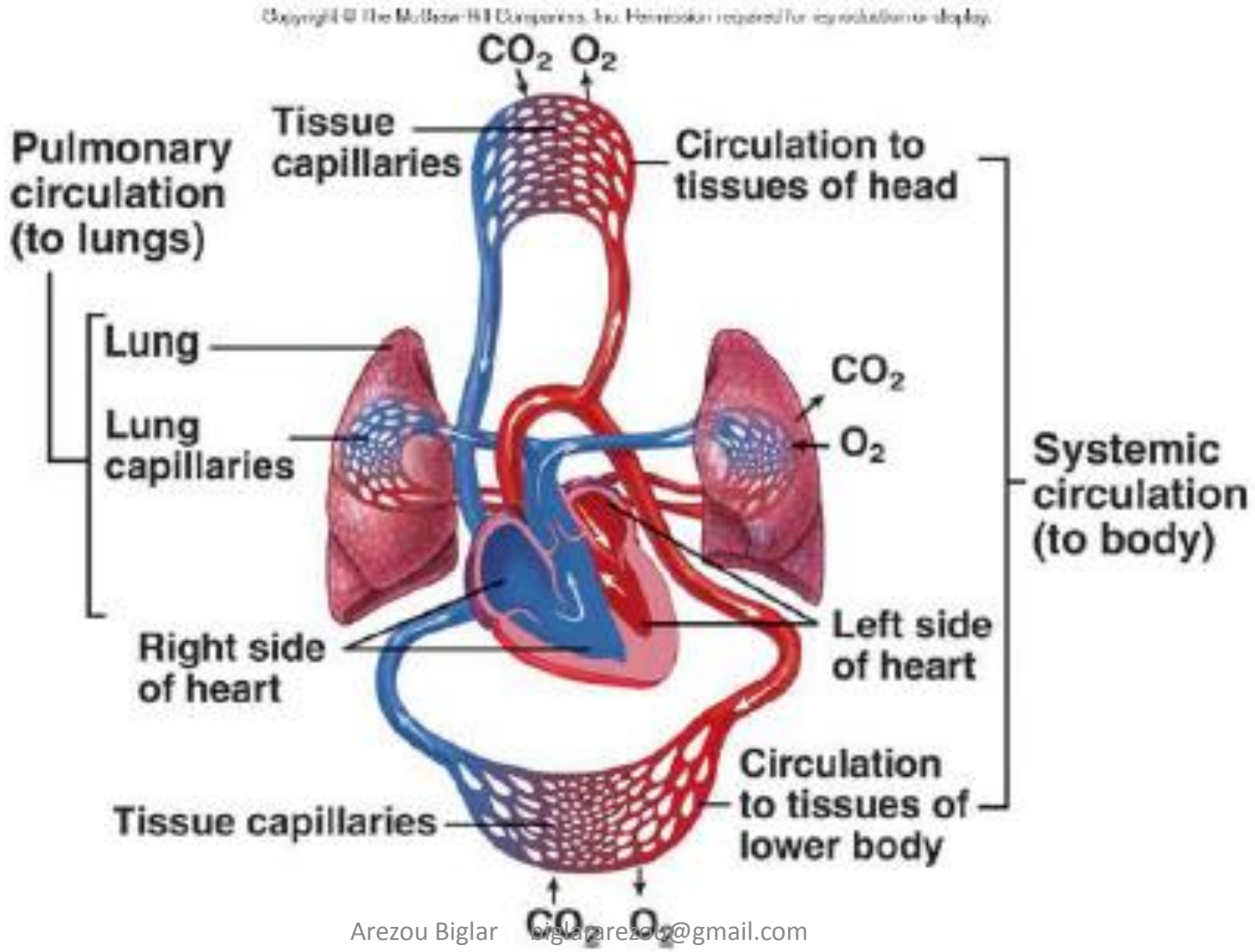
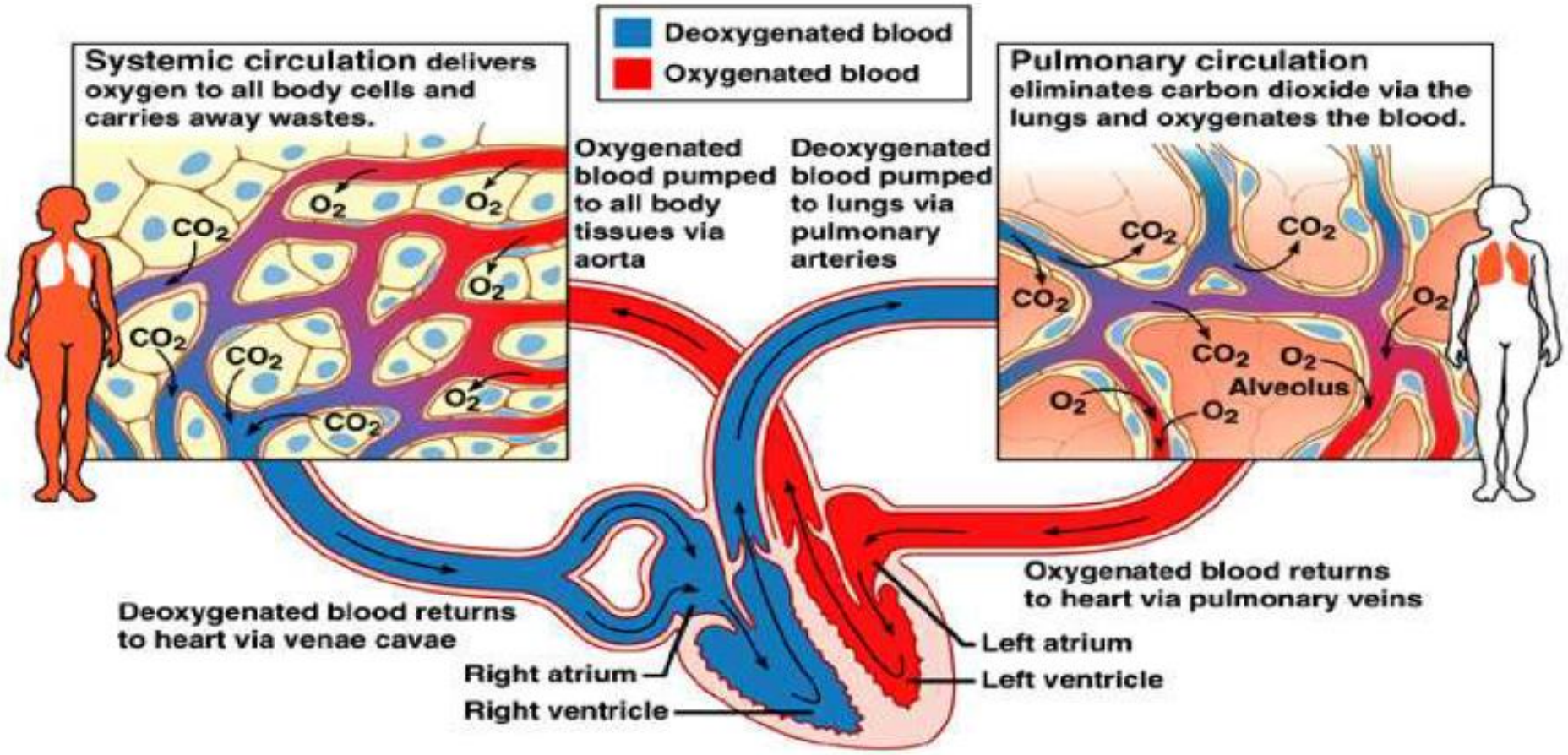
Superior vena cava
Aortic valve
Right pulmonary artery
Branches of right pulmonary veins
Right atrium
Opening of coronary sinus
Tricuspid valve
Right ventricle
Inferior vena cava
Aorta
Left pulmonary artery
Pulmonary trunk
Left pulmonary veins
Left atrium
Bicuspid valve
Chordae tendineae
Left ventricle
Papillary muscle
Interventricular septum

The Heart as a Pump



The Heart as a Pump



The Heart as a Pump

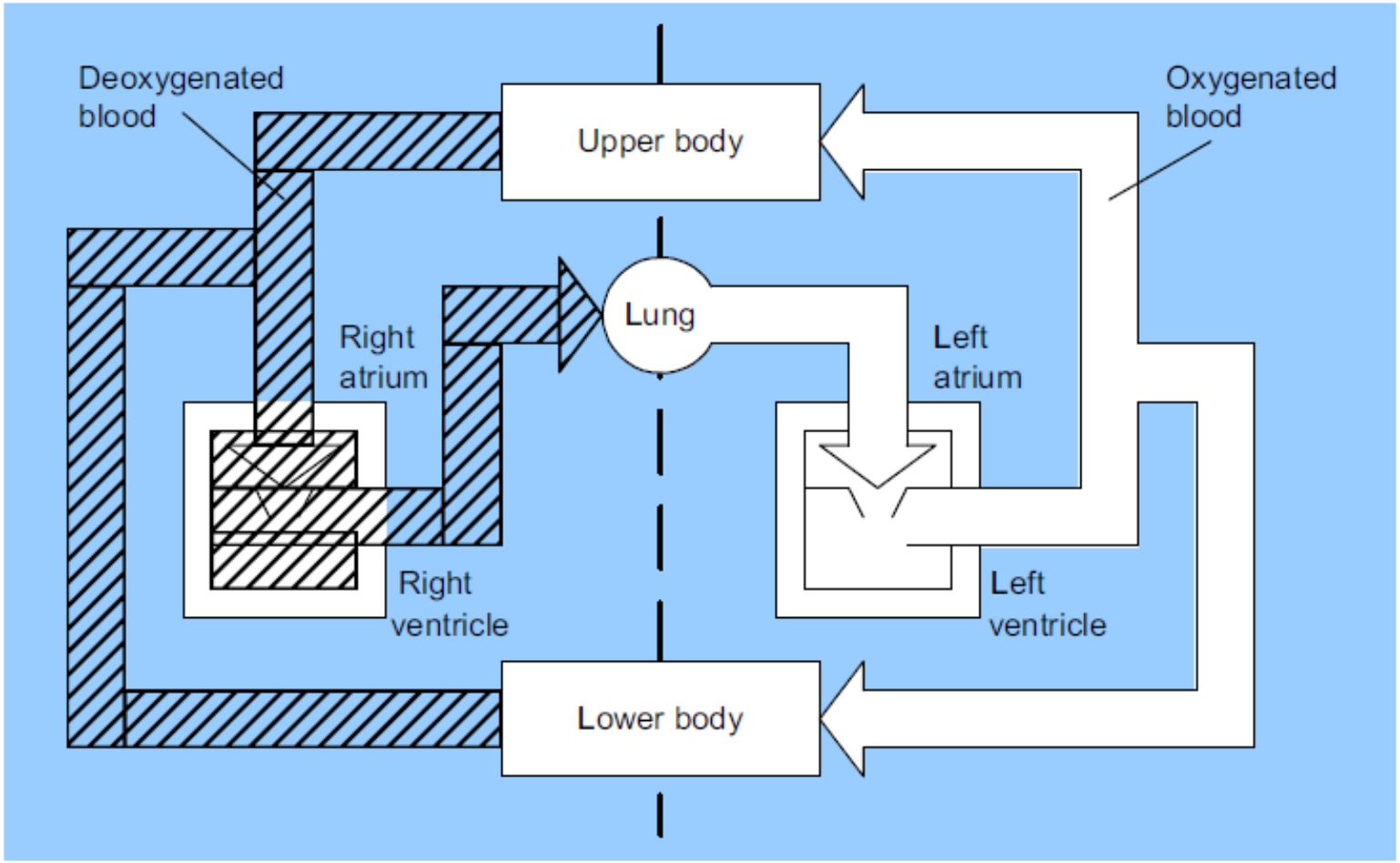
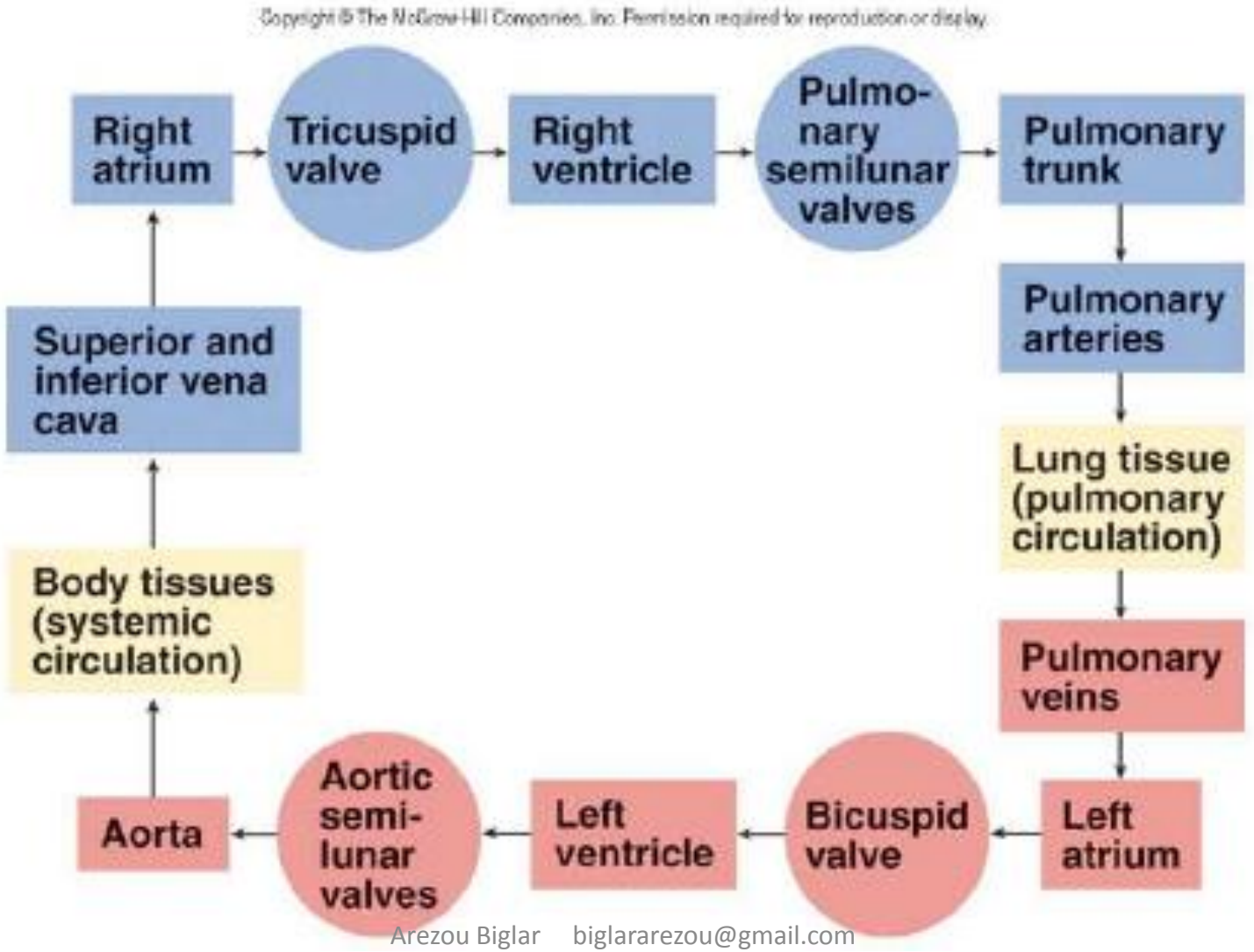
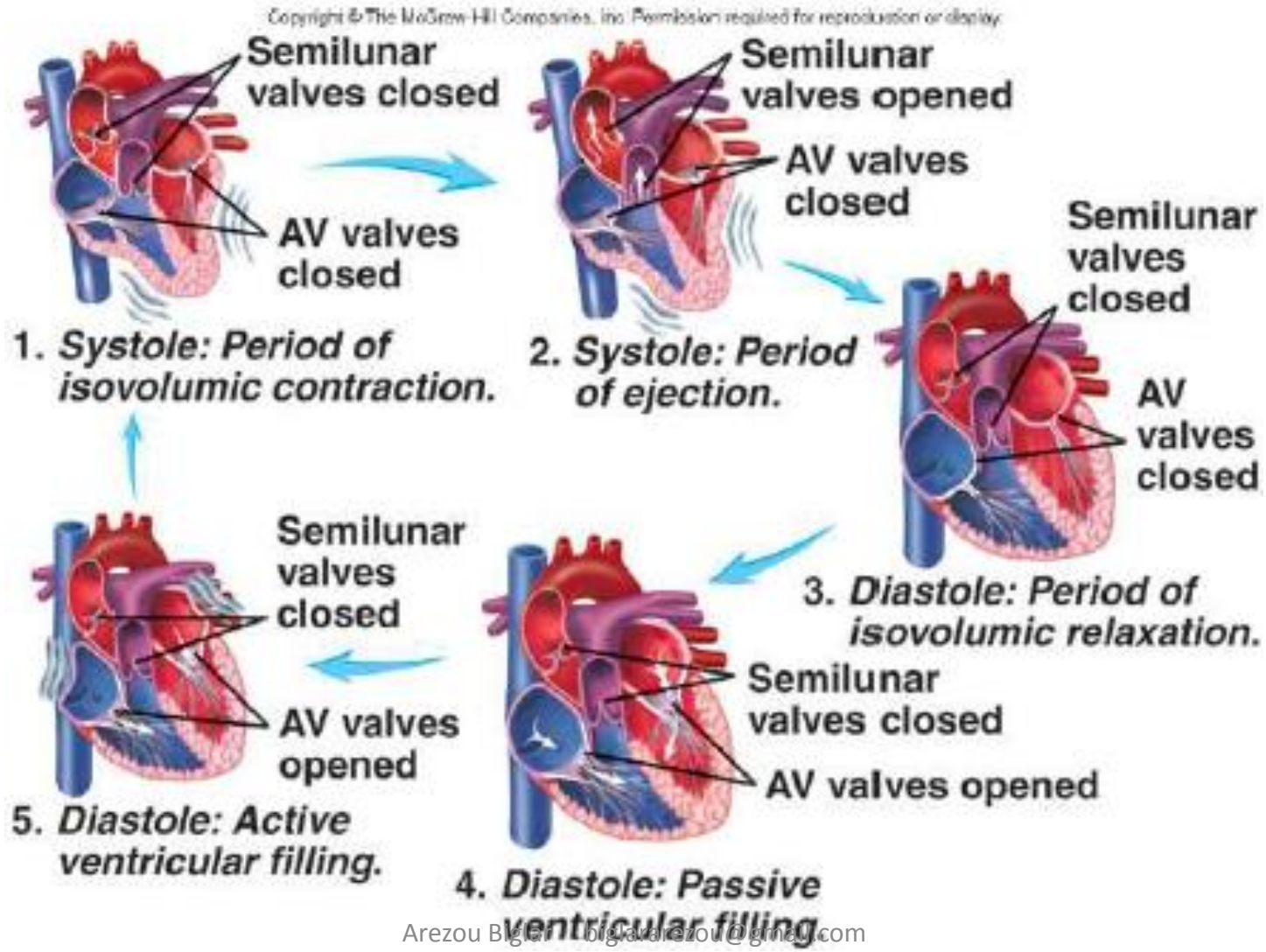


Figure: The simplified circulatory system. The blood is delivered from the right ventricle to the lung. The oxygenated blood from the lung is then returned to the left atrium before being sent throughout the body from left ventricle. Deoxygenated blood from the body flows back to the right atrium and the cycle repeats.

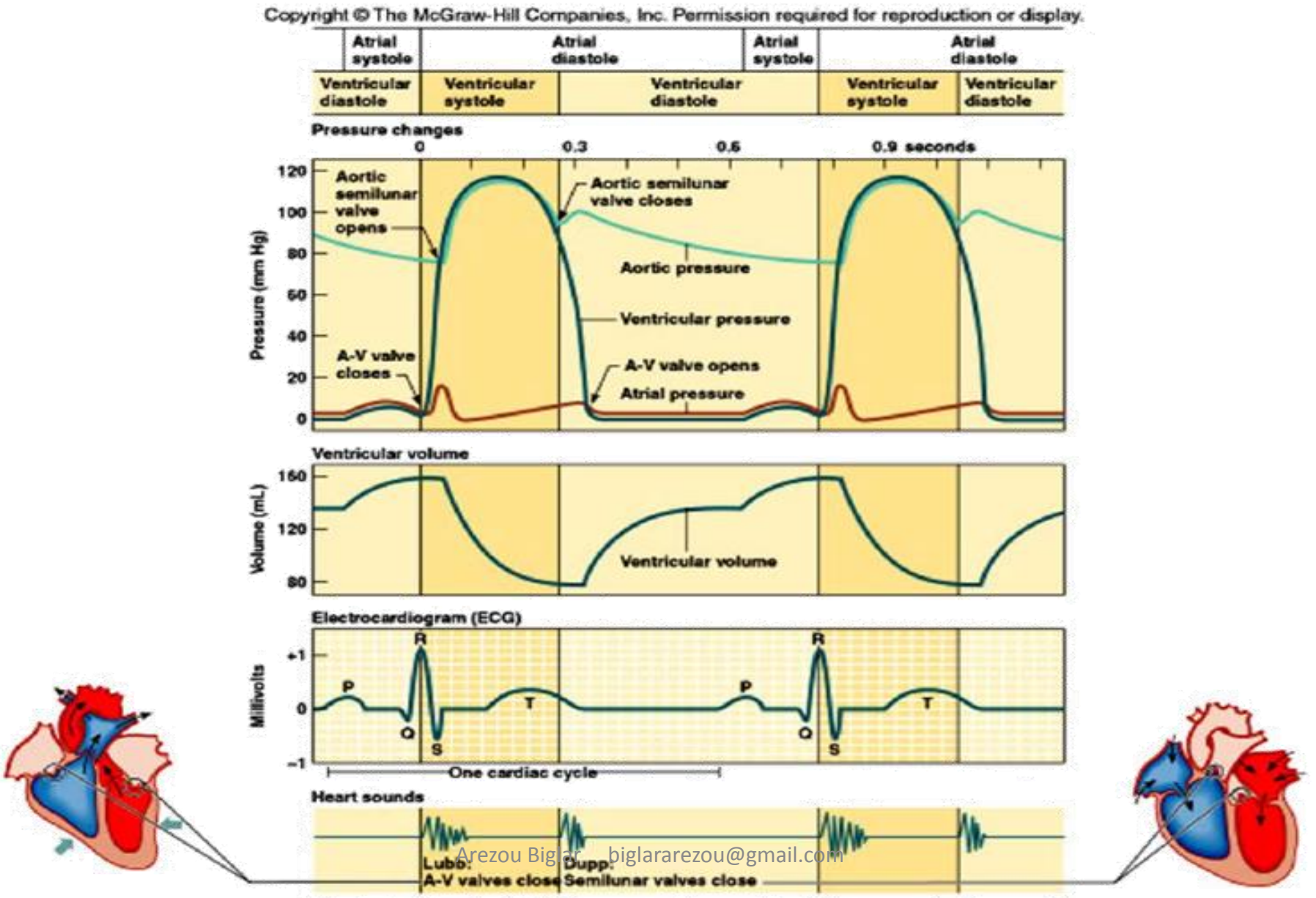
Blood Flow Cycle



Cardiac Cycle



The Heart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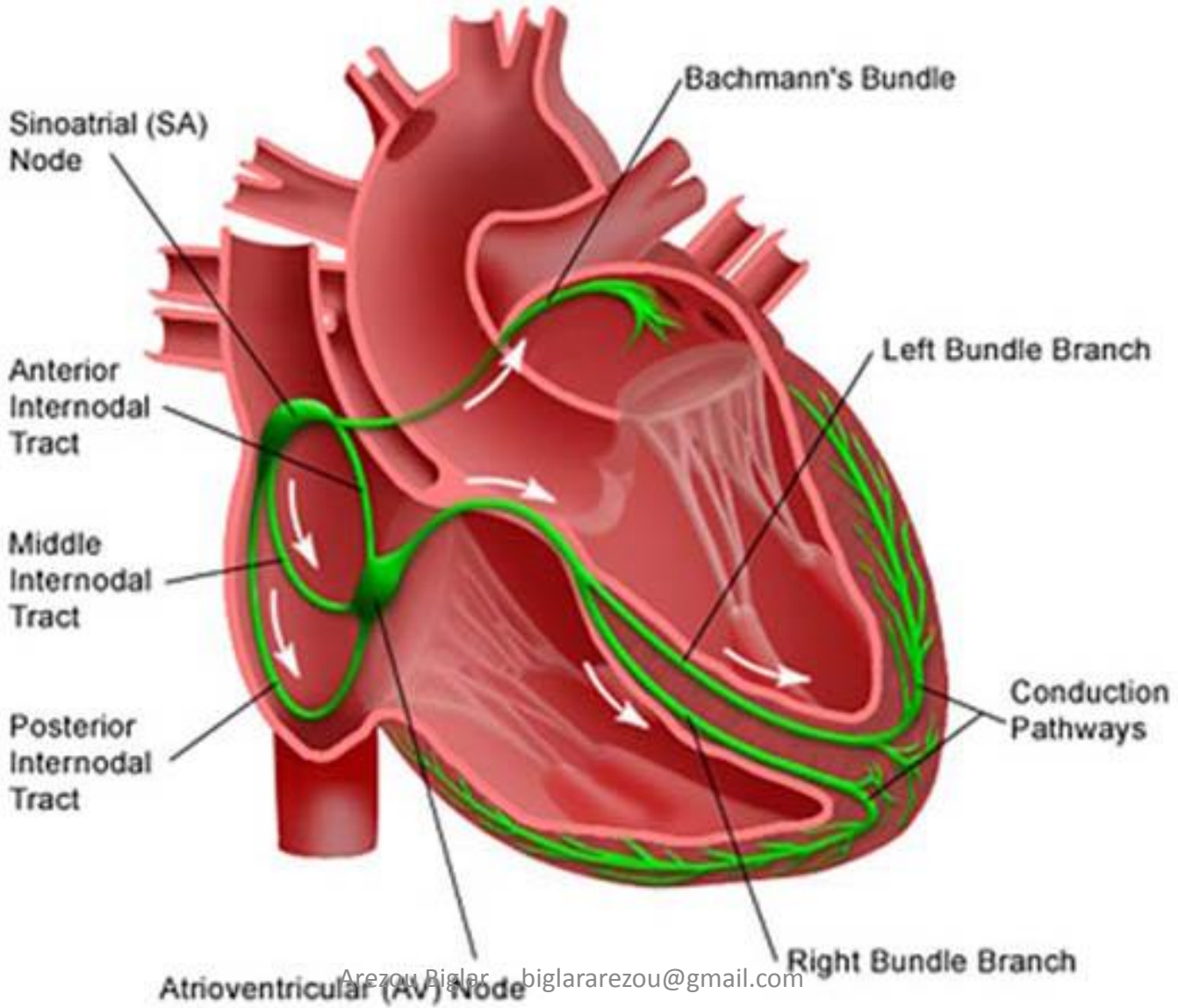
Atrial systole
Atrial diastole
Atrial systole
Atrial diastole
Ventricular diastole
Ventricular systole
Ventricular diastole
Ventricular systole
Ventricular diastole
Pressure changes
0
0.3
0.6
0.9 seconds
Pressure (mm Hg)
120
100
80
60
40
20
0
Aortic semilunar valve opens
Aortic semilunar valve closes
Aortic pressure
Ventricular pressure
A-V valve closes
A-V valve opens
Atrial pressure
Ventricular volume
Volume (mL)
160
120
80
Ventricular volume
Electrocardiogram (ECG)
Millivolts
+1
0
−1
R
P
Q
S
T
One cardiac cycle
Heart sounds
Lubb:
A-V valves close
Dupp:
Semilunar valves close

Electrical System of the Heart



Electrical System of the Heart

- Distribution of specialized conductive tissues in the atria and ventricles, showing the impulse-forming and conduction system of the heart.

