HUMAN PHYSIOLOGY (normal)

LECTURE 12. Physiology of Circulation. Physiology of the Heart

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The Heart

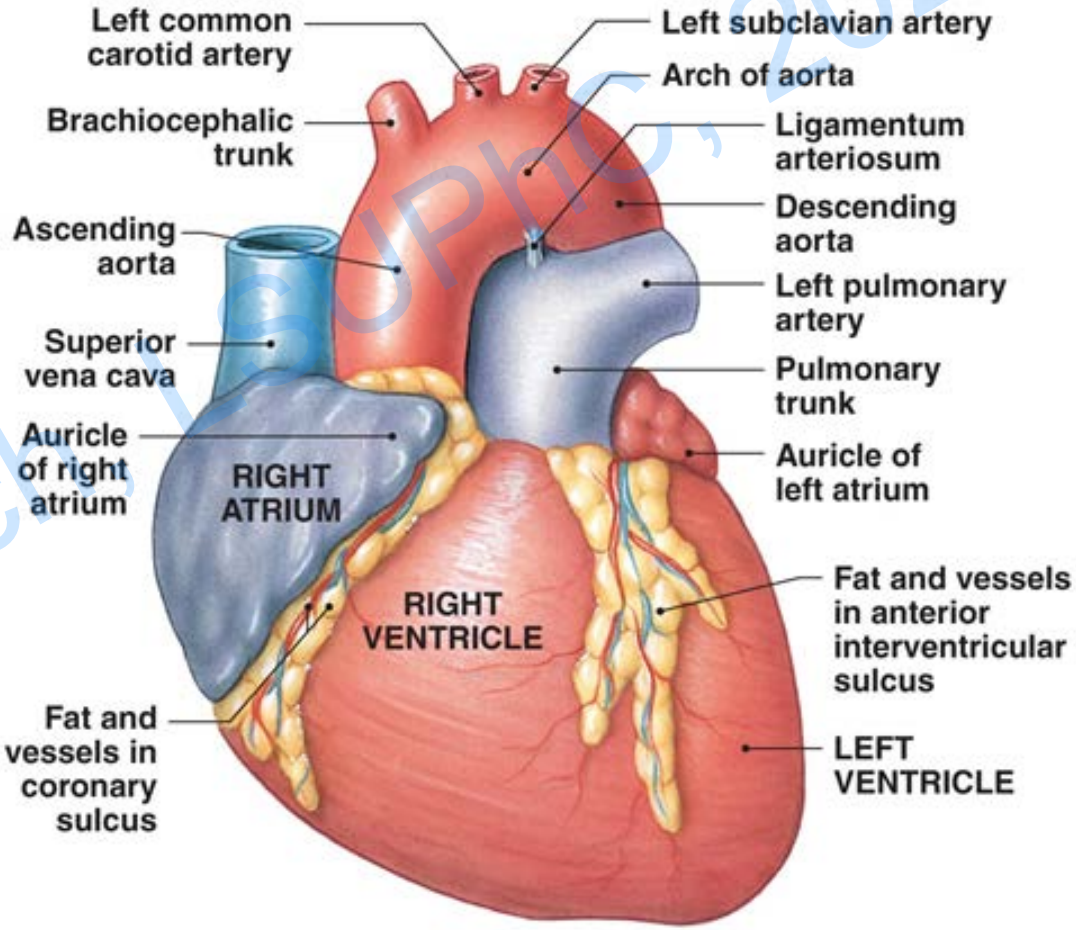
Chambers of the Heart:

Right atrium - collects blood from systemic circuit

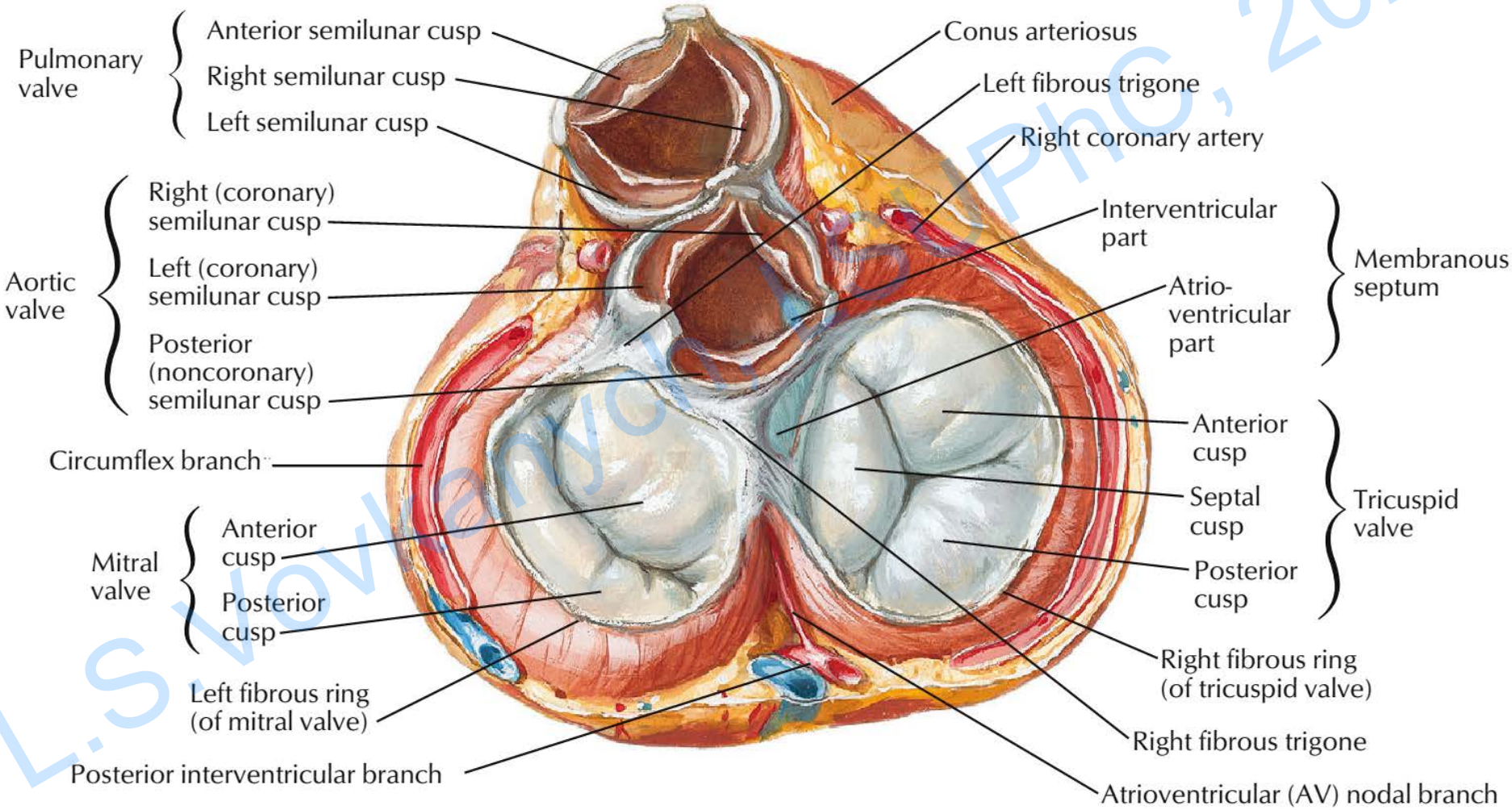
Right ventricle - pumps blood to pulmonary circuit

Left atrium - collects blood from pulmonary circuit

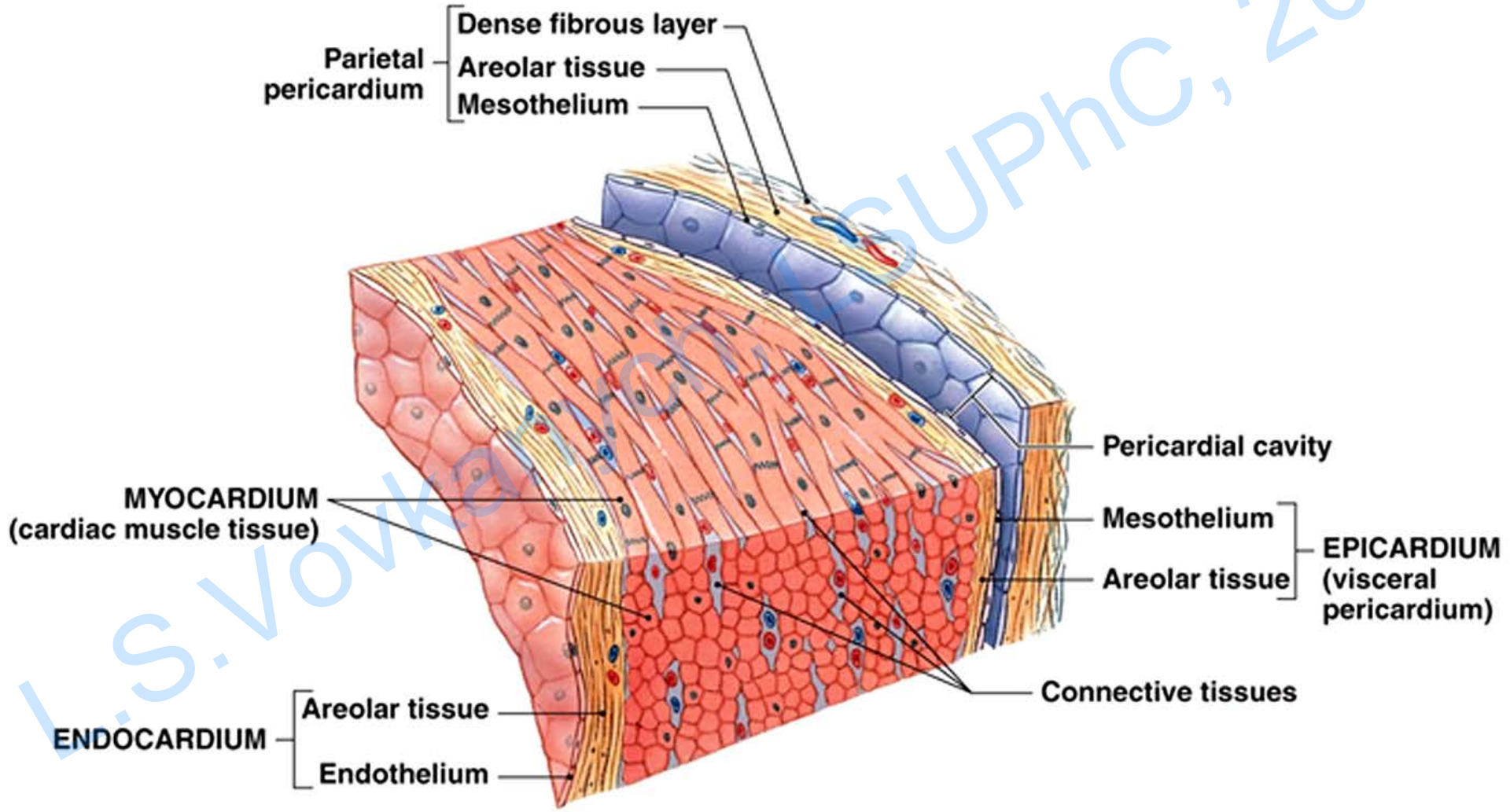
Left ventricle - pumps blood to systemic circuit



