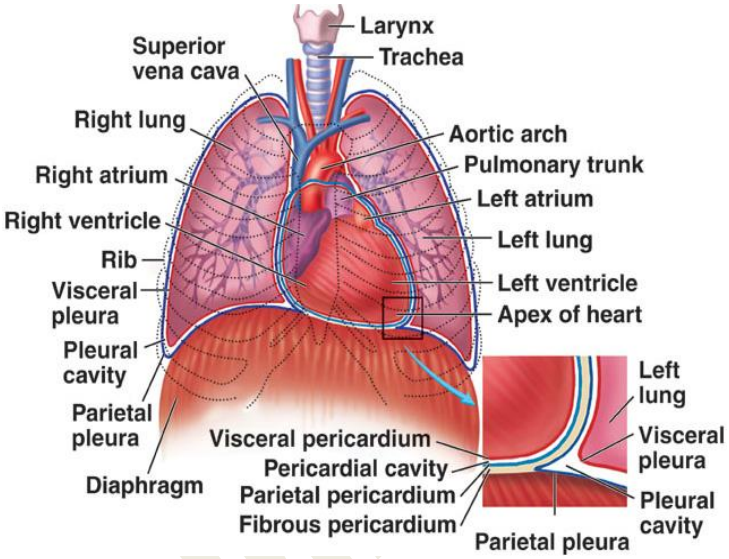
PHYSIOLOGY OF CARDIOVASCULAR SYSTEM

Cardiovascular system includes heart, arteries, veins, & lymph vessels.

Function of Cardiovascular System

- Transportation, everything transported by the blood
- Regulation of the cardiovascular system, intrinsic vis extrinsic
- Protection, against blood loss
- Production (enzymes &hormones)



The Heart

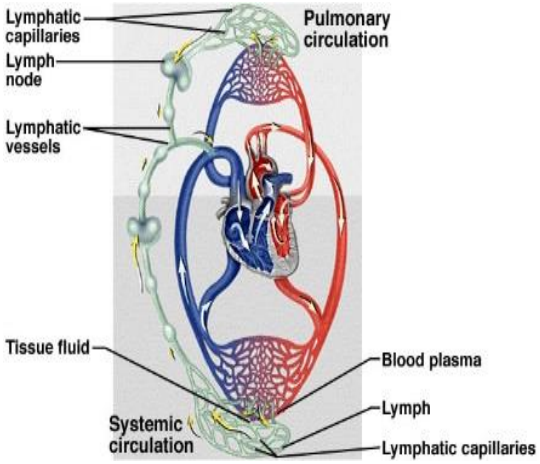
- Located in thoracic cavity in mediastinum
- The heart has a size of a closed fist, with apex: blunt rounded point of cone & the base: flat part at opposite end of cone.

Interesting Facts:

- The heart beat is strong enough to jet blood 30 feet
- The longer a boy's ring finger is, the less likely they are to have a heart attack (according to one study)
- Most heart attacks occur between 8-9 a.m.
- Entire volume of blood goes through your entire body once every minute
- Humans have ~60,000 miles of blood vessels in their bodies (more than twice the circumference of the earth!)
- Heart beats 100,000 times and pumps ~2000 gallons of blood every day
- Pig and baboon hearts have been transplanted into humans
- Give a tennis ball a good, hard squeeze. You are using about the same amount of force your heart uses to pump blood out to the body.
- Even at rest, the muscles of the heart work hard—twice as hard as the leg muscles of a person sprinting.

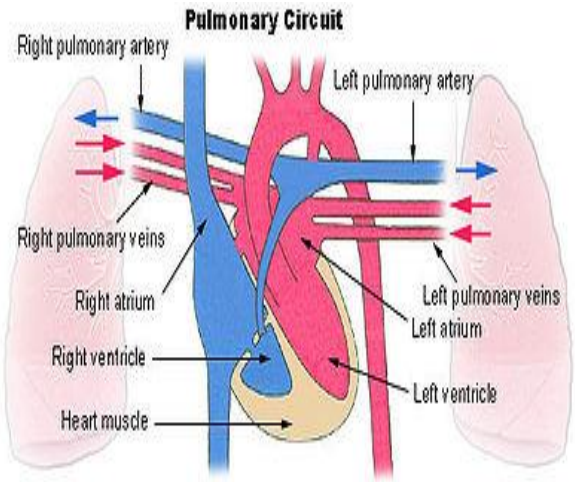
The Closed Circulatory System

Human have a closed circulatory system, in which blood is confined to vessels and is distinct from the interstitial fluid. The heart pumps blood into large vessels that branch into smaller ones leading into the organs. Materials are exchanged by diffusion between the blood and the interstitial fluid bathing the cells. During one complete circulation of the human body, blood travels twice through the heart.



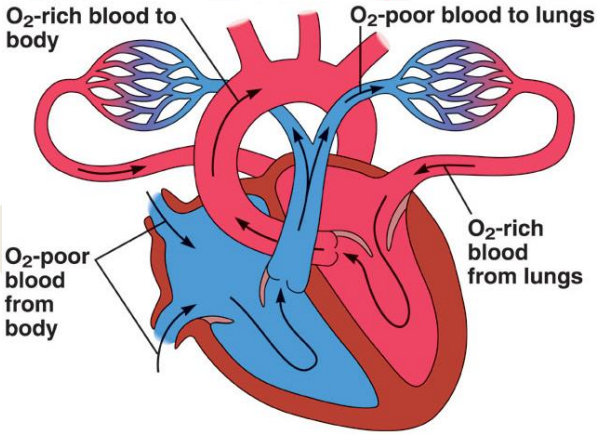
Pulmonary circuit

The blood pathway between the right side of the heart, to the lungs, and back to the left side of the heart. This oxygenated blood returns from the lungs through the pulmonary veins, which empty the content into the left atrium.



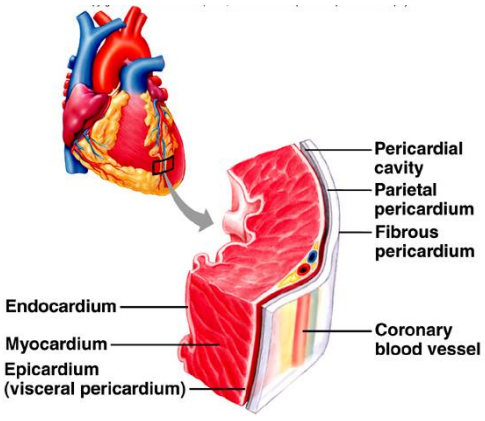
Systemic circuit

The pathway between the left and right sides of the heart. When left atrium is full, it contracts forcing blood into the left ventricle and then left ventricle contracts forcing blood into aorta. From the left ventricle, the blood is pumped to different parts of the body through aorta. When deoxygenated blood returns through the main veins (inferior & superior vena cava) to the right atrium, the double circulation is complete.