- The rhythmic cardiac impulse originates in pacemaking cells in the sinoatrial (SA) node, located at the junction of the superior vena cava and the right atrium.

- Note the three specialized pathways (anterior, middle, and posterior internodal tracts) between the SA and atrioventricular (AV) nodes.

- Bachmann's bundle (interatrial tract) comes off the anterior internodal tract leading to the left atrium.

- The impulse passes from the SA node in an organized manner through specialized conducting tracts in the atria to activate first the right and then the left atrium.

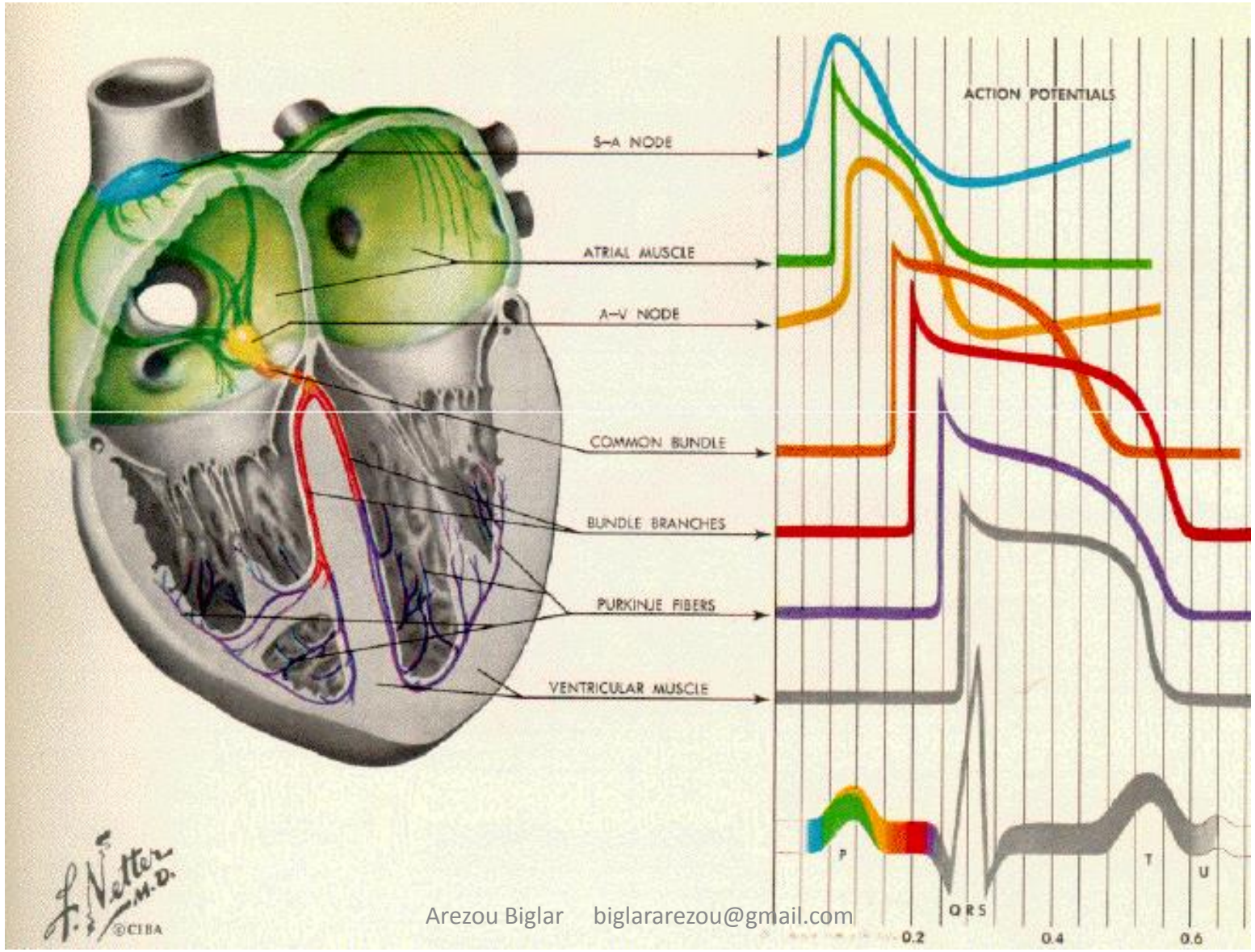
Electrical System of the Heart

- Passage of the impulse is delayed at the AV node before it continues into the bundle of His, the right bundle branch, the common left bundle branch, the anterior and posterior divisions of the left bundle branch, and the Purkinje network.

- The right bundle branch runs along the right side of the interventricular septum to the apex of the right ventricle before it gives off significant branches.

- The left common bundle crosses to the left side of the septum and splits into the anterior division (which is thin and long and goes under the aortic valve in the outflow tract to the anterolateral papillary muscle) and the posterior division (which is wide and short and goes to the posterior papillary 5 muscle lying in the inflow tract).

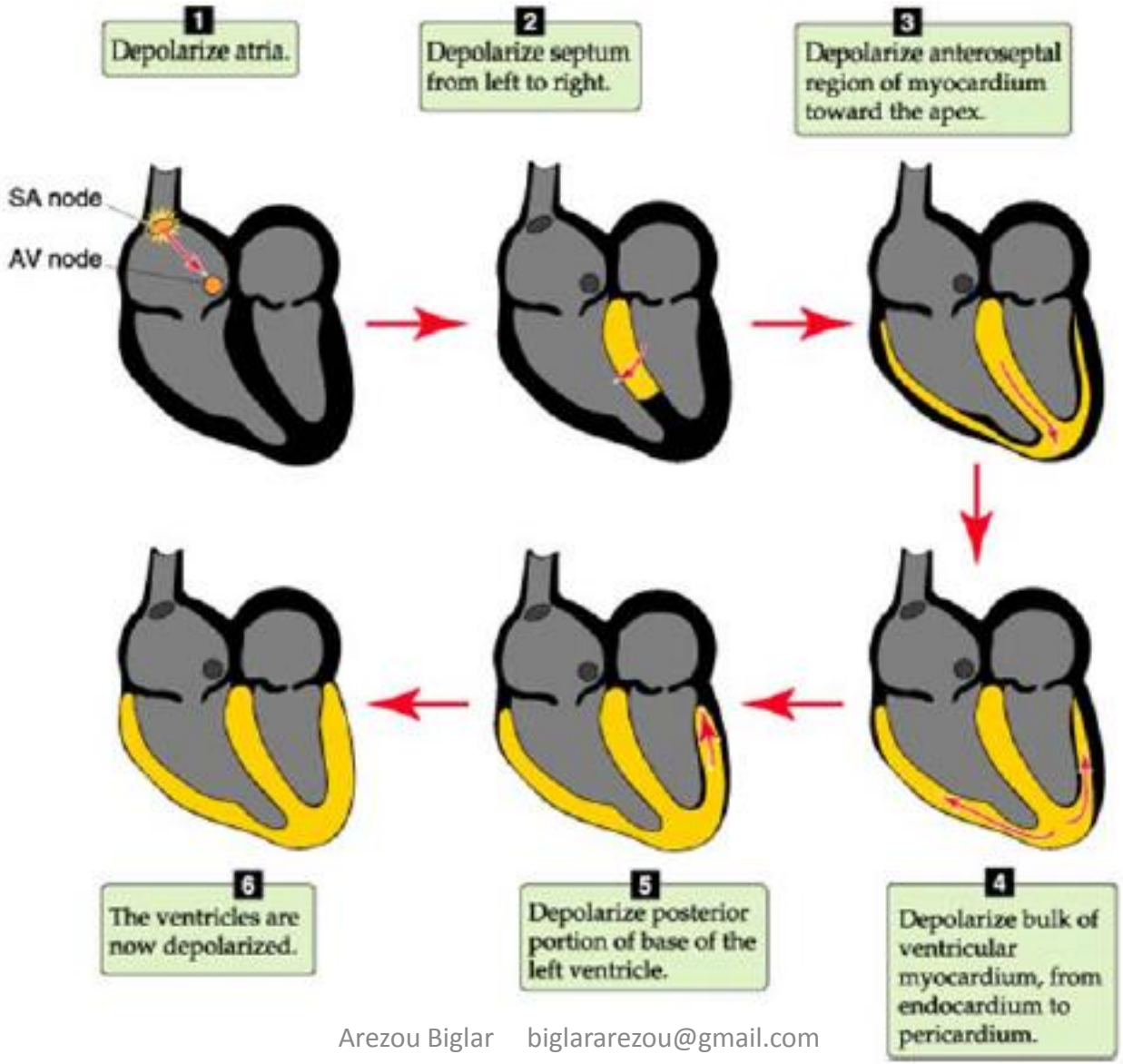
Electrical System of the Heart



Electrical System of the Heart

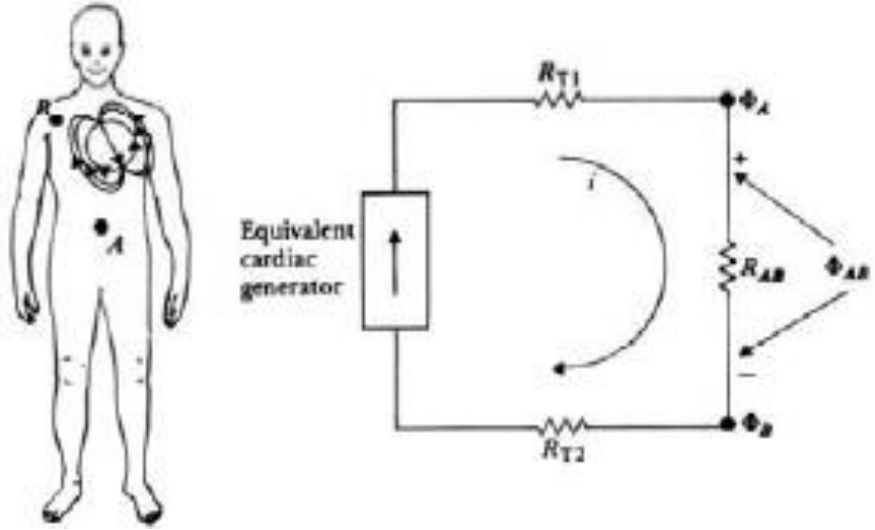
Location in the heart	Event	Time [ms]	ECG-terminology	Conduction velocity [m/s]	Intrinsic frequency [1/min]
SA node	impulse generated	0		0.05	70-80
atrium, Right	depolarization *)	5	P	0.8-1.0	
Left	depolarization	85	P	0.8-1.0	
AV node	arrival of impulse	50	P-Q interval	0.02-0.05	
	departure of impulse	125			
bundle of His	activated	130		1.0-1.5	
bundle branches	activated	145		1.0-1.5	
Purkinje fibers	activated	150		3.0-3.5	
endocardium					
Septum	depolarization	175	QRS	0.3 (axial)	20-40
Left ventricle	depolarization	190		-	
				0.8	
epicardium	depolarization	225		(transverse)	
Left ventricle	depolarization	250			
Right ventricle					
epicardium					
Left ventricle	repolarization	400	T	0.5	
Right ventricle	repolarization				
endocardium					
Left ventricle	repolarization	600			

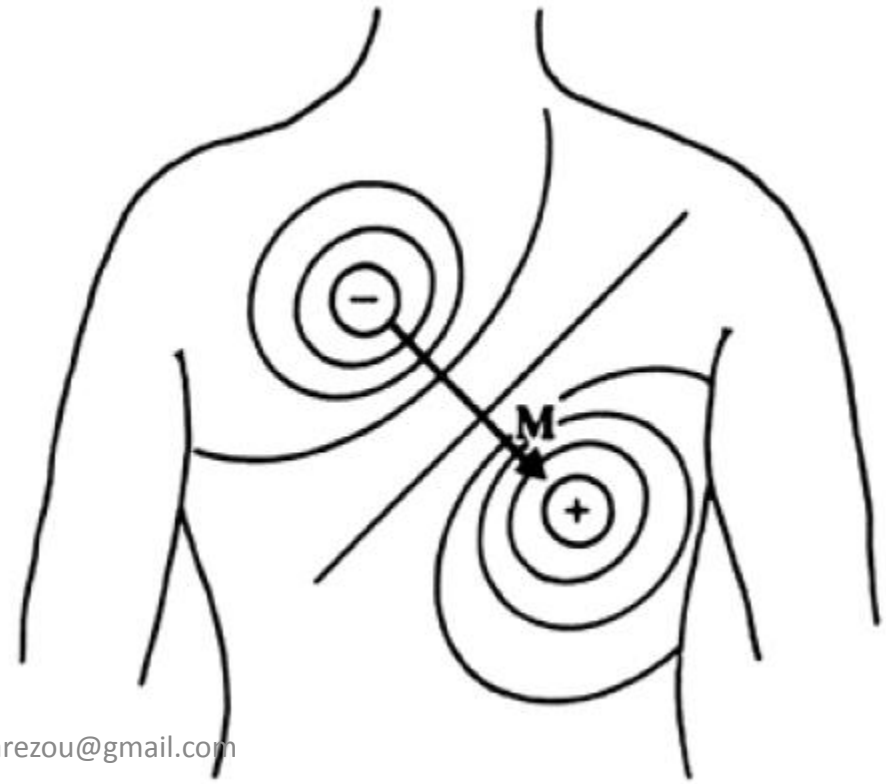
Electrical System of the Heart



Heart Dipole

- Heart considered as an electrical equivalent generator.
- The electrical activity represented by net equivalent current dipole located at the electrical centre of the heart.
- The electrical activity of the heart can be modelled with a vector quantity: an electric dipole, **M** whose magnitude and direction changes in time. Also called the **cardiac vector.**





Vector Algebra

A vector that connects a lead electrode pair is the **lead vector.**

If the cardiac vector **M** is known, the voltage generated at any lead can be easily computed.

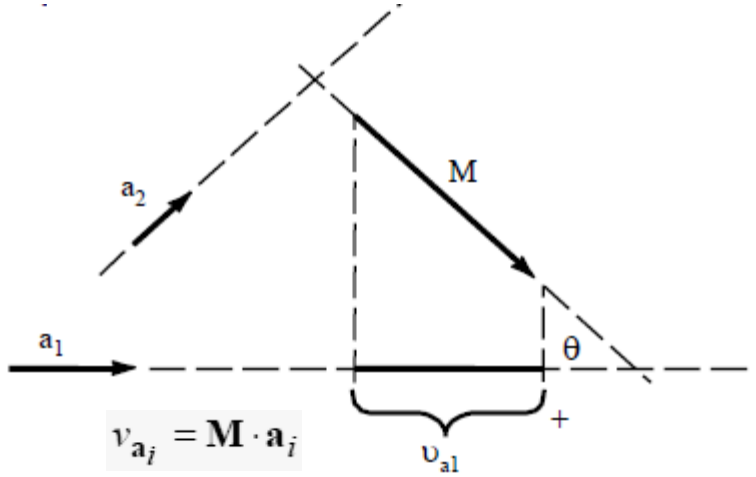
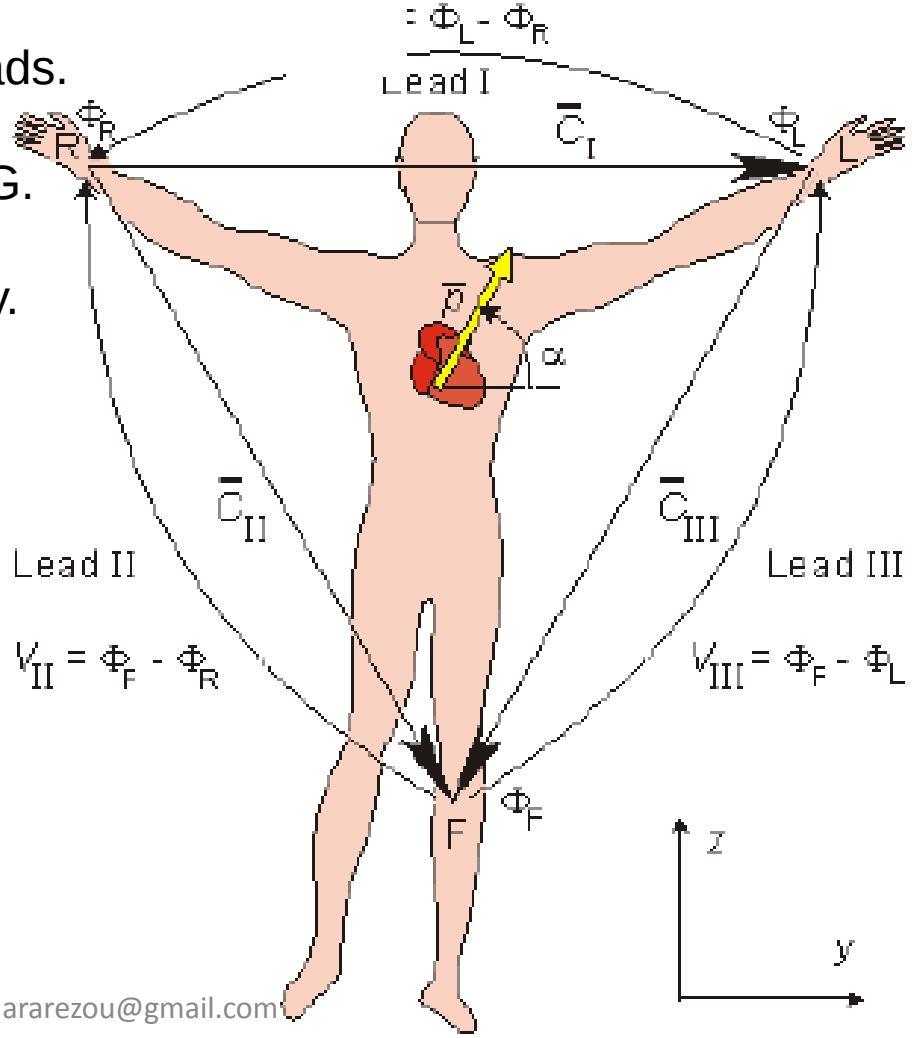


Figure 6.2 Relationships between the two lead vectors $\mathbf{a}_1$ and $\mathbf{a}_2$ and the cardiac vector **M**. The component of **M** in the direction of $\mathbf{a}_1$ is given by the dot product of these two vectors and denoted on the figure by v_{a1}. Lead vector $\mathbf{a}_2$ is perpendicular to the cardiac vector, so no voltage component is seen in this lead.

Einthoven Triangle

- Three vectors used to fully identify the electrical activity.
- Approximation of lead vectors of limb leads.
- Determines electrode placement for ECG.
- Vector shown in frontal plane of the body.



