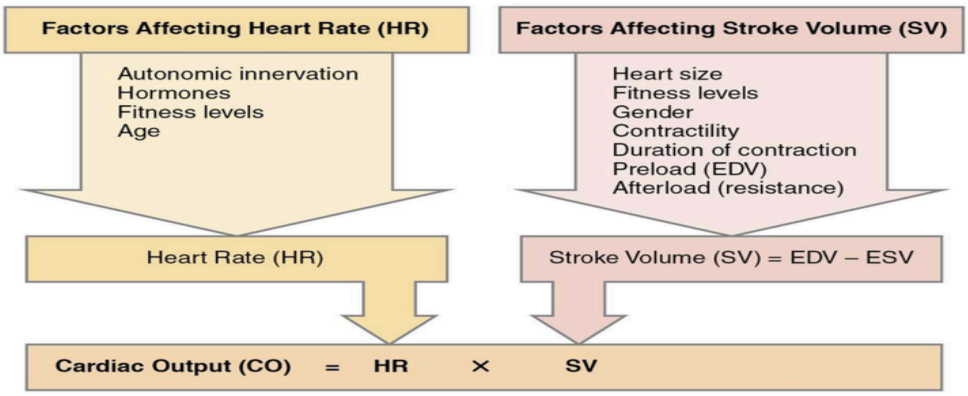
Cardiac Physiology – Part 1

Cardiac Cycle & Output / AV O_2 Difference

Dr. Gary Mumaugh – Campbellsville University

CO = HR x SV

- Cardiac Output is the amount of blood flowing through the heart in one minute
- Heart Rate is the beats per minute
- Stroke Volume is the strength of the contraction



Venous Return

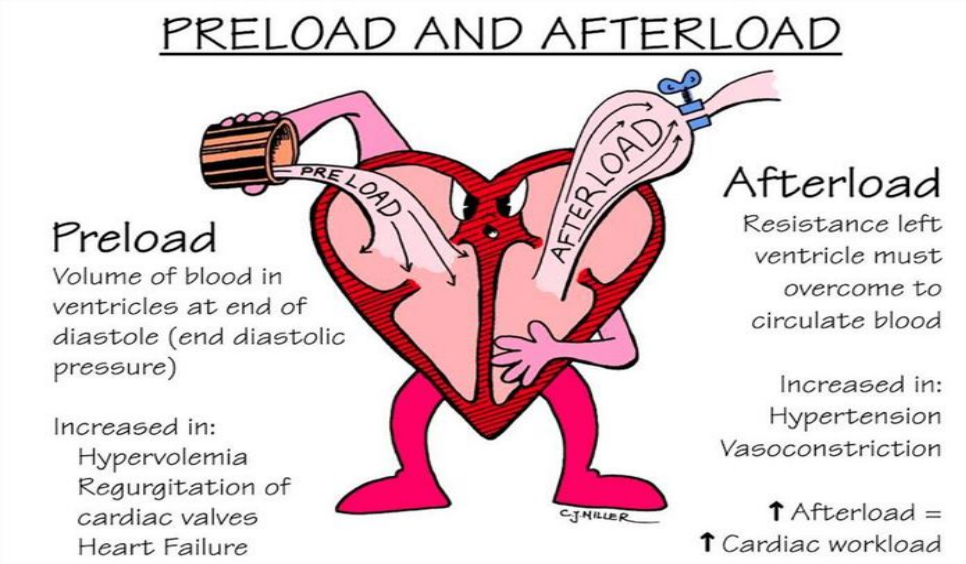
- This is the amount of blood that enters the Right Atrium through the veins per minute.
- After a certain time interval, the venous return becomes equal to the cardiac output.
- Venous return in turn, depends on following factors:
    - Respiratory pump
    - Muscle pump Gravity
    - Venous pressure

Force of Contraction

- The stroke volume and the cardiac output increases with the increase in the force of contraction.
- Frank Starling Law of the Heart states that when increased volume of blood flows into the heart, the cardiac muscle contracts with increased force and this empties the extra blood that has entered from the systemic circulation leading to --- increased cardiac output.

Preload and Afterload

- Preload
    - It is stretching of cardiac muscle fibers at the end of diastole, just before contraction.
    - Cardiac output is directly proportional to pre-load.
- Afterload
    - It is the force against which ventricles must contract and eject the blood.
    - Resistance left in the ventricle to overcome and circulate the blood.



Peripheral Resistance

- Peripheral resistance is the resistance offered to blood flow at the peripheral blood vessels.
- Peripheral resistance is the resistance or load against which the heart has to pump the blood.
- Cardiac output is inversely proportional to peripheral resistance.

Cardiac Index

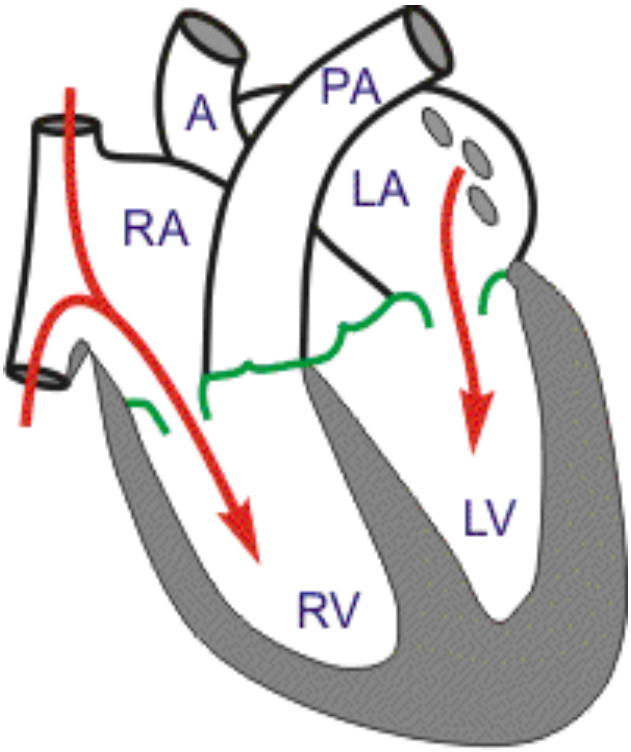
- Cardiac index is defined as the cardiac output divided by the body surface area.
- It is a hemodynamic parameter that relates the cardiac output from the left ventricle in one minute to the body surface area.
- Cardiac Index = Cardiac Output/Body Surface Area
- Stroke volume index is the stroke volume divided by the body surface area.

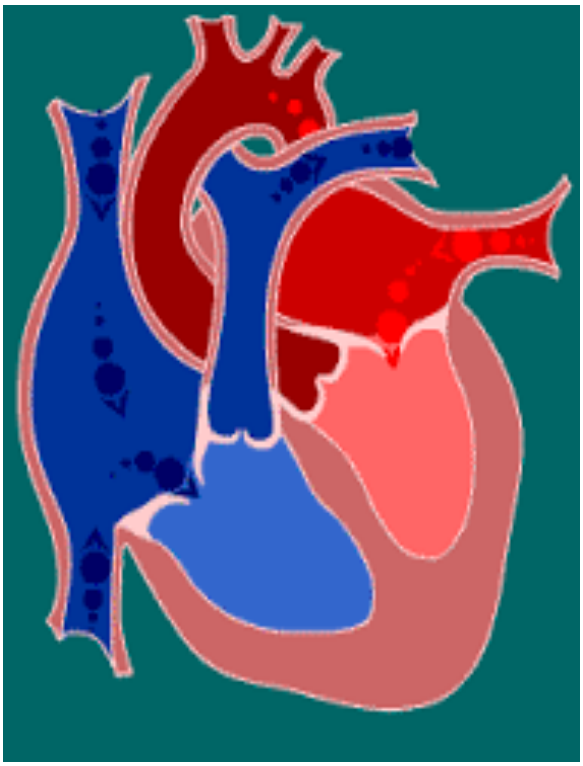
Systole vs. Diastole

- Systole is when the ventricles are contracting
- Diastole is when the ventricles are relaxing

Phases of cardiac filling and ejection

- **Filling Phase of Diastole**
    - The ventricles of the heart relaxes so that they can refill up with blood
        - The AV valves are both open and blood is flowing into the ventricle. Remember that we are calling the AV vales the “Inlet Valves”.
        - The SL valves are closed. Remember that we are calling the SL vales the “Outlet Valves”.
        - Because of the open AV valves and closed SL valves, blood fills the ventricles.