Functions of the Heart

- Generating blood pressure
- Routing blood, heart separates pulmonary and systemic circulations
- Ensuring one-way blood flow, heart valves ensure one-way flow
- Regulating blood supply, changes in contraction rate and force match blood delivery to changing metabolic needs



Heart Wall

Three layers of tissue

1- Pericardium: A thin, fibrous, double-layered sac surrounds the heart. Outer layer is *parietal* , and inner layer is the *visceral.* Epicardium is a serous membrane of smooth outer surface of heart.

2- Myocardium: Middle layer composed of cardiac muscle cell and responsibility for heart contracting

3- Endocardium: Smooth inner surface of heart chambers



Cardiac Muscle

- Branched interconnected
- Intercalated disks: specialized cell-cell contacts

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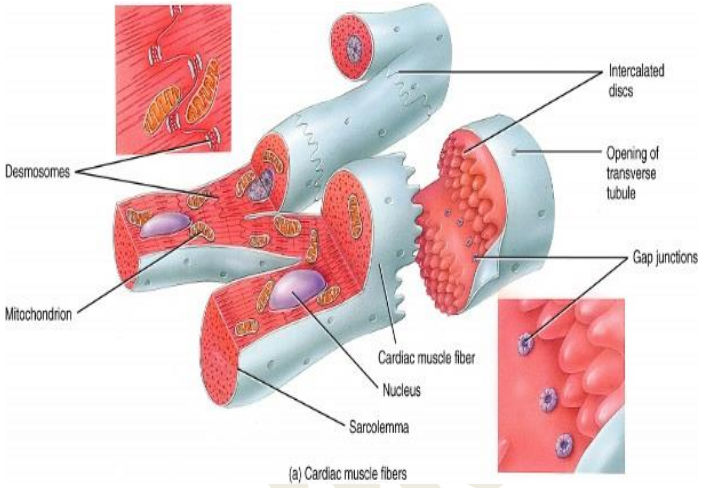
- Desmosomes hold cells together and gap junctions allow action potentials.
- Electrically, cardiac muscle behaves as single unit (syncytium).
- The individual fibers are separated by membranes, but depolarization spreads radially through them as if they were a syncytium because of the presence of "gap junctions".



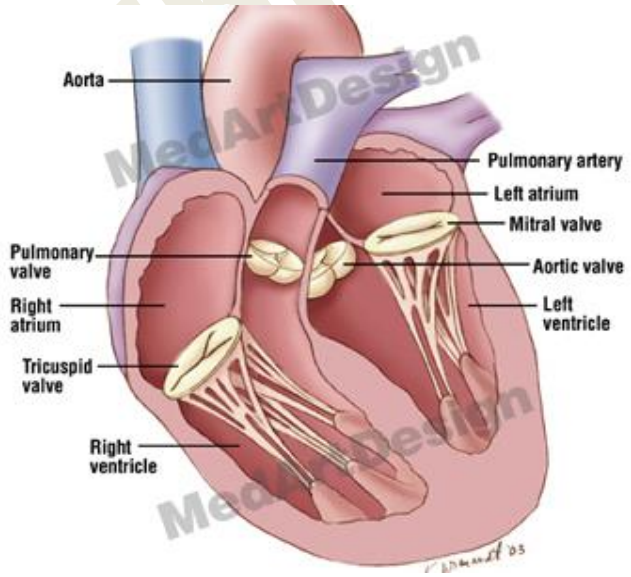
Regeneration of heart muscle cells

Until recently, it was commonly believed that cardiac muscle cells could not be regenerated. However, a study reported in the 2009. The researchers estimated that a 20 y old renews ≈ 1% of heart muscle cells per year, and 45 % of the heart muscle cells of a 50 y old were generated after born.

Heart Chambers

The heart has four chambers:

- Two atria: top of heart
  - Receive blood from veins
- Two ventricles: bottom of heart
  - pump blood through arteries



Septum: divides left from right heart

Valves: keep blood flowing in one direction

Four valves: two AV valves & 2 semilunar valves

Atrioventricular Valves

Act to prevent blood from flowing back.

AV valves: between atria &ventricles, When valves are open blood drains from atria into ventricle. When ventricle contract, valve flaps are forced shut, blocking blood from reentering atria.

Semilunar Valves

Aortic & pulmonary valves prevent backflow into ventricles. Located in arteries leaving ventricles:

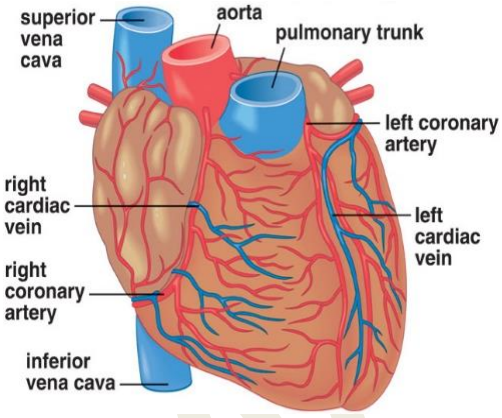
Pulmonic valve: at base of pulmonary artery.

Aortic valve: at base of aorta. When ventricles contract, valves are forced open & let blood flow. When ventricles relaxes, backflow of blood fills flaps of valve & forces them to shut.

Blood Flow to the Heart

Right & left coronary arteries (arise at base of aorta) while cardiac veins join to form

coronary sinus to empty into Rt atrium.



Workloads

Systemic circulation is 5 times as much resistance to blood flow as pulmonary circulation due to longer route and so; left ventricle is much larger & thicker to do more work

Properties of Cardiac Muscle Fibers

1. **Autorhythmicity:** The ability to initiate a heartbeat continuously and regularly without external stimulation
2. **Excitability:** The ability to respond to a stimulus of adequate strength and duration (i.e. threshold or more) by generating a propagated action potential
3. **Conductivity:** The ability to conduct excitation through the cardiac tissue
4. **Contractility:** The ability to contract in response to stimulation

Contraction:

- All cardiac muscle cells contract as a single unit
- Autorhythmicity
- Long refractory period: No tetanic contractions.

Cardiac muscle fibers are of two types:

-Autorythmic fibers (pacemaker cells) 1% of heart muscle, depolarize spontaneously

-Contractile muscle fibers: depolarize with pacemaker cell activities 99%.

Autorythmic fibers: have two important functions:

1. Act as pacemaker (set the rhythm of electrical excitation)
2. Form the conductive system (network of specialized cardiac muscle fibers that provide a path for each cycle of cardiac excitation to progress through the heart).