Einthoven Triangle

Kirchhoff's law is used for the three leads

$$I - II + III = 0$$

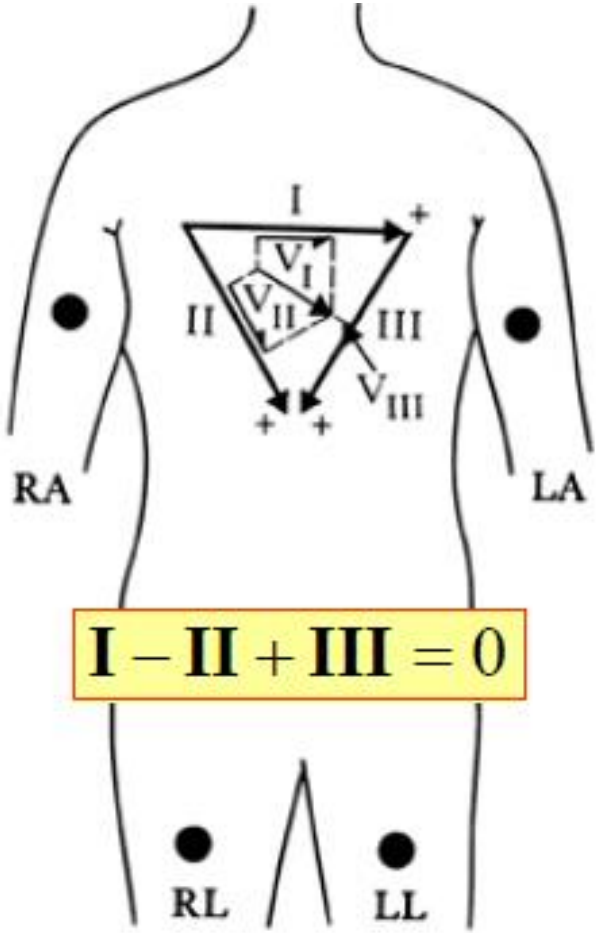
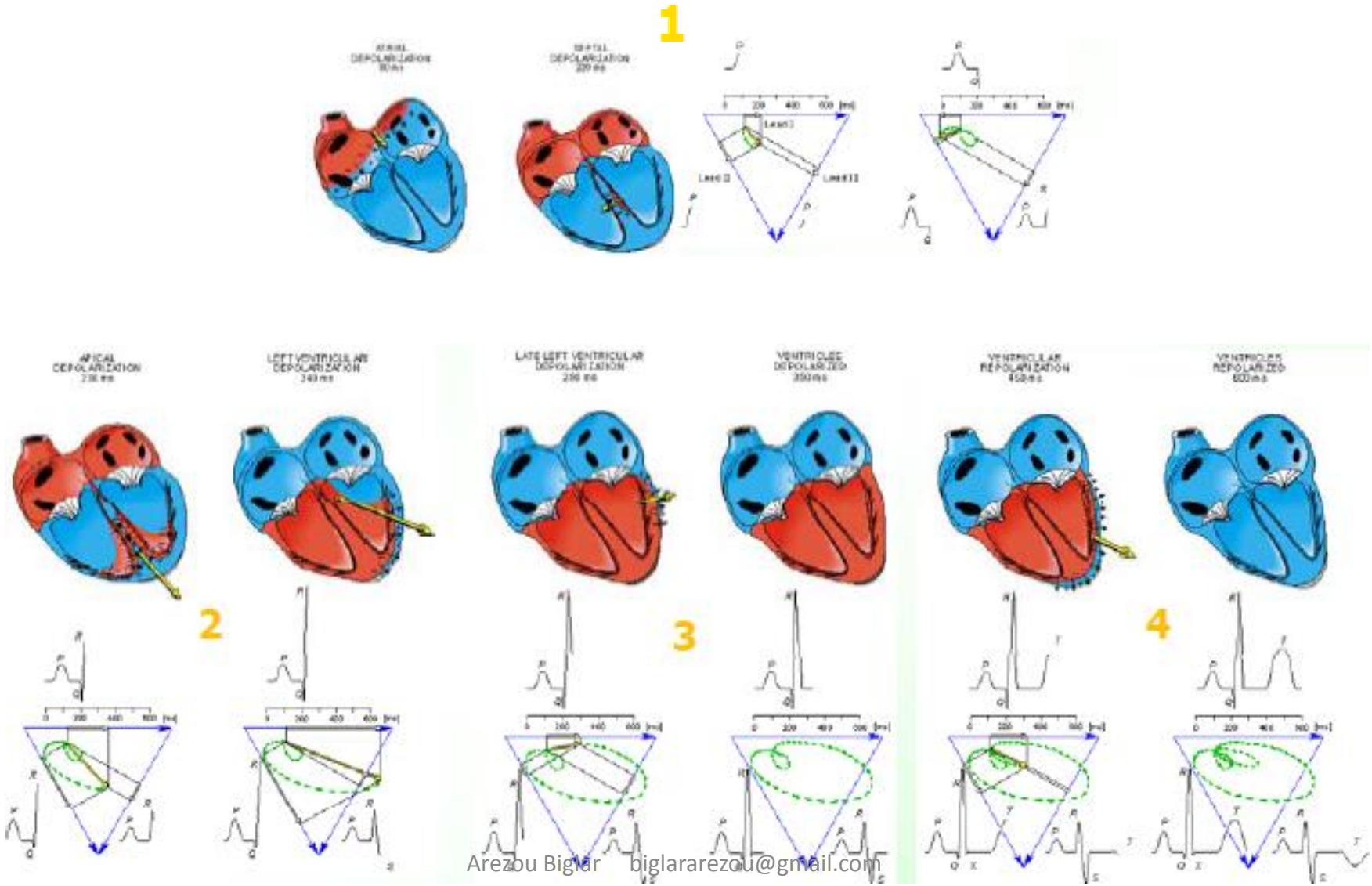
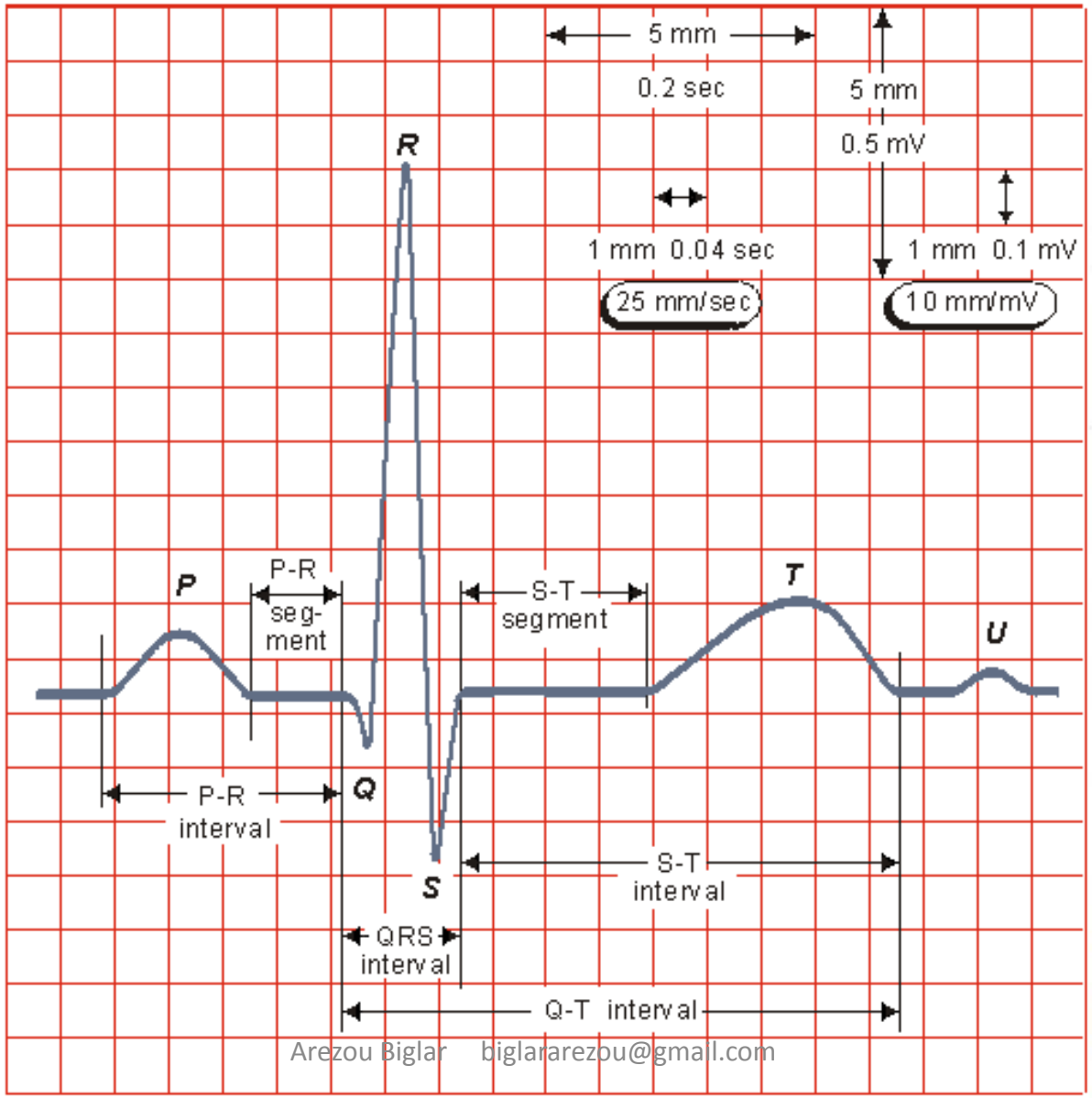


Figure 6.3 Cardiologists use a standard notation such that the direction of the lead vector for lead I is 0°, that of lead II is 60°, and that of lead III is 120°. An example of a cardiac vector at 30° with its scalar components seen for each lead is shown.

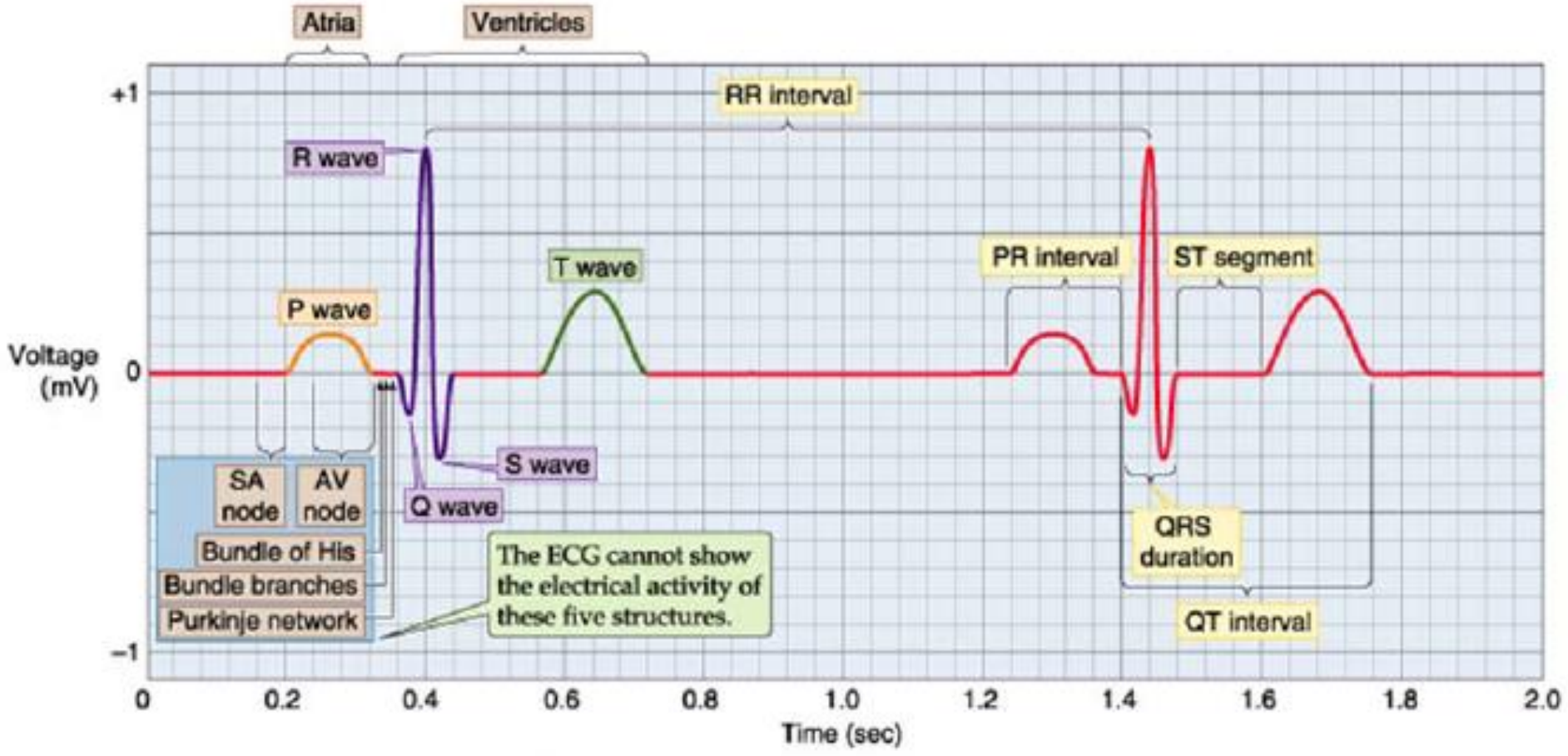
Einthoven Limb Leads



The Electrocardiogram (ECG)



The Electrocardiogram (ECG)



The Electrocardiogram (ECG)

Action potential to the heart starts at the sinoatrial or SA node and it travels through the heart with delay at each point. ECG represents superposition of all signals.

P wave – depolarization of atria

QRS complex – depolarization of ventricular muscle and repolarization of atria

T wave – repolarization of ventricular muscle

U-wave – if present, believed to be the after potentials in the ventricular muscles.

P-R interval – is caused by delay in the AV node

S-T segment – is related to the average duration of the plateau regions of the individual ventricular cells.

The Electrocardiogram (ECG)

- The electric potentials generated by the heart appear throughout the body and on its surface.
- The electrical signals of the Cardiac Conduction System can be picked up with sensors on the chest.
- These signals result in an ECG, or electrocardiogram (in Germany EKG).
- Different pairs of electrodes at different locations generally yield different voltages because of the spatial dependence of the electric field of the heart.
- This graph is frequently used to detect normal heart function.
- The familiar ECG is a reading of the different electrical signals that go off.
- The chart to the right explains the electrical significance of the different spikes in potential.

The Electrocardiogram (ECG)

The ECG Leads vs. Electrodes

- **Leads** are made of a combination of electrodes that form imaginary lines in the body along which the electrical signals are measured.

- A pair of electrodes, or a combination of several electrodes through a resistive network that gives an equivalent pair is called a **lead.**

- Each lead will be assigned with an axis and each of the axes will have an orientation: by convention the sense of the axis is toward the positive electrode.

- The projection of the cardiac vectors as function of time on the axis corresponding to a lead is actually the ECG trace in that particular lead.

The Electrocardiogram (ECG)

Abbreviations and Color Codes for ECG Electrodes

- **Chest Electrode (C): Brown**
- **Right Arm (RA): White**
- **Left Arm (LA): Black**
- **Left Leg (LL): Red**
- **Right Leg (RL): Green**

The Electrocardiogram (ECG)

The standard 12 Lead ECG System

3 Standard Limb Leads

3 Augmented Limb Leads

6 Precordial Leads

- 6 limb leads – define electrical activity in frontal plane.
- 6 precordial leads – define electrical activity in transverse plane.

The Electrocardiogram (ECG)

The standard 12 Lead ECG System

	Limb Leads	Precordial Leads
Bipolar	I, II, III (standard limb leads)	-
Unipolar	aVR, aVL, aVF (augmented limb leads)	V_1-V_6

The Electrocardiogram (ECG)

The standard 12 Lead ECG System

	Positive electrode	Negative electrode
Standard limb leads		
Lead I	Left arm	Right arm
Lead II	Left leg	Right arm
Lead III	Left leg	Left arm
Augmented unipolar leads		
aVL	Left arm	All other limbs
aVR	Right arm	All other limbs
aVF	Left leg	All other limbs
Precordial (chest) leads		
V1–V6	Corresponding chest electrode	"Common terminal" of all the limb electrodes

The Electrocardiogram (ECG)

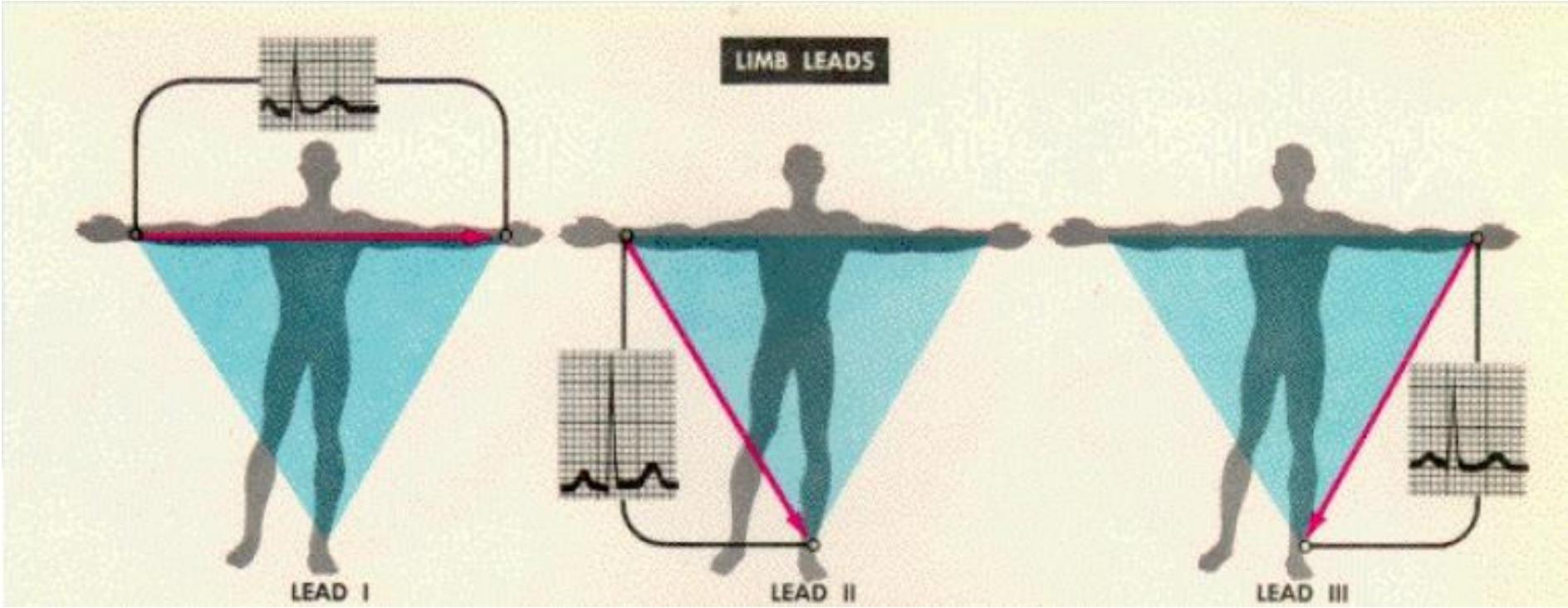
The standard Bipolar Limb Lead

- **Lead I:** LEFT ARM (LA) and RIGHT ARM (RA)
- **Lead II:** LEFT LEG (LL) and RIGHT ARM (RA)
- **Lead III:** LEFT LEG (LL) and LEFT ARM (LA)

Note: In standard bipolar limb lead system, four electrodes are place on the limbs. However the electrode on the right leg is used for ground reference.

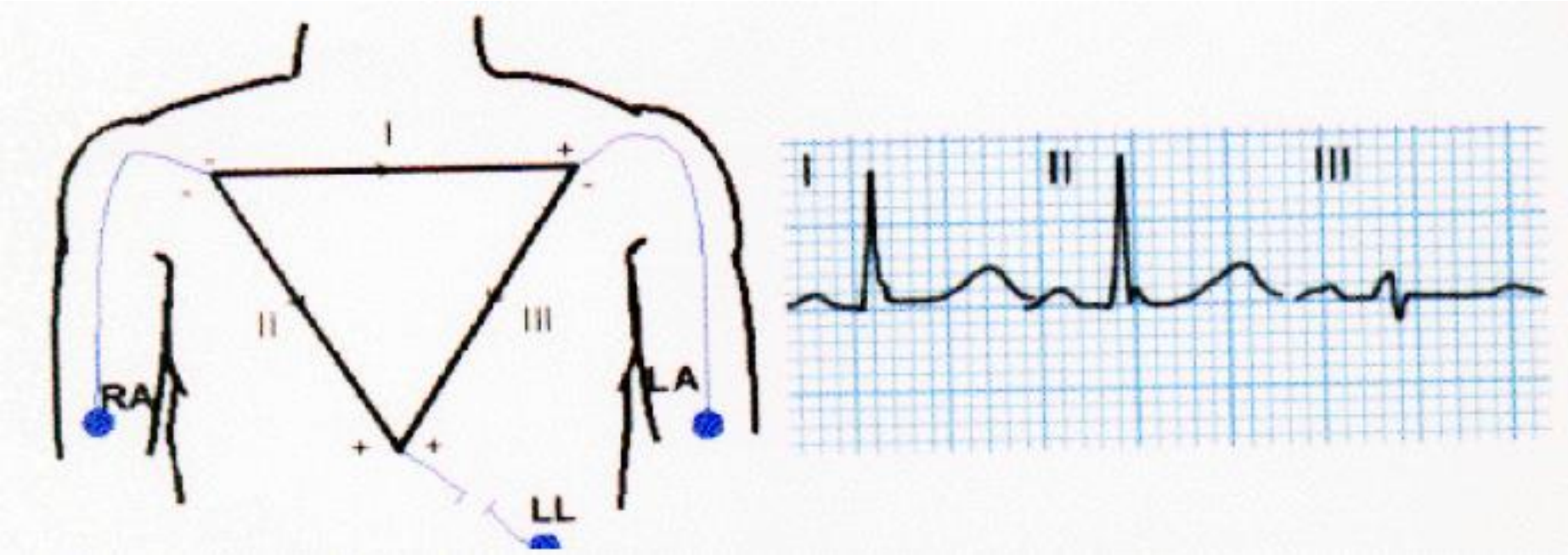
The Electrocardiogram (ECG)

The standard Bipolar Limb Leads



The Electrocardiogram (ECG)

The standard Bipolar Limb Leads



The Electrocardiogram (ECG)

The standard Bipolar Limb Lead

- The three bipolar limb lead selections first introduced by Einthoven.
- The three leads are called bipolar because for each lead the electrocardiogram is recorded from any two electrodes and the third electrode is not connected.
- The R-wave of the ECG is positive in all three bipolar limb leads, however Lead-II produces greatest R-wave potential.
- The R-wave amplitude of Lead II is equal to the sum of R wave amplitudes of Lead I and Lead III.

The Electrocardiogram (ECG)

The standard Bipolar Limb Lead I

- Lead I is the first of three standard limb leads (I, II, III).
- Limb leads measure cardiac depolarization in the frontal (coronal) plane.
- The negative electrode is connected to the RIGHT ARM (RA).
- The positive electrode is connected to the LEFT ARM (LA).
- The axis is 0^{o} degrees.
- When an action potential starts on the right and proceeds toward the left side of the heart, a positive inflection will be seen in lead one. This holds true for all leads. Whenever a current proceeds toward a positive electrode, an upright inflection is seen on the EKG tracing.

The Electrocardiogram (ECG)

The standard Bipolar Limb Lead II

- Lead II is used alone quite frequently.
- Normal rhythms present with a prominent P-wave and a tall QRS complex.
- The negative electrode is connected to the RIGHT ARM (RA).
- The positive electrode is connected to the LEFT LEG (LL).
- The axis is $+60^{o}$ degrees.
- In all the limb leads, the electrodes may be positioned close to the torso. For convenience, they are often placed at the shoulders and hips.

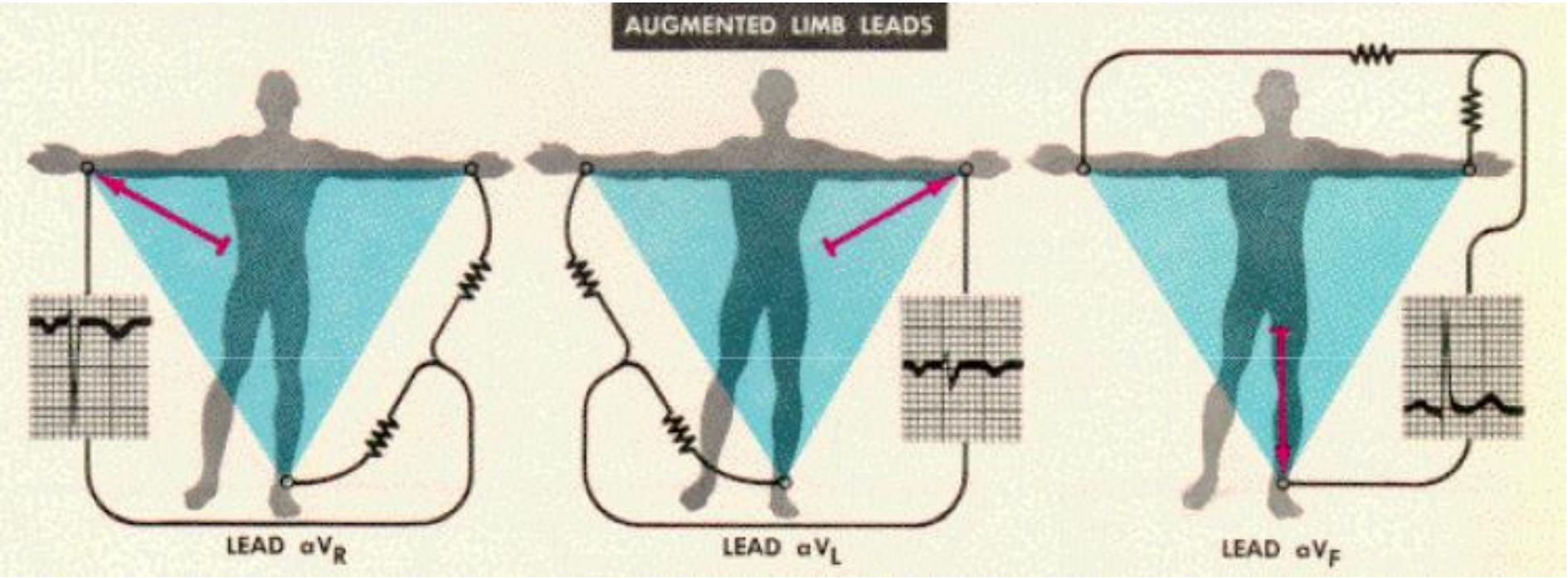
The Electrocardiogram (ECG)

The standard Bipolar Limb Lead III

- Lead III is the last of the three standard limb leads.
- The negative electrode is connected to the LEFT ARM (LA).
- The positive electrode is connected to the LEFT LEG (LL).
- The axis is 120^{o} degrees.