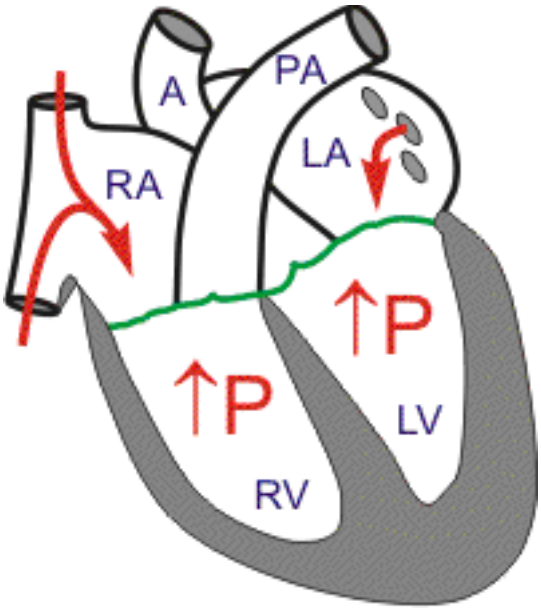


Filling Phase of Diastole

Ventricle are relaxed and filling up

Phases of cardiac cycle

- **Isovolumetric Contraction of Systole**
    - Increased muscle tension and contraction
    - All four valves are shut and no more blood is entering the ventricle
        - Because no more blood is coming in or leaving, the volume of blood stays the same. = Isovolumetric = Same Volume
    - The walls of the ventricles are starting to contract and they are building up pressure.
    - The pressure is rising because the walls are starting to contract.
    - Once sufficient pressure has occurred, the heart muscle begins to contract and it starts to eject out blood.



Isovolumetric Contraction of Systole

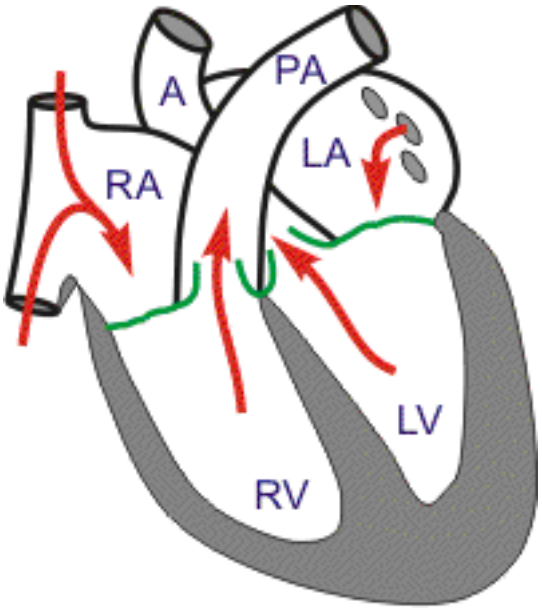
All valves are closed and pressure is building up
(Isometric Phase of Muscle Contraction)

Remember this about muscle contractions:

Muscles contract in two phases:

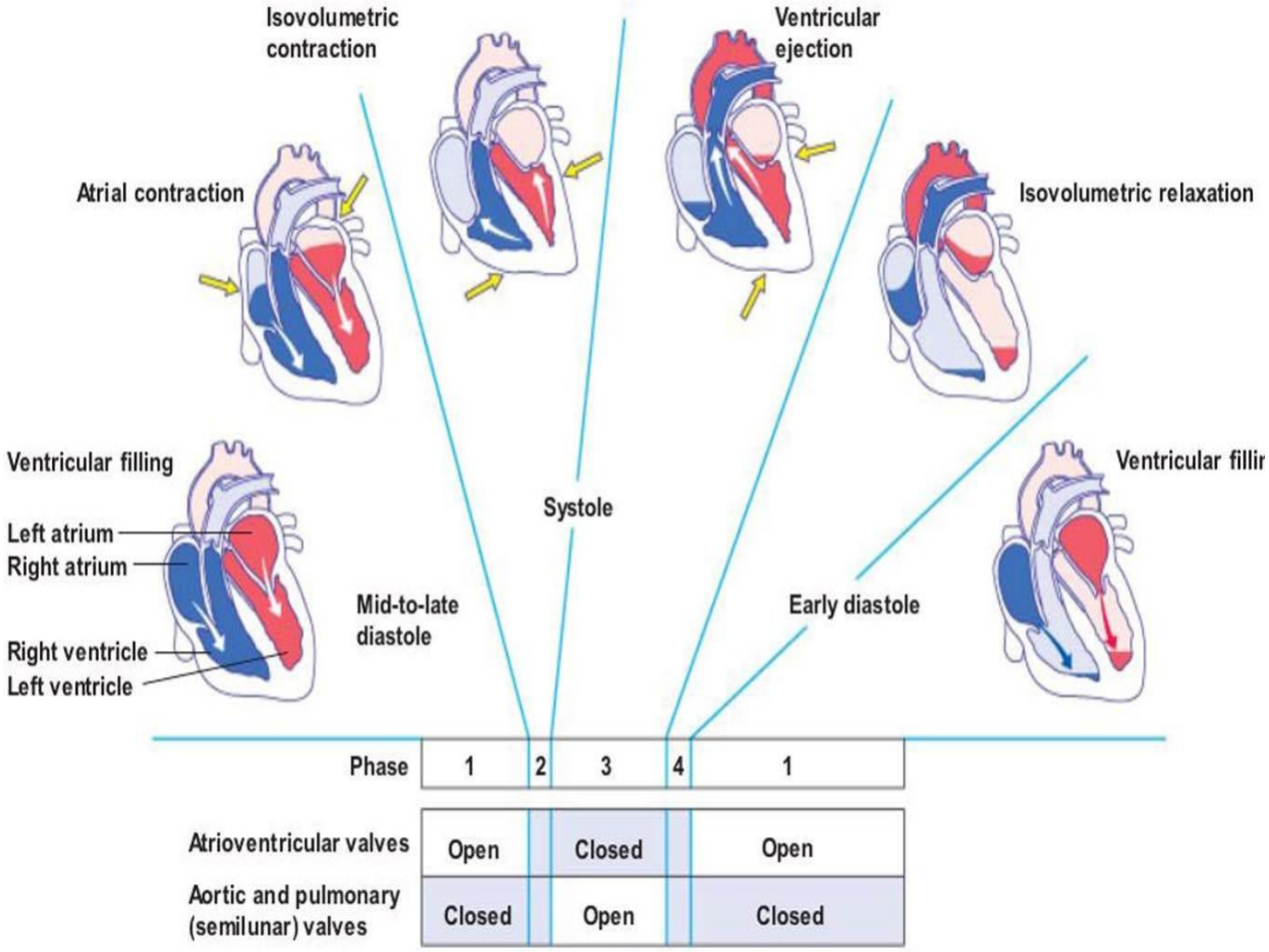
1. Isometric Phase – there is and increase of tension and an increase of pressure but there is no movement
2. Isotonic Phase – there is movement or shortening of the muscle but no change in the muscle tension

- **Ejection Phase of Systole**
  - The heart muscle is now contracting and shortening. (Isotoonic)
  - The pulmonary valve opens and blood is ejected into the pulmonary trunk going to the lungs.
  - The aortic valve opens and blood is ejected into the aorta going to the body.
  - After all the blood is ejected into the SL valves, it goes back into diastole wher it relaxes and refills with blood again.