Valves of the Heart

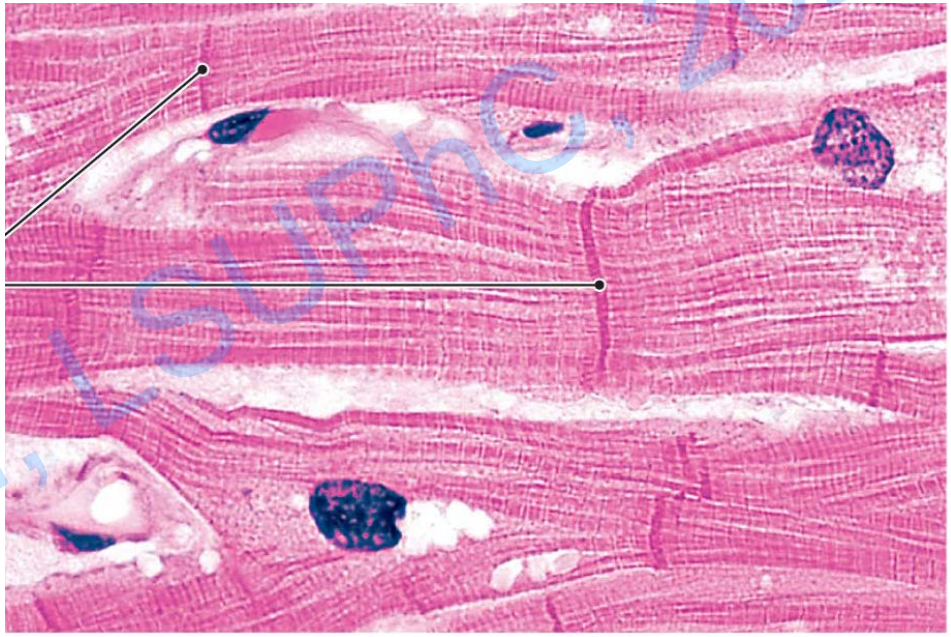


The Heart Wall

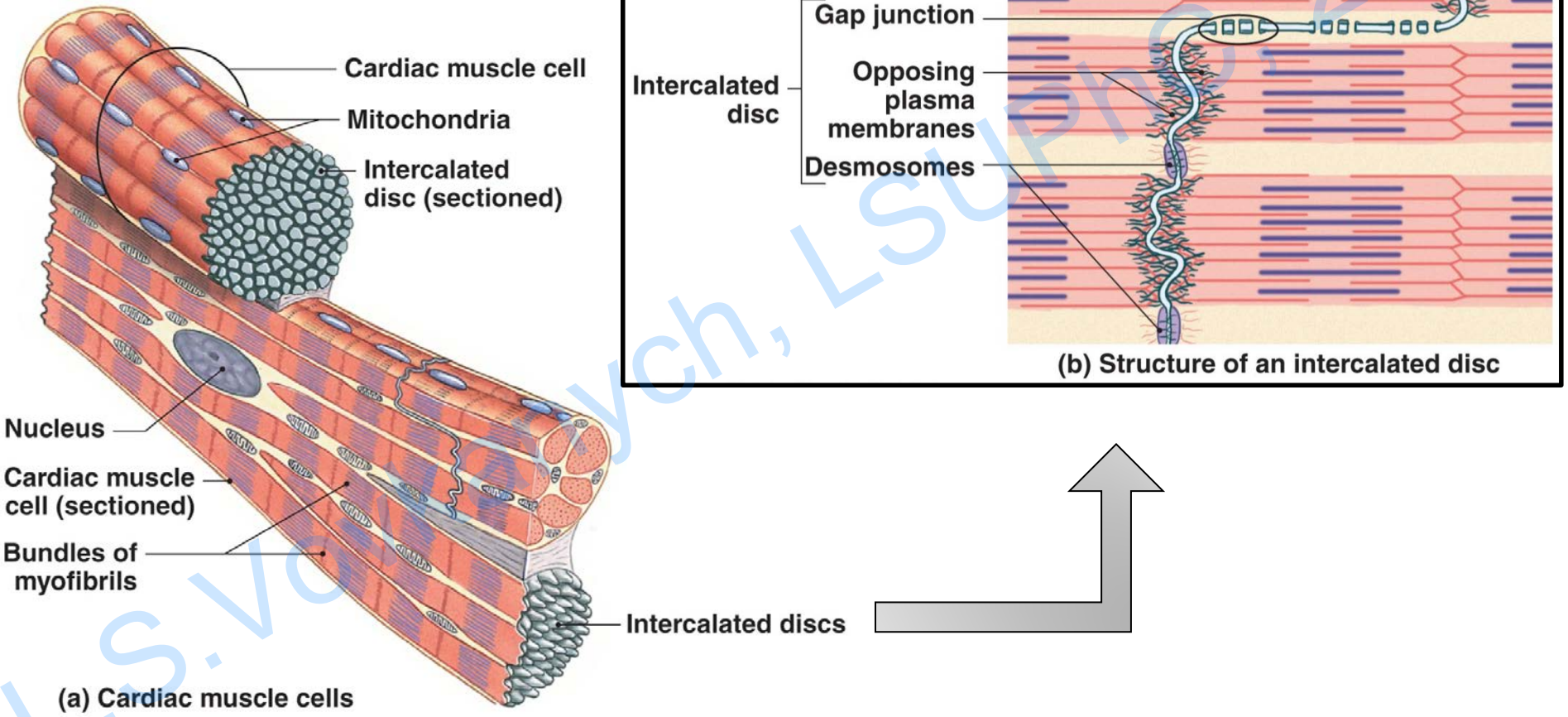


Cardiac Muscle Cell

- One **nuclei,** striated
- **Size** - 10-20 µm x 50-100 µm
- **Sarcomeres** with myofibrils
- **No** motor-end plates (synapses)
- Large number of **mitochondria** (up to 25% of cell volume)
- Primarily **aerobic metabolism**
- Plasma membranes locked together at **intercalated discs**
- **Slow twitches** with long refractory period
- **No tetanus**, **all or none** contraction



Cardiac Muscle Cell



The Functioning of the Heart

Heartbeat - a single contraction of the heart

The **Cardiac Cycle**

- Begins with action potential at SA node
- Transmitted through conducting system
- Produces action potentials in cardiac muscle cells (contractile cells)

Two Types of Cardiac Muscle Cells

- Cells of **Conducting system** (controls and coordinates heartbeat)
- **Contractile cells** (produce contractions that propel blood)

Properties of Cardiac Muscle

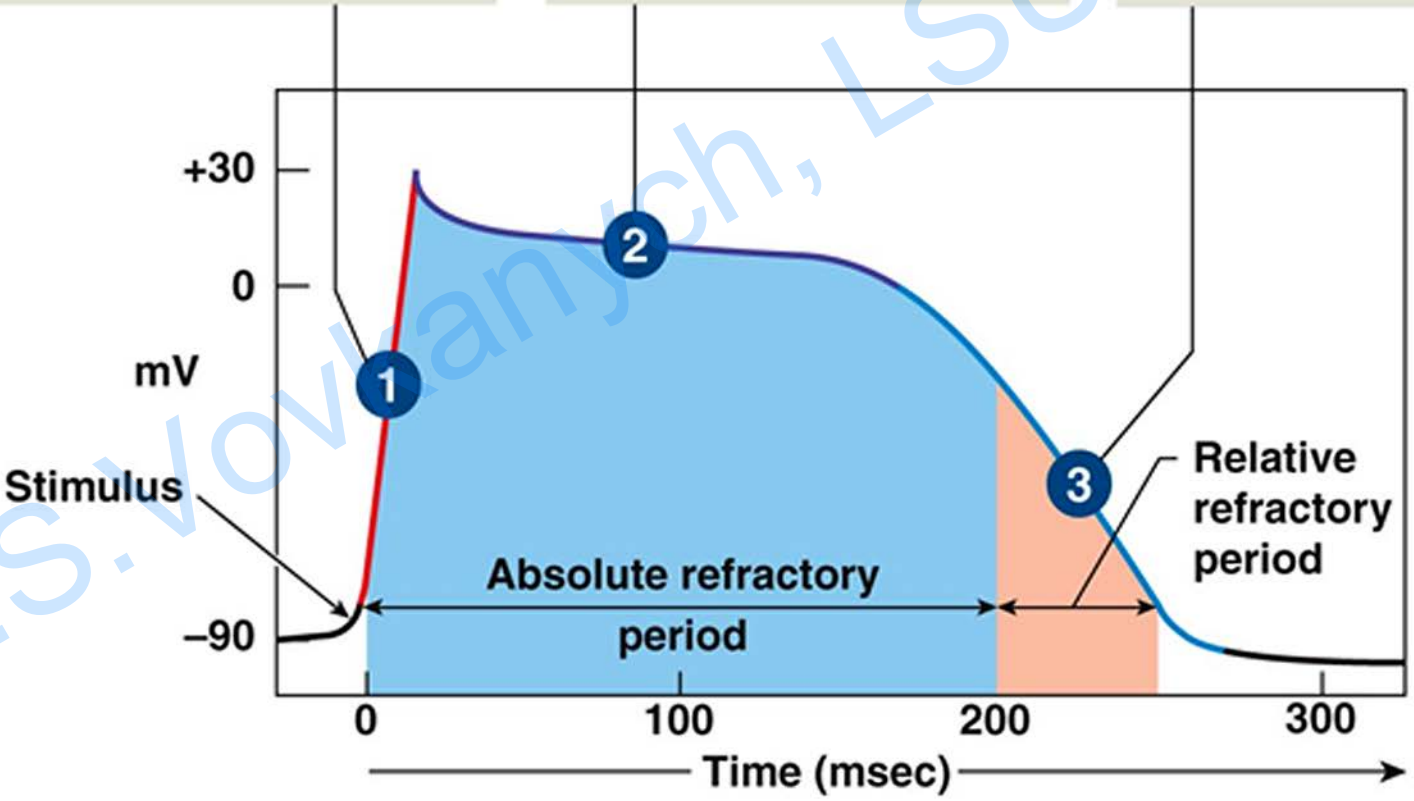
- **Excitability** - the ability of a living tissue to give response to a stimulus. In all the tissues, initial response to a stimulus is electrical activity in the form of **action potential**.
- **Automaticity** (rhythmicity) - the ability of a tissue to produce its own impulses regularly
- **Conductivity** – ability of electrical signal transmission in the living tissue
- **Contractility** - ability of the tissue to shorten in length (contraction) after receiving a stimulus

The Action Potential in Cardiac Muscle

1 Rapid Depolarization
Cause: Na^+ entry
Duration: 3–5 msec
Ends with: Closure of voltage-gated (fast) sodium channels

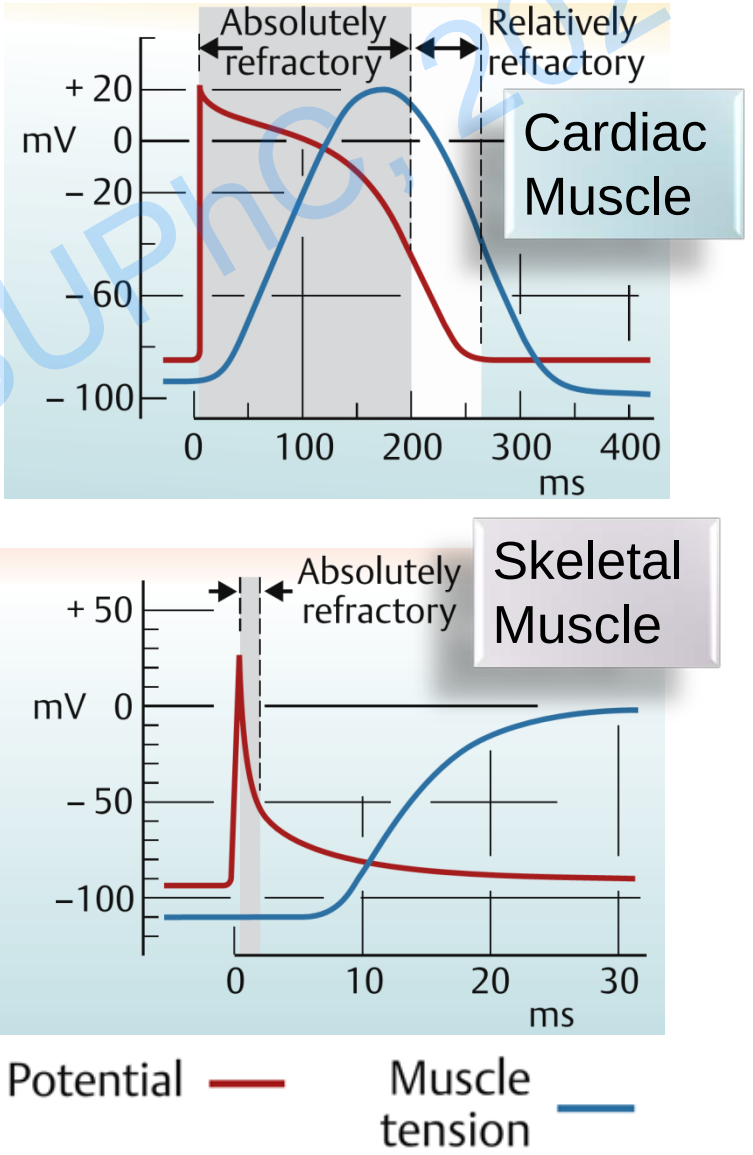
2 The Plateau
Cause: Ca^{2+} entry
Duration: ~175 msec
Ends with: Closure of slow calcium channels

3 Repolarization
Cause: K^+ loss
Duration: 75 msec
Ends with: Closure of slow potassium channels



Excitation and Contraction in Cardiac Muscle

- **Duration** of the action potential - 250 to 350 ms
- **Plateau** in action potential curve (depolarized state) lasts for 200-300 ms
- Plateau is due to the slow opening of **calcium channels** and calcium influx into the cells
- **Calcium ions** are important in the contractile process
- The plateau phase determines the **long refractory period** and **absence of tetanic contraction** in cardiac muscle

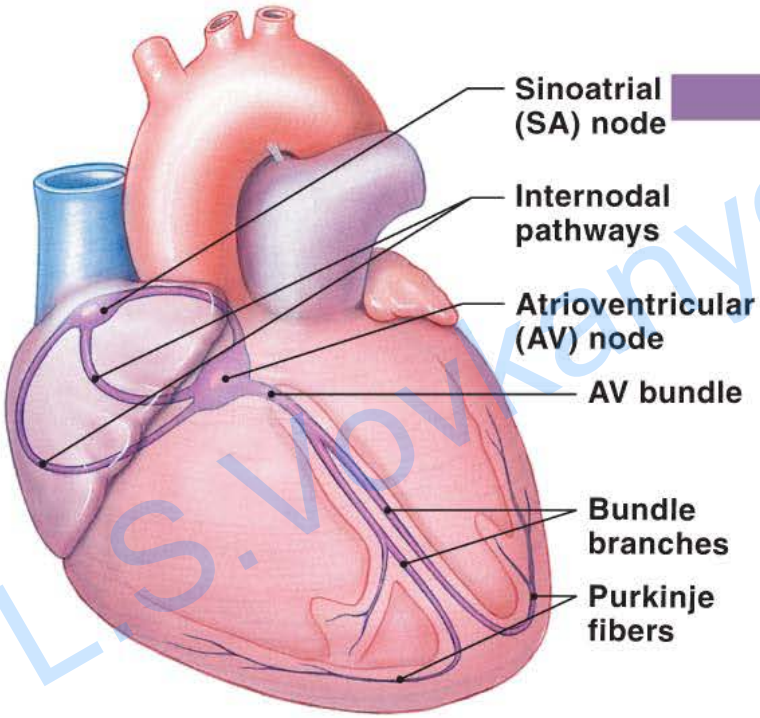


Automaticity (rhythmicity)

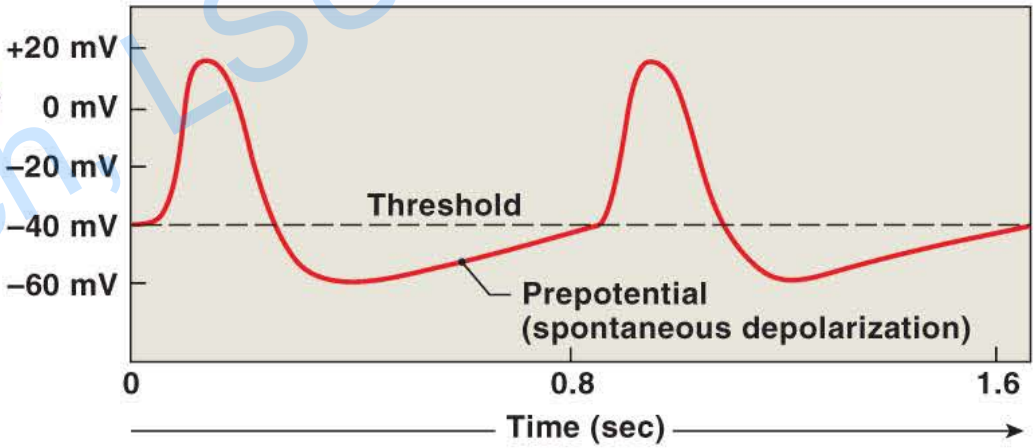
- Heart has a **specialized excitatory structure** - **pacemaker**
- **Pacemaker** is the structure of heart from which the impulses for heartbeat are produced. It is formed by the **pacemaker cells** called P cells
- Resting membrane potential is not stable in pacemaker cells. The **slow depolarization** is caused by slow **influx of sodium ions** and slow influx of calcium ions
- In mammalian heart, the **primary pacemaker** is **sinu-atrial** node (SA node), which generates 70-80 impulses per minute
- From here, the impulses **spread** to other parts through the specialized **conductive system**
- Other parts of heart such as **atrioventricular** (AV) **node**, atria and ventricle also can produce the impulses and function as pacemakers, but with much less frequency

Automaticity (rhythmicity)

- Resting potential of cells of the nodes gradually depolarizes toward threshold
- This cause the action potential generation
- SA node depolarizes first, establishing heart rate