The Electrocardiogram (ECG)

The Augmented (Unipolar) Limb Leads



The Electrocardiogram (ECG)

The Augmented (Unipolar) Limb Leads

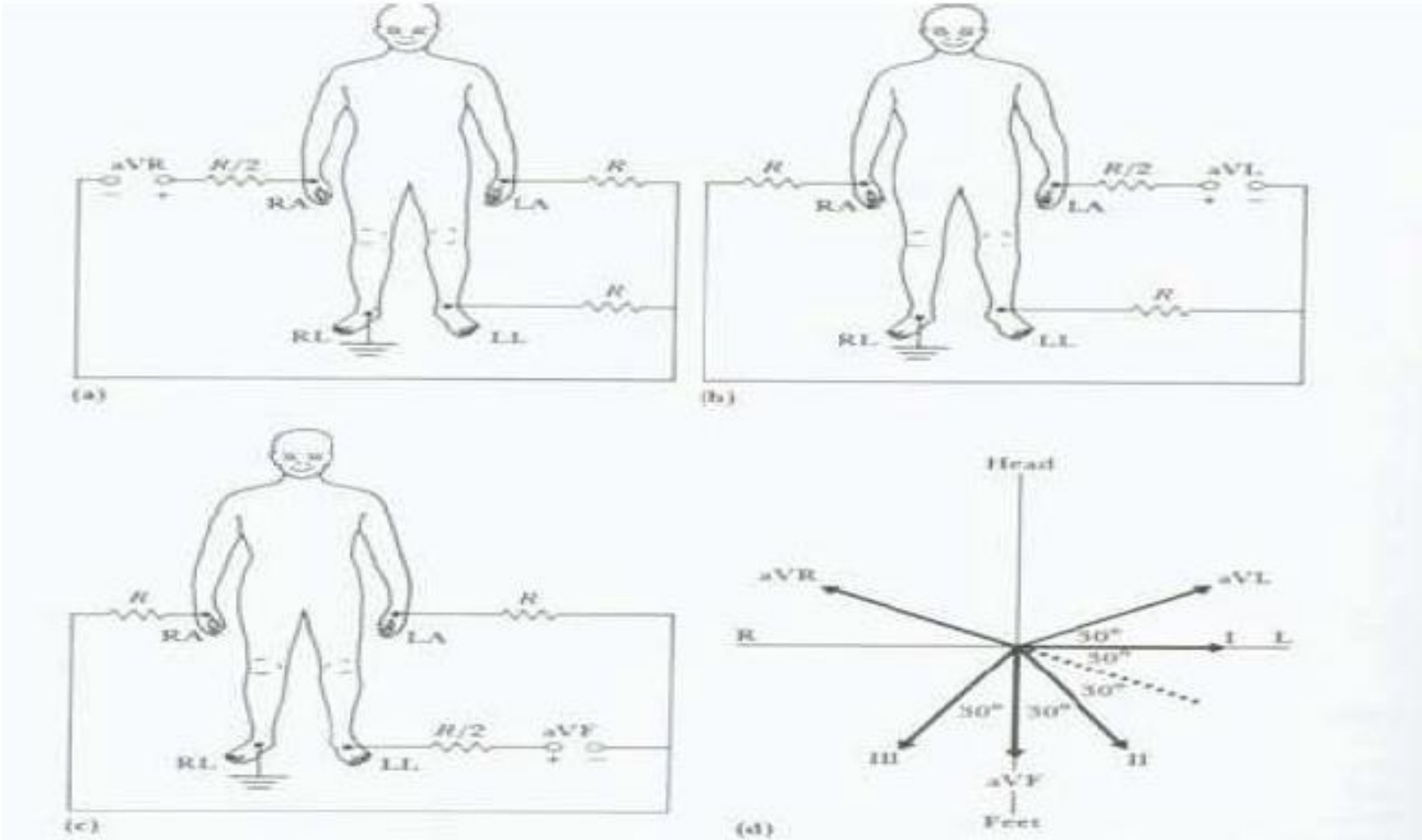
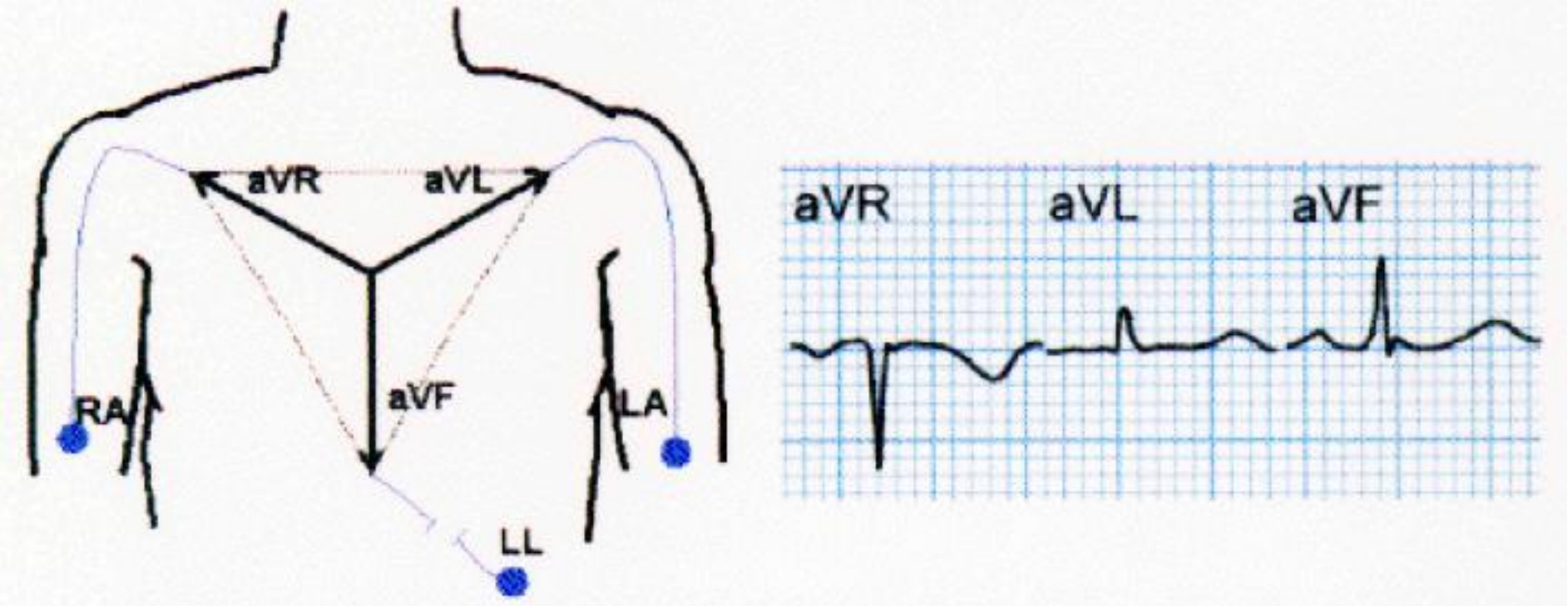


Figure 6.5 (a), (b), (c) Connections of electrodes for the three augmented limb leads. (d) Vector diagram showing standard and augmented lead-vector directions in the frontal plane.

The Electrocardiogram (ECG)

The Augmented (Unipolar) Limb Leads



The Electrocardiogram (ECG)

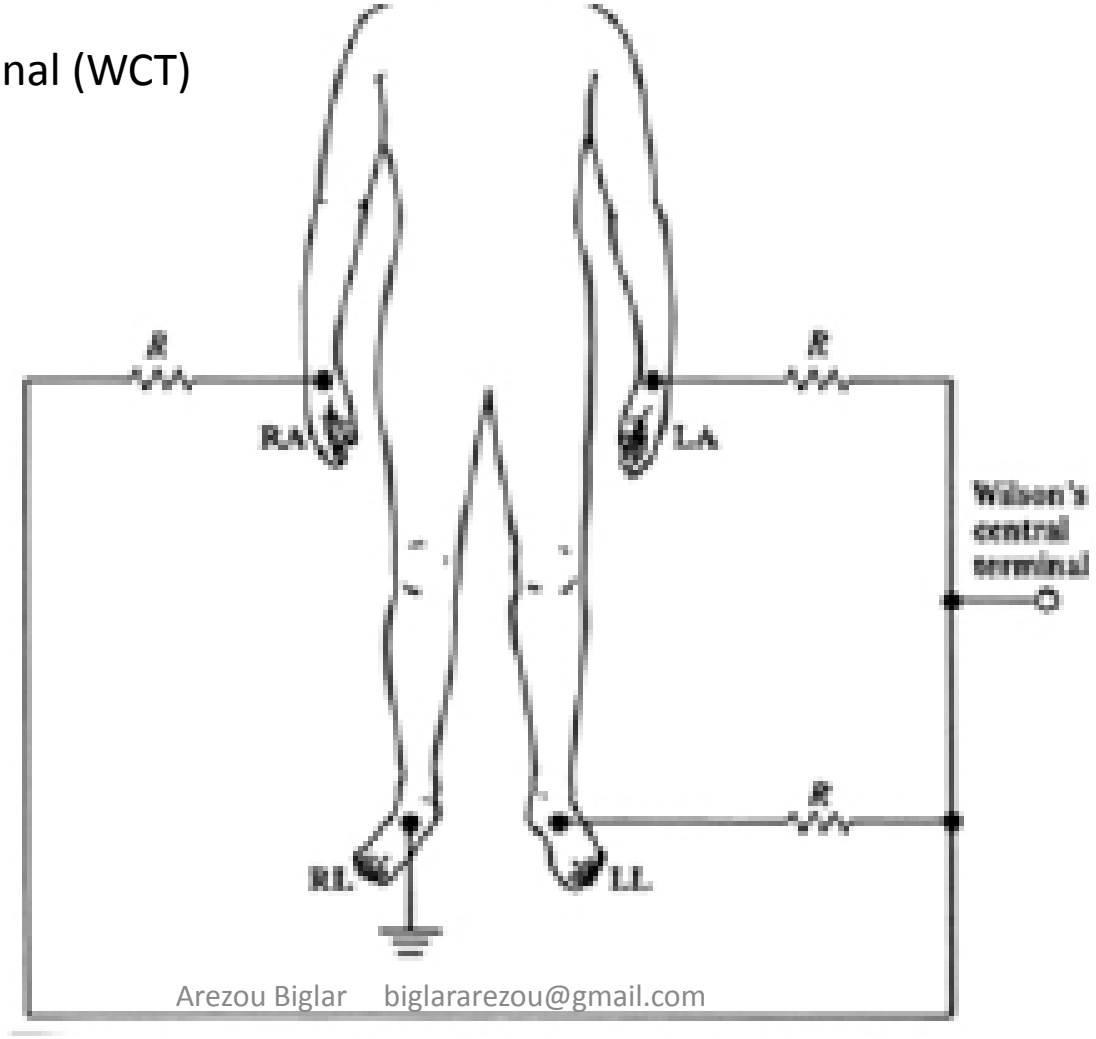
The Augmented (Unipolar) Limb Leads

- Three additional leads are used for frontal plane measurements.
- These are the measurements at the specific electrodes, with respect to a reference electrode.
- One commonly used reference electrode is the Wilson Central Terminal (WCT), obtained through a resistive network, combining limb electrodes.
- The new set of leads obtained by combining the standard limb electrodes to the Wilson terminal form the augmented leads.
- These leads provide additional vector views of cardiac depolarization in the frontal plane.
- Unlike leads I, II, III, the augmented leads utilize WCT, a central negative terminal.
- This virtual "electrode" is calculated by the EKG computer to measure vectors originating roughly at the center of the heart.
- Note that the voltage at Wilson’s terminal is zero.

The Electrocardiogram (ECG)

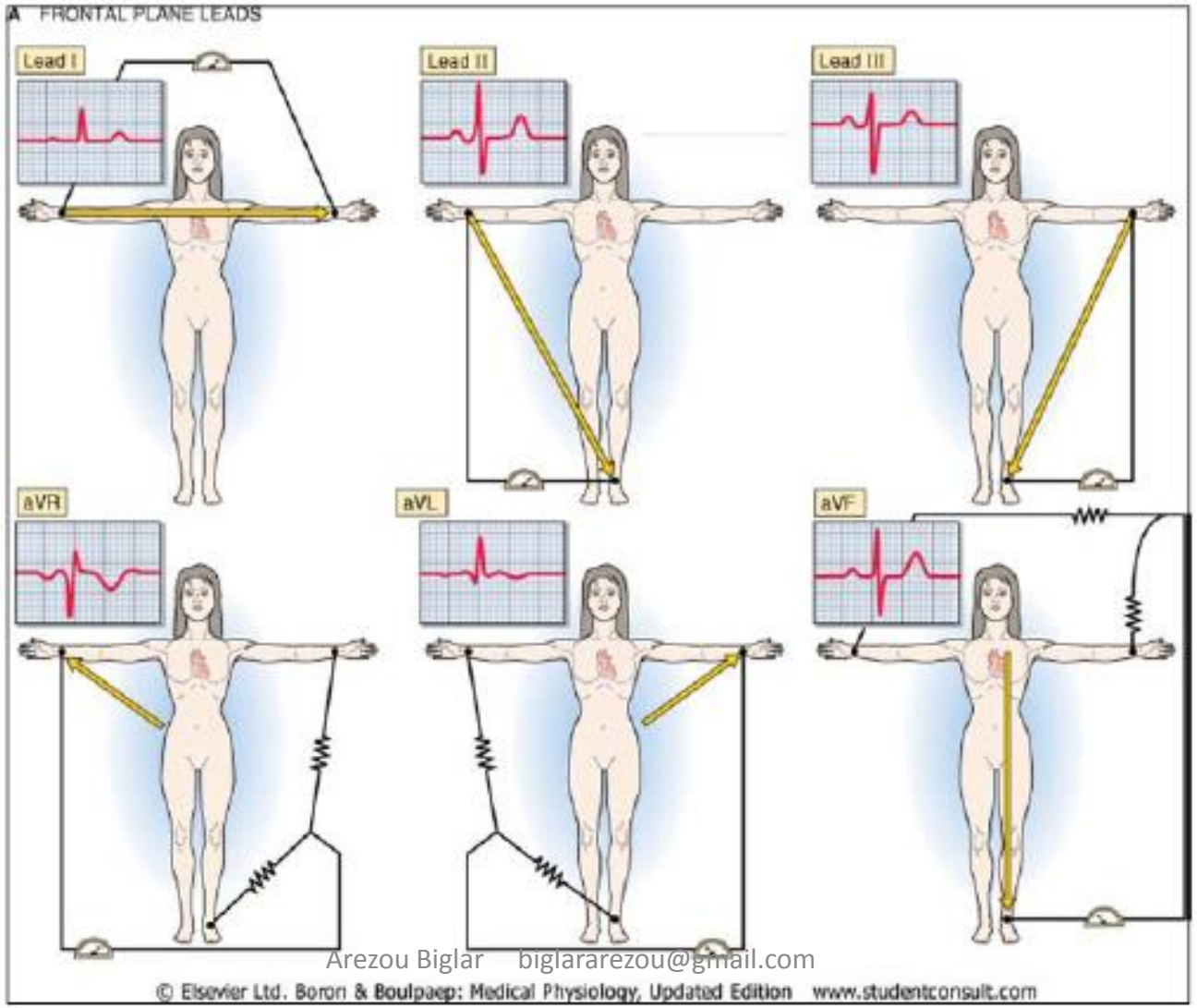
The Augmented (Unipolar) Limb Leads

Wilson Central Terminal (WCT)



The Electrocardiogram (ECG)

The Augmented (Unipolar) Limb Leads



The Electrocardiogram (ECG)

The Augmented (Unipolar) Limb Leads

The 3 augmented leads (aVR, aVL, aVF) compare one limb electrode to the average of the other two electrodes.

The Electrocardiogram (ECG)

The Augmented (Unipolar) Limb Leads

- Augmented Lead (RIGHT) **avR.**
- The negative electrode is the central terminal.
- The positive electrode is connected to the RIGHT ARM (RA).
- The axis is -150^{o} degrees.

The Electrocardiogram (ECG)

The Augmented (Unipolar) Limb Leads

- Augmented Lead (LEFT) **avL.**
- The negative electrode is the central terminal.
- The positive electrode is connected to the LEFT ARM (LA).
- The axis is -30^{o} degrees.

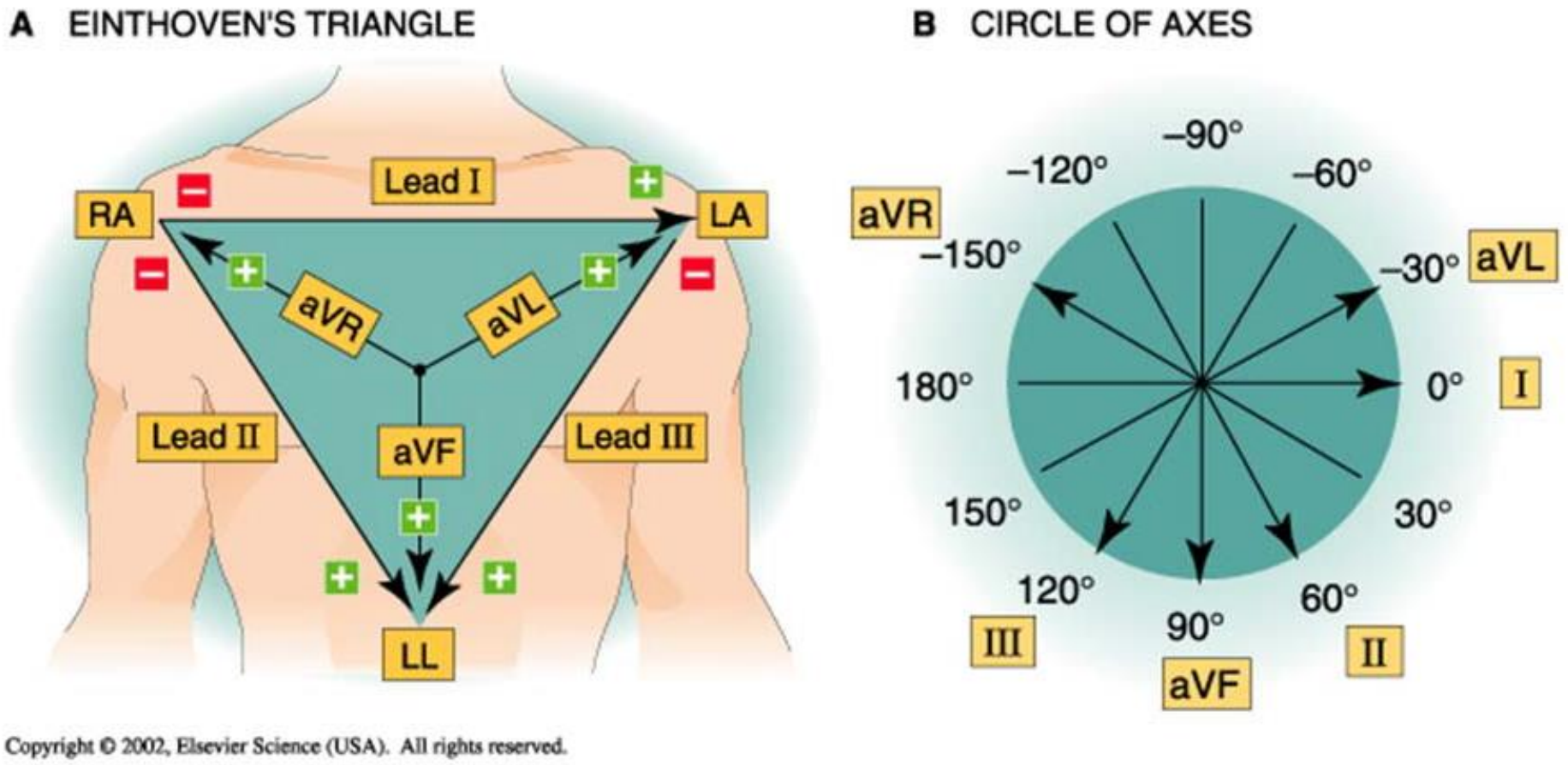
The Electrocardiogram (ECG)

The Augmented (Unipolar) Limb Leads

- Augmented Lead (FEET) **avF.**
- The negative electrode is the central terminal.
- The positive electrode is connected to the LEFT LEG (LL).
- The axis is +90^{o} degrees.

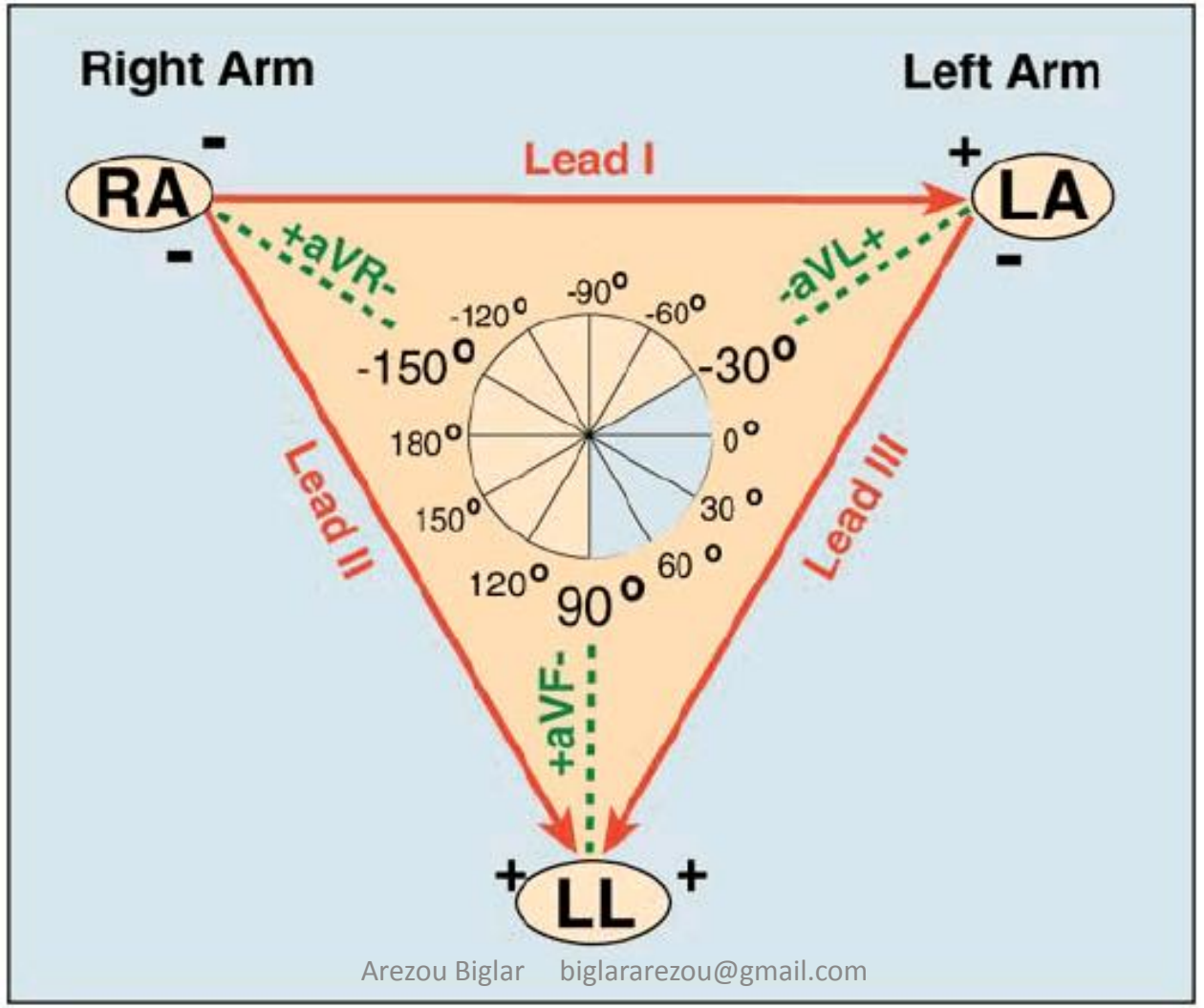
The Electrocardiogram (ECG)

The Einthoven Triangle



The Electrocardiogram (ECG)

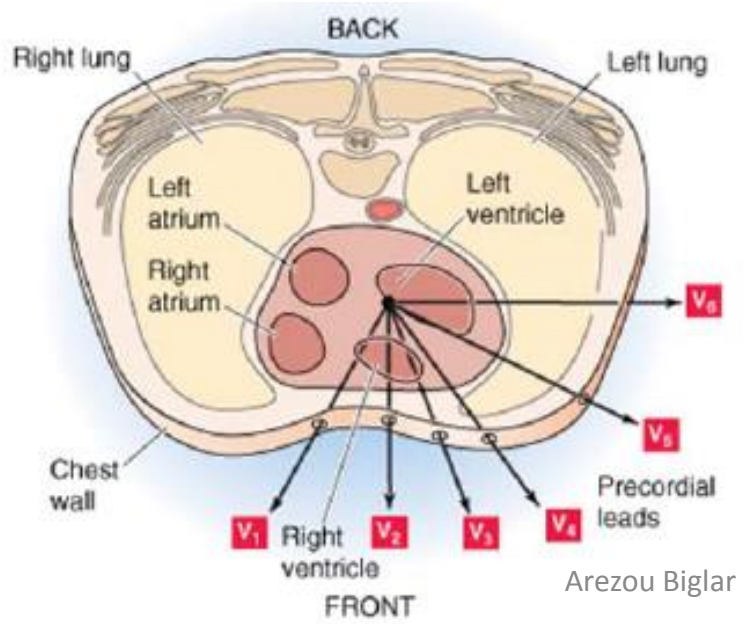
The Einthoven Triangle

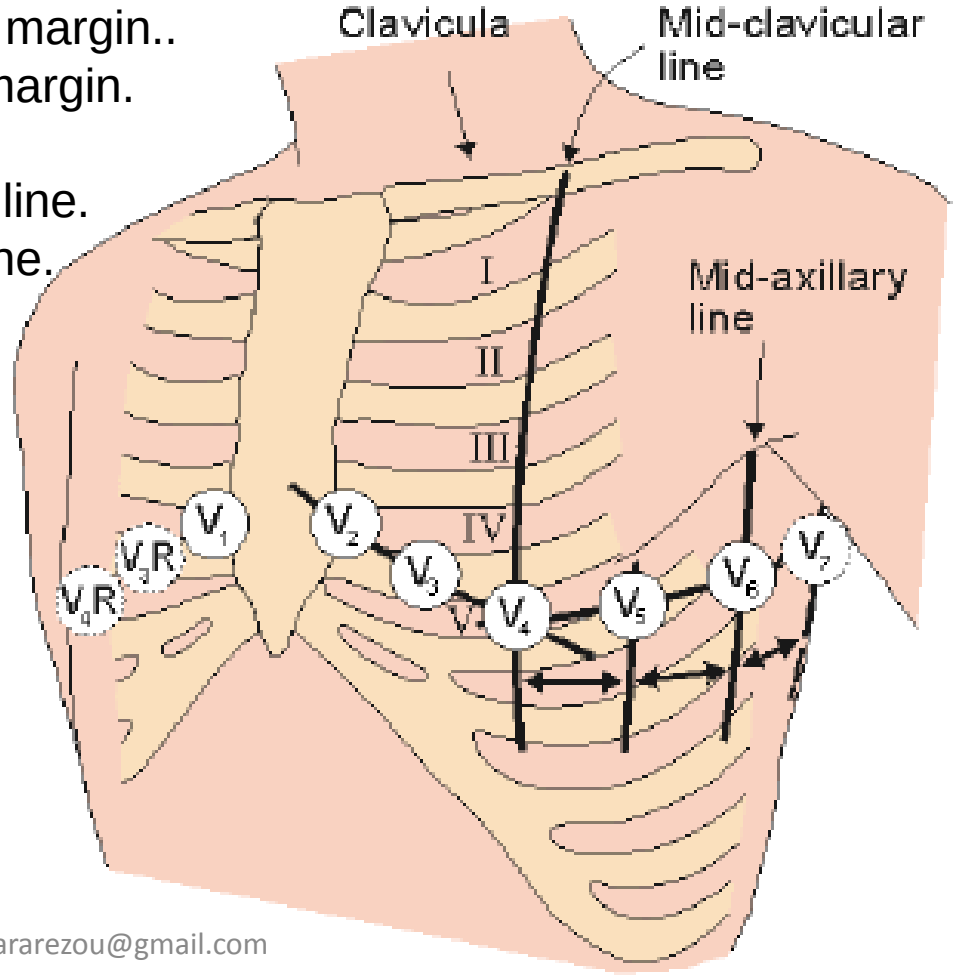


The Electrocardiogram (ECG)

The Precordial Unipolar Chest Leads

V1: Fourth intercostal space at right sternal margin..
V2: Fourth intercostal space at left sternal margin.
V3: Midway between V2 and V4.
V4: Fifth intercostal space at mid-clavicular line.
V5: Same level as V4, on anterior axillary line.
V6: Same level as V4, on mid axillary line.