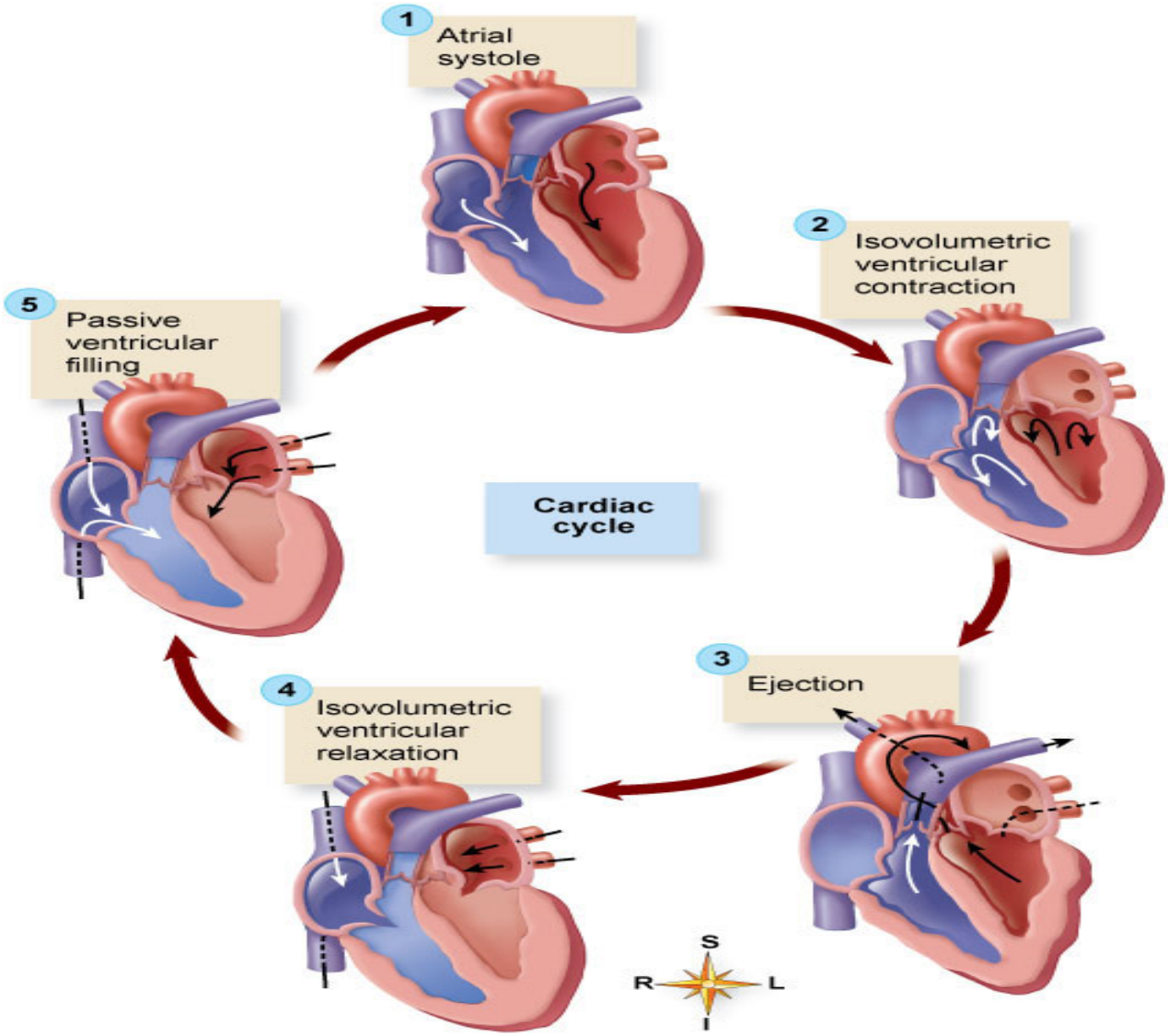
Ejection Phase of Systole

The SL are open and the muscle is ejecting blood
(Isotonic Phase of Muscle Contraction)



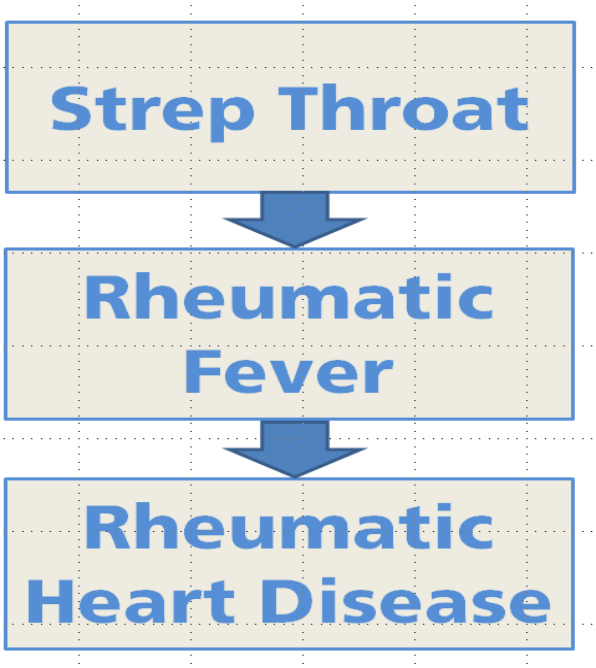
Cardiac Cycle

- Cardiac cycle: a complete heartbeat consisting of contraction (systole) and relaxation (diastole) of both atria and both ventricles
- When the heart muscle contracts (pushes in) it is called systole
- When the heart muscle relaxes (stops pushing in), this is called diastole
- Both atria do systole together
- Both ventricles do systole together
- But the atria do systole *before* the ventricles
- Even though the atrial systole comes before ventricular systole, all four chambers do diastole at the same time
    - This is called cardiac diastole
- The order is: atrial systole > ventricular systole >cardiac diastole
- When this happens one time, it is called a cardiac cycle



Pathophysiology of Valve Disease

- The valves are important because they ensure that the blood is moving in only one direction.
- If the valves are not working correctly, then all the blood backs up and regurgitates.
- Etiology (cause) of valve disease
    - Congenital
    - Rheumatic Heart Disease
        - This is an autoimmune disease that attacks the endocardium and valves.
        - It is usually triggered by and infection, and it is usually Strep Throat.
        - Most can get strep and take the antibiotics and there is no residua. But for some people, every time they get strep, the immune system starts to attack the bacteria and it also attacks the endocardium and the valves.
        - It is am immune cross reaction between the strep infection and the valves of the heart.
        - Prophylactic (preventative) use of antibiotics before procedures, especially dental procedures.