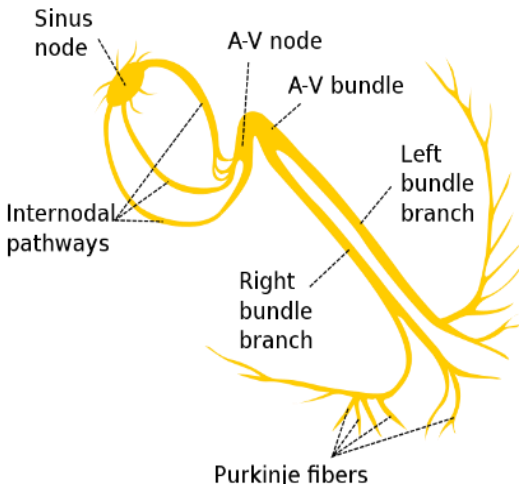
Characteristics of pacemaker cells:

- Smaller than contractile cells
- Don't contain many myofibrils
- No organized sarcomere structure
- Don't contribute to the contractile force of the heart

Intrinsic conduction system:

It consisting of autorhythmic, unstable RMP with pacemaker potentials. It includes the:

1. Sinoatrial (SA) node
2. Atrioventricular (AV) node



3. Atrioventricular bundle (of His)
4. Bundle branches & Purkinje fibers.

- **SAN** (Heart's Pacemaker): It situated in Rt atrium, normally sets the pace of 60 – 70 b/min but can increase rate when stimulated by drugs, fever, or sympathetic NS. Fastest cells in the system.
- **AVN**: lies between atria & ventricles, intrinsic rate of 40 – 60 b/min. Special tissues transmit signal from SA to AVN.
- **Bundle of His:** Transmits impulse to ventricles, rate is 30–40 b/m.
- **Bundle Branches:** within ventricular muscles, rate 20–30 b/m.
- **Purkinje fibers**: terminal end of branches.
  - If SAN is damaged or its signal is blocked, the AVN takes over setting the pace (40-60/min)
  - If AVN is next damaged, the bundles set the rate (20 – 40/min)

What is a Pacemaker?

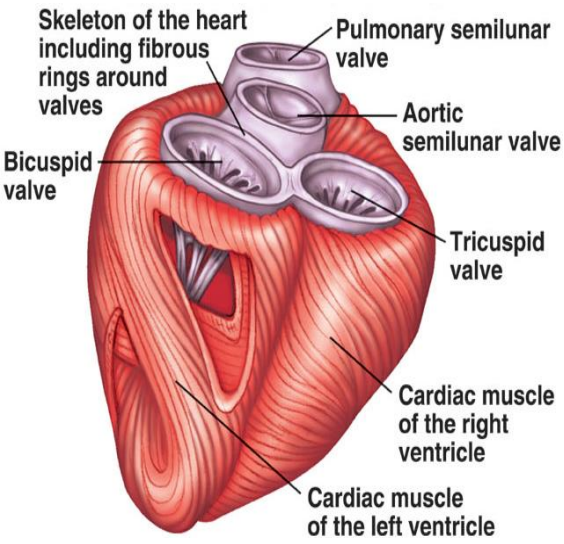
If heart is unable to generate impulse, or pace is too slow, mechanical pacemaker is surgically implanted to provide artificial impulses

Heart Skeleton

Consists of plate of fibrous tissue between atria & ventricles**.** Forming a fibrous rings around valves to support**.** It serves as electrical insulation between atria & ventricles and provides site for muscle attachment**.**

Cardiac muscle is highly resistant to fatigue. Why?

- It has a large number of mitochondria.
- Numerous myoglobin (O_2-storing pigment)
- A rich blood supply, which provides nutrients and oxygen enabling *continuous aerobic respiration* via oxidative phosphorylation.
- Prolonged action potential.
- Presence of refractory period.



Cardiac Cycle (Coordinating the activity)

It is the sequence of events as blood enters the atria, leaves the ventricles & then starts over. Synchronizing this is the ''Intrinsic Electrical Conduction System''.Influencing the rate (chronotropy & dromotropy) is done by the sympathetic and parasympathetic divisions of the ANS. The cardiac cycle is the order of events making up one heartbeat. Cycle lasts for approx. 0.8 seconds and occurs approx. 72 times a minute. Cardiac cycle

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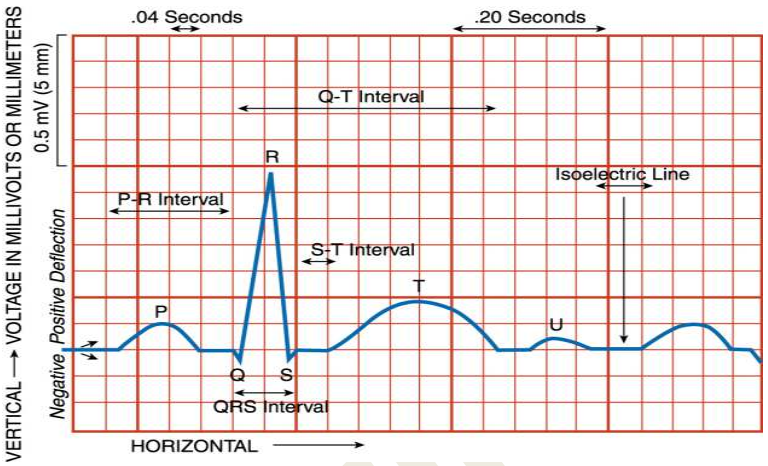
includes a period of relaxation, known as diastole (0.5 secs), followed by a period of contraction, known as systole (0.3 secs)

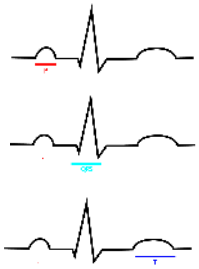
Electrocardiogram (ECG):

An electrocardiogram is a recording of the electrical changes that occur in the myocardium during a cardiac cycle.



Normal ECG waves, segments & intervals

ECG Waves

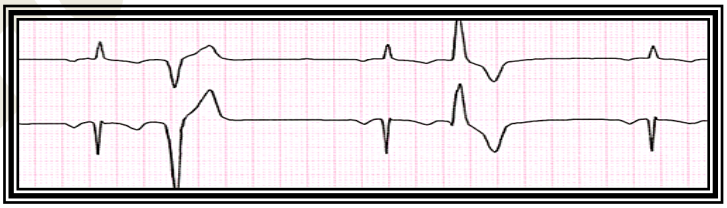


P wave: Depolarization moving from SA node through atria

QRS complex: Ventricular depolarization precedes contraction

T wave: Ventricular repolarization,

- Normal heart rate is 60-80. If the rate is more than 100 b/m, the condition then called sinus tachycardia. If the rate is lower than 60 b/m then the condition called sinus bradycardia
- Ectopic beat: any discharge from an abnormal focus, could be atrial or ventricular in origin.

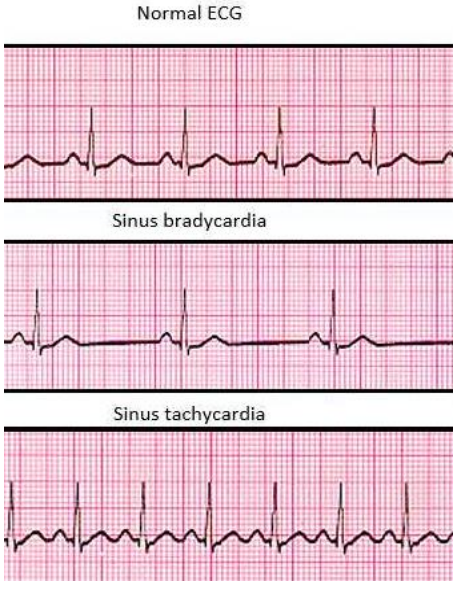


Sinus Tachycardia:

- Rate ≥100 beats/minute, regular rhythm.
- All intervals are within normal limits
- There is a P for every QRS and a QRS for every P
- The P waves all look the same
- Causes: fever, stress, caffeine, nicotine, exercise, or sympathetic tone.