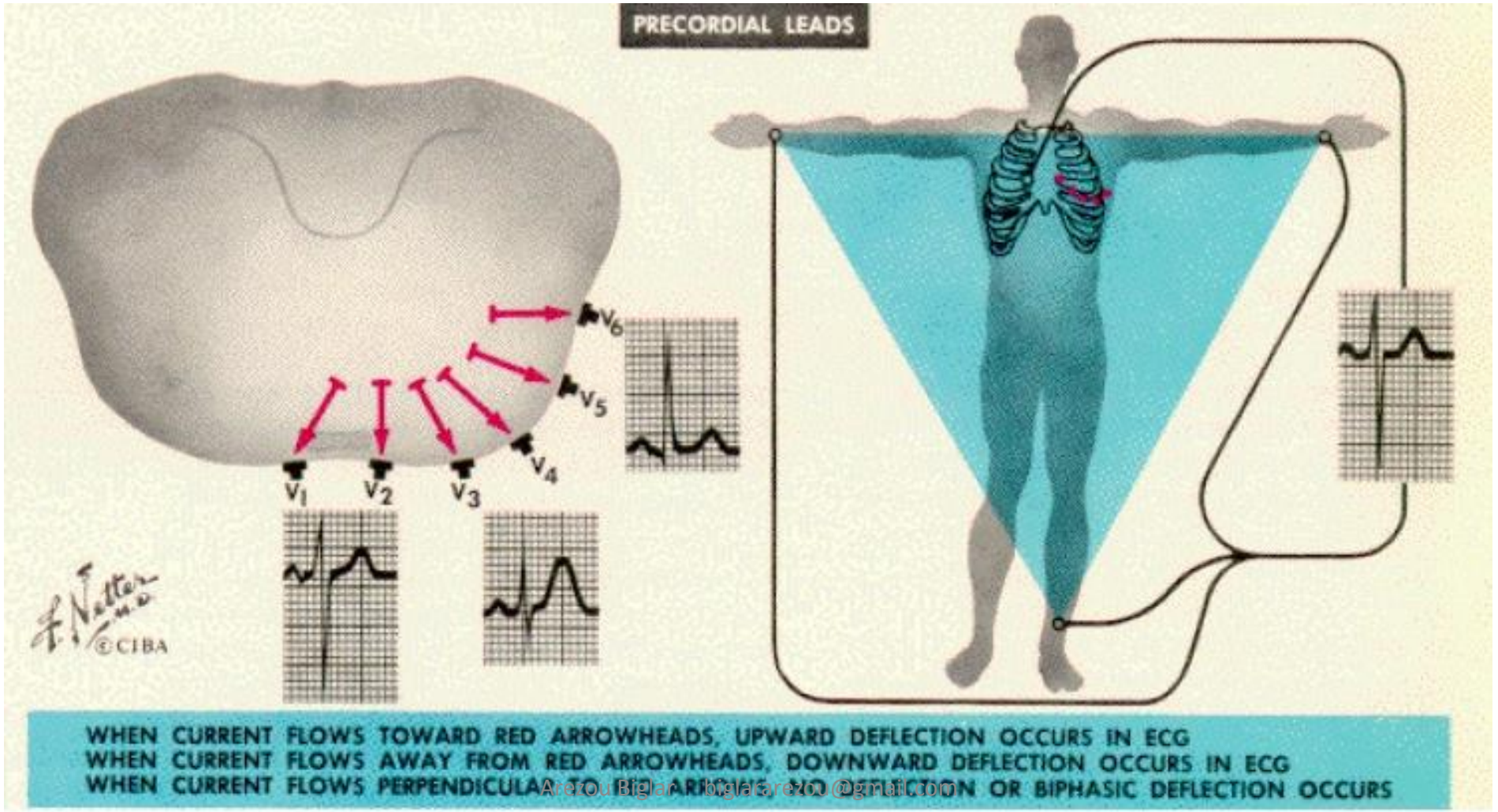
The Electrocardiogram (ECG)

The Precordial Unipolar Chest Leads

- Additional set of six leads, placed on the chest, also known as the **precordial leads**.
- These too are unipolar, that is they measure the potential with respect to Wilson Central Terminal (WCT).
- The main reason for recording all 12 leads is that it enhances pattern recognition.
- This combination of leads gives the clinician an opportunity to compare the projections of the resultant vectors in two orthogonal planes and at different angles.

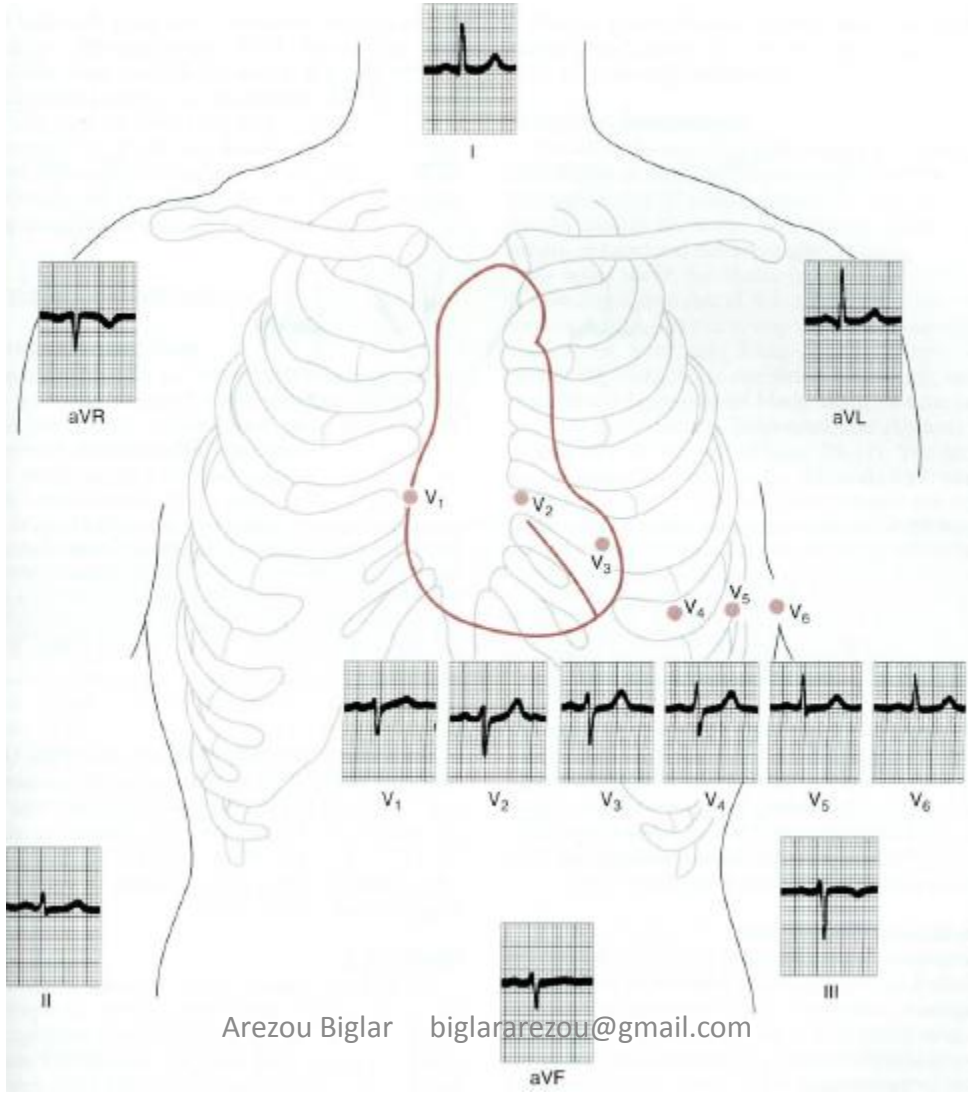
The Electrocardiogram (ECG)

The Precordial Unipolar Chest Leads



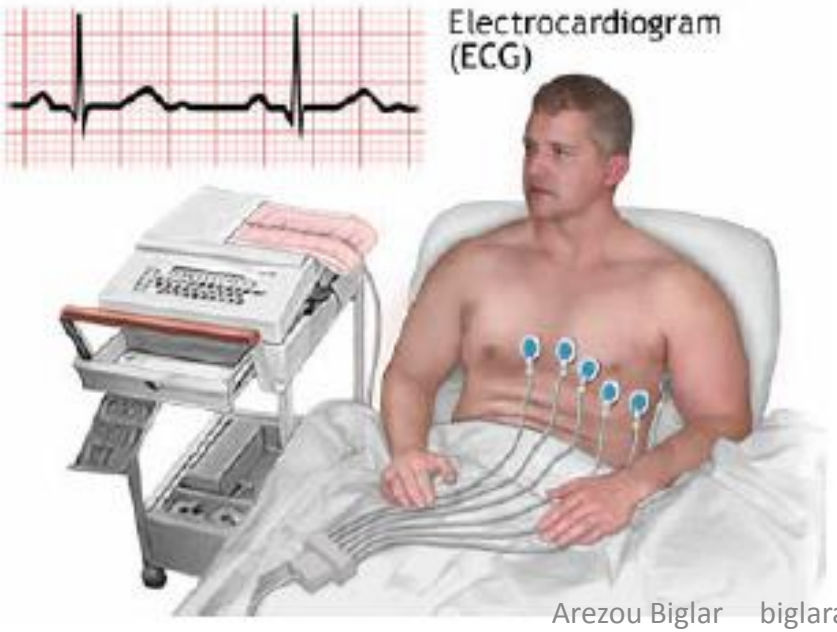
The Electrocardiogram (ECG)

The Precordial Unipolar Chest Leads



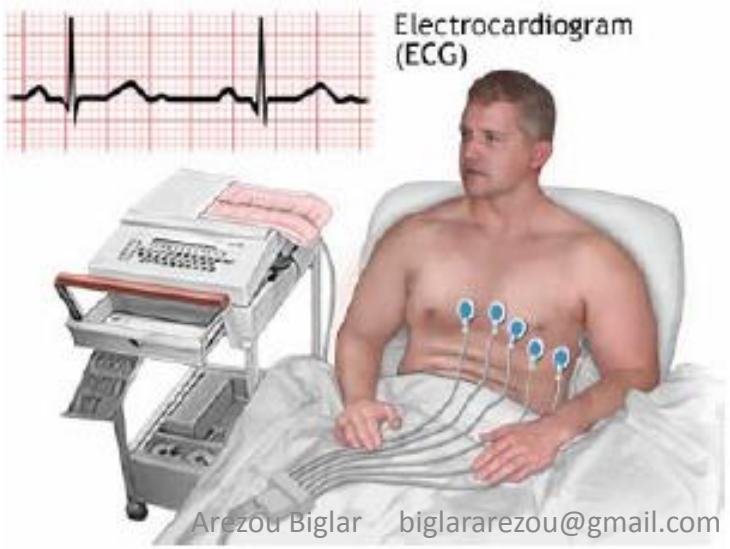
Electrocardiography

Electrocardiography (abb. ECG or EKG)- a standard noninvasive procedure for recording electrical potentials of the heart. The record (electrocardiogram), consists of waves that relate to the electrical activity of the heart during each beat. Results - printed on paper or displayed on monitor.



Electrocardiography

Old & Modern ECG System



Electrocardiography

Types of ECG Recorders

1. Single Channel ECG Recorder.

2. Three Channel ECG Recorder.

3. Vector Electrocardiograph.

4. Electrocardiograph System for Stress Testing.

5. Electrocardiograph System for Computer Processing.

6. Continuous ECG recorder (Holter Recorder).

The Electrocardiogram (ECG)

Cardiac Rhythms - Normal & Abnormal

Normal

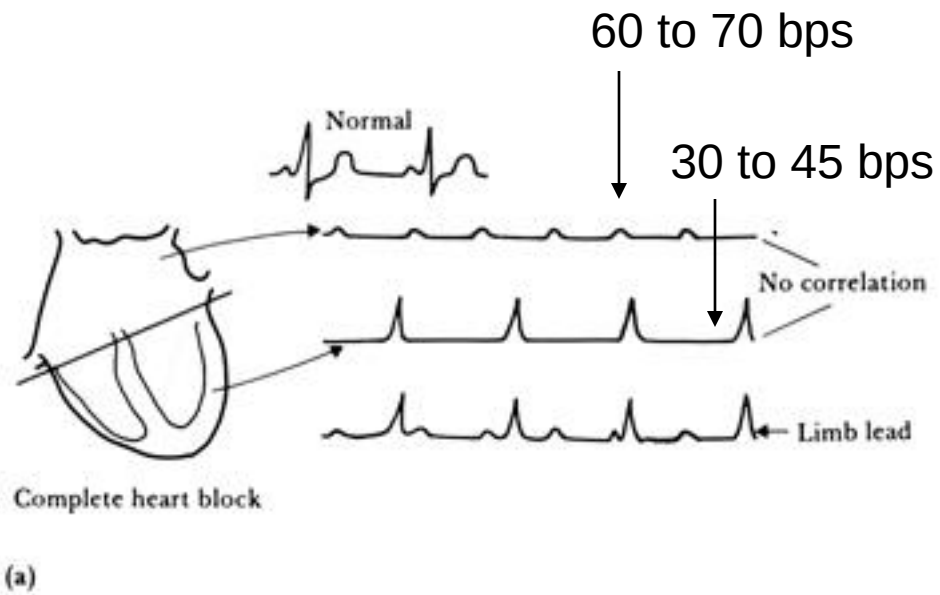
- Heart rate is about 70 beats per minute (bpm)
- Bradycardia: slower that normal (during sleep)
- Tachycardia: higher than normal (during exercise, emotional episodes, fever, fright)

Abnormal

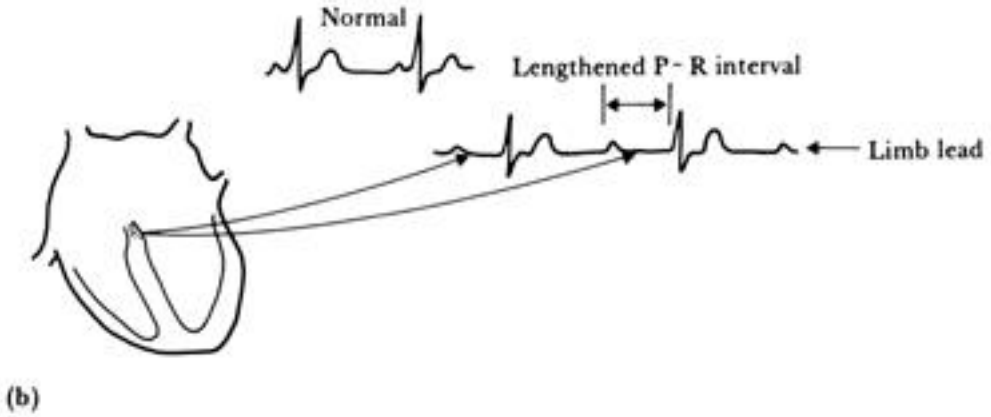
- Idioventricular heart rate is about 30 - 45 bpm (ventricles and atria beat independly)
- Disease can alter the conducting pathways (e.g., rheumatic heart disease and viral infections)
- Infarction (loss of blood supply and muscle death) can alter the heart muscle conducting pattern

Heart Block (dysfunctional His Bundle)

(a) Complete heart block.
Cells in the AV node are dead and activity cannot pass from atria to ventricles. Atria and ventricles beat independently, ventricles being driven by an ectopic (other-than-normal) pacemaker.



(b) First-degree heart block.
AV block wherein the node is diseased (examples include rheumatic heart disease and viral infections of the heart). Although each wave from the atria reaches the ventricles, the AV nodal delay is greatly increased.



Cardiac Arrhythmias

A portion of the myocardium sometimes becomes “irritable” and discharge independently.

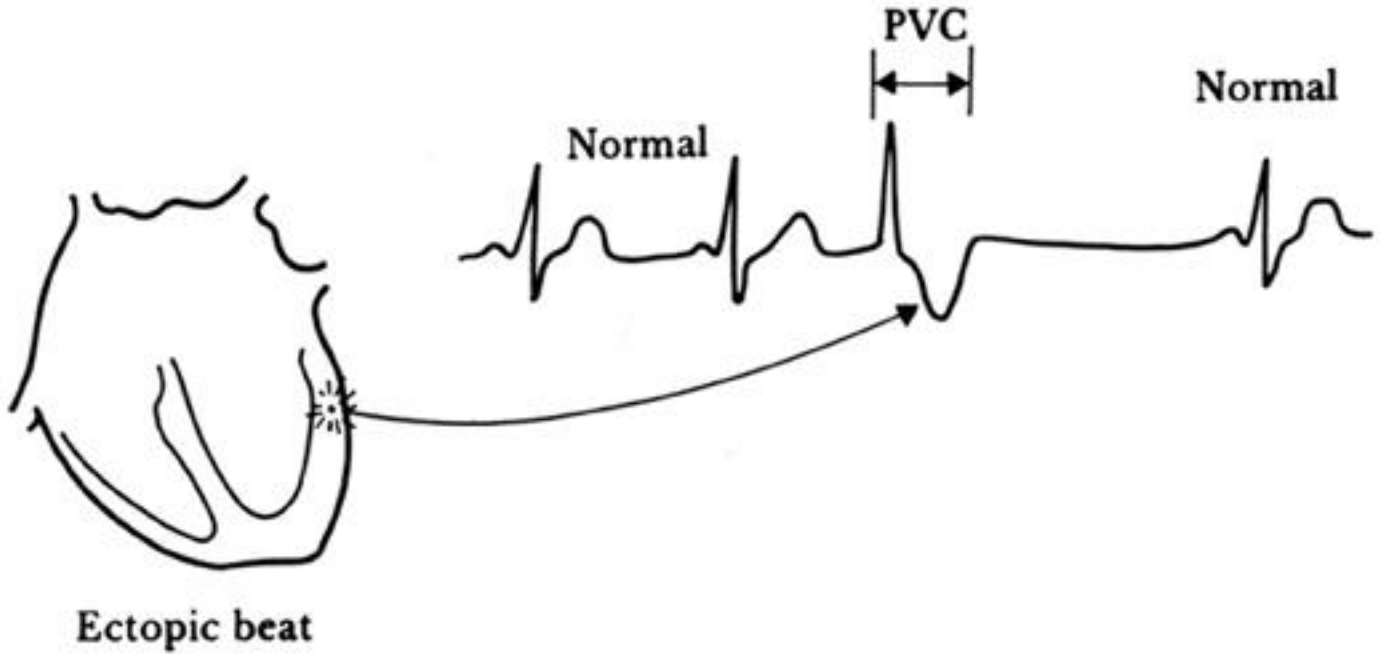


Figure 4.18 Normal ECG followed by an ectopic beat An irritable focus, or *ectopic pacemaker*, within the ventricle or specialized conduction system may discharge, producing an extra beat, or *extrasystole*, that interrupts the normal rhythm. This extrasystole is also referred to as a premature ventricular contraction (PVC).

Cardiac Arrhythmias

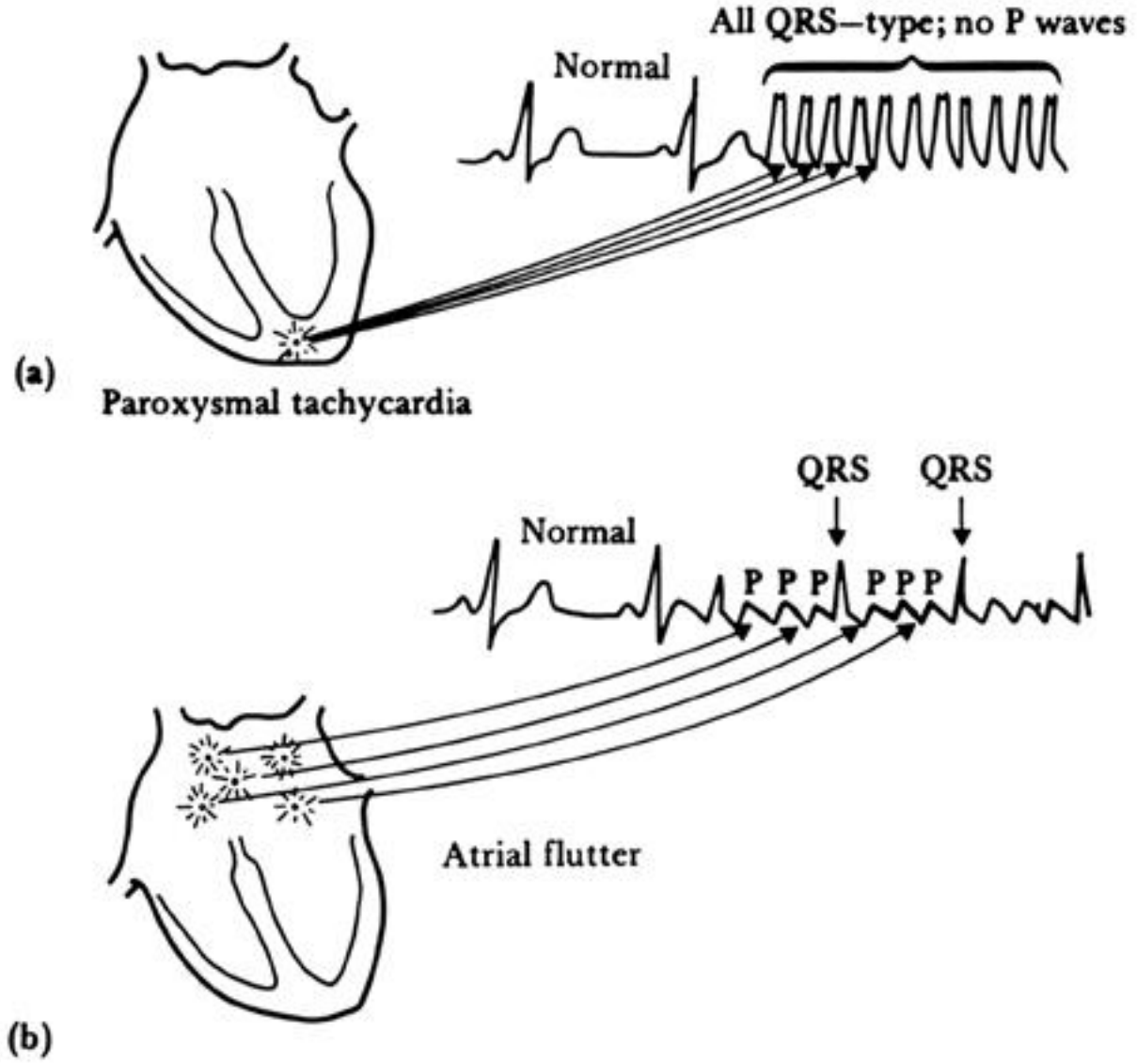


Figure 4.19 (a) Paroxysmal tachycardia. An ectopic focus may repetitively discharge at a rapid regular rate for minutes, hours, or even days. (B) Atrial flutter. The atria begin a very rapid, perfectly regular "flapping" movement, beating at rates of 200 to 300 beats/min.