(a) The conducting system



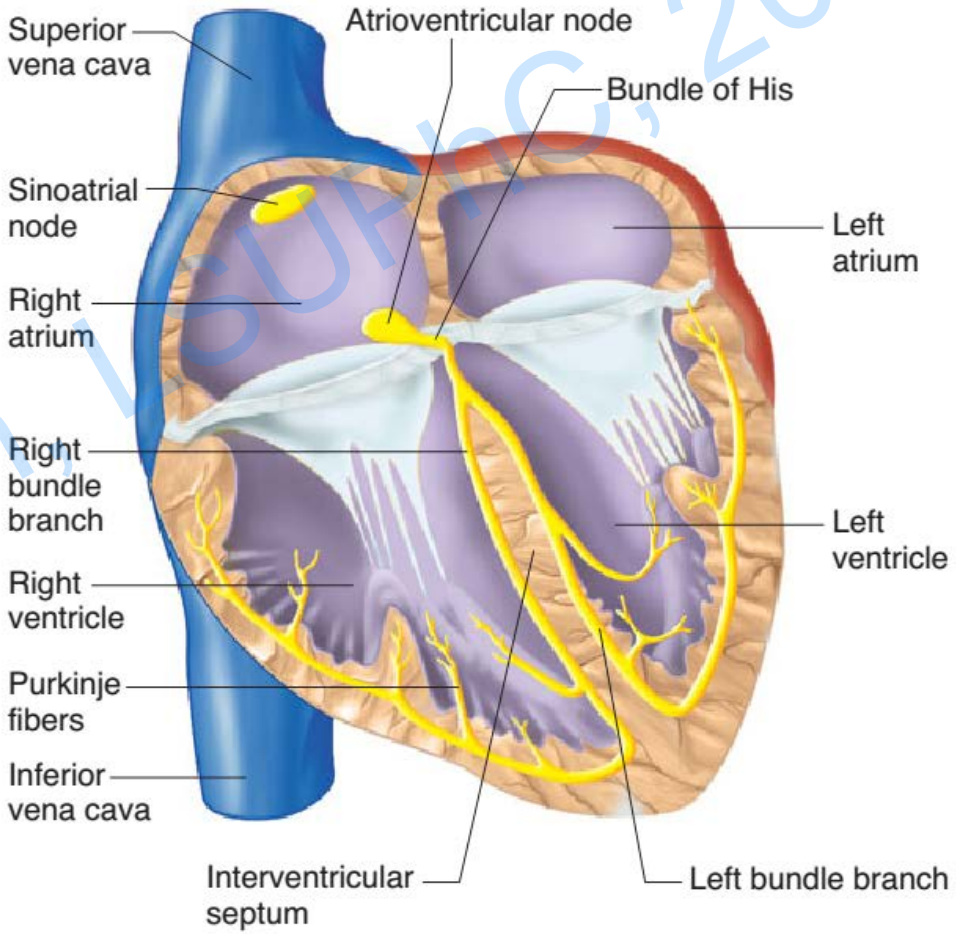
(b) Depolarization at the SA node

The Conducting System

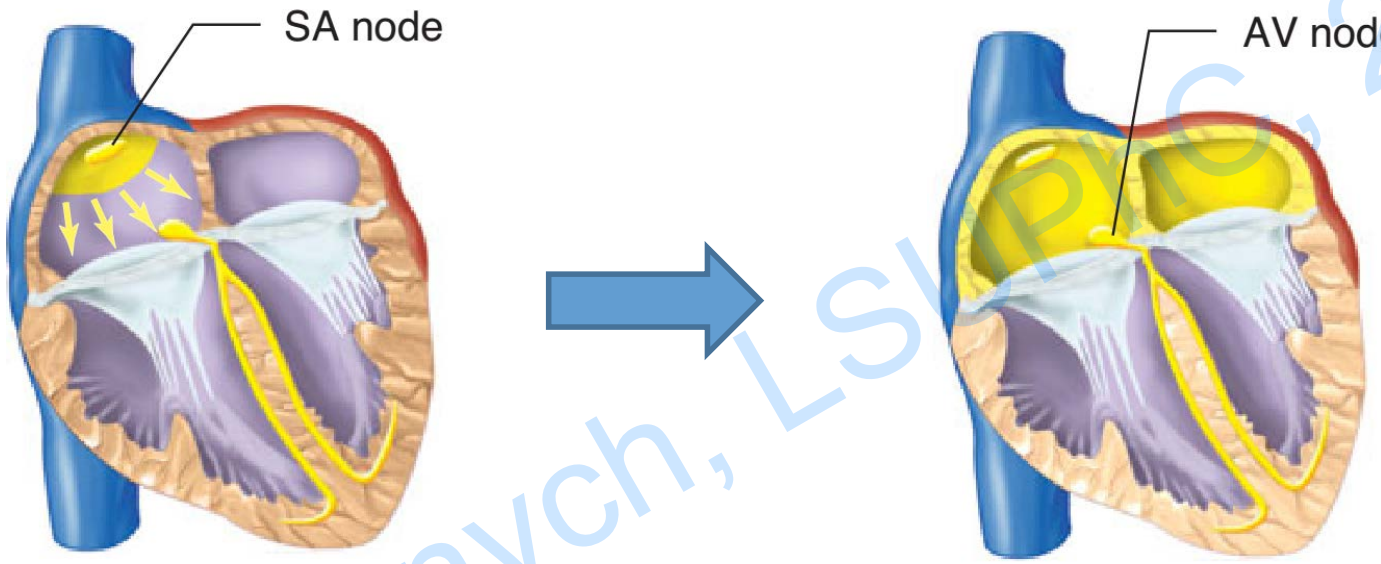
A system of **specialized cardiac muscle cells**

Initiates and distributes **electrical impulses** that stimulate contraction

- **Sinu-atrial** (Sinoatrial, SA) node
- **Atrioventricular** (AV) node
- **Atrioventricular bundle** (AV bundle, bundle of His)
- **Right and left cruses** (branches)
- **Subendocardial branches** (Purkinje fibers)



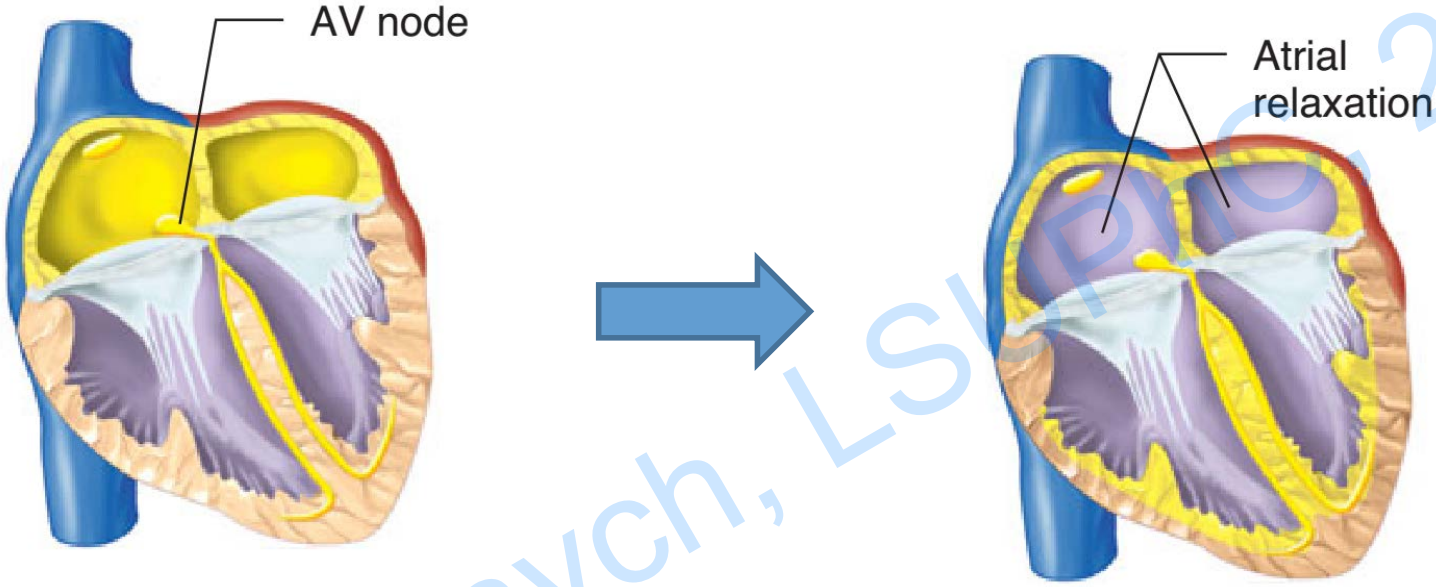
Impulse Conduction through the Heart



- The Sinoatrial (SA) Node begins atrial activation

- The Atrioventricular (AV) Node receives impulse from SA node
- Delays impulse (0.10-0.12 s)
- Atrial contraction begins

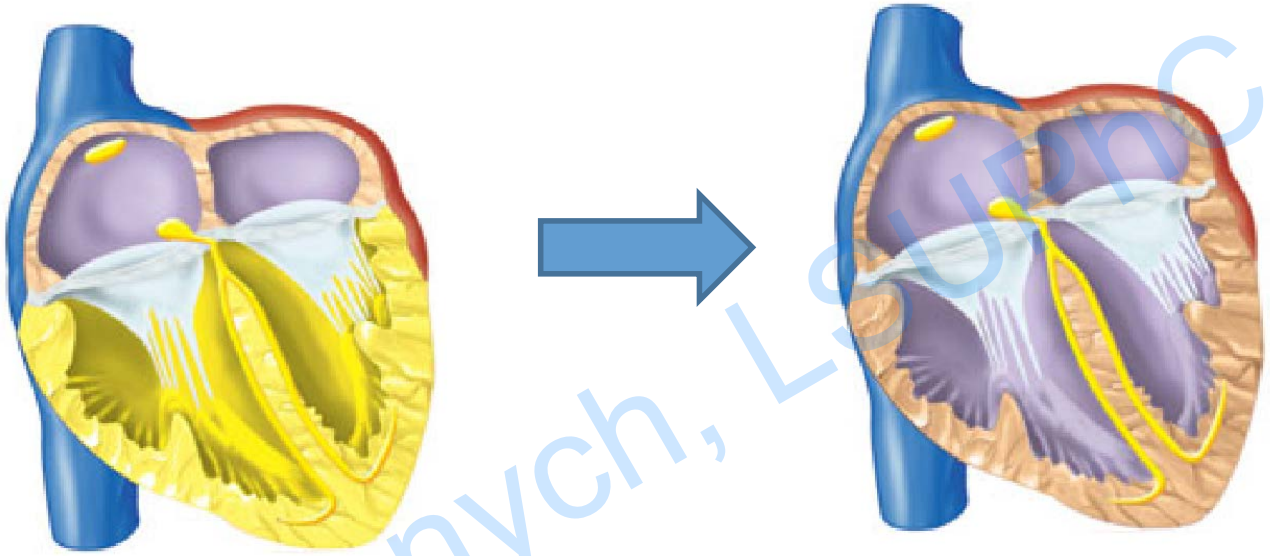
Impulse Conduction through the Heart



- The AV Bundle carries impulse to left and right bundle cruses (branches)
- The impulse travels along the cruses and to the subendocardial branches (Purkinje fibers)

- They distribute impulse through ventricles
- Atrial contraction is completed
- Ventricular contraction begins

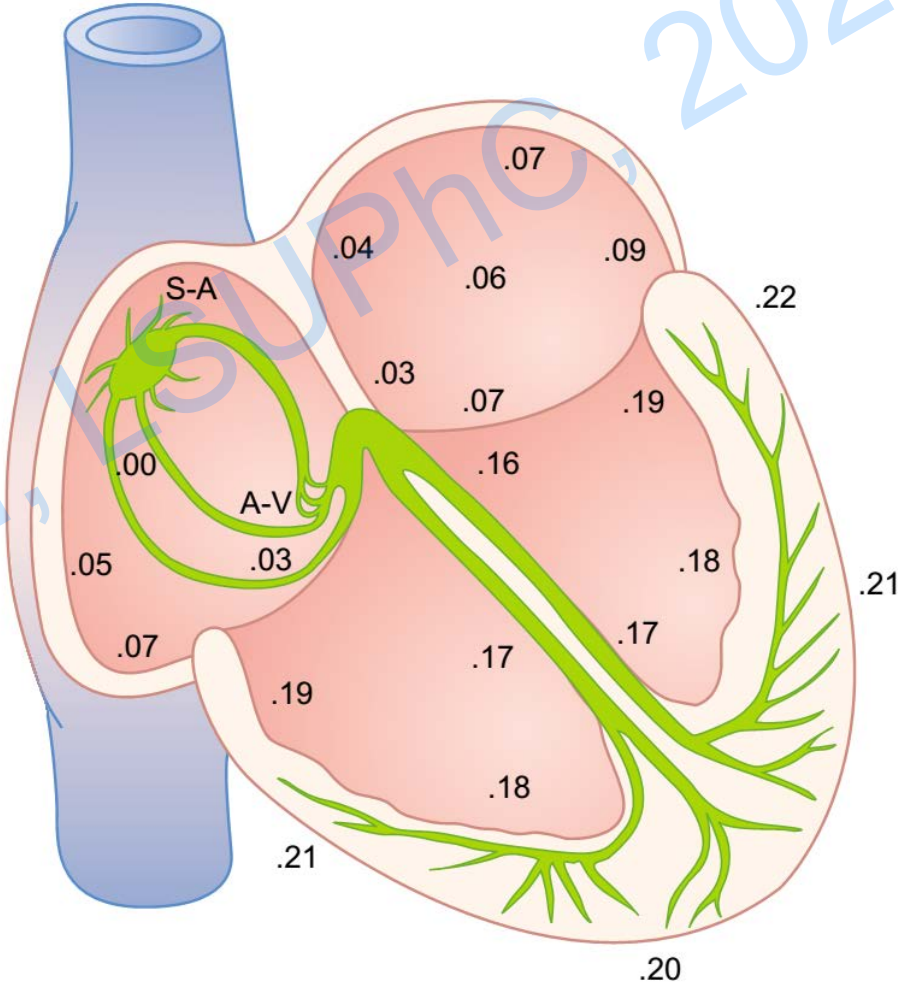
Impulse Conduction through the Heart



- Ventricular contraction
- Ventricular relaxation and repolarization

Conduction Speeds in Cardiac Tissue

Tissue	Conduction Rate (m/s)
SA node	0.05
Atrial pathways (internodal fibers)	1
Atrial muscle fibers	0.3
AV node	0.05
Bundle of His	1
Purkinje system	4
Ventricular muscle	0.5-1.0



Time delay (s) of impulse appearance

Abnormal Pacemaker Function

- **Bradycardia**: abnormally slow heart rate (< 60 bpm)
- **Tachycardia**: abnormally fast heart rate (> 90 bpm)
- **Ectopic pacemaker**
  - Abnormal cells
  - Generate high rate of action potentials
  - Bypass conducting system
  - Disrupt ventricular contractions

Contractility of the Myocardium

- **All-or-none law**: when a stimulus is applied, the whole cardiac muscle gives response or it does not give any response at all
- Cardiac muscle has a **long refractory period*** compared to skeletal muscle, which has three consequences:
  - **no summation** of contractions,
  - **no fatigue**,
  - **no tetanus**

- Special intrinsic regulatory mechanisms of the contraction force in the myocardium:
  - **Staircase phenomenon -** gradual increase in the force of contraction in case of rhythmical stimulation
  - **Frank-Starling law** - force of contraction of heart is directly proportional to the initial length of muscle fibers

* - When a stimulus is applied during the relative refractory period the extrasystole or premature contraction occurs. Extrasystole is followed by prolonged diastole - compensatory pause

Electrocardiogram (ECG)

The ECG records **potential differences** (few m/V) caused by cardiac excitation.