Sinus Bradycardia:

- Rate is ≤60 beats/minute, regular rhythm.



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- All intervals are within normal limits
- There is a P for every QRS and a QRS for every P
- The P waves all look the same
- Causes: drugs, athletes or parasympathetic tone.

Sinus Arrhythmia:

- Rate is between 60 and 100 beats/minute
- The rhythm is irregular, SAN rate increase or decrease with respirations
- All intervals are within normal limits
- There is a P for every QRS and a QRS for every P
- The P waves all look the same
- More common in children and athletes



Heart Rate regulation:

A. Neural mechanisms
B. Chemical mechanisms
C. Physical mechanisms

A. Neural mechanisms:

- Central hypothalamic centers: - Cardioaccelatory center; increase the HR.
  - Cardioinhibitory center; decrease the HR.
- Peripheral autonomic nervous system (ANS): Sympathetic & Parasympathetic.

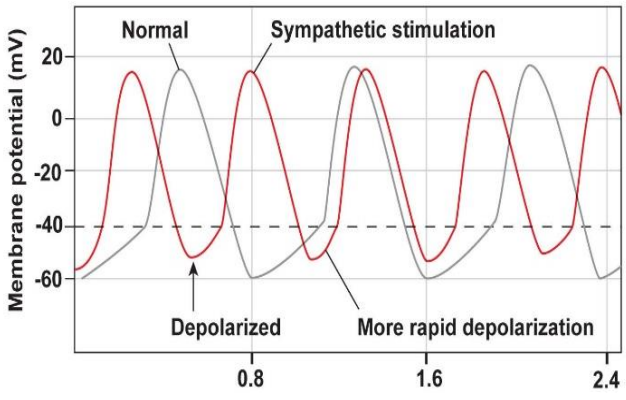
Sympathetic Activity Summary	**Parasympathetic Activity Summary**
Increased chronotropic effects	Decreased chronotropic effects
↑heart rate	↓heart rate
Increased dromotropic effects	Decreased dromotropic effects
↑conduction of Aps	↓ conduction of Aps
Increased inotropic effects	Decreased inotropic effects
↑contractility	↓ contractility

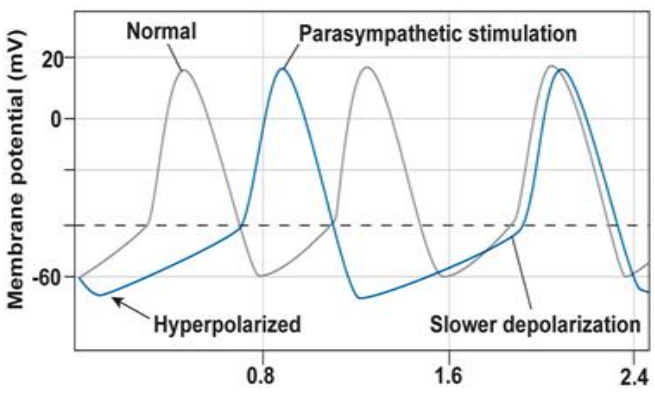
Parasympathetic:

Secretes acetylcholine (slows rate). It cause hyperpolarization, so **IF** increase (↓ HR) or decrease (↑ HR). From medulla oblongata (vagus nerve) to SAN &AVN.

Sympathetic:

From sympathetic ganglia, caused by flight, fright, fight and sex, Secrets noradrenaline at cardiac targets. Cause depolarization, so **IF** increase (↑HR) & ↑Ca^{2+} influx.





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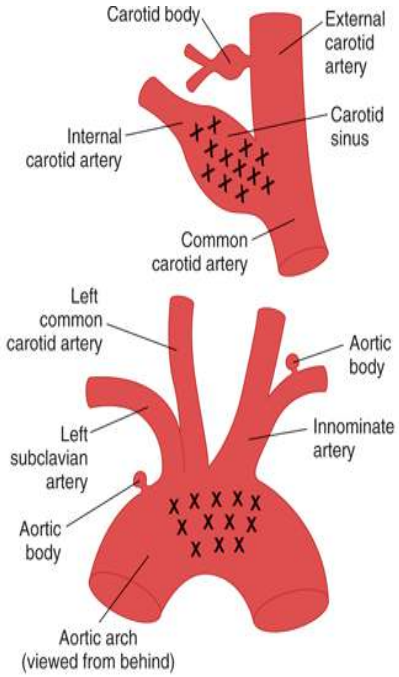
B- Chemical regulation:

1. Hormones: thyroxin, adrenaline.
2. Ions: Ca excess increase HR & K ions excess decreases it.
3. Chemicals: PH, O2, CO2.

C- Physical factors:

1. Age: Inverse relation
2. Gender: Female faster
3. Exercise: Increases HR
4. Body temperature: Increases HR
5. Blood pressure: baroreceptors.



Baroreceptors

They are stretch receptors in the walls of the heart and major blood vessels. The carotid sinus and aortic arch receptors monitor the arterial circulation, as well as in the pulmonary circulation. These receptors in the low-pressure part of the circulation are referred to collectively as the cardiopulmonary receptors.

Blood Distribution in Vascular System & Tissues

A- Vascular System:

- Pulmonary vessels - 9%
- Heart – 7%
- Systemic Arteries & Arterioles – 13%
- Systemic Capillaries – 7%
- Systemic Veins & Venules – 64%Tissue Perfusion

B- Body tissue: differ according to the activity of the body

1- At rest a. Brain: 13%
b. Heart 4%
c. Kidney: 20%
d. Abdominal organs: 24%

2- During exercise: a. Skin, muscles and heart increase
b. Other tissues either same or decrease

Cardiovascular Drift

Phenomenon occurs during running with little or no change in speed; increased HR, decreased MAP & SV with no parallel increased in effort (workload), breathing rate, or calories burned. Decreased SV is due to dehydration that accompany rise in internal temperature.

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Drift is affected by factors :

- Ambient temperature (more at thermal states)
- Internal temperature
- Hydration
- Amount of muscle tissue activated during exercise.

To promote cooling, blood flow to the skin (more fluids from plasma to the skin). This results in a fall in pulmonary art. BP & reduced SV. To keep CO at reduced BP, the HR must be raised.

Cardiac Output (CO):

Cardiac output is the amount of blood pumped out of the ventricle. The CO in a resting adult is about 5 L per minute but varies greatly depending on the metabolic needs of the body. CO is computed by multiplying the stroke volume by the heart rate.