Cardiac Arrhythmias

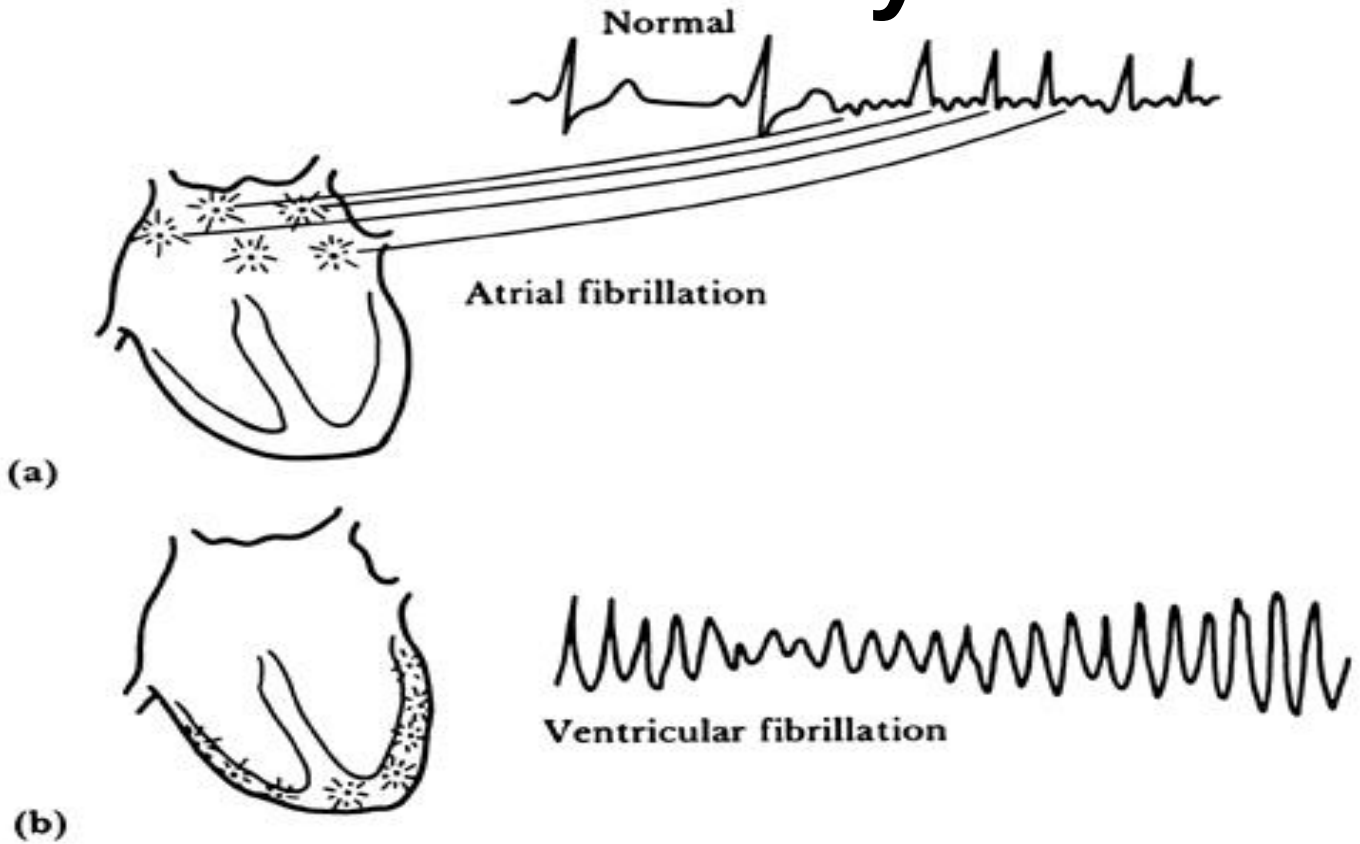


Figure 4.20 (a) Atrial fibrillation. The atria stop their regular beat and begin a feeble, uncoordinated twitching. Concomitantly, low-amplitude, irregular waves appear in the ECG, as shown. This type of recording can be clearly distinguished from the very regular ECG waveform containing atrial flutter. (b) Ventricular fibrillation. Mechanically the ventricles twitch in a feeble, uncoordinated fashion with no blood being pumped from the heart. The ECG is likewise very uncoordinated, as shown

Alteration of Potential Waveforms in Ischemia

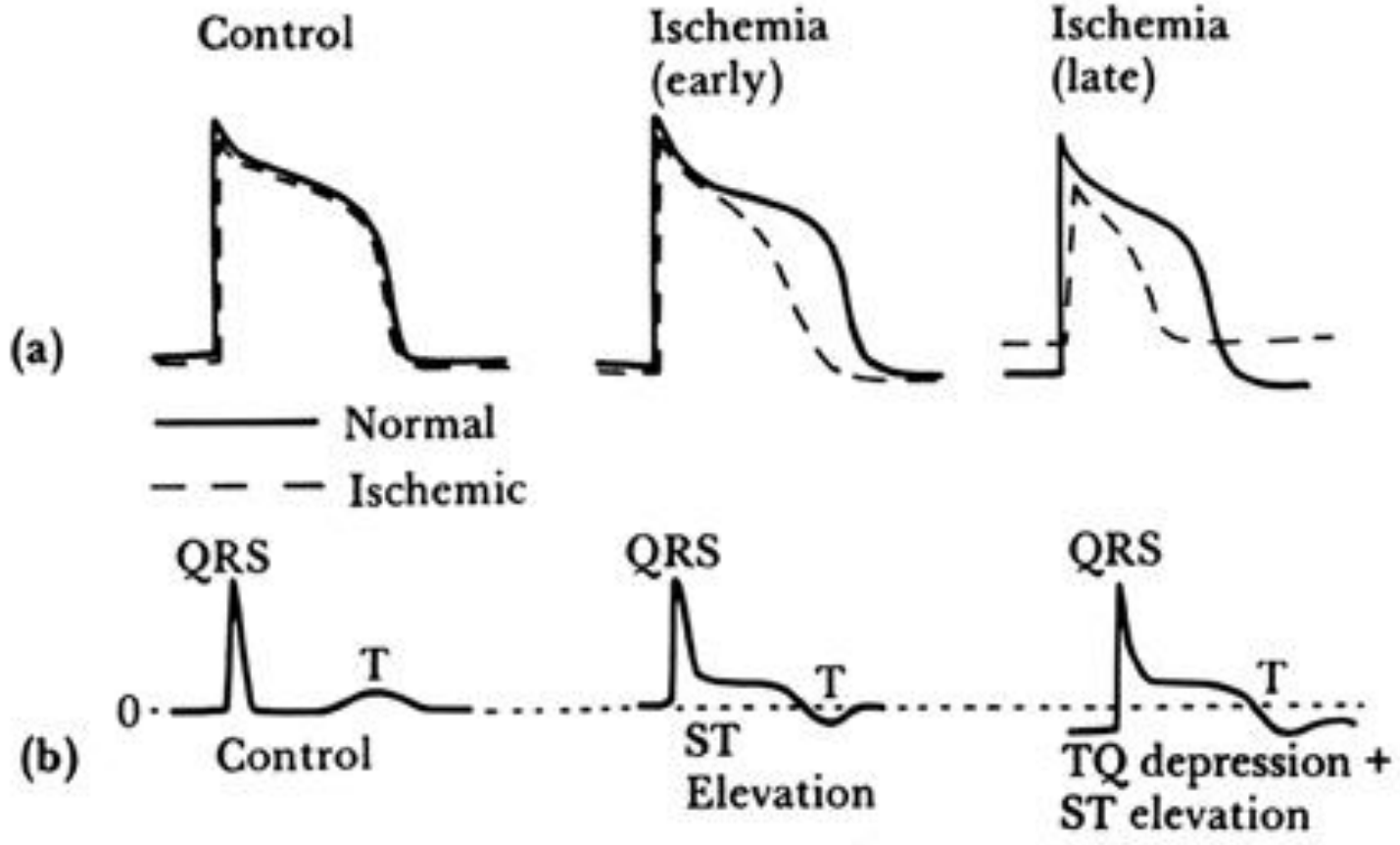
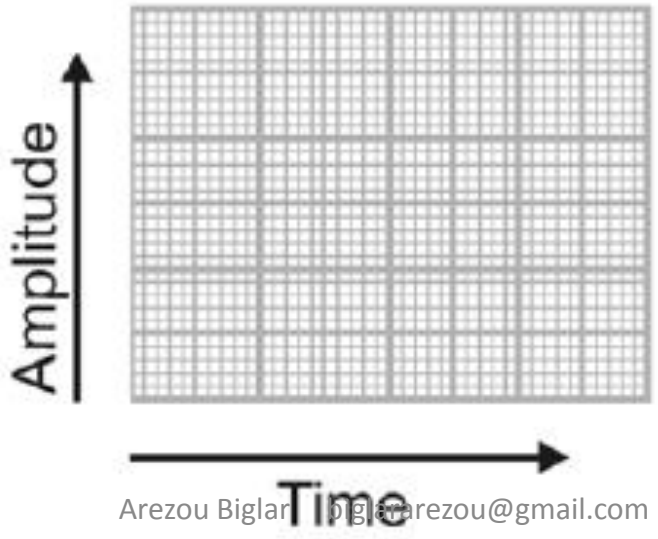


Figure 4.21 (a) Action potentials recorded from normal (solid lines) and ischemic (dashed lines) myocardium in a dog. Control is before coronary occlusion. (b) During the control period prior to coronary occlusion, there is no ECG S-T segment shift; after ischemia, there is such a shift.

Electrocardiograph

- ECG machines can run at 50 or 25 mm/sec.
- Major grid lines are 5 mm apart, at standard 25 mm/s, 5 mm corresponds to .20 seconds.
- Minor lines are 1 mm apart, at standard 25 mm/s, 1 mm corresponds to .04 seconds.
- Voltage is measured on vertical axis.
- Standard calibration is 0.1 mV per mm of deflection.
- When myocardial muscle is completely polarized or depolarized, the ECG will not record any electrical potential but rather a flat line, isoelectric line.



Electrocardiograph

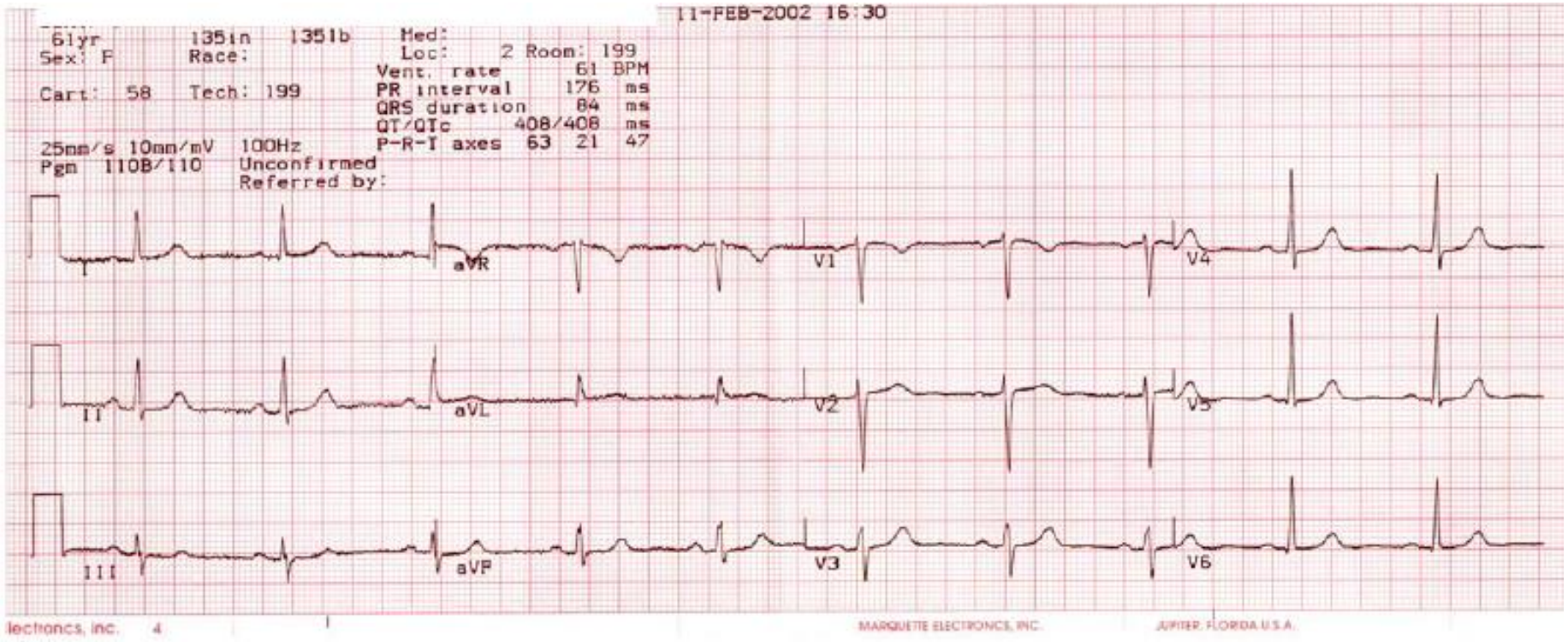
ECG Signals have two components:

1. ECG Waveform
   - 0.05 Hz to 150 Hz bandwidth per Medical Standards
   - Average R Wave Amplitude is 1.8 mV
   - Some waveforms can be as big as 10 mV p-p.
   - T wave is only a few micro volts in amplitude

2. Pacing Artifact
   - Medical Standards require 2 mV and 200 µs detection
   - Average pulse is 1 mV and 500 µs but can be much smaller

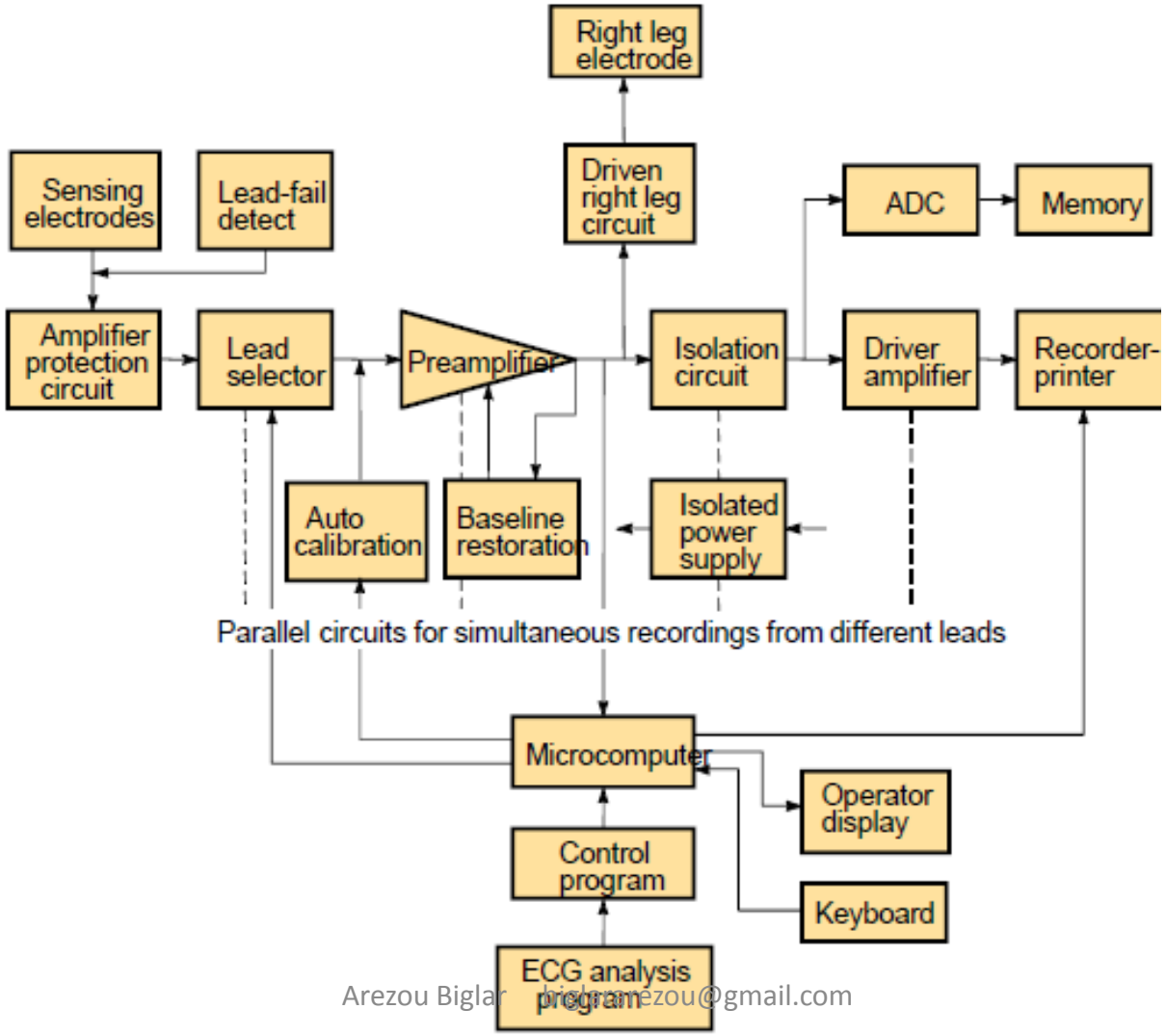
Electrocardiograph

Typical ECG waveforms



Electrocardiograph

Block Diagram of ECG System



Electrocardiograph

Frequent Problems in ECG System

Frequency distortion

- High-frequency loss rounds the sharp edges of the QRS complex.
- Low-frequency loss can distort the baseline (no longer horizontal) or cause monophasic waveforms to appear biphasic.

Saturation/cutoff distortion

- Combination of input amplitude & offset voltage drives amplifier into saturation
- Positive case: clips off the top of the R wave
- Negative case: clips off the Q, S, P and T waves

Electrocardiograph

Frequent Problems in ECG System

Ground loops

- Patients are connected to multiple pieces of equipment; each has a ground (power line or common room ground wire).
- If more than one instrument has a ground electrode connected to the patient, a ground loop exists. Power line ground can be different for each item of equipment, sending current through the patient and introducing common-mode noise.

Open lead wires

- Can be detected by impedance monitoring.

Electrocardiograph

ECG Artefacts

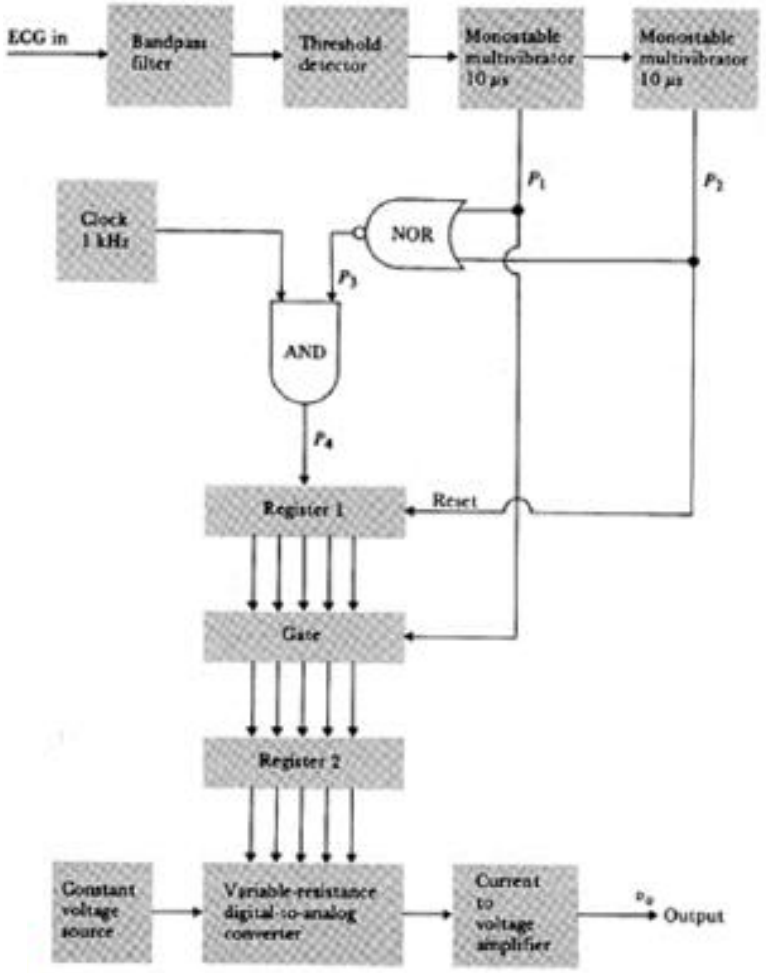
Coupling of 50 Hz Power Line Noise

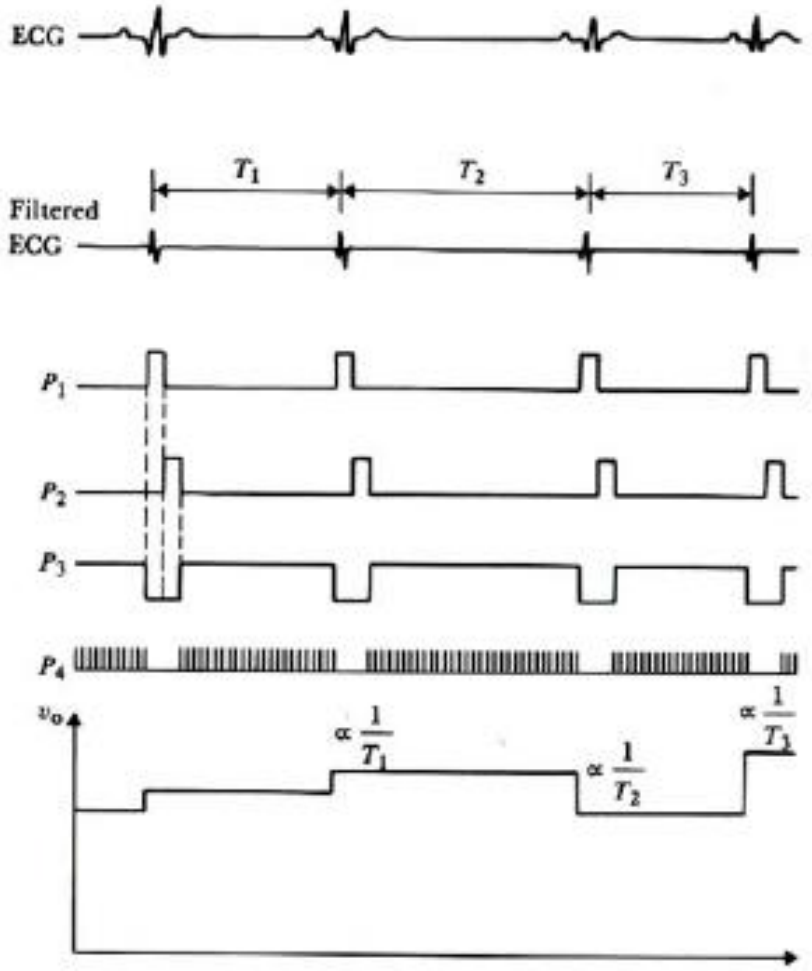
Electrocardiograph

ECG Artefacts

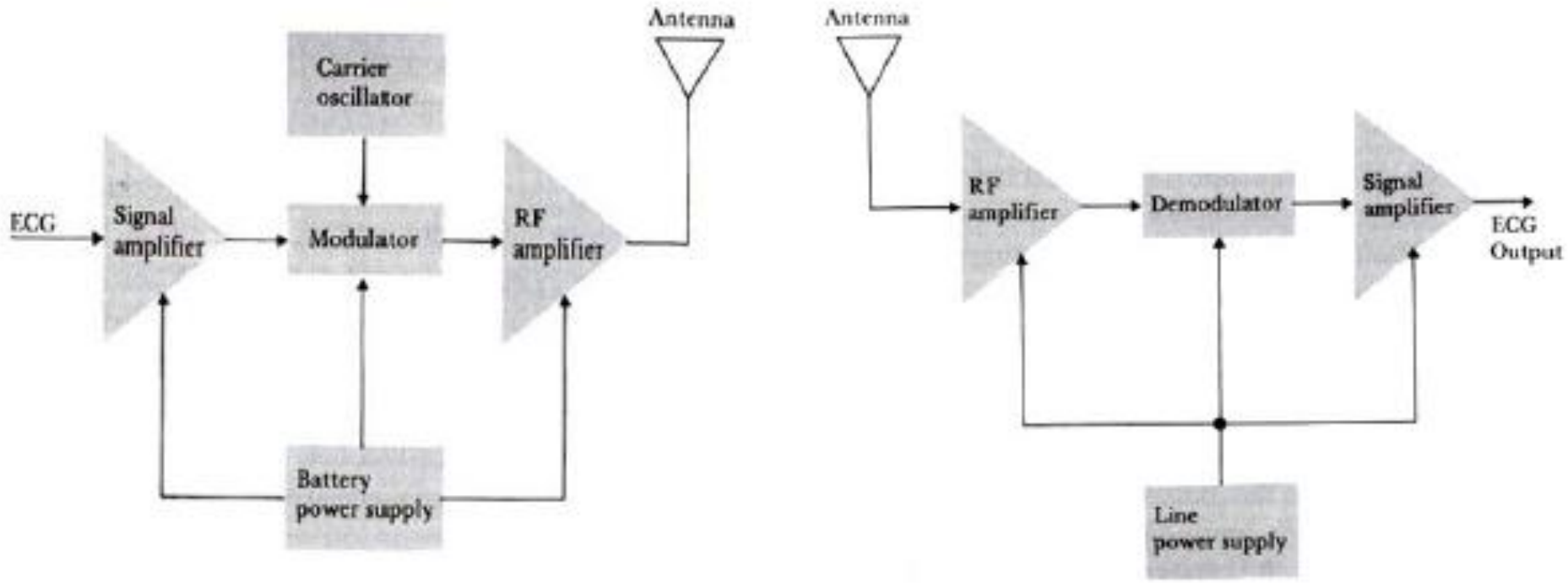
Coupling of Electromyogram (EMG) Noise

Cardio Tachometer





ECG Telemetry System



Biomedical Instrumentation I

Lecture-3: Biomedical Instrumentation

ULTRASONOGRAPHY

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Basic Principles of Ultrasound

- Ultrasonic waves in the frequency range of 1 million to 10 million Hz are used in diagnostic ultrasonography.
  - The lower the frequency, the deeper the penetration and the higher the frequency, the more superficial the penetration.

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- The ultrasonic waves are transmitted into a medium in the form of a narrow beam.
  - Depending on the density of the medium, the sound waves are either
    - refracted,
    - absorbed or
    - reflected,

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Basic Instrumentation

- The sound waves are produced by electrically-stimulating crystals which are arranged within an instrument called a transducer.
  - There are various types of transducers in which the crystals are arranged differently so that when the crystals are stimulated they are “fired” at different frequencies for optimum penetration.