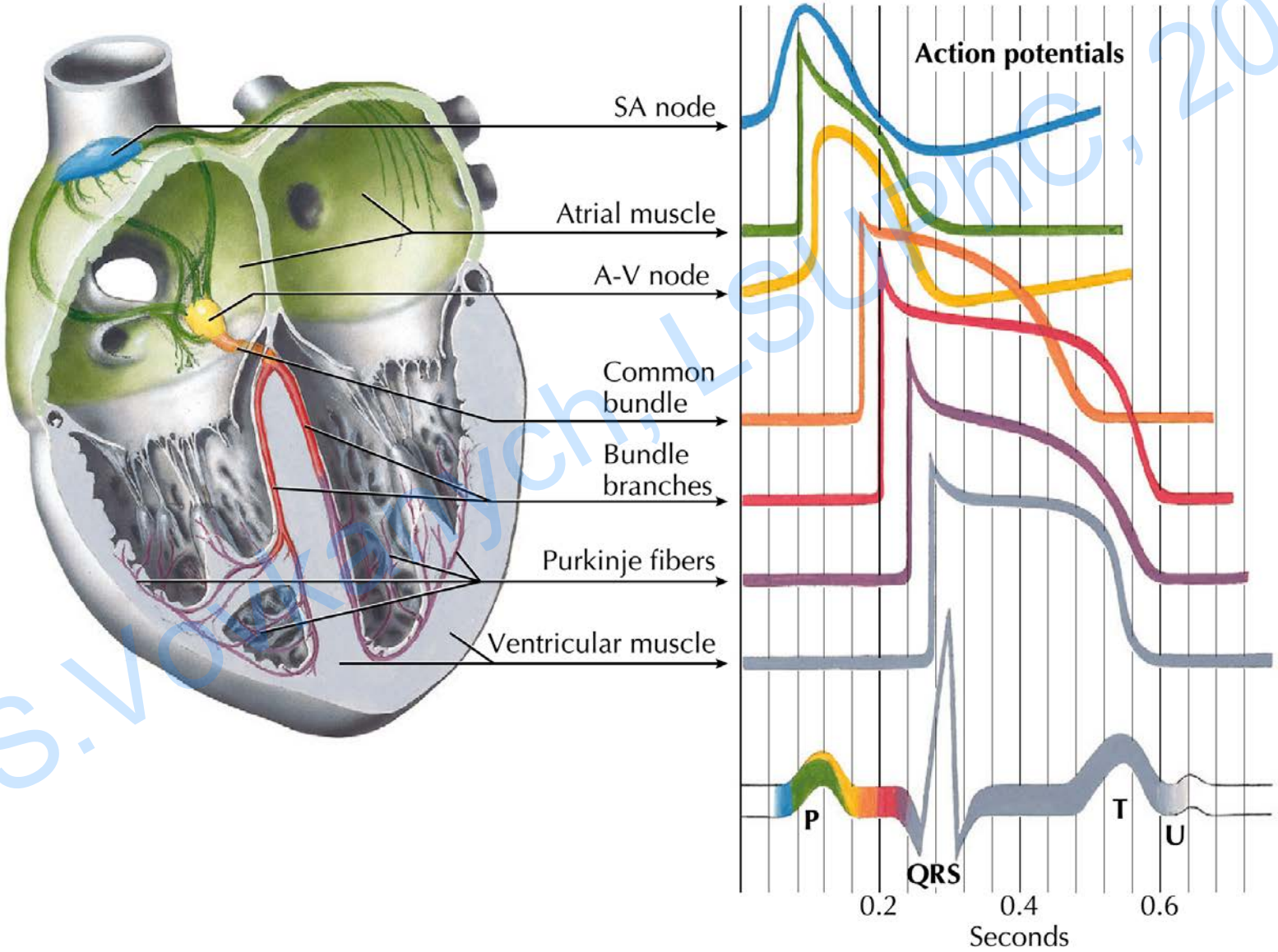
ECG **provides information** on:

- heart rhythm
- impulse origin/propagation
- rhythm/conduction disturbances
- extent and location of myocardial ischemia
- heart position
- relative chamber size

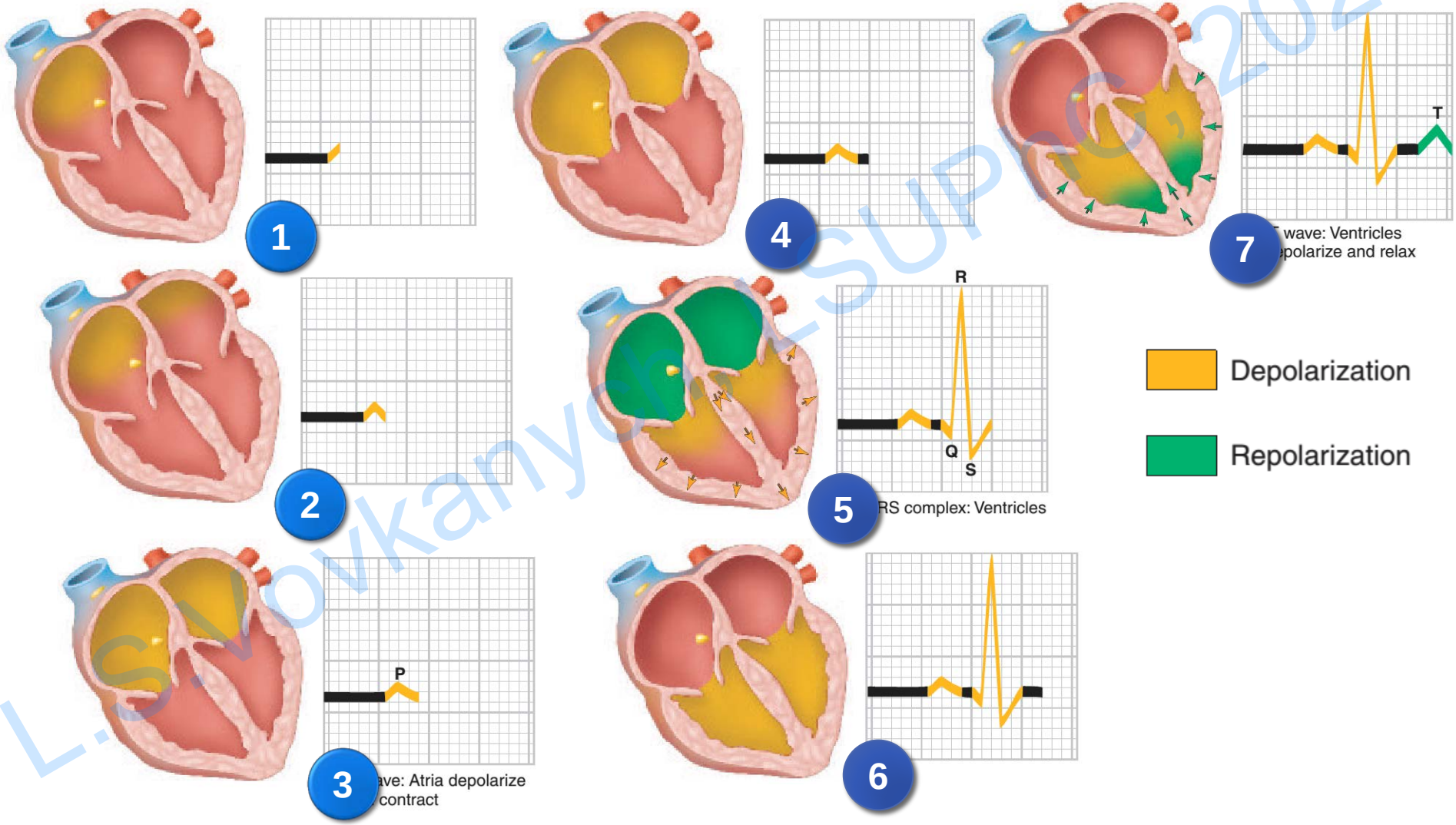
It **does not** provide data on

- cardiac contraction and pumping function.

Electrocardiogram (ECG)

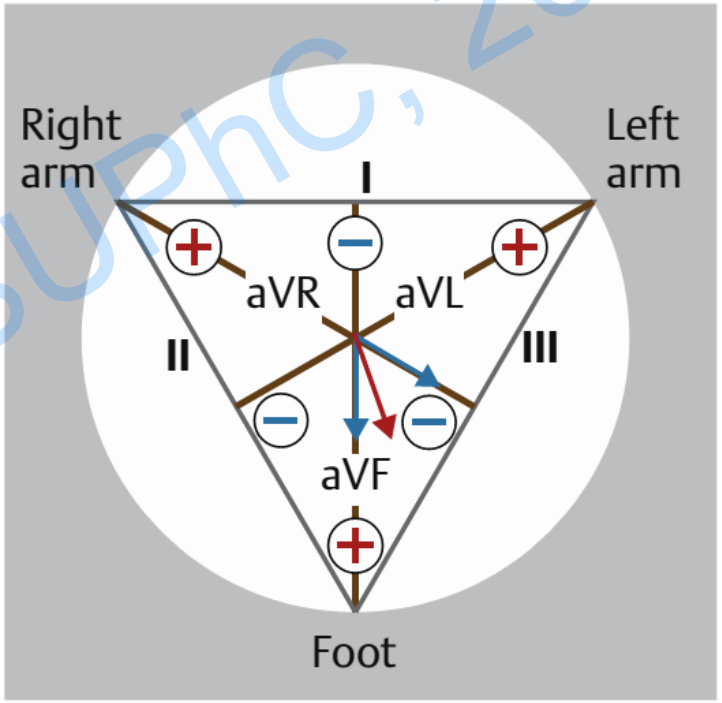


Impulse Conduction and the ECG

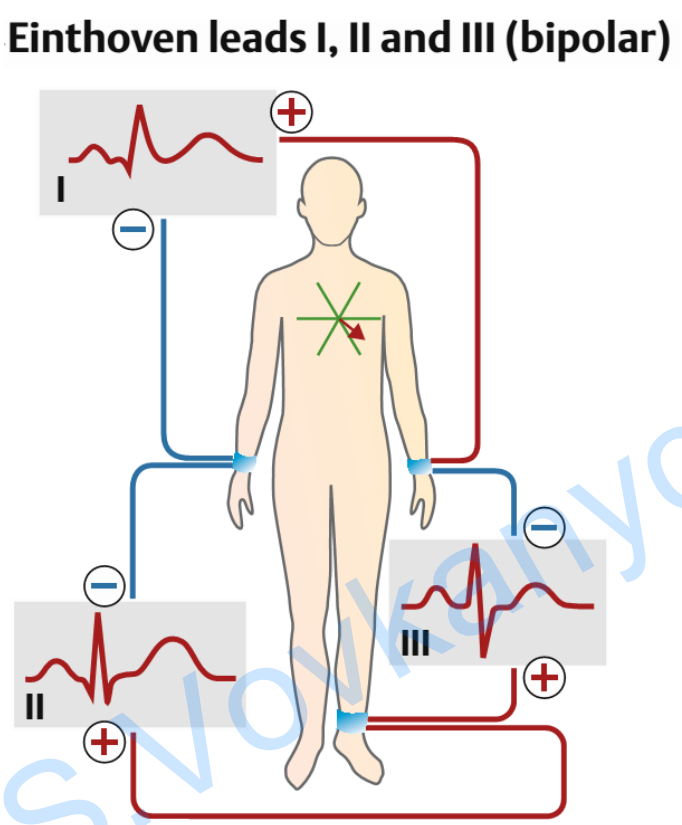


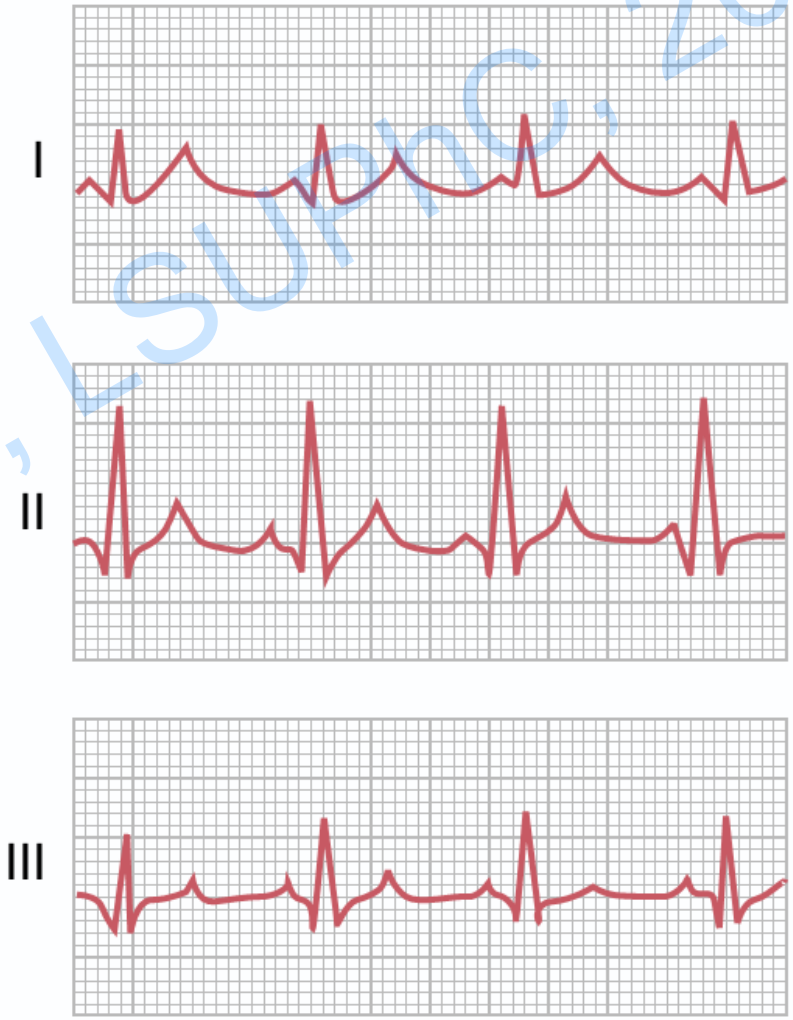
Electrocardiogram (ECG)