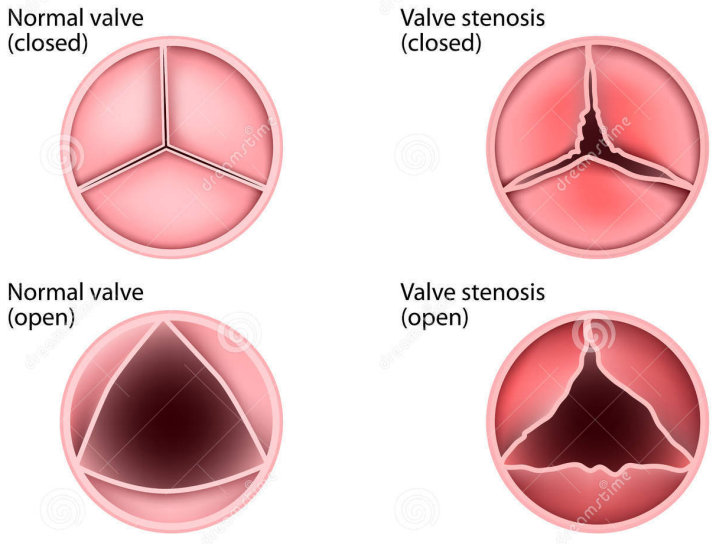


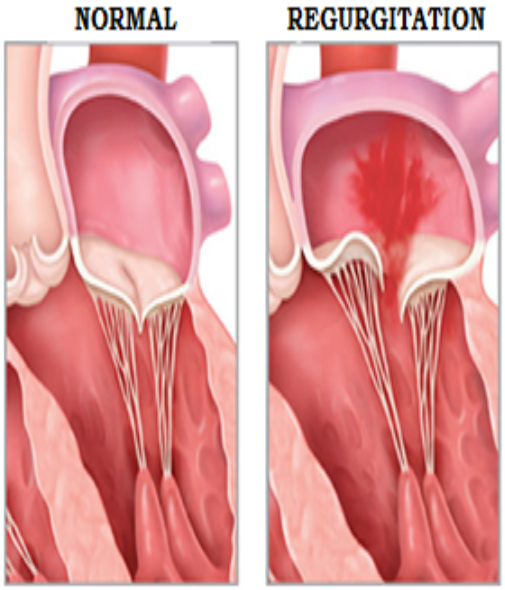
Two Main Types of Valve Problems

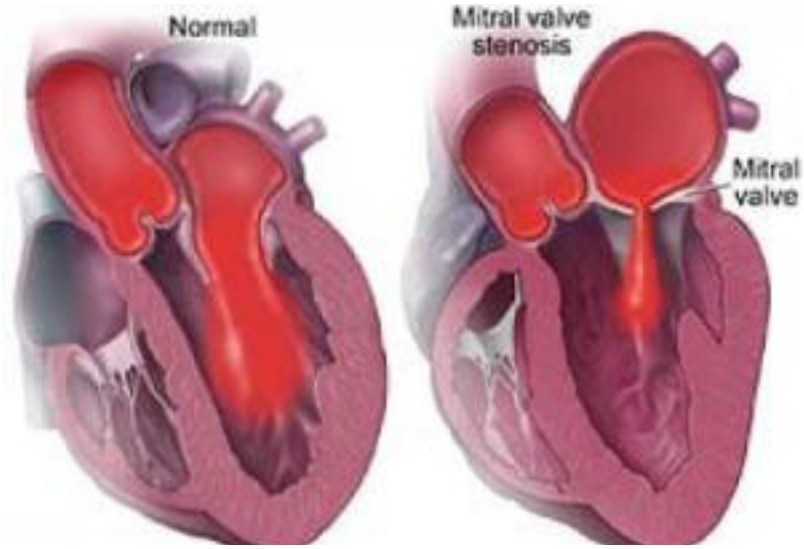
- **Stenotic (constricted) Valves**
    - The valve shuts, but can not open all the way
    - There is a narrowing of the opening
    - This decreases blood flow through the valves
- **Insufficient Valves**
    - The valve opens all the way, but does not shut all the way and is said to be insufficient.
    - This decreases the blood flow through the valves.
- **Regurgitation**
    - In both stenotic and insufficient valves, the blood regurgitates backwards through the valves.
    - There is a decrease of the forward movement of the blood.

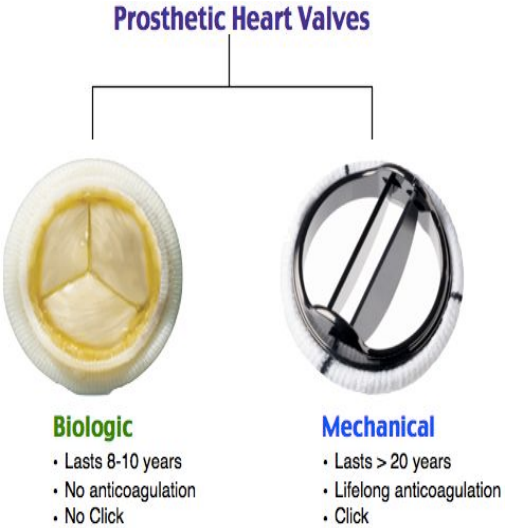
Valve Problem Diagnosis and Treatment

- Auscultation for murmurs
- Murmurs – abnormal sound caused by the turbulent blood flow through and stenotic or insufficient valve.
- Treatment is with a prosthetic valve replacement