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- When the crystals are “fired”, a signal is sent out which strikes the tissues in the body.
  - Some of the waves are absorbed into the tissue,
  - some are bent or refracted and become scatter, and
  - some are reflected.
    - The reflected waves are sent back to the transducer as echoes.
    - The echoes are converted into electrical impulses and displayed on a computerized screen.
    - This becomes an image of the specific body area.

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- The sound waves can not travel into the body without a waterbased medium.
  - Ultrasound will not produce an image when traveling through air.
    - For this reason, a substance called acoustic coupling gel must be placed on the skin over the area to be imaged.
    - The gel blocks out air so the sound beam can penetrate the body.
      - The transducer is placed directly into the gel.

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Usefulness of Ultrasound

- In clinical practice today, ultrasonography may be divided into separate subgroups.
  - Each group consists of a special area of ultrasound.
  - These groups may be
    - general ultrasonography,
    - echocardiography and
    - vascular technology.

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General Ultrasonography

- Four specific areas:
  1. Abdomen (AB),
  2. Neurosonography (NS),
  3. Obstetrics/Gynecology (OB/GYN),
  4. Ophthalmology (OP).

- Examinations in this area may include
  - organs and tissue in the abdomen and pelvis for location of tumors and abnormalities,
  - obstetric exams, including fetal growth parameters and anomalies, as well as breast tissue exams for location of tumors.
  - In addition, ultrasound guided invasive procedures are performed to remove body fluids and tissue for analysis.

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Echocardiography

- Ultrasound is used in this area to image
  - the chambers of the heart,
  - the heart valves and
  - the function of the heart,
  - as well as location of pathology.

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- Ultrasonic equipment serves a variety of functions in medicine.
  - It is used for imaging internal organs noninvasively.
  - It is used to apply massage and deep-heat therapy to muscle tissue.
  - And it is used to measure blood flow and blood pressure noninvasively.

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- The principle of imaging, or making pictures of internal organs, is that of ultrasonic wave reflection.
  - Ultrasonic waves reflect from the boundaries of two tissues.
  - Because the amount of reflection differs in different tissues, it is possible to distinguish between materials and make images of them using ultrasonics.

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- The quality that makes ultrasonic waves therapeutic is that they cause tissue matter to vibrate and heat up.
  - It is the heat that has therapeutic effects.

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- Blood pressure and blood flow are measured by application of the Doppler effect.
  - This effect is the increase in frequency of a sound reflected by a body approaching the source of the sound.
    - To observe this effect, sing a steady tone, then move your hand rapidly toward your mouth.
    - You will hear the increase in the pitch due to the motion of your hand.

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Piezoelectric Transducers

- The piezoelectric crystal used for ultrasound occurs naturally as quartz.
  - Practical transducers are constructed of ammonium dihydrogen phosphate (ADP) or lead zirconate titanate (PZT).
    - ADP dissolves in water, but it can be used in high-power applications.
    - PZT is a commonly used transducer made from ceramic.

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- The crystal is cut to one half wavelength, $\lambda/2$, at the frequency of the ultrasonic signal.
  - This causes it to resonate at that frequency and give its maximum power output.

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- In order to get the electric field throughout the crystal, the two ends perpendicular to the half wavelength axis are metalized.
  - This forms a parallel plate capacitor.
- These are wired to the voltage generator, and the structure is covered with electrical insulation.

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- In order to direct the energy out of one surface of the crystal, a backing material is applied to the surface opposite the tissue.
  - This reflects ultrasonics; therefore, waves travel out of only one surface of the transducer.

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Ultrasonic Imaging Equipment

- The voltage generator in ultrasonic imaging devices hits the piezoelectric transducer with a short pulse and causes it to oscillate at its resonant frequency.
  - It is also possible to use a pulse-modulated generator to drive the piezoelectric crystal.
    - The pulse generated would be long compared to the period of the 1 to 10 MHz ultrasonic oscillation.
    - It would be short compared to the acoustic transmission time in the tissue.
      - Sound velocity in the body averages about 1540 m/s.
      - Therefore, 1 mm in distance requires 0.65 μs on the average.

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- The pulse of ultrasonic energy travels into the tissue.
- It is reflected from tissue boundaries, causing echoes.
  - By the time the echoes reach the transducer, the pulse generator has turned off, and the echo creates an oscillation in the transducer again.
  - The echo is like that of a drum beat reverberating off a wall, except the drum operates at a lower, audible frequency.

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- The electronic signal from the transducer induced by the ultrasonic echo would go into the limiter.
  - The function of the limiter is to protect the receiver from the transmitted pulse.
  - The small echo, from 40 to 100 dB below the transmitted pulse, is passed by the limiter.
  - However, the transmitter pulse is severely clipped off to provide the protection.

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- The receiver is a conventional radio frequency (RF) unit operating in the 1 to 10 MHz range.
  - It contains a detector circuit that filters out the ultrasonic frequencies and delivers the pulse to the output.
  - The reflected pulse then appears on the display unit.

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The Display Unit

- A simple image display can be made from a conventional oscilloscope.
- This is called an A-mode display.
  - A trigger from the pulse generator initiates the horizontal sweep when the pulse is transmitted.
  - The beam then travels along the horizontal axis.
  - The horizontal scale is calibrated approximately according to the speed of sound in most body tissue.
  - Based on the 1540 m/s average speed, it takes 1 μs for ultrasound to pass through 1.54 mm of tissue one way.

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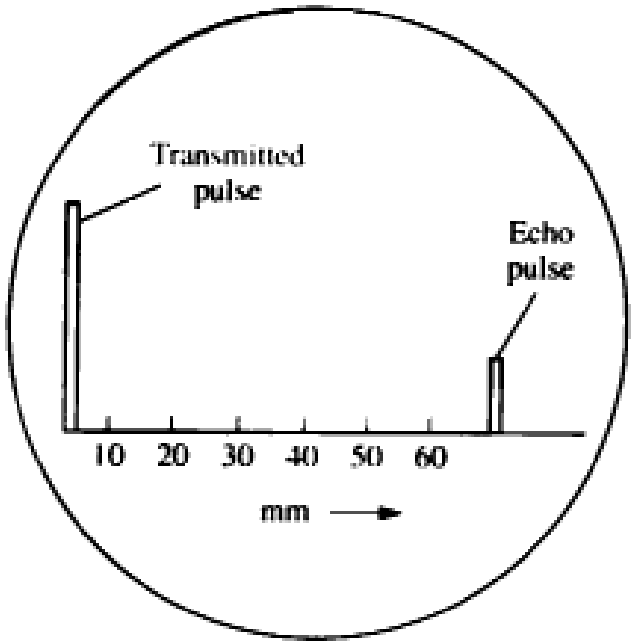
- On the A-scope it makes a round trip.
  - Therefore 1μs on the A-scope horizontal display is equivalent to 0.77 mm of tissue thickness.



1 μs = 0.77 mm tissue thickness, round trip

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- Controls at the receiver may be set so that the receiver gain increases in proportion to the distance along the sweep.
  - This tends to make the echoes equal in size and compensates for tissue attenuation of the ultrasound echo.

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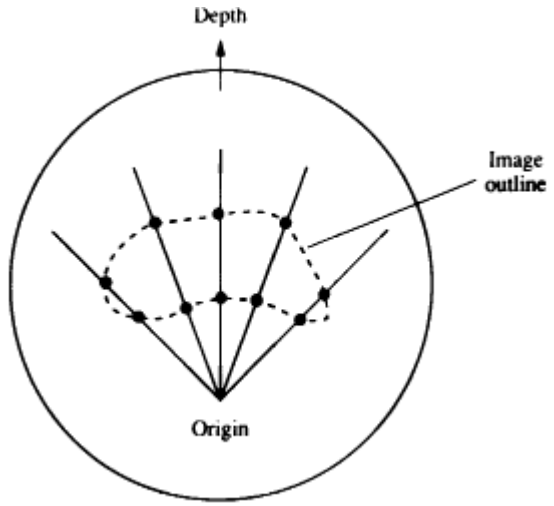
Scanning-Type Displays

- The A-mode display gives information about the distance between tissue boundaries.
  - For example, it may be used to measure organ thickness.
  - In order to add a dimension, and give breadth information, scanning-type displays are used.
- A *B-mode display* may be generated by pivoting the transducer on an axis, causing it to rotate through an arc.
  - The rotational speed, being mechanical, is slow compared with the time required for each sweep.

- The transmitted pulse appears at the origin.



- The depth is proportional to the distance along each radial line.
  - Ultrasonic echoes appear as an intensity-modulated dot.
    - The result is an outline of the body tissue in two dimensions.

- A B-mode display may also be generated with a phased array transducer.
  - A phased array transducer consists of a set of piezoelectric transducers placed along a line.
  - Each transducer is pulsed successively in time.
- Depending upon the time between the firing of each transducer, constructive interference of the transmitted wave will occur along a particular radial line. The direction of the radial line is varied by changing the firing time between successive transducers in the display.
- The phased array transducer can be scanned faster than the rotating transducer, because the control pulses are electronic and travel at the speed of light. In a practical application, a linear phased array may be useful for getting images of the heart from a site between the ribs, for example.

- Depending upon the time between the firing of each transducer, constructive interference of the transmitted wave will occur along a particular radial line.
  - The direction of the radial line is varied by changing the firing time between successive transducers in the display.
- The phased array transducer can be scanned faster than the rotating transducer, because the control pulses are electronic and travel at the speed of light.

- A single transducer is used to generate an *M-mode display,* where the M stands for motion, because it measures the motion of the tissue.
- As with the B-mode display, the intensity of the reflections from the tissue is recorded as an intensity of the spot on the CRT.
- The horizontal axis of the CRT is slowly scanned so that if the tissue is moving, as in the case of a heart valve, the new position will be recorded on successive scans.
  - From the scan rate, usually on the order of seconds per scan, it is possible to calculate the rate of motion of the tissue.

ULTRASONIC WAVES

- Ultrasonic equipment is used to generate and measure ultrasonic waves.
  - Ultrasonic waves are similar to the pressure and flow waves.
  - A pressure difference, p, across two points in matter, whether air, tissue, or metal, causes a displacement of the atoms, giving them a velocity, *v.*
  - The atoms do not move very far because they are bound by elastic forces.
  - However, the energy of one atom is transferred to other atoms, and it propagates through the matter at its own velocity, *c.*

- There exists an analogy of ultrasonic waves to voltage waves:
  - Ultrasonic pressure, p, is analogous to voltage, and the particle velocity, *v,* of ultrasonic waves is analogous to current.
  - The acoustic impedance is analogous to the impedance of an electrical circuit.

- An ultrasonic wave is a traveling pressure wave.
  - If you were to drop a rock into a smooth lake, waves would propagate out from the point of impact.
    - The force that causes the undulation of the water that we observe is a pressure wave.

- A mathematical expression that describes it is

$$p = P_o e^{-\alpha x} \cos(\beta x - \omega t)$$

  - p is pressure,
  - β is the phase constant,
  - x is position,
  - ω is the radian frequency,
  - t is time, and
  - α is an attenuation constant.
    - For clarity of presentation, and because it is not of primary importance in ultrasonic imaging, we will restrict ourselves to the case that $\alpha = 0$, the lossless case.

- Thus the description of the traveling wave is

  - where P_0 is the magnitude of the pressure wave.

$$p = P_o \cos(\beta x - \omega t)$$

EXAMPLE 16.1

- Plot the following pressure wave equation for the case

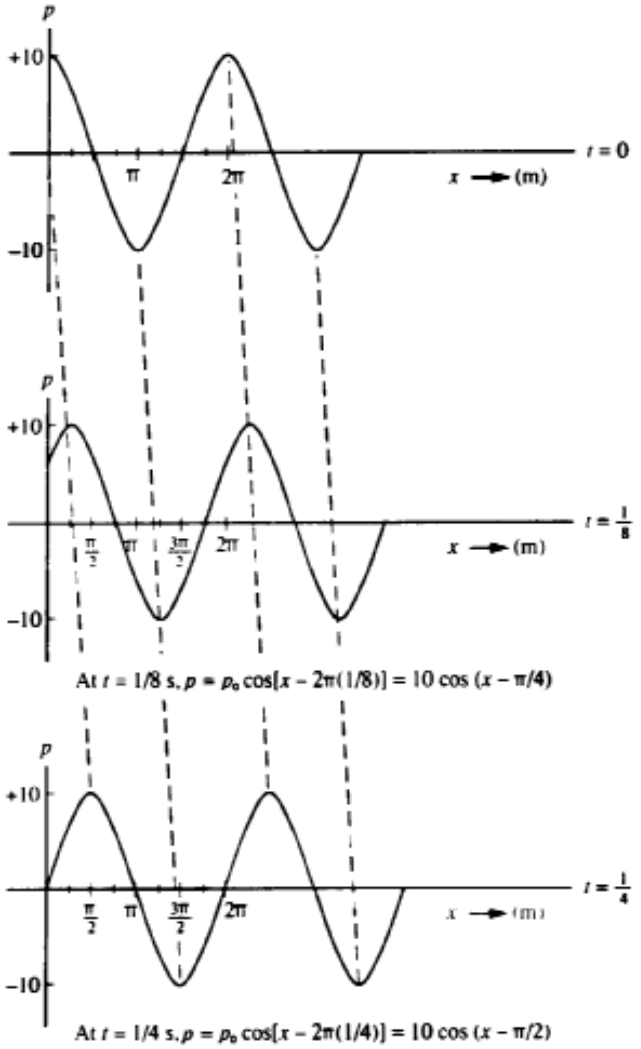
$$p = P_o \cos(\beta x - \omega t)$$

  - where β = 1 rad/m,
  - f = 1 Hz, and
  - P_0 = 10 N/m^2.

- Is this a forward-traveling wave or a backward-traveling wave?

SOLUTION

- See the figure. Note that in the successive graphs taken at t = 0, ⅛, and ¼ seconds, the crest of the wave has moved in position to the right.
  - Therefore we conclude that this is a forward-traveling wave.



- The crest velocity is derived from *dx/dt* when the pressure, *p*, is constant.
  - That is,

$$\beta x - \omega t = constant$$

  - Differentiating both sides gives

$$\beta \frac{dx}{dt} - \omega = 0$$

  - Therefore, defining the crest velocity *c* = *dx/dt* yields

$$c = \frac{\omega}{\beta}$$

- The wavelength, λ, is the distance between wave crests at any time *t*.
  - For example, at *t = 0*,
    - becomes $p = P_o \cos(\beta x - \omega t)$
    - and $p = P_o \cos(\beta x)$

$$\lambda = \frac{2\pi}{\beta}$$

- Combining

$$c = \frac{\omega}{\beta}$$

- and

- yields

$$\lambda = \frac{2\pi}{\beta}$$

$$c = \lambda f$$

- The wave travels in the positive x-direction.
  - Changing the sign in the argument reverses the direction of the wave.
  - That is,

  - travels in the negative *x*-direction and is called a backward-traveling wave.

$$p = P_o \cos(\beta x + \omega t)$$

- Because the wave crest travels through the medium, we call it a propagating wave.
  - The propagating pressure wave causes a displacement of the particles of matter through which it travels.
  - A mathematical expression describing the velocity, v, is

$$v = V_o \cos(\beta x - \omega t)$$

- Note that
  - and $$v = V_o \cos(\beta x - \omega t)$$ $$p = P_o \cos(\beta x - \omega t)$$
  - have the same mathematical form.
    - The velocity, v, is a propagating wave and is analogous to current in an electric wave which is the velocity of charges.

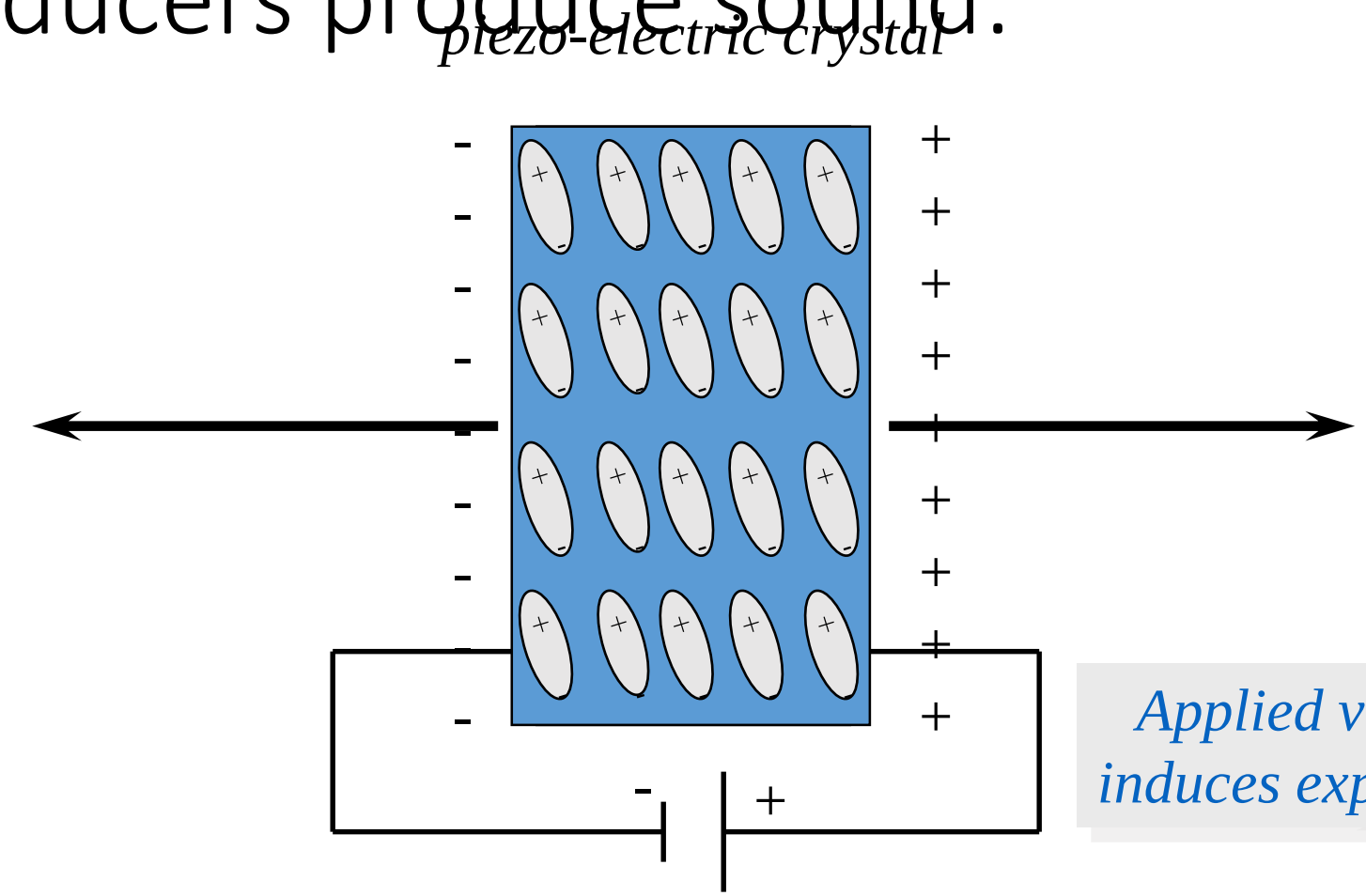
- Completing the analogy, we can define the impedance of a forward traveling wave as the *characteristic impedance, Z_0*.
  - That is,

- and

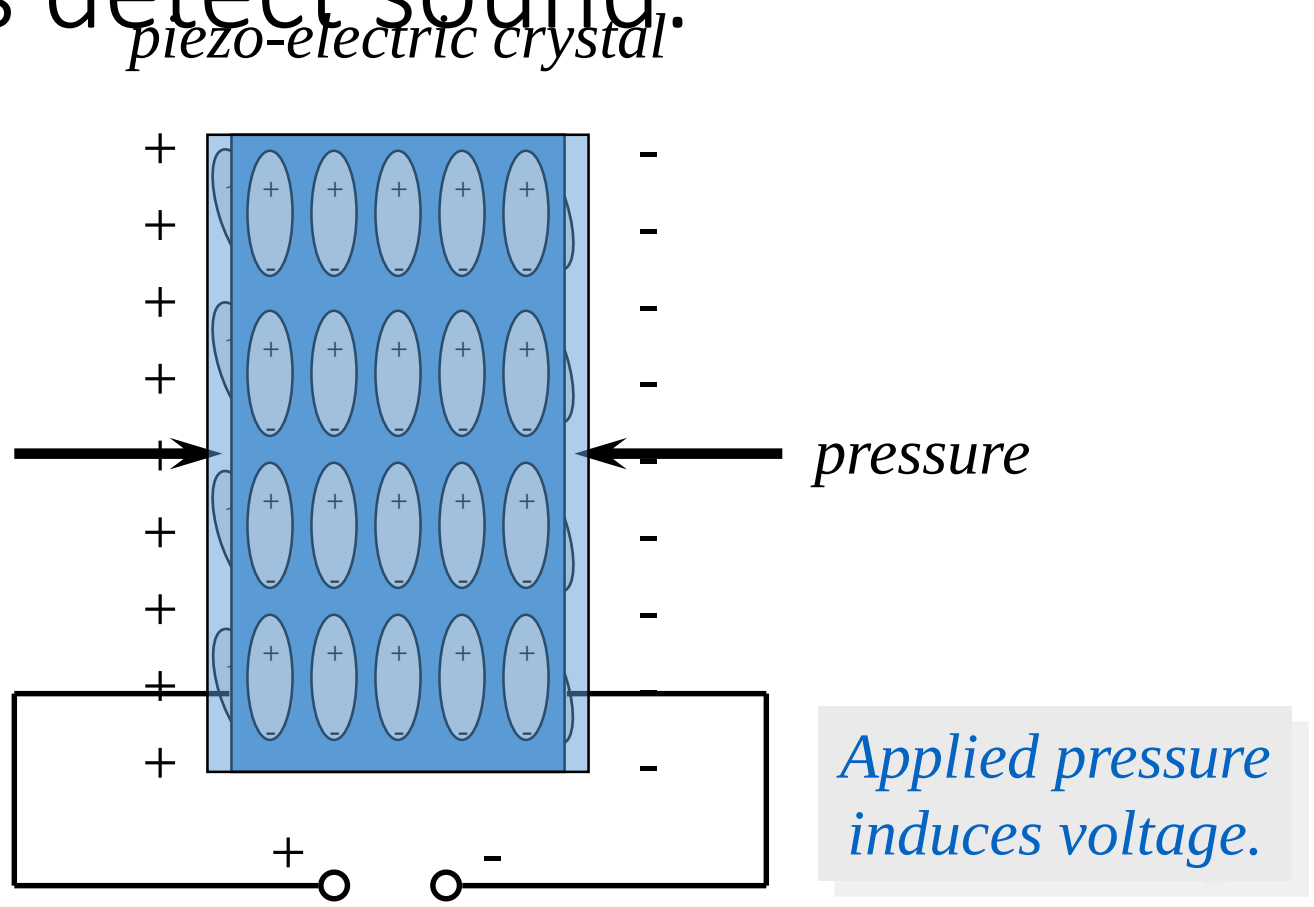
$$Z_o = \frac{p}{v} = \frac{P_o \cos(\beta x - \omega t)}{V_o \cos(\beta x - \omega t)}$$

$$Z_o = \frac{P_o}{V_o}$$

Transducers produce sound:



Transducers detect sound:

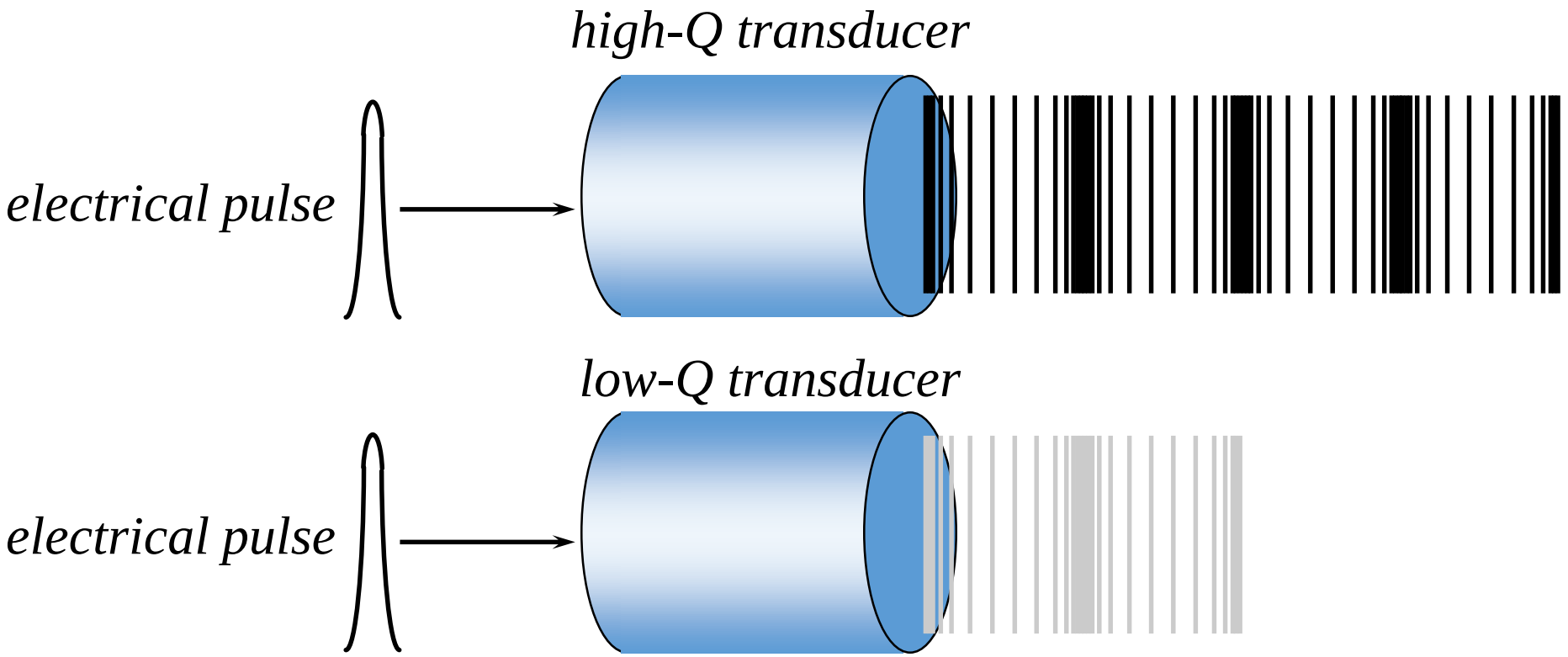


Applied pressure induces voltage.