- The heart is able to determine its own rate and rhythm.
- Stroke volume (SV): The amount of blood ejected by the left ventricle with each heartbeat.

SV= EDV- ESV = 120 – 50 = 70ml

- The average resting stroke volume is about 70 mL, and CO can be affected by changes in either SV or HR.
- The percentage of the end-diastolic volume that is ejected with each stroke is called the ejection fraction (EF) **: (EF) = 50-70%**

Cardiac Output (CO) = SV X HR = 70ml X 72bpm = 5L

Factors that affect stroke volume:

1. Preload: degree of stretch prior to contraction (volume of ventricle at end diastole)
2. Contractility: increase in contractile strength
3. Afterload: arterial BP, resistance to ventricular ejection

Heart Homeostasis:

- Effect of blood pressure
  - Baroreceptors monitor blood pressure
- Effect of pH, carbon dioxide, oxygen
  - Chemoreceptors monitor
- Effect of extracellular ion concentration
  - ↑ or ↓ in extracellular K^+ ↓ HR
- Effect of body temperature
  - HR ↑ when body temperature ↑, HR ↓ when body temperature ↓.

Why is exercise good for the heart?

- A trained heart is bigger

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- Pumps blood more efficiently (at a lower rate)
- Stroke volume increases (due to stronger contractions, allowing for lower rate)
- Other benefits: higher aerobic capacity (contributing to efficiency)

Cardiac Conduction

Before mechanical contraction, an action potential travels quickly over each cell membrane and down into each cell's. The parts of the heart normally beat in a sequence & the heart continues to beat after all the nerves to it are sectioned. Indeed, if the heart cut into pieces, the pieces continue to beat. The heartbeat originates in a specialized cardiac conduction system and spreads because of special properties of their cell membrane the way in which charged particles (ions) pass through it.
Three physiologic characteristics of cells, provide this synchronization:

1- **Automaticity**: ability to initiate an electrical impulse
2- **Excitability**: ability to respond to an electrical impulse
3- **Conductivity**: ability to transmit an impulse from one cell to another
4- **Contractility** (rhythmicity): is the ability of cardiac cells to shorten and cause cardiac muscle contraction in response to an electrical stimulus.

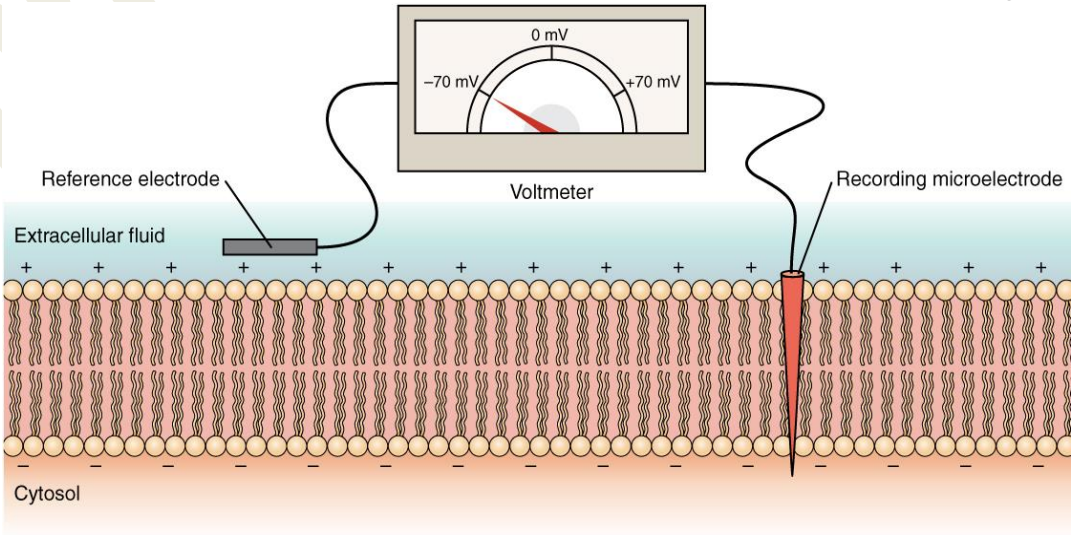
Node is heart tissue that stimulate heart muscle to depolarize (contract) & the depolarization moves from base to apex. Hence, before mechanical contraction, an action potential travels over each cell membrane and down into each cell. Different areas of the heart have different nodes, each with a different rate. Node rate gets slower as it moves downwards, therefore faster nodes will override slower nodes.

SAN → **AVN** → **His Bundle** → **Bundle Branches** → **Purkijie Fibers**

All conduction fibers connected to myocytes over gap junctions in the intercalated discs.

Resting membrane potential and action potential

All living cells (whether animal or plant cells) show potential difference across their cell membranes when microelectrodes are inserted ins the cells. The membrane interior is negative in relation to the membrane exterior. This is called resting membrane

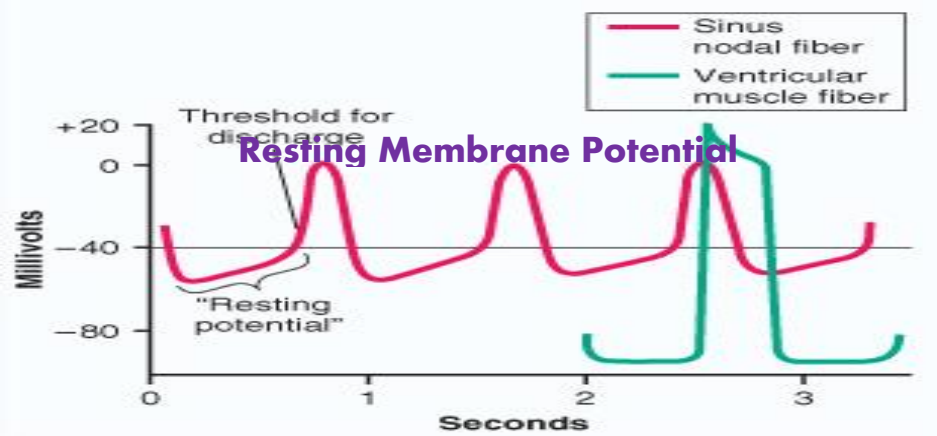


potential (**RMP**) and it is due to uneven distribution of ions inside and outside the membrane.