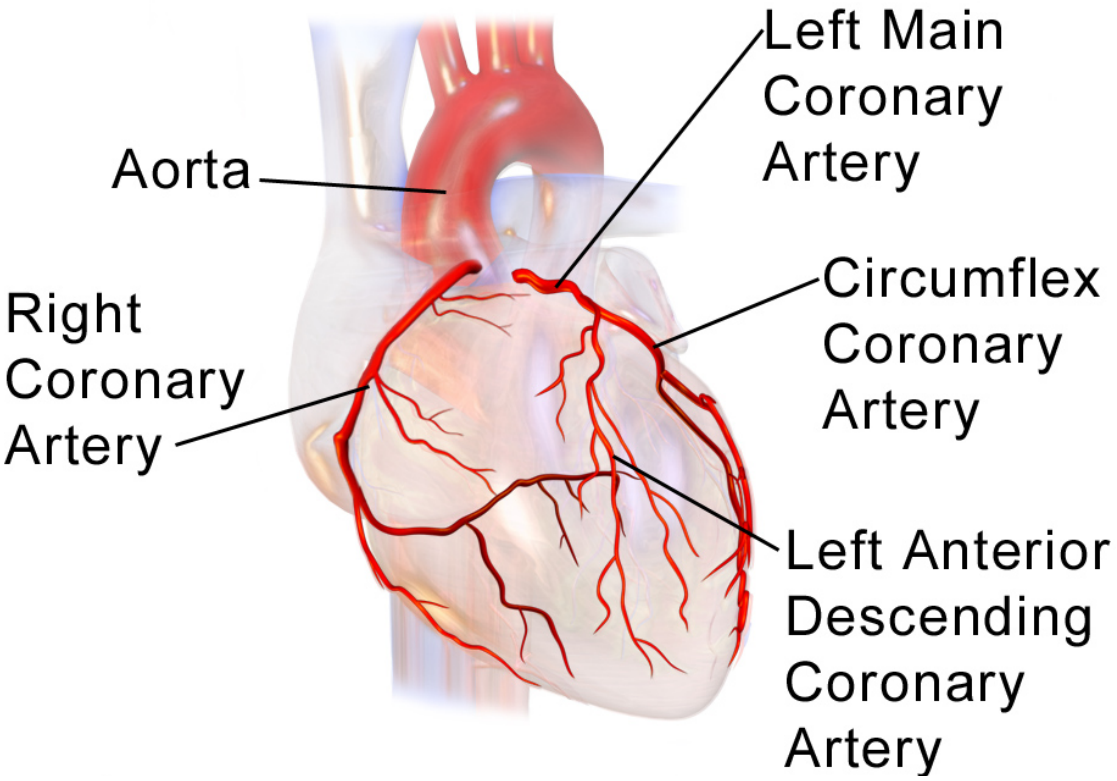






Blood Flow to the Myocardium of the Heart

- **Right and Left Coronary ("crown") Arteries**
  - Branches off the aorta just after the aortic valve
  - Circles the heart along the coronary sulcus (groove) between the atria and ventricles
  - They form many anastomoses with each other
    - Collateral circulation
    - The anastomosis are important because they bring collateral circulation to all of the heart muscles.
    - If there is a blockage, then it knows another way to get the blood around to the heart muscle cells.
    - You increase the collateral circulation or anastomoses with cardio aerobic exercises.
- **Coronary Sinus**
  - Located in the coronary sulcus on the posterior aspect of the heart
  - Empties into the right atrium near the opening of the IVC



Review Terms

- **Systole** – period of ventricular contraction (**ejection of blood**)
- **Diastole** – period of ventricular relaxation (**filling of blood**)

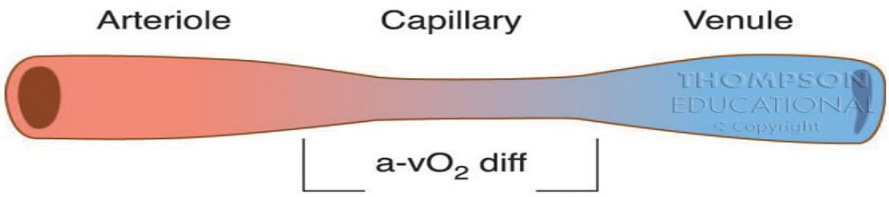
Intermittent Blood Flow Through the Coronary Circuit

- The heart is the organ most prone to ischemia (lack of oxygen). This is called **myocardial ischemia.**
- There are three reasons for the ischemia:
    - The pumping of the heart uses high ATP production
        - Needs a lot of oxygen for cell respiration
        - It works very hard and uses a vast amount of oxygen and ATP
    - The heart properties and like the "slow twitch" skeletal muscle fibers.
        - Think of endurance and dependence upon aerobic respiration to produce the ATP
    - Intermittent blood flow to the heart 24/7
        - Most tissues of the body receive a continuous flow of blood, but the heart only receives blood intermittently.
        - Remember that when a muscle contracts it compresses and squeezes the blood vessels in the muscle.
        - When the blood vessels are compressed, they loose their blood supply.
        - Now the muscle has shut off blood and lacks oxygen.

The heart is the organ most prone to ischemia

- Oxygen consumption by the heart is calculated by the arterial-venous oxygen difference
- **Arterial-Venous Oxygen Difference**
    - The difference of the renal artery and renal vein is 10%
        - i.e. the kidneys only uses up 10% of the oxygen and gives back to the circulation 90% of the oxygen in the renal vein
    - The difference of the hepatic artery and hepatic vein is 20%
        - i.e. the liver only uses up 20% of the oxygen and gives back to the circulation 80% of the oxygen in the hepatic vein
    - The difference of the muscles is 25%
        - i.e. the muscles only use up 25% of the oxygen and gives back to the circulation 75% of the oxygen in the veins
    - The difference of the carotid artery and jugular vein is 30%
        - i.e. the brain only uses up 30% of the oxygen and gives back to the circulation 70% of the oxygen in the jugular vein
    - The difference of the coronary arteries and coronary sinus is 70%
        - i.e. the heart uses up 70% of the oxygen and gives back to the circulation 30% of the oxygen in the coronary sinus
- This dramatic oxygen depletion is at rest. At exercise and work the difference is 80% to 90%.
    - At exercise and work, the heart is only giving back 10% to 20% of the oxygen!!
- And all of this depends on normal, patent open coronary arteries.