Piezo-electric crystal properties

- Applied voltage induces crystal contraction/expansion.
- Contraction/expansion produces pressure pulse.
- Applied pressure induces voltage change.
- Can be used as both transmitter and receiver.

Acoustic pulse production



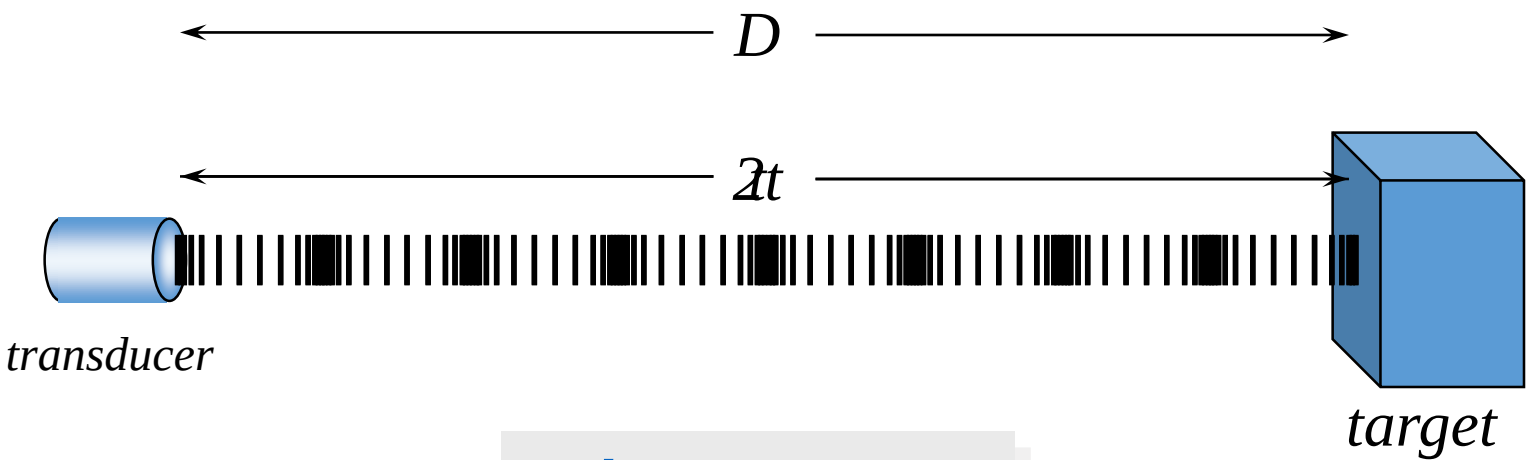
Acoustic pulse production

- A medical transducer produces a “characteristic” frequency.
- For each electrical impulse, a pulse “train” that consists of N sinusiodal cycles is produced.
- The “Q” of a transducer is a measure of the number of cycles in a pulse train.

High- versus low-Q transducers

- High-Q transducers
  - High intensity
  - Long-duration pulse “train”
- Low-Q transducers
  - Lower intensity
  - Shorter-duration pulse train

Pulse-echo principle



Delay time, T = 2t

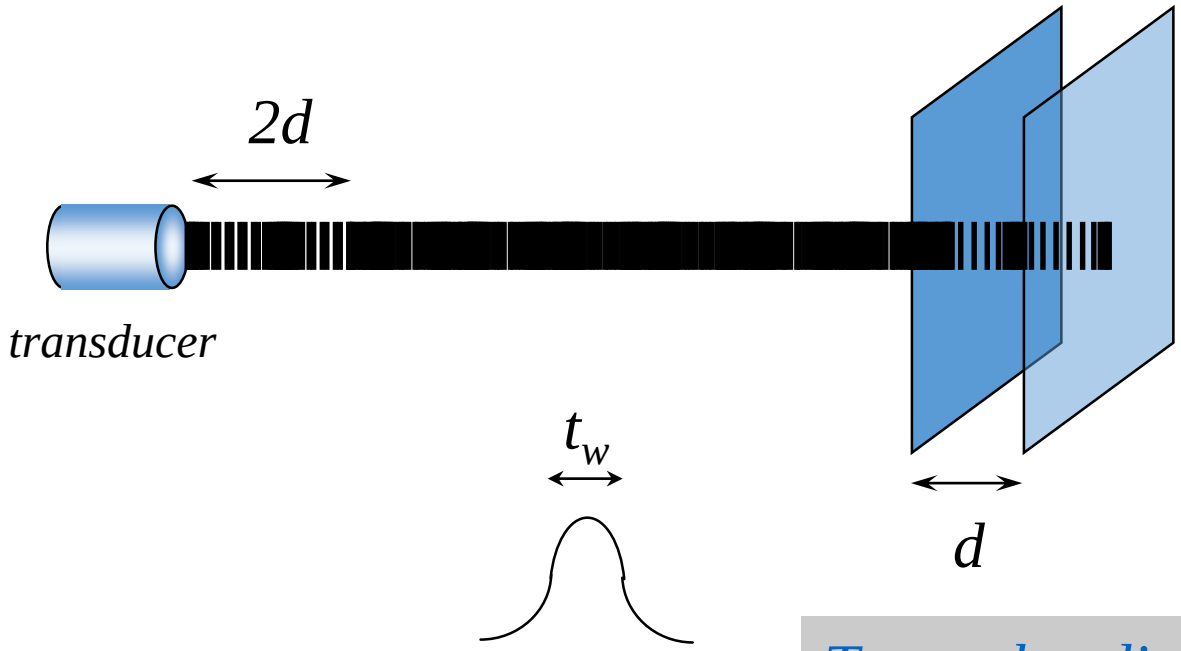
D=(v/2)(2t)

D = vT/2

Pulse-echo principle

- Pressure pulse is “launched” into tissue.
- Acoustic energy is reflected at boundaries separating regions of differing acoustic impedances.
- Fraction of sonic energy returns to transducer.
- Overall delay time is proportional to distance to boundary.

Depth (axial) resolution



To resolve distance, d, $vt_w<2d$

Axial resolution

- “Axial” resolution is defined as the ability to distinguish between two objects along the axis of the sound beam.
- For a given frequency, axial resolution improves as Q decreases.
- For a given Q, axial resolution improves with increasing transducer frequency.

Time-gain compensation

Attenuation of soundwave (dB) is approximatley proportional to distance (delay time).

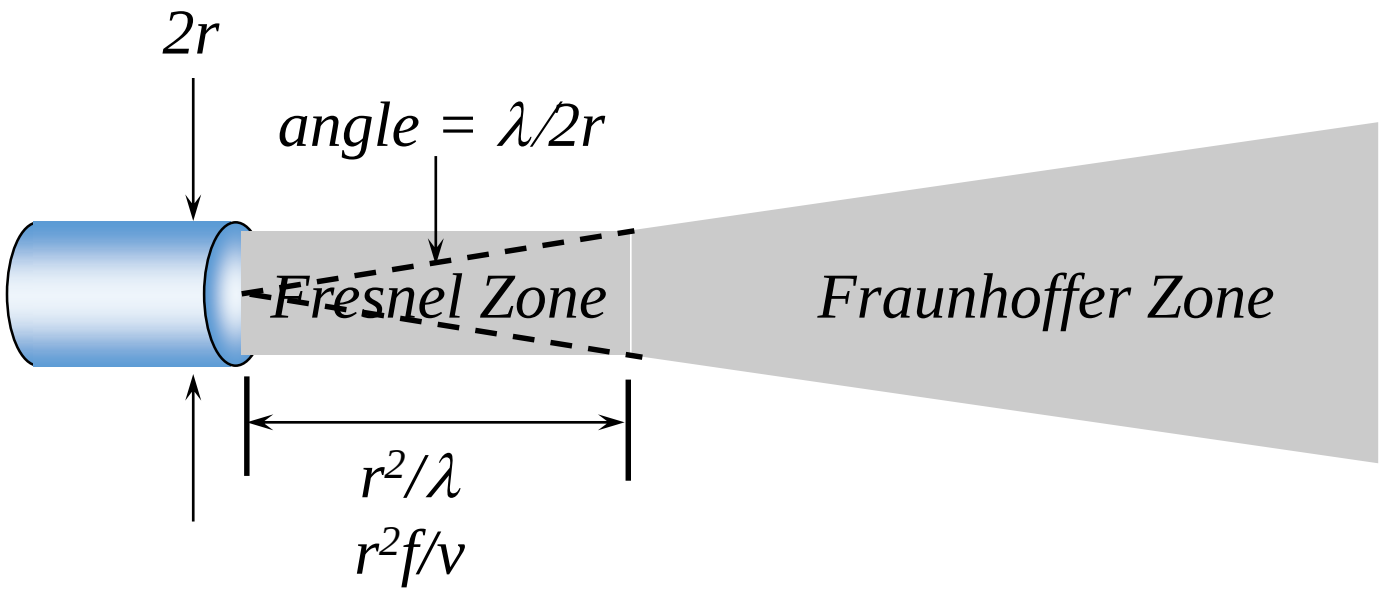
Acoustic attenuation

- Sound is absorbed as it propagates through tissue.
- As a result, reflected sound is attenuated with depth (delay time).
- Attenuation is proportional to frequency.

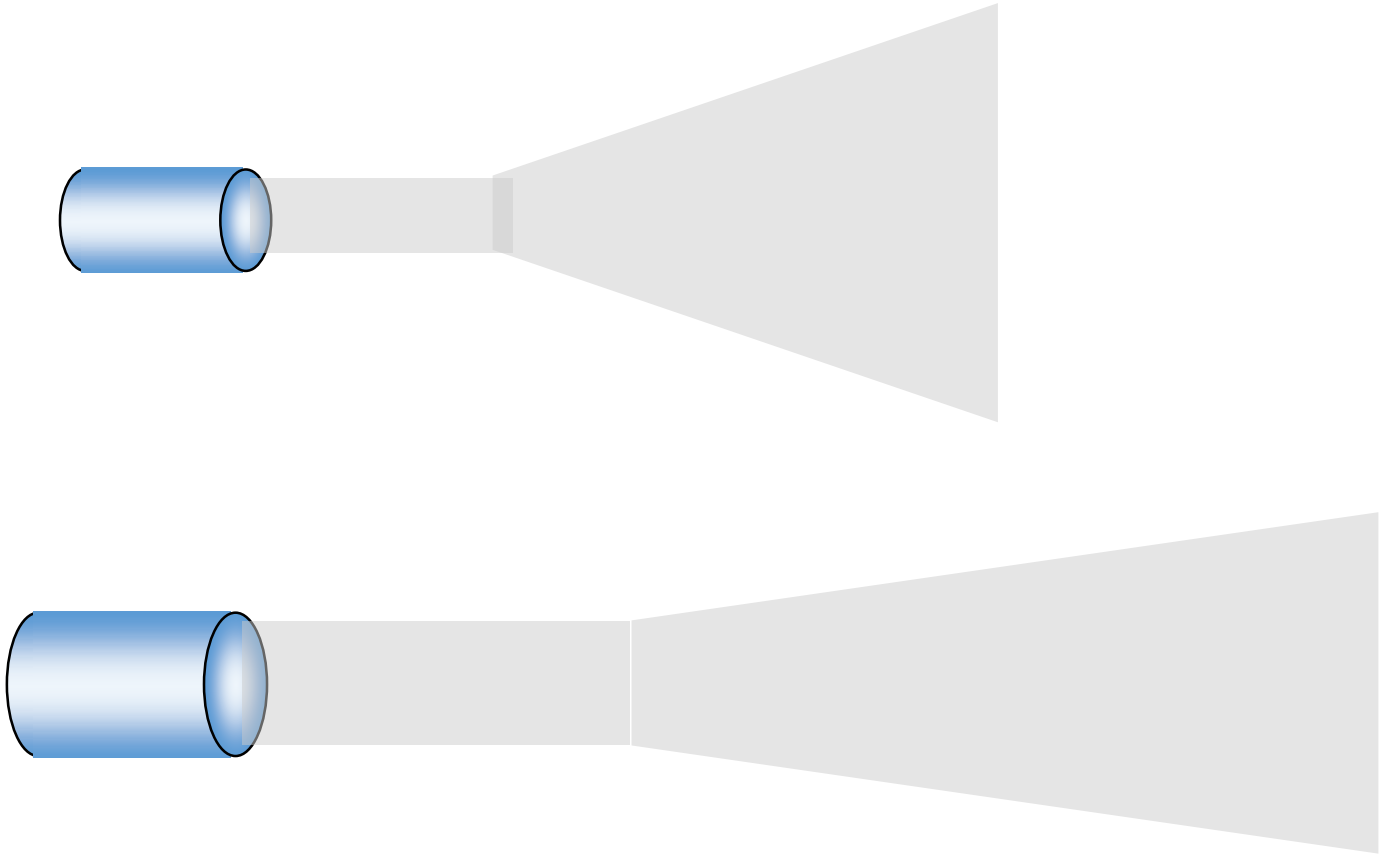
Time-gain compensation

- Acoustic attenuation can be compensated (to some degree) by varying gain of detection amplifier.
- Gain is automatically increased as a function of time following an acoustic “pulse.”

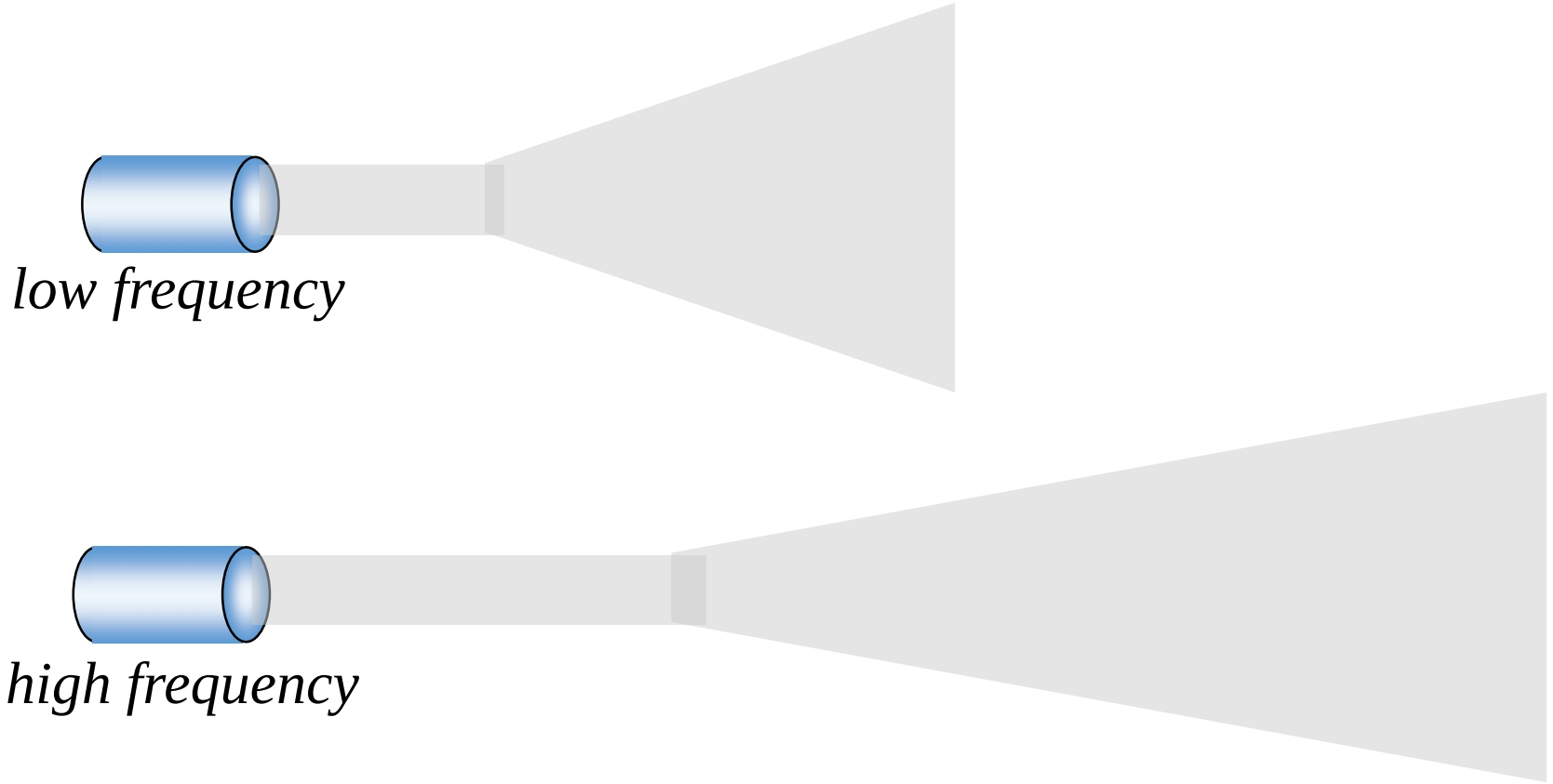
Transducer beam shape



Small versus large transducer



High versus low frequency



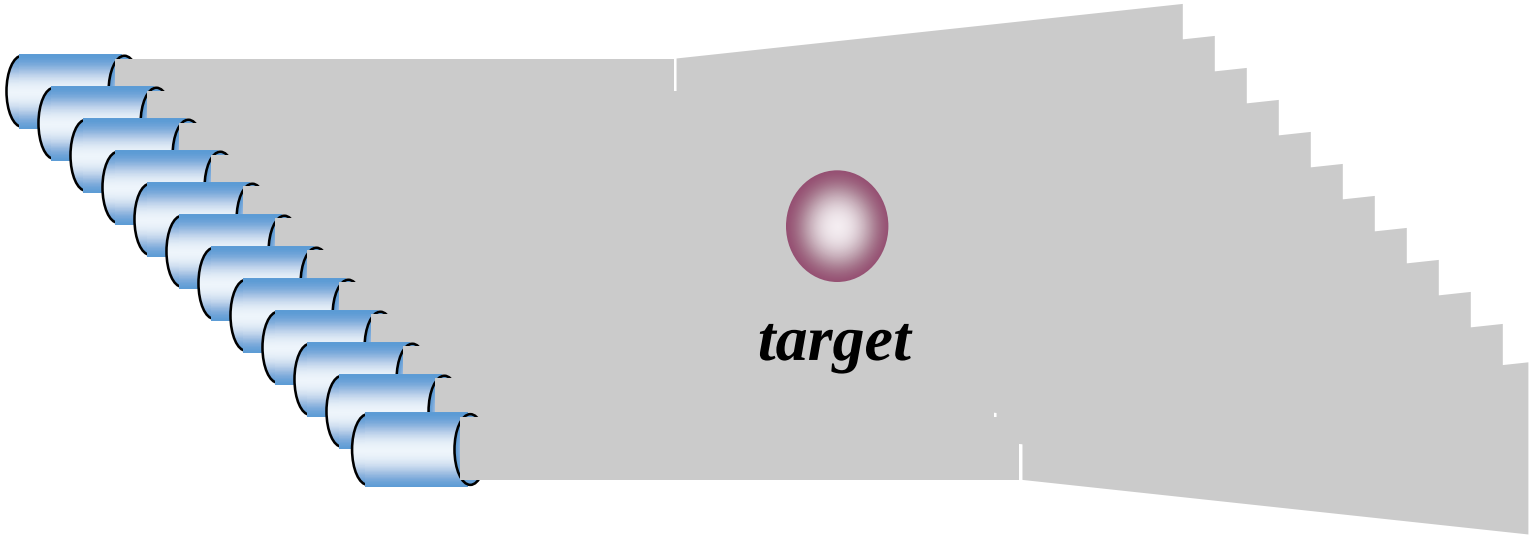
Transducer beam shape

- The shape of the sound beam has two distinct regions:
  - Fresnel (near field)
  - Fraunhoffer (far field)
- Near field characterized by nearly constant beam width.
- Far field characterized by divergent beam width.

Transducer beam shape

- Near field extends to a distance = r^2/λ, where λ is the wavelength of the sound wave.
- The higher the frequency the longer the near field region.
- Divergence in far field = $\lambda/2r$.
- Divergence decreases with higher frequency.

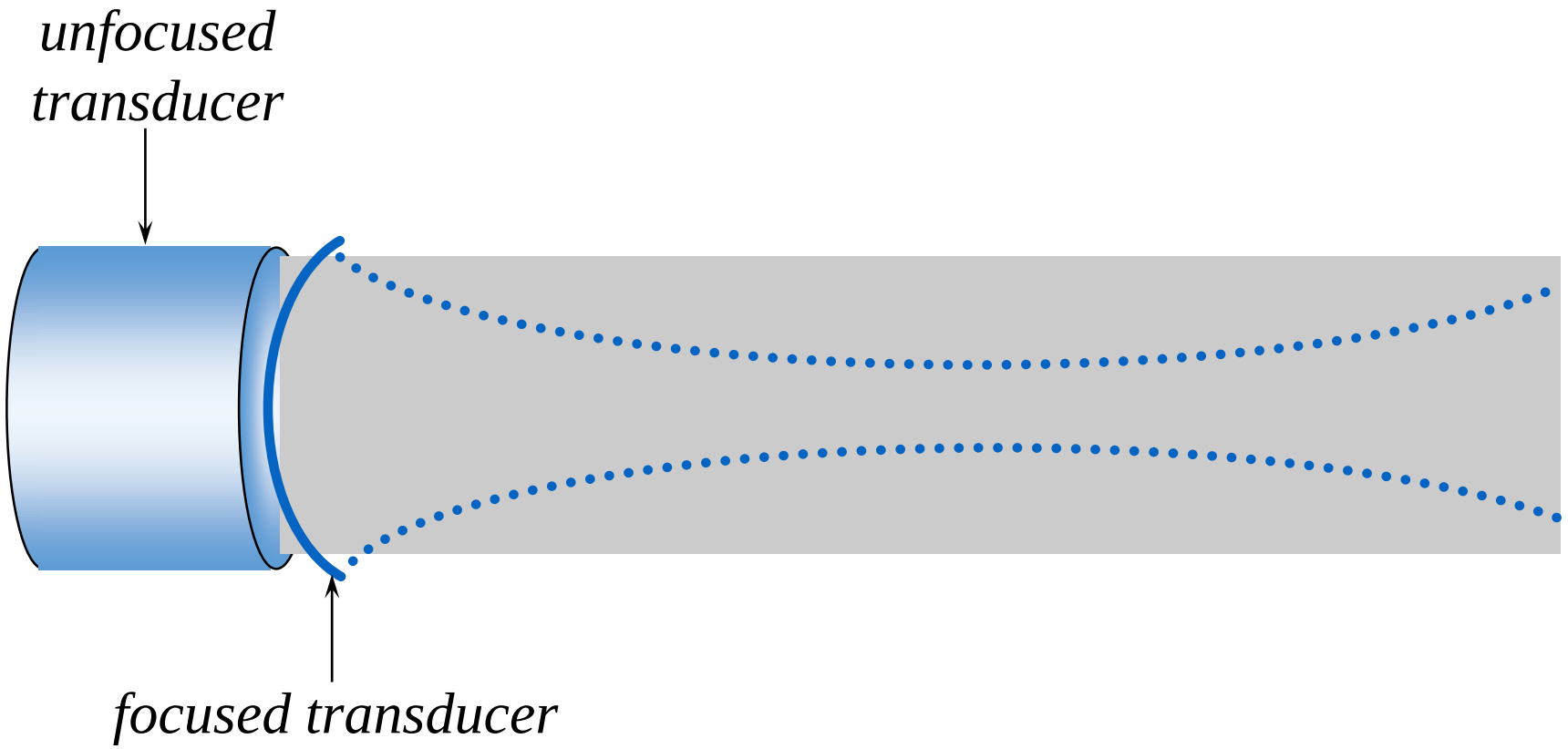
B-mode scan



B-mode scan

- At each lateral position of the transducer the echo signal as a function of time is recorded.
- Transducer is moved laterally to new position and a new pulse-echo sequence is acquired.
- Two-dimensional image is assembled one line at a time.
- Lateral resolution is dependent on beam width

Focused transducer



Electronic focusing