Mechanism of Autorhytmicity:

- Autorythmic cells do not have stable resting membrane potential (RMP)
- Natural leakiness to Na & Ca→ spontaneous and gradual depolarization
- Unstable resting membrane potential (= pacemaker potential)
- Gradual depolarization reaches threshold (-40 mv) → spontaneous AP generation

Mechanism of Autorhytmicity

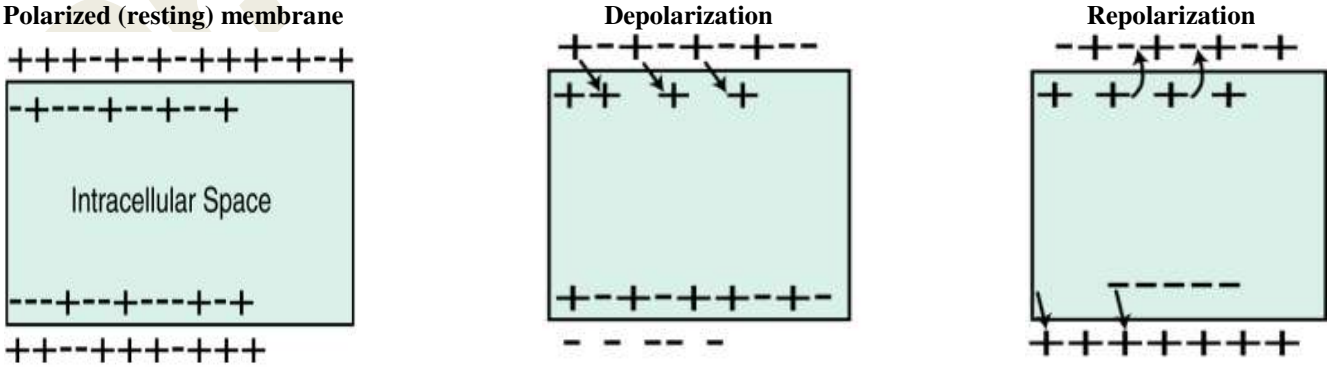


Action Potential

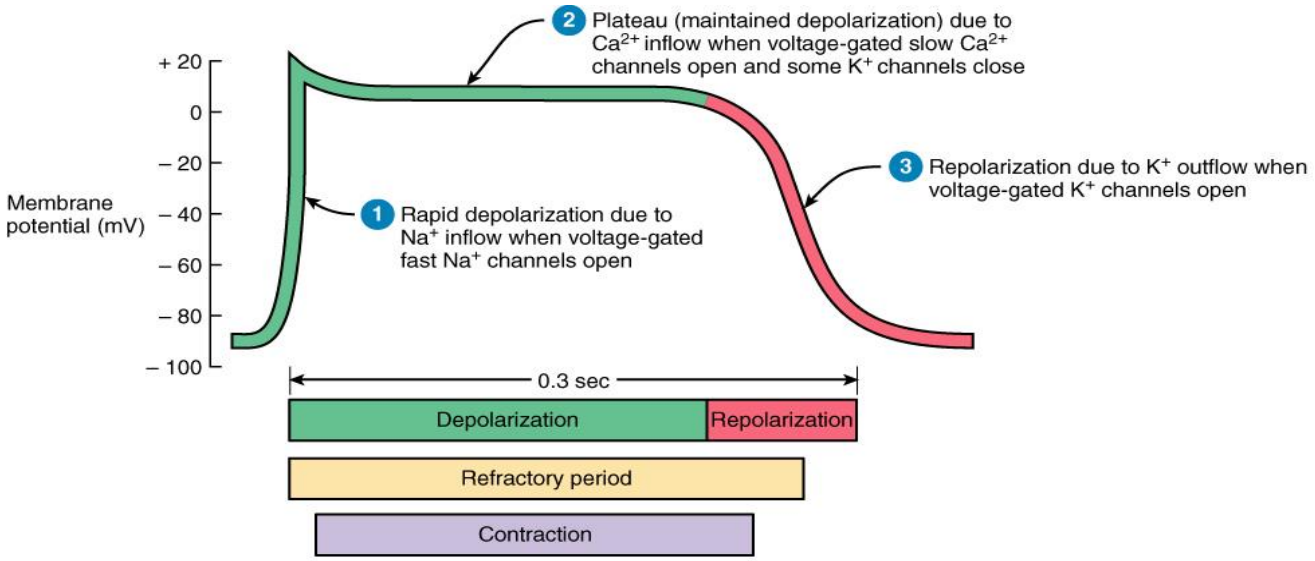
Myocytes are excitable cells i.e. they have the ability to reverse the negativity of their membrane potential in **"response**" to a sufficient external "**stimulus"**. This change in membrane potential is called **"action potential"** & response is "**contraction"**.

Cardiac action potential has the following steps:

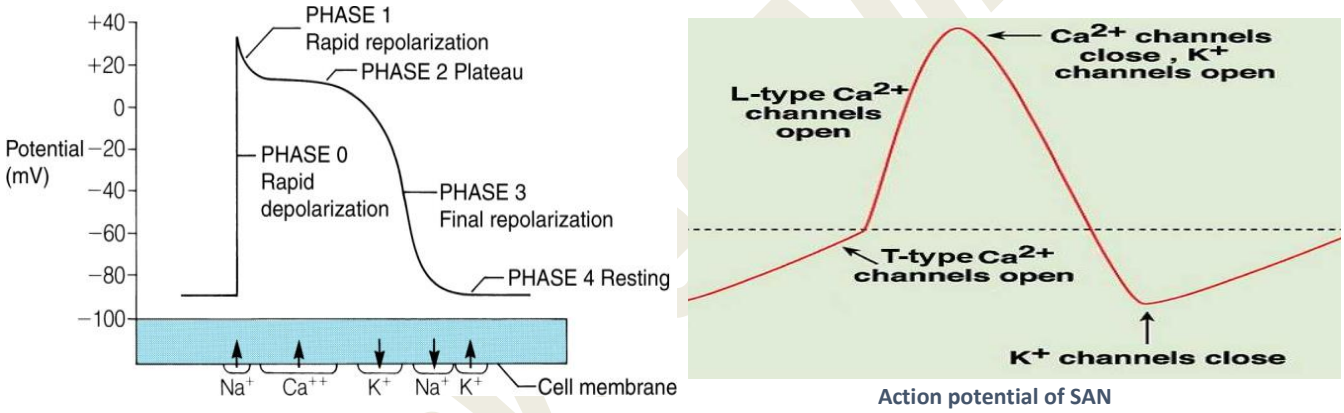
- Rapid depolarization followed by
- Rapid, partial early repolarization
- Prolonged period of plateau phase (slow repolarization)
- Rapid repolarization phase



Cardiomyocyte action potential phases



Cardiomyocytic action potential phases, refractory period & contraction



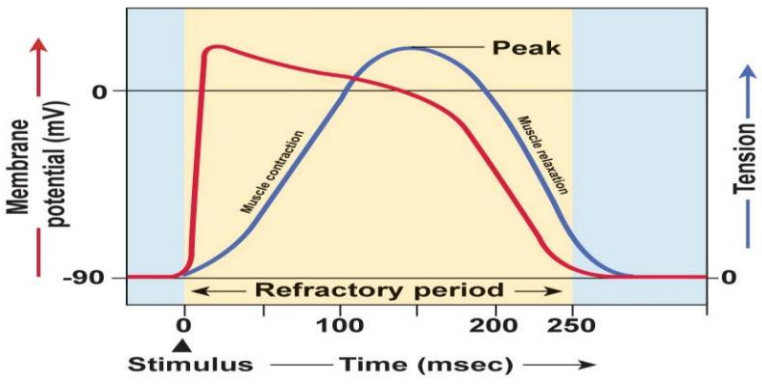
Action Potentials in Skeletal and Cardiac Muscle