- Obtained by **electrodes** at specific body locations (leads)
- **Einthoven leads** I, II, and III are bipolar limb leads positioned in the frontal plane
- **Goldberger leads** (aVR, aVL, aVF) are unipolar augmented limb leads in the frontal plane
- **Wilson leads** (V_1–V_6) are unipolar chest leads positioned on the left side of the thorax in a nearly horizontal plane

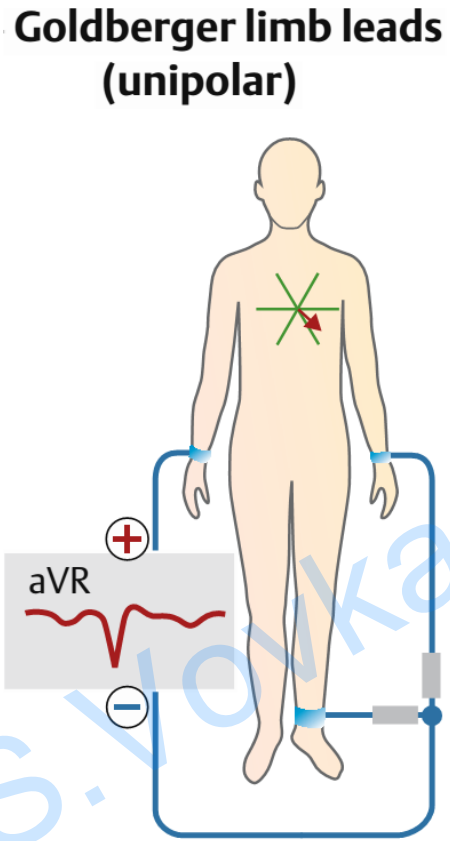


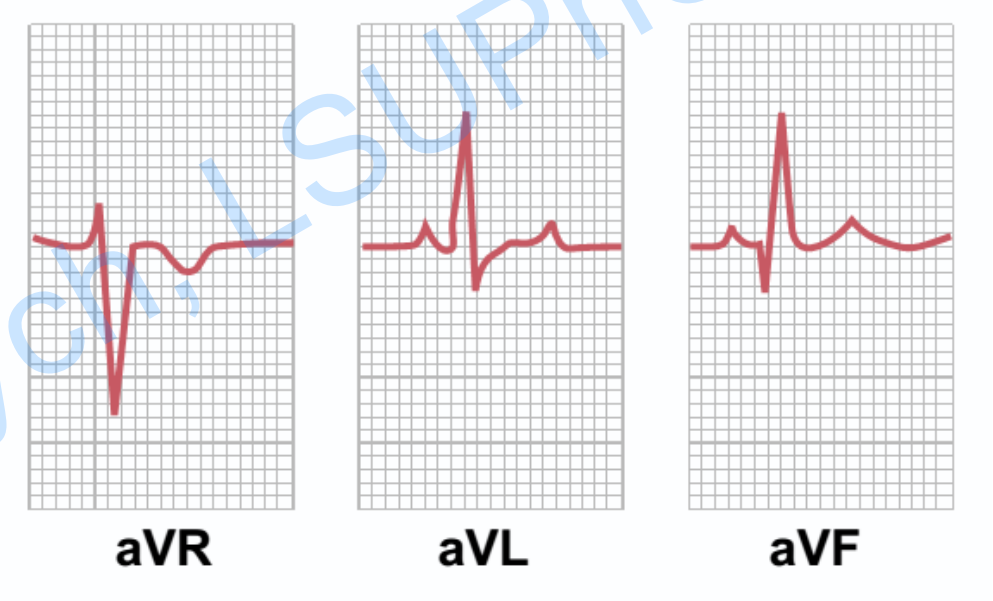
Einthoven Leads



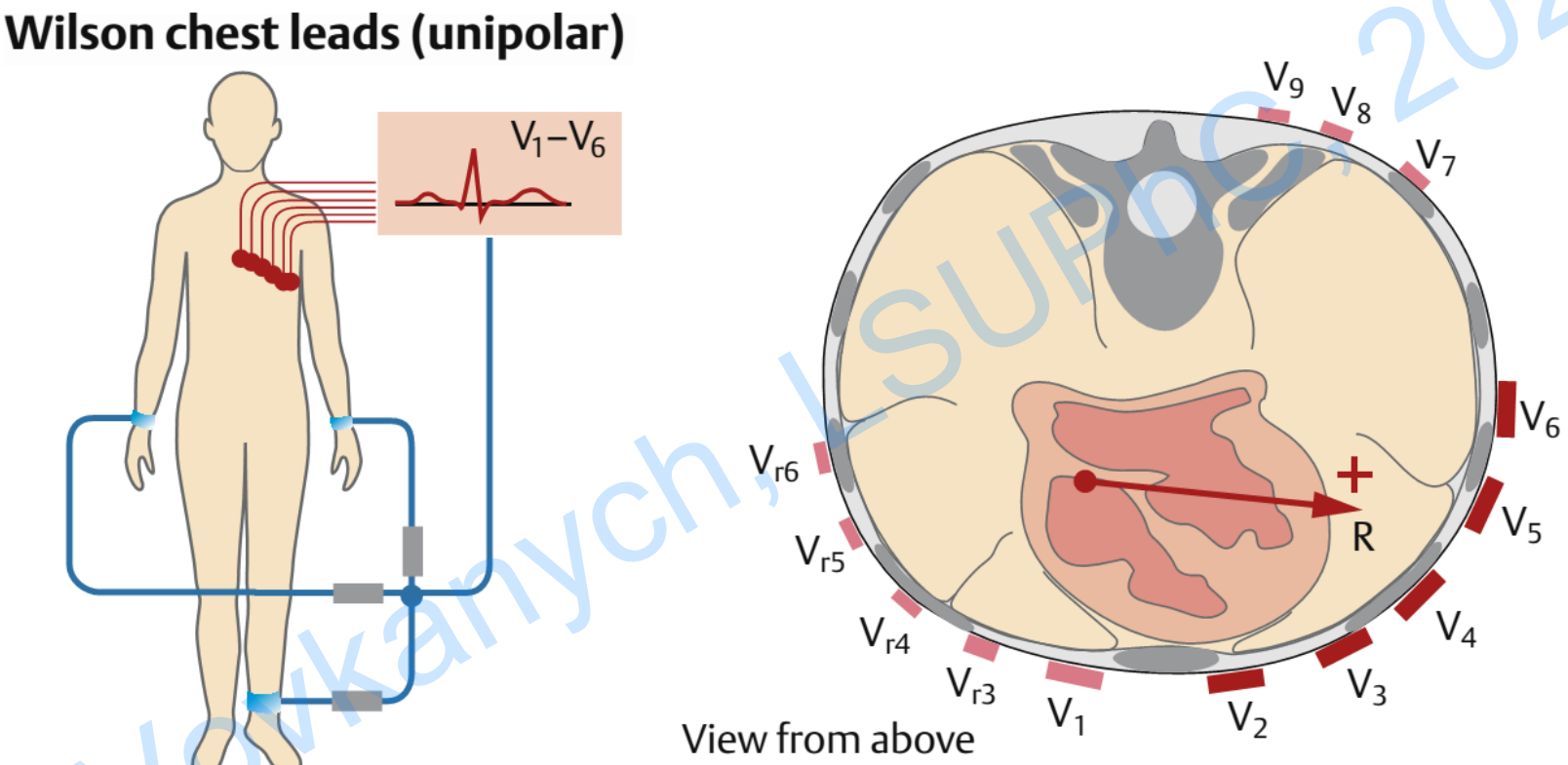


Goldberger Leads





Wilson Leads



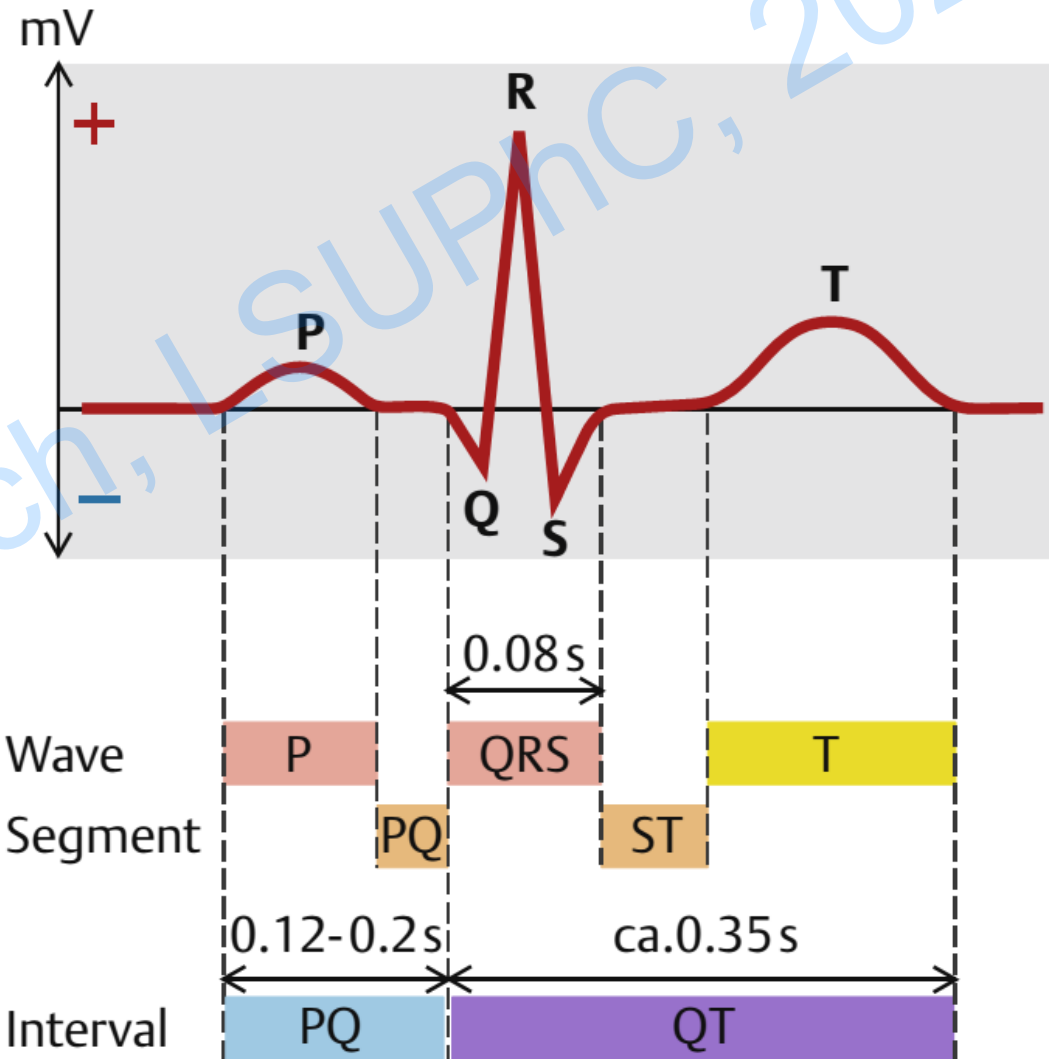
Electrocardiogram (ECG)

An ECG depicts electrical activity as **waves**,

segments, and

intervals,

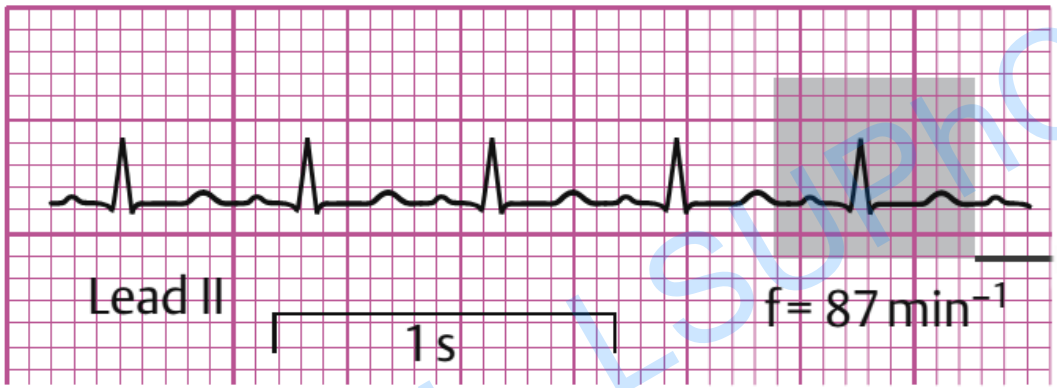
Upward deflection of the waves is defined as **positive**, and downward deflection as **negative**



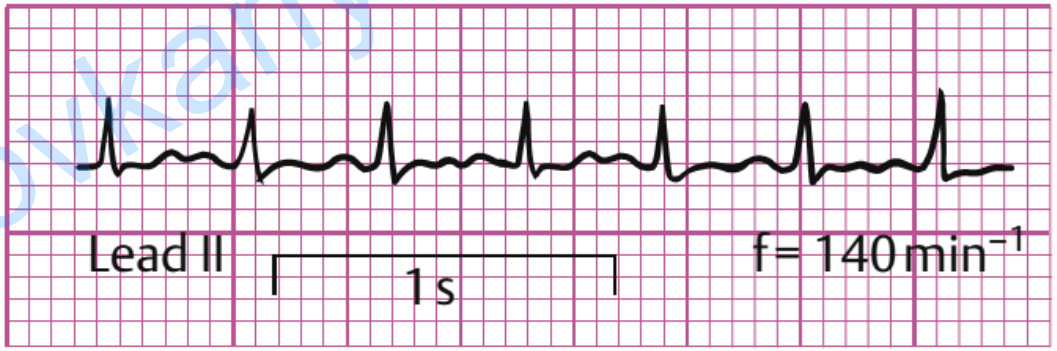
Waves and Segments of normal ECG

Wave/Segment	Cause	Duration (sec)	Amplitude (mV)
P wave	Atrial depolarization	0.1	0.1 to 0.12
P-R interval	Atrial depolarization and conduction through AV node	0.18 (0.12 to 0.2)	-
QRS complex	Ventricular depolarization and atrial repolarization	0.08 to 0.10	Q = 0.1 to 0.2 R = I S = 0.4
Q-T interval	Ventricular depolarization and ventricular repolarization	0.4 to 0.42	-
T wave	Ventricular repolarization	0.2	0.3