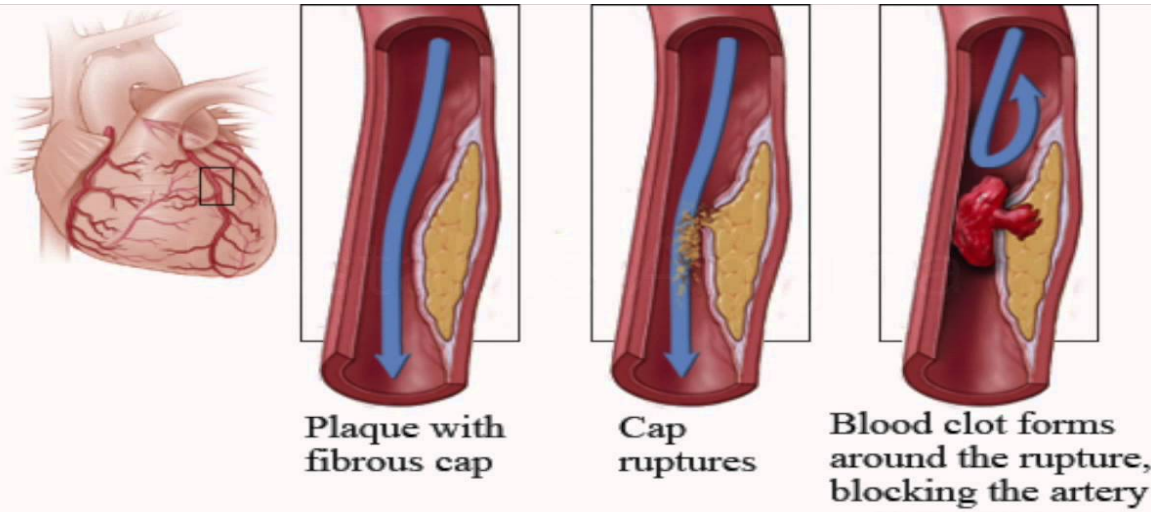
a-vO2 Difference

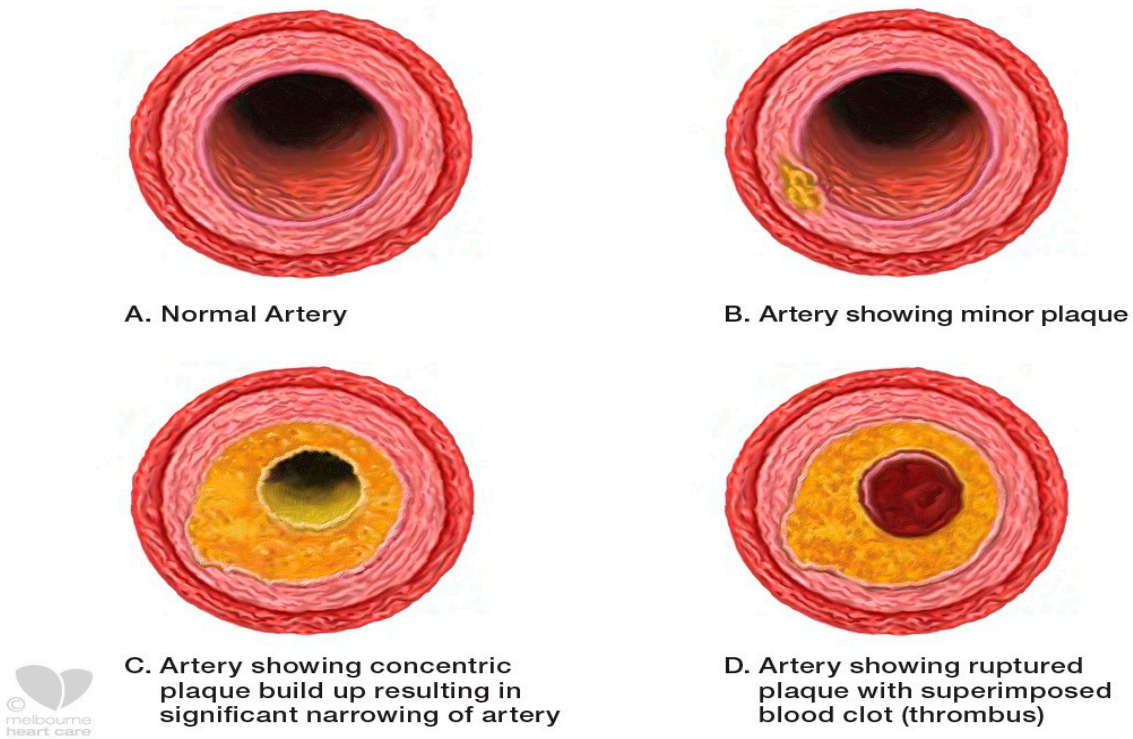


Arteriovenous oxygen difference, or a-vO_2 diff, is the difference in the oxygen content of the blood between the arterial blood and the venous blood. It's a good way to see how much O_2 is delivered and used by muscle

Pathophysiology of Coronary Arterial Disease

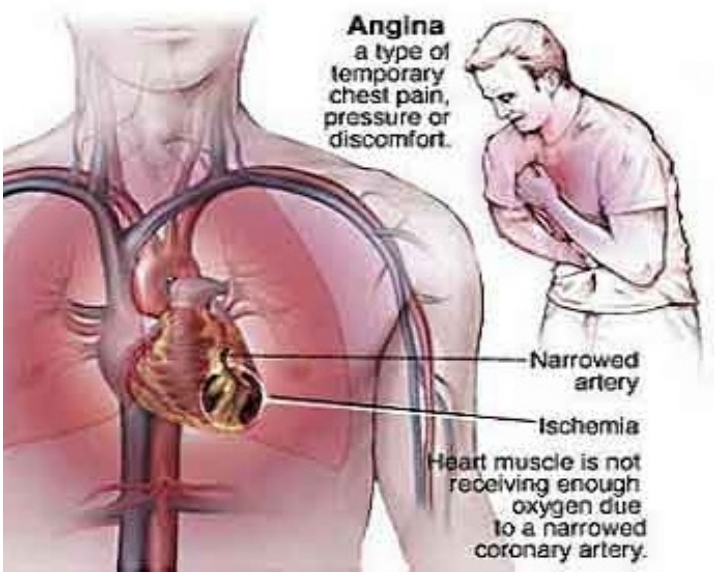
- **Etiology**
  - The accumulation of fat, calcium and cholesterol (called atherosclerotic plaque) on the walls of the blood vessels.
  - This plaguing occurs in all the arteries of the body. But the consequences of a clogging of a pancreatic artery or renal artery are not as critical as the heart because they have lots of excess blood flow.
    - Remember the A-V O2 difference on the prior page.





- **Stenosis of the lumen causes decreased coronary blood flow causes myocardial ischemia**
  - **Angina Pectoris**
    - A referred pain to the left shoulder and arm
    - Caused by myocardial ischemia
    - Occurs during states of stress (increased cardiac workload)

- **Treatment of lumen stenosis**
  - Coronary vasodilation
    - Nitroglycerine (mimics NO Nitrous Oxide)
    - This is only temporary relief
  - Coronary angioplasty
    - Putting a stent into the lumen
  - Coronary Arterial Bypass Surgery (CABG)



Rough surfaces of the lumen causes coronary thrombosis

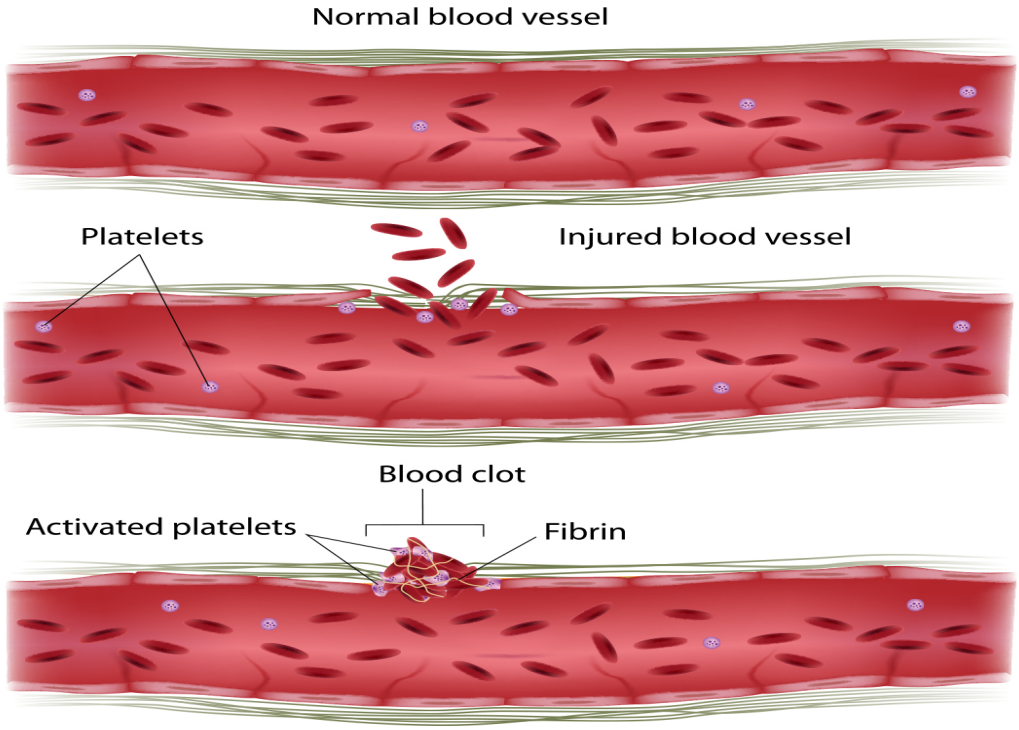
- Circulating blood platelets (thrombocytes) attaches to the rough edges of the plaque forming in the lumen.
- This causes blood platelets to release platelet factor which triggers a fibrin clot to form.
- **CAD >>>>>> coronary thrombosis (blood clot) >>>>>> no oxygen flows through the vessels >>>>>> myocardial infarction**
    - Myocardial Infarction = "Dead Cells" = Heart Attack
- **TPA** – Tissue Plasminogen Activator can be used to trigger circulating plasminogen to dissolve the blood clot
    - This is called fibrinolysis