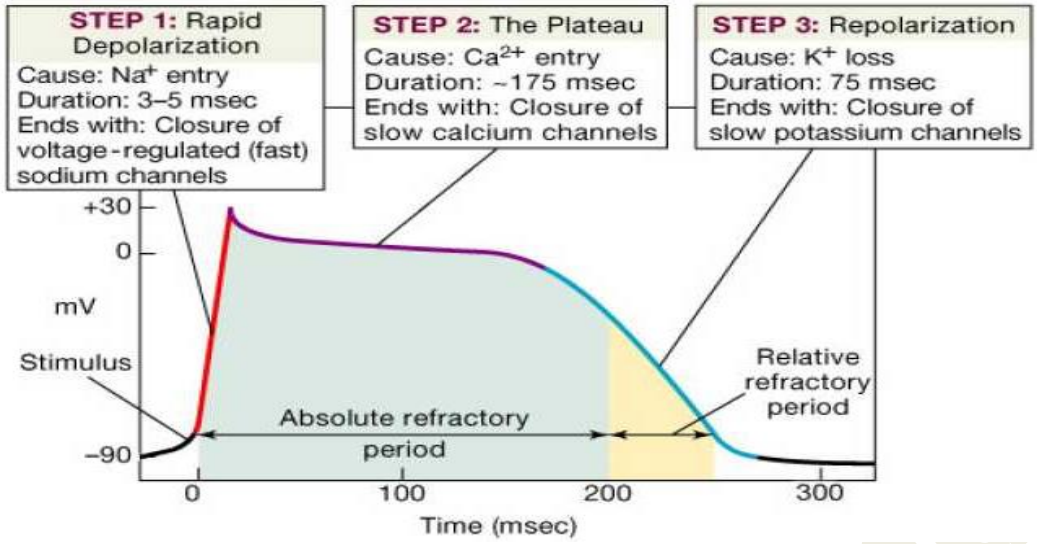
Refractory Period (RP):

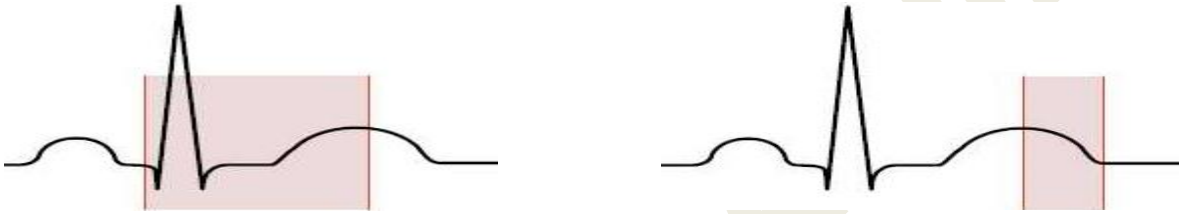
The period during which, membrane is refractory to further stimulation until contraction is over. It gives time to heart to relax after each contraction, prevent fatigue. It allows time for the heart chambers to fill during diastole before next contraction. Heart has a long refractory period (250 msec) compared to skeletal muscle (3msec). It lasts longer than muscle contraction thus, prevents tetanus.

Refractory period consist of two periods:

- Absolute RP: period where an AP can't be elicited, even with a strong stimulus
- Relative RP: period where a weaker AP elicited, but with stronger stimulus







Absolute RP Relative RP

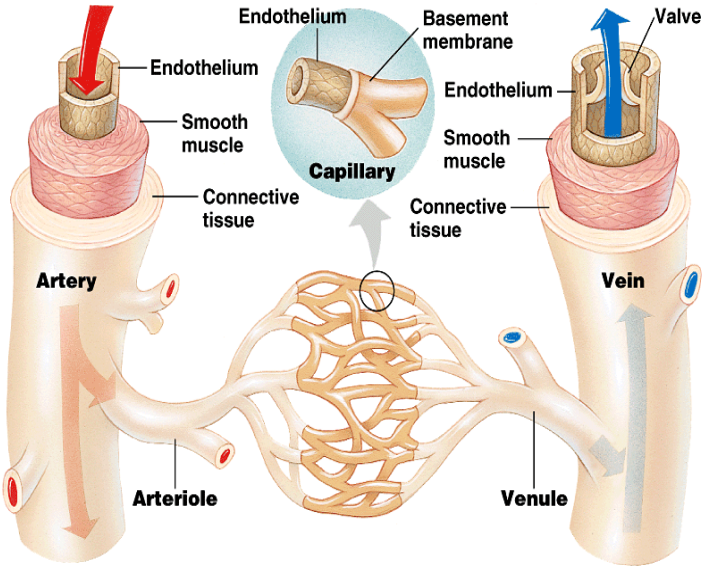
Cardiac Reserve

- CO is the amount of blood pumped by each ventricle in one minute.
- CO is the product of heart rate (HR) and stroke volume (SV).
- Cardiac reserve is the difference between resting and maximal CO.

Vascular Physiology

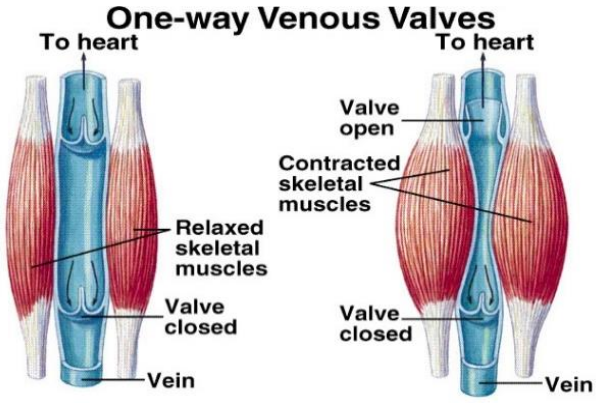
The cardiovascular system has three types of blood vessels (network of tubes):

- Arteries → arterioles move away from the heart
  - Elastic Fibers
  - Circular Smooth Muscle
- Capillaries → where nutrient & gas exchange takes place.
  - One cell thick
  - Serves the Respiratory System
- Veins → Venules moves blood towards the heart
  - Skeletal Muscles contract to force blood back from legs.



- One way valves
- When they break - varicose veins form

Systemic Blood Pressure



- Pumping generates blood flow
- When flow is opposed by resistance, pressure results
- Blood flows along a pressure gradient from (highest in aorta & lowest in right atrium).

Blood flow: volume per unit time

$$\text{Blood Flow (F)} = \Delta \mathbf{P/PR}$$

Blood pressure: force per unit area

Resistance: opposition to flow generally encountered in the systemic circuit (peripheral resistance: PR). *Sources of resistance are*:

- Blood viscosity
- Total blood vessel length
- B. vessel diameter, resistance $1/r^4$

What is hypertension?