Electrocardiogram (ECG)

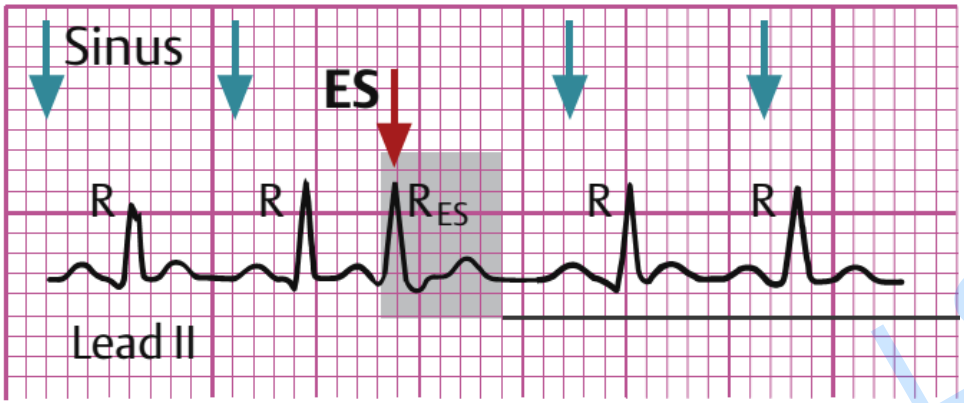


1 Normal sinus rhythm

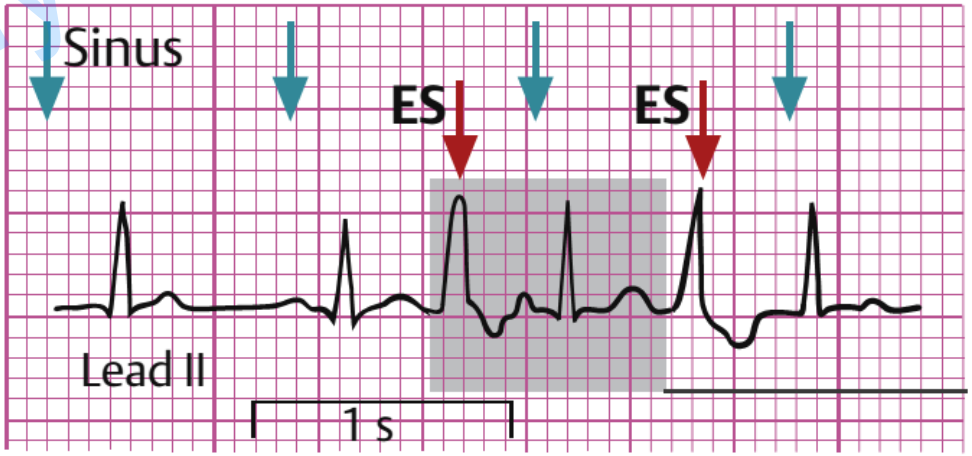


2 Sinus tachycardia

Electrocardiogram (ECG)



1 Nodal (AV) extrasystole (ES) with post-extrasystolic pause



2 Interpolated ventricular extrasystole (ES)

The Cardiac Cycle

Is the **sequence of coordinated events** taking place in the heart during each beat

Includes both contraction (**systole**) and relaxation (**diastole**)

At **75 beats per minute** cardiac cycle lasts about **800 msec**

When **heart rate increases** all phases of cardiac cycle **shorten**, particularly diastole

The Cardiac Cycle

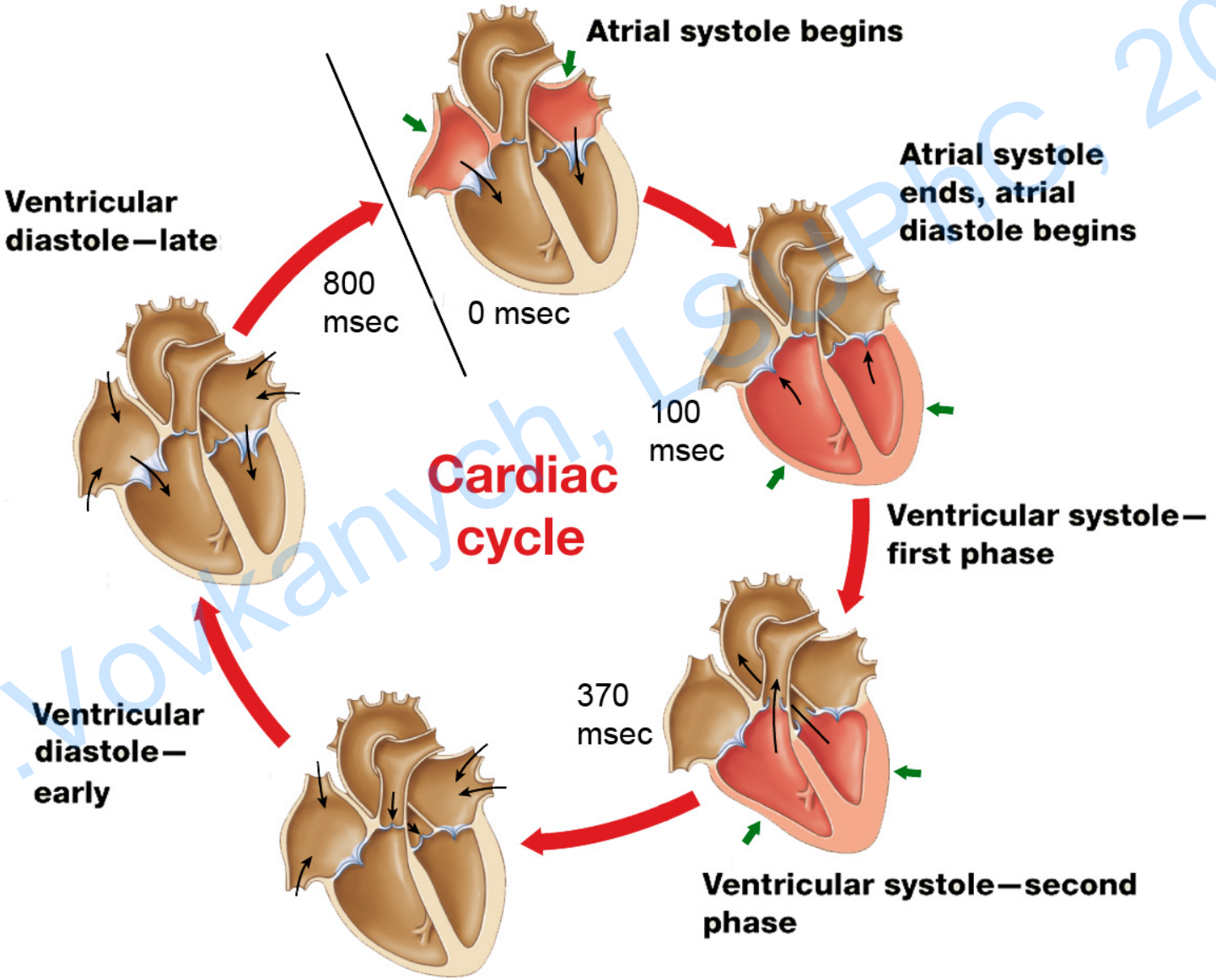
Systole (contraction):

- Myocardium **excitation**, myocardium **contraction**
- **Blood pressure** increase inside the chamber
- The **valve closes** (in one direction, by pressure gradient)
- The other **valve opens** (by pressure gradient)
- **Blood flows** out of chamber (from high to low pressure)

Diastole (relaxation)

- Myocardium **repolarization**, myocardium **relaxation**
- **Blood pressure** decrease inside the chamber
- The **valve closes** (in one direction, by pressure gradient)
- **Blood flows stop**
- The other **valve opens** (by pressure gradient)
- The **volume of chamber increase** due to the elasticity of walls
- **Blood flows into** chamber (from high to low pressure)

The Cardiac Cycle



Main Steps in the Cardiac Cycle

Atrial systole

- Atrial contraction begins
- Right and left AV valves are open

Atria eject blood into ventricles

- Filling ventricles

Atrial systole ends

- Ventricles contain maximum blood volume
- Known as end-diastolic volume (**EDV = 130-150 ml**)

Main Steps in the Cardiac Cycle

Ventricular systole, first phase

- **Isometric** (Isovolumetric) ventricular contraction
- Pressure in ventricles rises
- AV valves close (**First heart sound**)

Ventricular systole, second period (ejection)

- Semilunar valves open
- Blood flows into pulmonary and aortic trunks
- Stroke volume (**SV, 60-80 ml**) = 60% of end-diastolic volume

Main Steps in the Cardiac Cycle

Ventricular diastole, protodiastole

- Semilunar valves close (**Second heart sound**)
- Ventricles contain **end-systolic volume** (ESV), about 40% of end-diastolic volume

Ventricular diastole, early phase

- Ventricular pressure is higher than atrial pressure
- All heart valves are closed
- Ventricles relax (isovolumetric relaxation), pressure falls

Ventricular diastole, late phase

- AV valves open
- Rapid and slow passive atrial filling
- Passive ventricular filling

Duration of the Cardiac Cycle

Event	Heart rate 75 bpm	Heart rate 200 bpm
Duration of cardiac cycle, sec (% from HR 75 bpm)	0.80	0.30 (37%)
Duration of systole, sec	0.27	0.16 (59%)
Duration of action potential, sec	0.25	0.15 (60%)
Duration of absolute refractory period, sec	0.20	0.13 (65%)
Duration of diastole, sec	0.53	0.14 (26%)

Heart Sounds

Are produced by **mechanical activities** of heart during each cardiac cycle:

- **closure of valves** of the heart
- **flow of blood** through cardiac chambers
- **contraction** of cardiac muscle

Are heard by using a **stethoscope** (first and second) or recorded by **microphone** (four sounds)

Heart Sounds

First sound - S_1

- Loud sounds, long, soft and low pitched, resembles ‘LUBB’
- Produced by closing of AV valves at the start of isometric contraction period of ventricles
- Coincides with peak of R wave on ECG

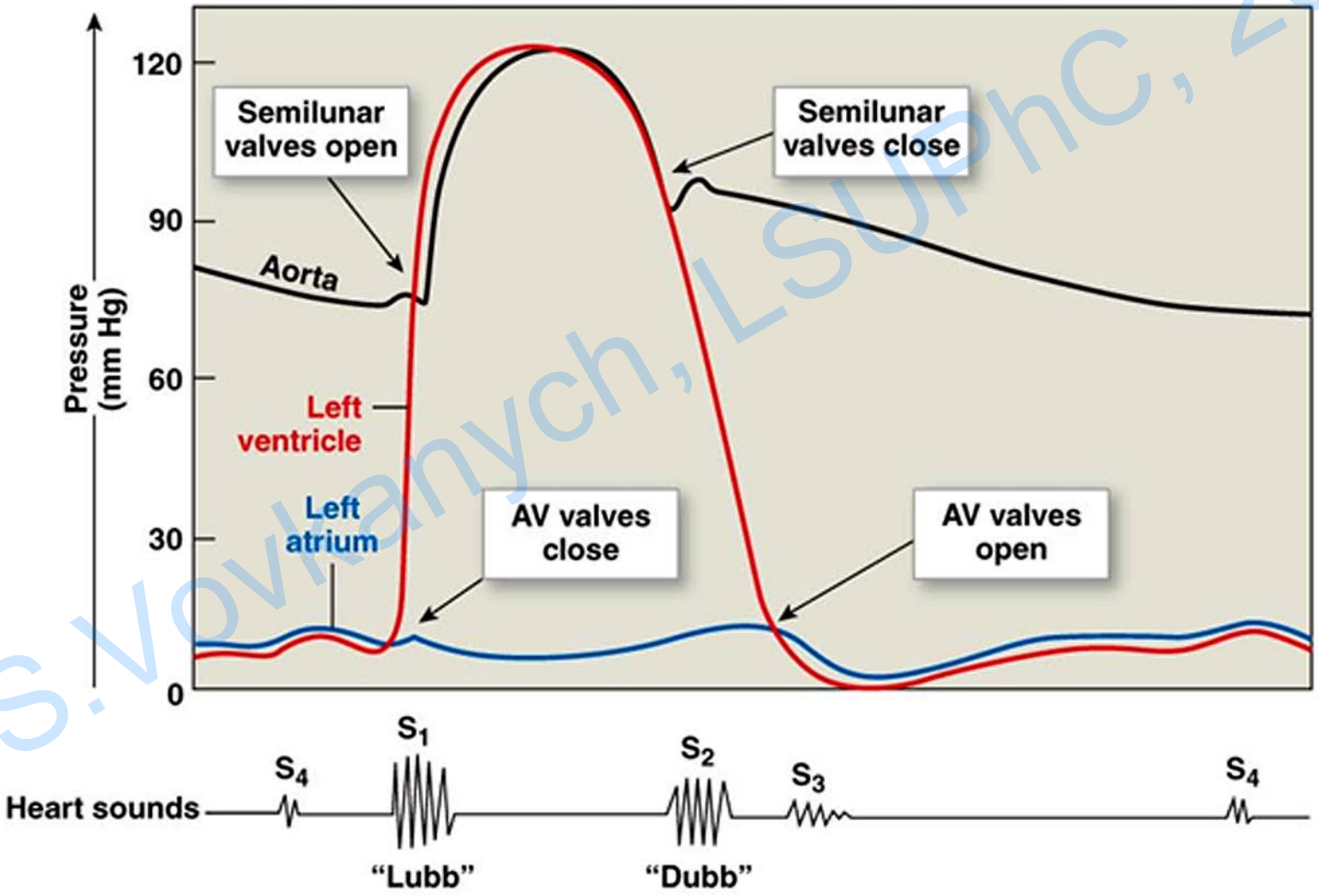
Second sound - S_2

- Loud sounds, short, sharp and high pitched , resembles ‘DUP’
- Produced by closing of semilunar valves, start of protodiastole phase
- Near the peak of T wave of ECG