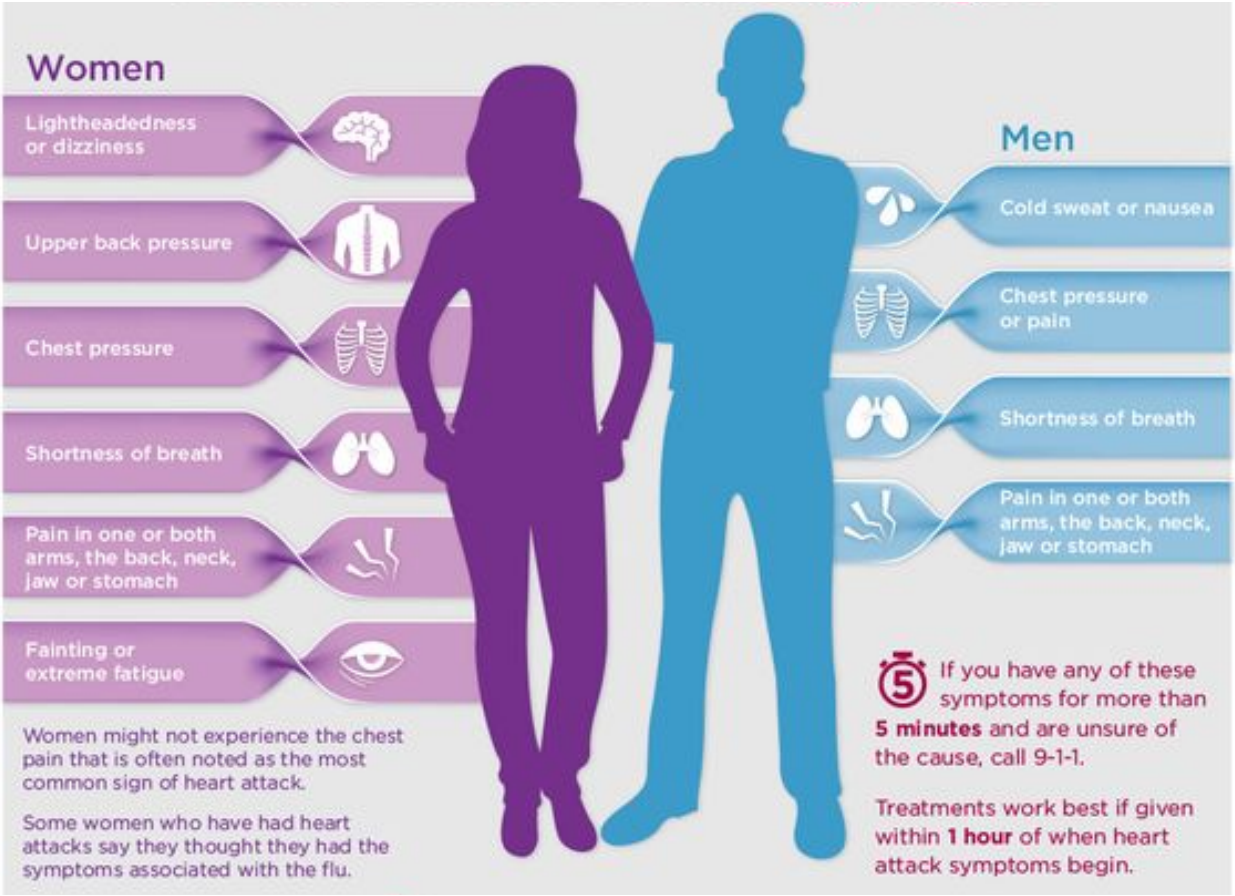
Myocardial Infarction

- Heart attack – Coronary
- Caused by complete obstruction of blood flow
- Clinical signs
    - Changes in the EKG
    - Leaking of myocardial enzymes into the blood stream from infarcted tissue
        - CPK – Creatine Phosphkinase is an enzyme found in all muscle cells
            - The higher the CPK rises, the more the damage to the heart muscle.
            - The longer the CPK being elevated means more damage to the heart muscle.
- Treatment of M.I.
    - Use of anticoagulants
        - "Blood thinners" – example Heparin
    - Use of enzymes to digest blood clots
        - TPA – Tissue Plasminogen Activator

Thrombosis vs. Embolism

- **Thrombosis –** blood clot in a vessel
- **Embolism** – dislodged blood clot

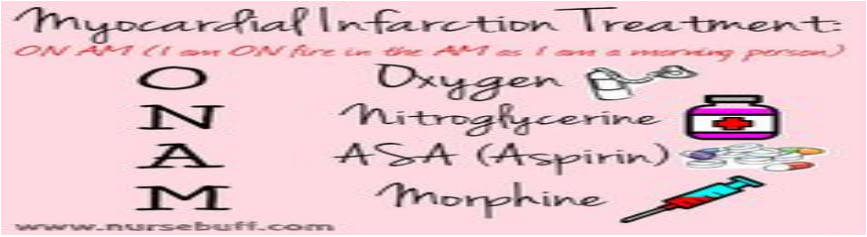

Normal blood vessel
Platelets
Injured blood vessel
Blood clot
Activated platelets
Fibrin


Women
Lightheadedness or dizziness
Upper back pressure
Chest pressure
Shortness of breath
Pain in one or both arms, the back, neck, jaw or stomach
Fainting or extreme fatigue
Women might not experience the chest pain that is often noted as the most common sign of heart attack.
Some women who have had heart attacks say they thought they had the symptoms associated with the flu.
Men
Cold sweat or nausea
Chest pressure or pain
Shortness of breath
Pain in one or both arms, the back, neck, jaw or stomach
If you have any of these symptoms for more than 5 minutes and are unsure of the cause, call 9-1-1.
Treatments work best if given within 1 hour of when heart attack symptoms begin.

Medication given to heart attack patients

- **Anti-coagulant**
    - Blood thinner – prevents blood clots from forming any fibrin clots
    - Example – Heparin
- **TPA – Tissue Plasminogen Activator**
    - An enzyme which activates plasmin to dissolve clots
    - TPA >>>>>> Plasmin >>>>>> Fibrinolysis
- **Beta Blocker**
    - This blocks the adrenergic receptors sites to prevent adrenaline from increasing the heart rate.
- **Morphine drip for pain**
- **Statins and lipid lowering medications**
- **ACE inhibitors for blood pressure**

Clinical note: Skeletal muscle cells have a sarcoplasmic reticulum & lateral sacs (terminal cisterns) that store calcium. Heart muscle cells do NOT store calcium like skeletal muscle which is why heart muscle cells need calcium to flow in for it to contract. Calcium channel blockers (used in angina) slow the heart rate down by decreasing the influx of calcium into the cardiac muscle cells.



Electrical Activity of the Heart - Excitation of the Heart

- **Pacemaker cells**
    - The cells with the fastest intrinsic rates of activity = automaticity
    - The heart is **myogenic,** which means that it can generate it's own impulse and does not need nerves to work.
        - Note: skeletal muscle is neurogenic because it needs nerves to work.
    - Not all heart cells generates an action potential at the same speed. Some generate AP (action potentials) at a very fast speed (pacemaker cells) and some generate an AP (action potential) as at much slower speed.
    - Myogenic muscle tissue includes visceral and cardiac muscle.
        - Exhibits **intrinsic activity = automaticity = myogenic**

Electrical Activity of the Heart - Excitation of the Heart

- Cardiac muscle cells are electrically joined together by **gap junctions.**
    - This enables electricity to travel faster.
- AP (action potentials) generated by the pacemaker cells normally spread throughout the heart before the other cells have a chance to generate and action potential.
- **The heart functions as a single unit.**

Spontaneous increase of the permeability of sodium >>>>>> spontaneous depolarization (called pacemaker potential) >>>>>> Action Potential >>>>>> contraction