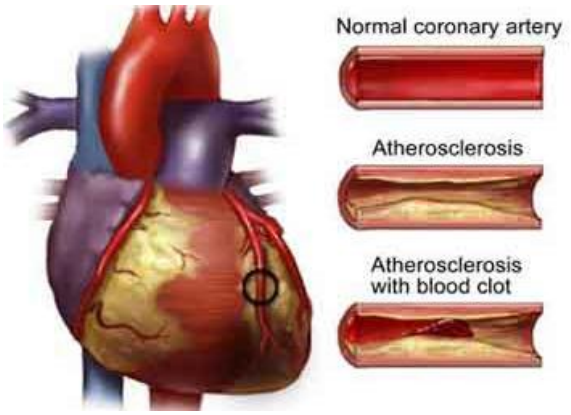
Arterial pressure is too high. Cause is unknown, or is secondary to disease. Variety of risk factors are known: sedentary lifestyle, smoking, obesity, diet (excess sodium; cholesterol; calories in general), stress, arteriosclerosis & genetic factors.

Coronary Arteries:

The coronary arteries are perfused during diastole. An increase in heart rate shortens diastole & can decrease myocardial perfusion. Patients, mainly those with coronary artery disease (CAD), can develop **myocardial ischemia** (inadequate oxygen supply) when the heart rate accelerates.

Atherosclerosis

Atherosclerosis is due to a build-up of fatty material (*plaque*), mainly cholesterol, under the inner lining of arteries. The plaque can cause a *thrombus* (blood clot) to form. The thrombus can dislodge as an *embolus* and lead to *thromboembolism*. Narrowing of vessel lumen due to plaque/fat formation on inside of walls



Causes: diet high in fat, cholesterol, salt; inactive lifestyle; smoking

Risk Factors: high BP, enlarged heart, embolus-blocking circulation & stroke.

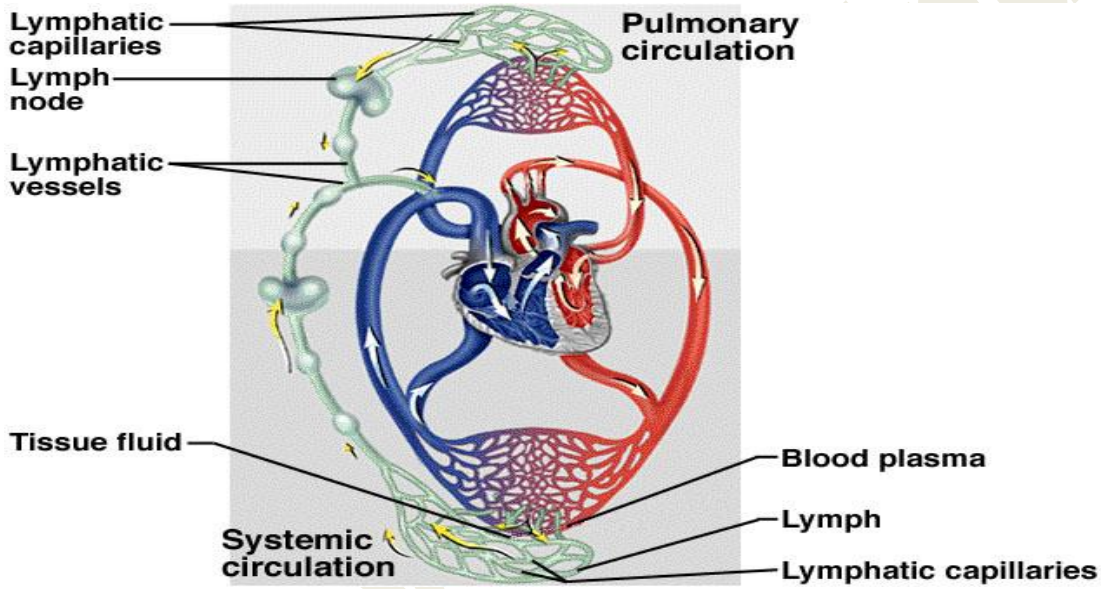
Dr. Hayder Alhi

Myocardial Infarction

The heart has large metabolic requirements, extracting approximately 70% to 80% of the oxygen delivered (other organs consume, on average, 25%). When the coronary vessels are blocked, the heart muscle becomes starved for oxygen. Resulting chest pain is called angina. If oxygen is deprived for a long time, the heart muscle will be damaged and result in myocardial infarction which may result to death.

The Lymphatic System

System of transporting vessels designed to collect fluid & proteins that leak out of the capillaries into the interstitial tissue and return them to the blood stream proper.



Effects of Aging

On the Heart:

- Gradual changes in heart function, more significant during exercise.
- Left ventricle hypertrophy.
- Maximum heart rate decreases.
- Increased valvular dysfunction & arrhythmias.
- Increased O2 consumption required to pump same amount of blood

On Arteries:

- Atherosclerosis
- Coronary thrombosis & heart attack increase
- Occurrence of varicose veins increases
  - Thromboembolism
  - Pulmonary embolism

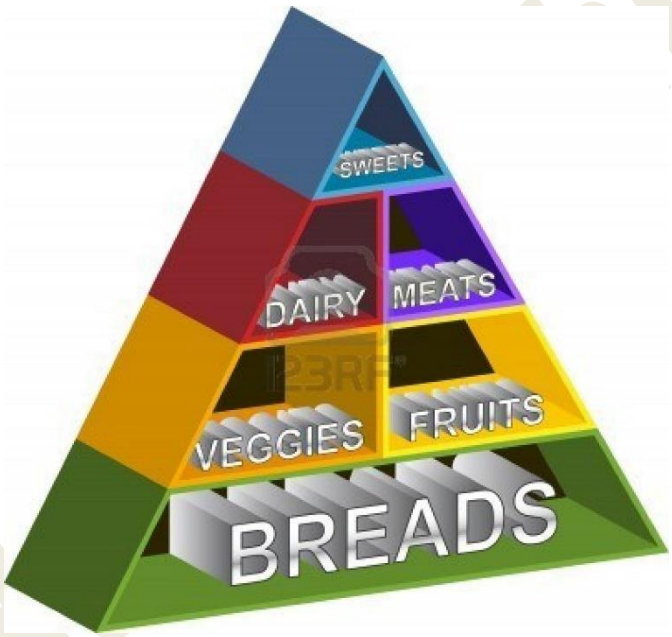
Heart and a healthy lifestyle

- What is the heart's main adaptation to sustained involvement in physical activity?

- Hypertrophy = increase SV
  = decreased resting HR
- Increased potential to supply oxygen
- Bradycardia = heart under less strain at rest
  = over lifetime could delay deterioration of heart
  = improved quality of life

A Healthy Heart is a Happy Heart

1. Exercise on a regular basis. Get outside and play. Keep that body moving (walk, jog, run, bike, skate, jump, swim).
2. Eat Healthy. Remember the Food pyramid and make sure your eating your food from the bottom to top.
3. Don't Smoke! Don't Smoke! Don't Smoke! Don't Smoke!



Food Pyramid.