Third and fourth sounds - S_3, S_4

- Soft sounds
- Blood flow into ventricles and atrial contraction

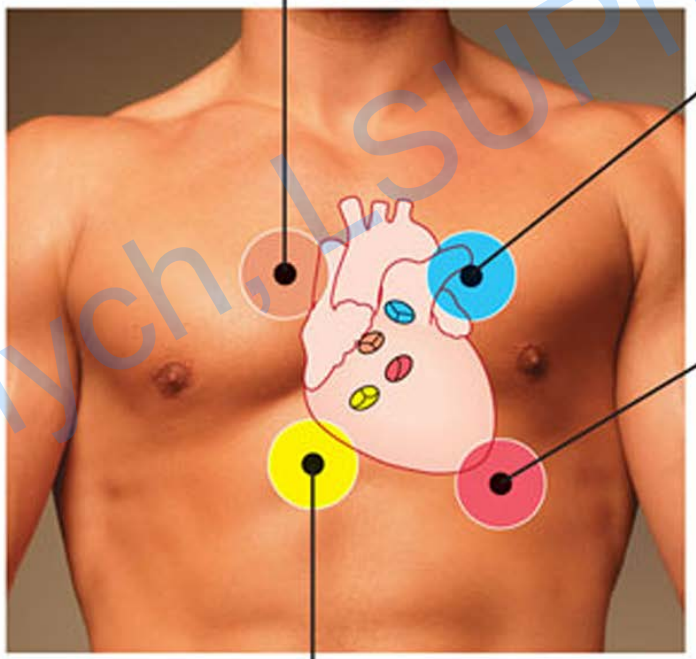
Heart Sounds



Methods of Study of Heart Sounds

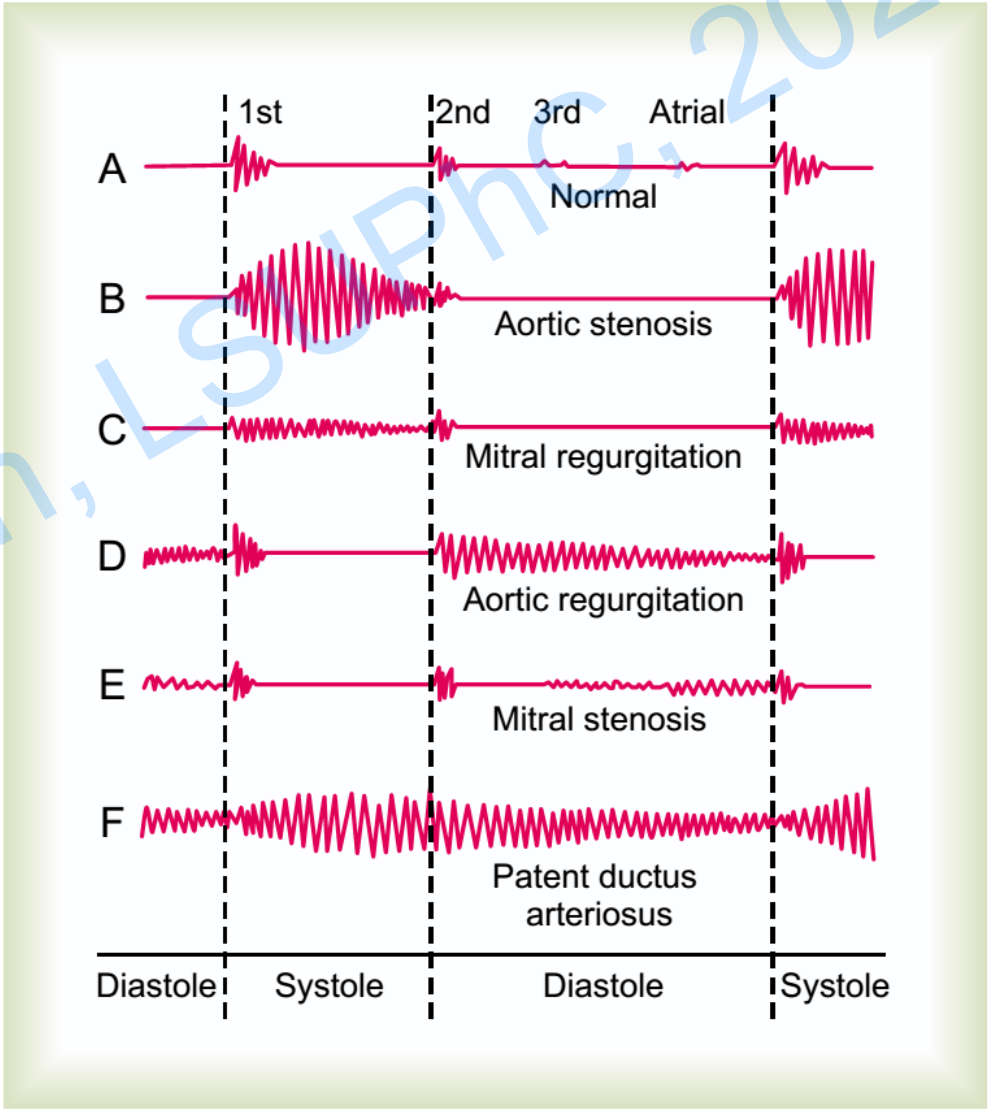
Heart sounds are studied by **three methods**:

1. By using **stethoscope**
2. By using **microphone**
3. By using **phonocardiogram**



Sounds of Normal and Abnormal Heart

- **Splitting of S_1** - stenosis of AV valves and atrial septal defect
- **Splitting of S_2** - asynchronous closure of semilunar valves
- **Heart murmur** (pathological sounds) - produced by regurgitation of blood through valves
- Murmur is produced because of **valvular diseases**, **septal defects** and **vascular defects**

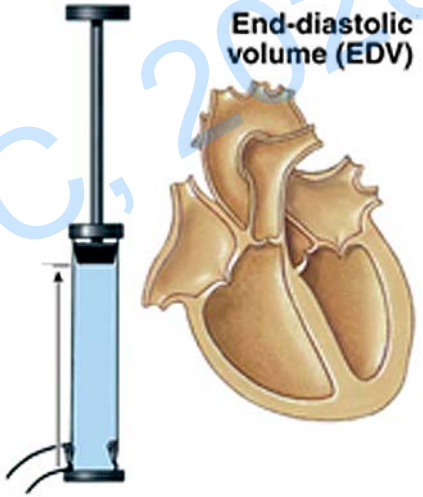


Main Indices of Heart Functioning

- **Heart rate** (HR, beats/min, bpm)
- **Stroke volume** (SV, mL, mL/beat)

SV = EDV – ESV

  - End-diastolic volume (EDV, mL)
  - End-systolic volume (ESV, mL)

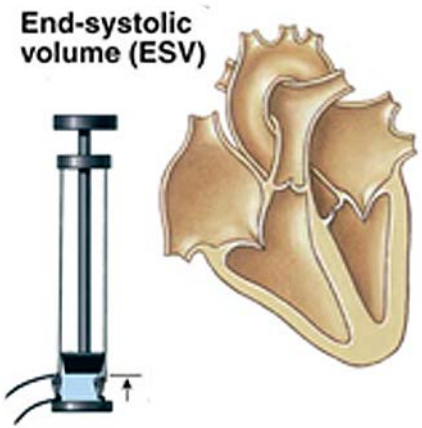


- **Ejection fraction** (EF, %) - the percentage of EDV represented by SV

EF = 100 * (SV / EDV)

- **Cardiac output** (CO, mL/min) - the volume pumped by left ventricle in 1 minute

CO = HR * SV



End-diastolic Volume

- The **End-diastolic volume** (**EDV)**: amount of blood a ventricle contains at the end of diastole
- Depends on
  - **filling time** (duration of ventricular diastole)
  - **venous return** (rate of blood flow during ventricular diastole)
- **Preload** - the degree of ventricular stretching during ventricular diastole, is directly proportional to EDV
- At **rest** EDV is low, with **exercise** EDV increases
- **Ejection fraction** is the fraction of end diastolic volume that is ejected out by each ventricle (normal value - 60% to 65%)

EF = **100 * (SV / EDV)**

End-systolic Volume

- The **End-systolic volume (ESV)** - the amount of blood that remains in the ventricle at the end of ventricular systole
- Factors that affect ESV:
  - **preload** - ventricular stretching during diastole (depends on EDV, changes the contractility)
  - **contractility** - force produced during contraction, at a given preload
    - The Frank–Starling Principle: as EDV increases, stroke volume increases
  - **Afterload** - tension the ventricle produces to open the semilunar valve and eject blood
    - As afterload increases, stroke volume decreases

Indices

- **Stroke volume** (SV) is the amount of blood pumped out by each ventricle during each beat (normal value at rest: 60 - 80 mL)

  SV = EDV – ESV

- **Cardiac output** (CO) or minute volume is the amount of blood pumped out by each ventricle in one minute (normal value at rest: 5 L/minute)

  CO = HR * SV

- **Cardiac index** - minute volume per square meter of body surface (normal value at rest: 2.8 ± 0.3 L/square meter)
- **Cardiac reserve** is the maximum amount of blood that can be pumped out by heart above the normal value. In a normal young healthy adult – 15 L/minute (300%)

Regulation of Heart Functioning

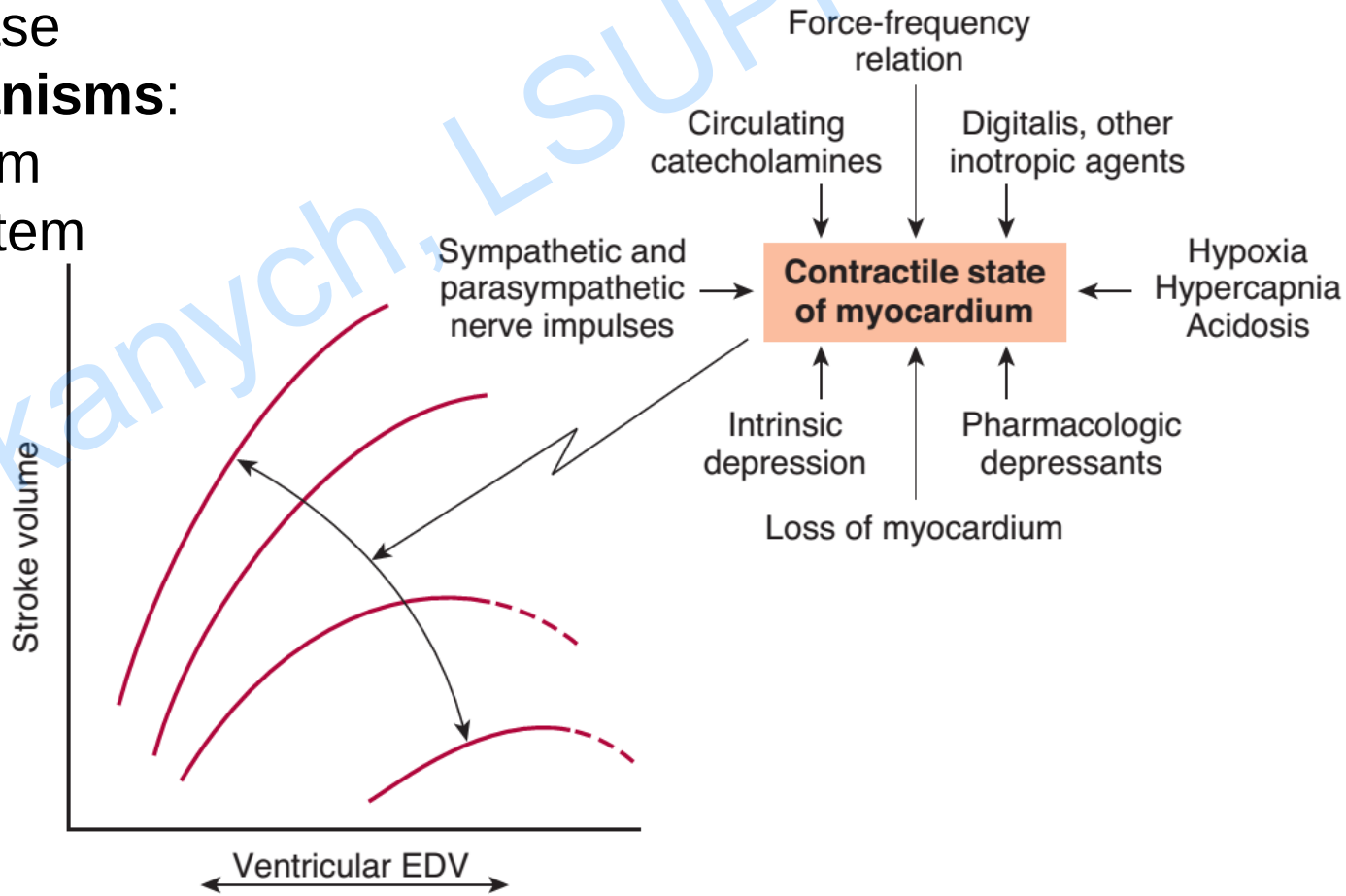
Intrinsic mechanisms:

- Staircase phenomenon
- Frank-Starling law
- Increase of contraction force

if afterload increase

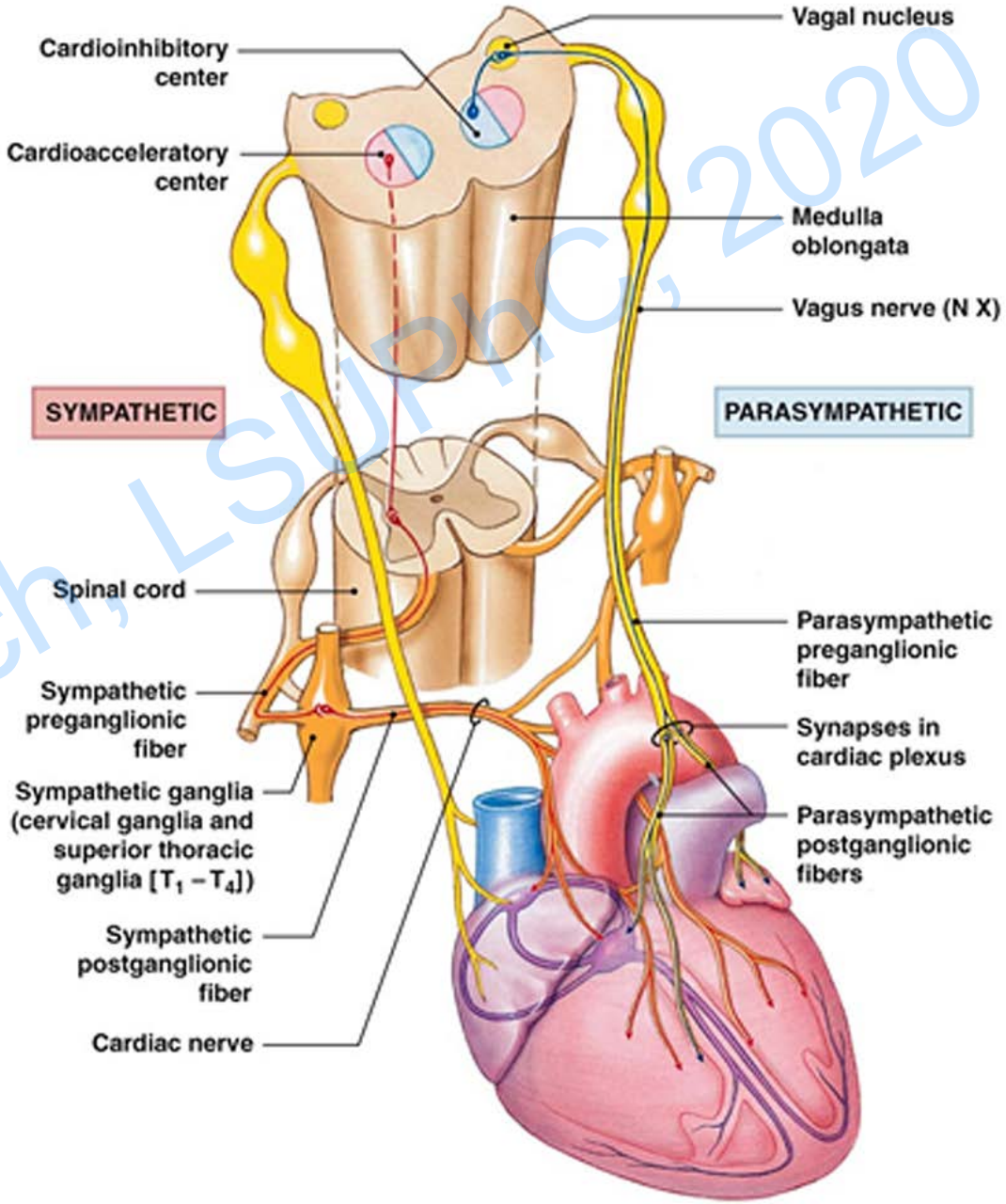
Extrinsic mechanisms:

- Nervous system
- Endocrine system



Vasomotor Center

- **Nervous center** that regulates the heart rate and the blood pressure
- Located in the reticular formation of **medulla oblongata**
- Heart receives **efferent nerves** from both the divisions of **autonomic nervous system**

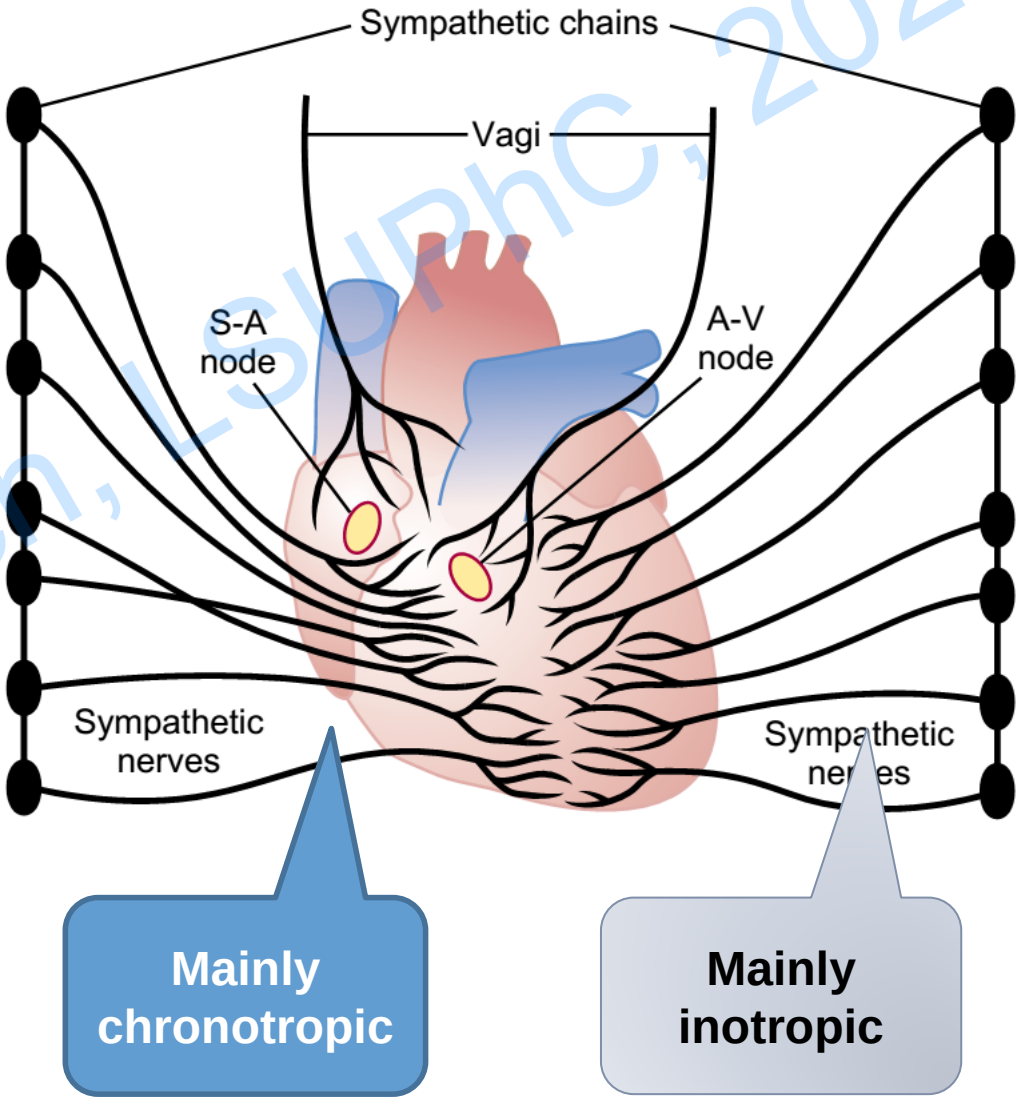


Nerve Regulation

Parasympathetic fibers - from the medulla oblongata by **vagus nerve,** have the cardioinhibitory effects

Sympathetic fibers - from upper thoracic (T1 to T4) segments of spinal cord, have the cardioaccelerating effects:

- increase the cardiac rate (**chronotropic** effect),
- conductivity (**dromotropic** effect)
- force of contraction (**inotropic** effect)



Control of Vasomotor Center

Baroreceptors - give response to change in blood pressure. Main locations:

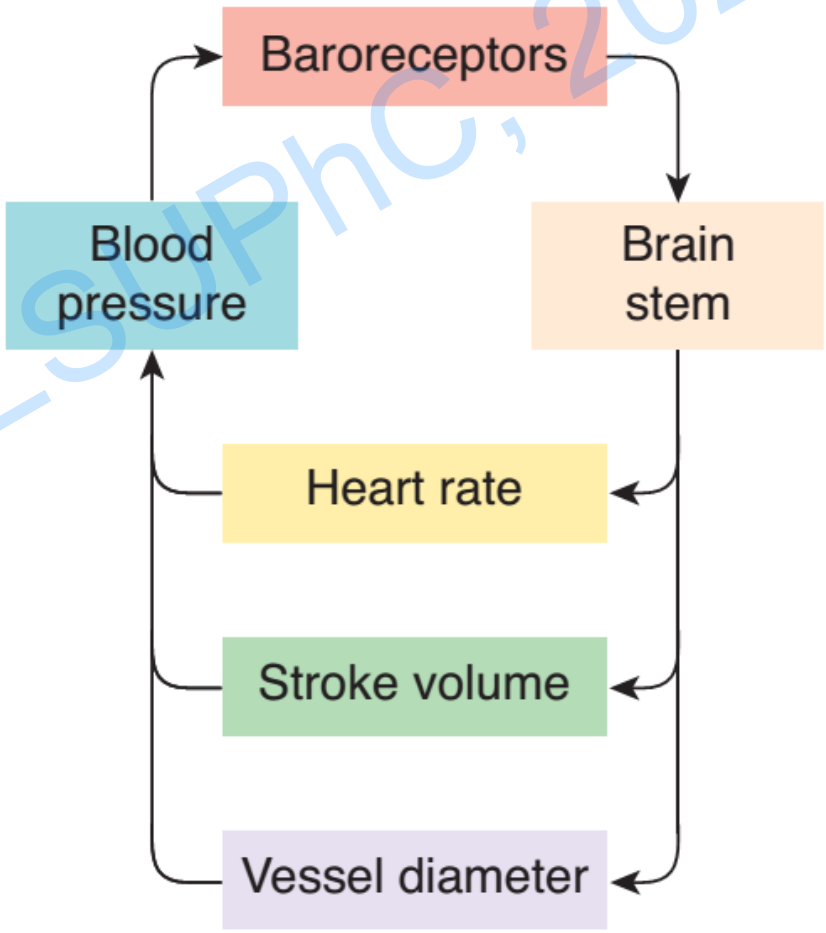
- Carotid baroreceptors
- Aortic baroreceptors

Main reflex - Marey reflex (decreases heart rate when blood pressure increases)

Stretch receptors – responded on the stretch of the wall of blood vessels or heart chambers.

Location: wall of right atrium

Main reflex - Bainbridge reflex (increases the heart rate when venous return is increased)



Control of Vasomotor Center

- Mainly controlled by the impulses from **higher centers** in cerebral cortex and hypothalamus
- Interaction with **respiratory center** - heart rate increases during inspiration and decreases during expiration. It is called respiratory sinus arrhythmia
- Influence of **chemoreceptors** impulses. In the case of hypoxia, hypercapnea and increased hydrogen ions concentration in the blood vagal tone decreases and heart rate increases

Endocrine System Effect

- Hormonal Effects on Heart Rate
- Increase heart rate (by sympathetic stimulation of SA node)
- Epinephrine (E)
- Norepinephrine (NE)
- Thyroid hormone

Effect of Changes in Electrolyte Concentration on Heart

Changes in **Sodium** ion concentration - no significant effect, very low level reduces the electrical activity of cardiac muscle

Changes in **Potassium** ion concentration (normally 3.5 to 5 mEq/L)

- **hyperkalemia** (> 6 mEq/L) – decreases the excitability of the myocardium, ECG changes, ventricular fibrillation or stoppage of heart (if > 9 mEq/L)
- **hypokalemia** (< 2 mEq/L) - decreases the sensitivity of heart muscle, changes on ECG

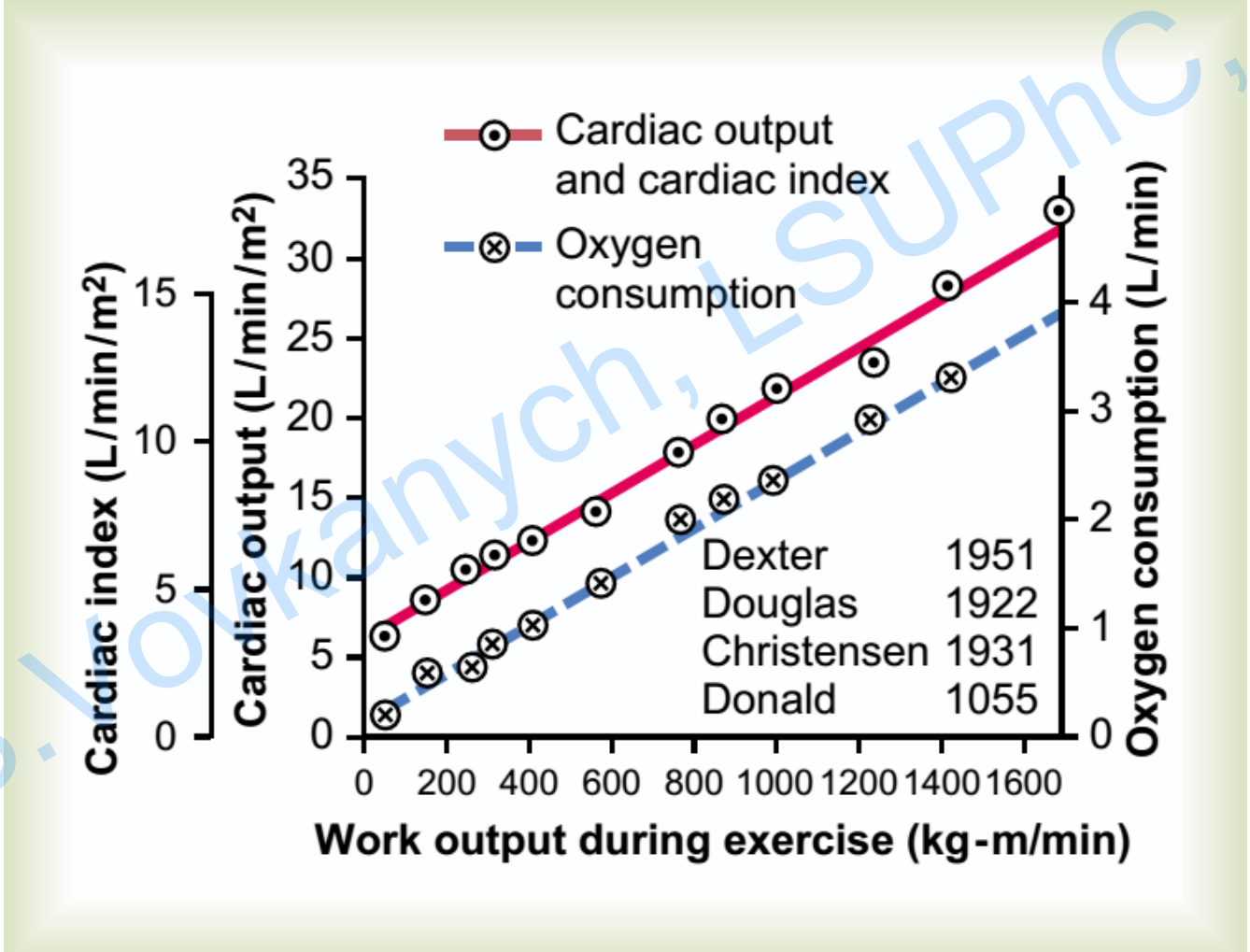
Changes in **Calcium** ion concentration (4.5 to 5.5 mEq/L)

- **hypercalcemia** (is very rare) - increases the excitability and contractility of myocardium (in experimental animals by infusing large quantity of calcium - stoppage of the heart in systole)
- **hypocalcemia** - reduces the excitability of the cardiac muscle

Effect of Exercise on Cardiac Output

Work (kg/min)	HR (bpm)	SV (mL)	CO (L/min)	O_2 uptake (mL/min)
rest	64	100	6.4	267
288	104	126	13.1	910
540	122	125	15.2	1430
900	161	110	17.8	2143
1260	173	120	20.9	3007

Effect of Exercise on Cardiac Output



References

Martini R., Nath J. **Fundamentals of Anatomy & Physiology.** Eighth Edition

Guyton, Arthur C. **Textbook of medical physiology** / Arthur C. Guyton, John E. Hall. - 11th ed.

Sembulingam K., Sembulingam P. **Essentials of Medical Physiology**. Sixth Edition

Scanlon, Valerie C. **Essentials of anatomy and physiology** / Valerie C. Scanlon, Tina Sanders. — 5th ed.

Fox: Human Physiology. Eighth Edition

Silbernagl S., Despopoulos A. **Color Atlas of Physiology.** 6th edition