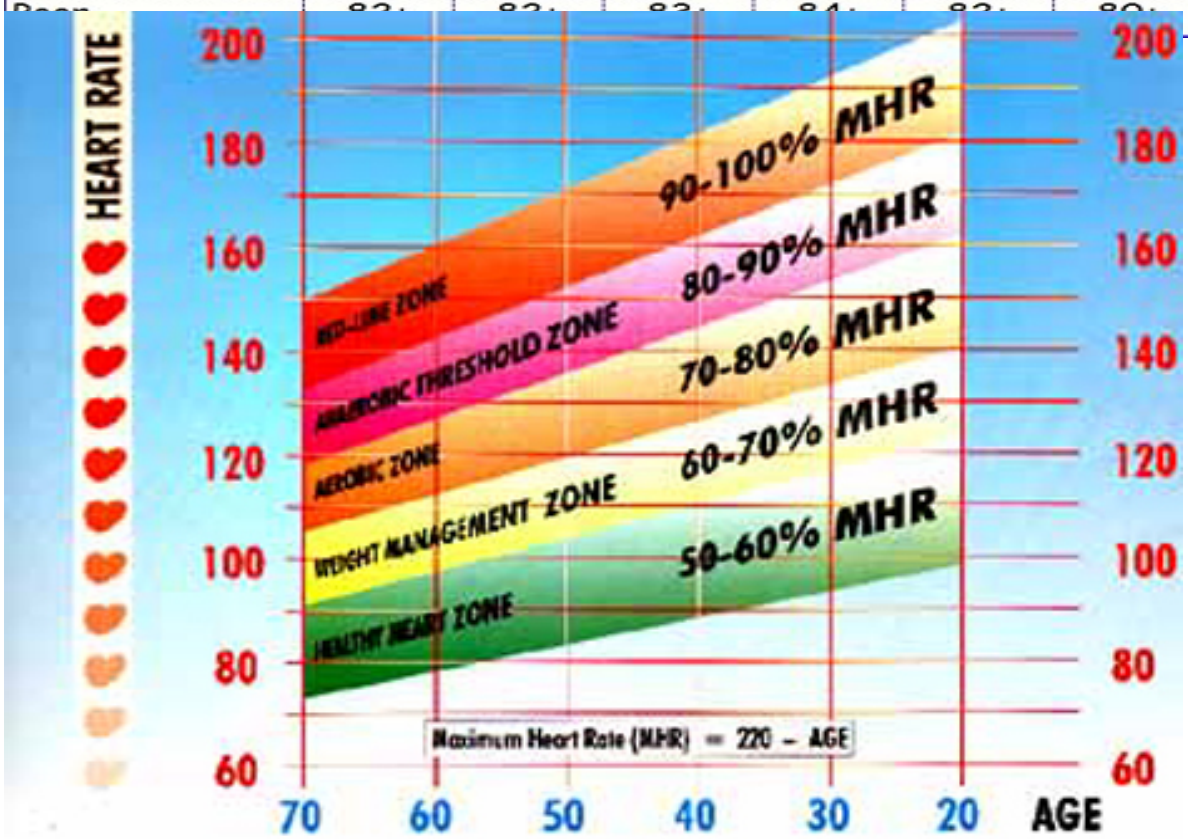
Why do we even have autonomic nerves?

Electrical Refractory (resting) Period of the Heart

- Minimal recovery period following an action potential
  - In the non-pacemaker cells is about .3 sec = 300 / millisecond
  - This is due to the sustained action potential (period of reversed polarity) in most cardiac cells.
- The heart can only "twitch". It cannot exhibit a sustained (tetanic) contraction.
  - By the time the heart can generate a second action potential, it has almost fully relaxed.

Theoretical Maximum Heart Rate = 200 BPM

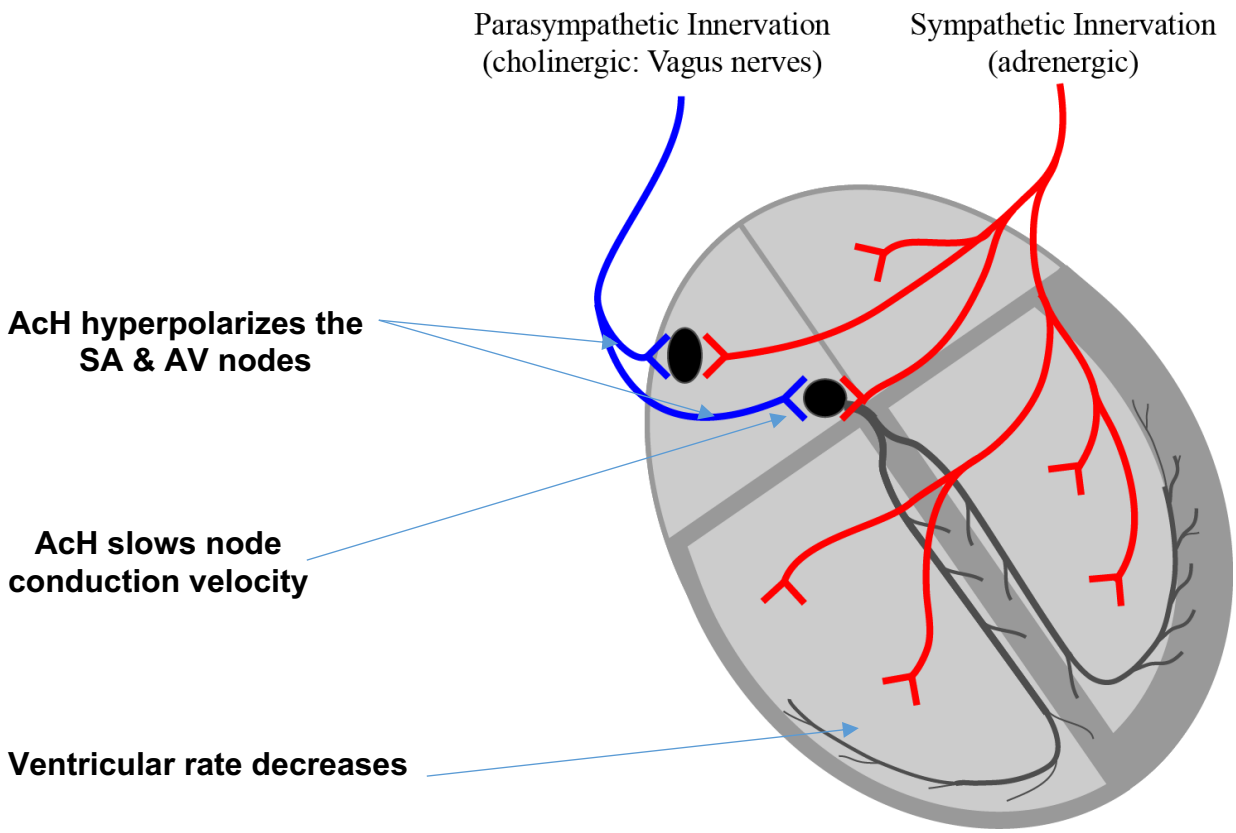
Age	18-25	26-35	36-45	46-55	56-65	65+
Athlete	49-55	49-54	50-56	50-57	51-56	50-55
Excellent	56-61	55-61	57-62	58-63	57-61	56-61
Good	62-65	62-65	63-66	64-67	62-67	62-65
Above Average	66-69	66-70	67-70	68-71	68-71	66-69
Average	70-73	71-74	71-75	72-76	72-75	70-73
Below Average	74-81	75-81	76-82	77-83	76-81	74-79



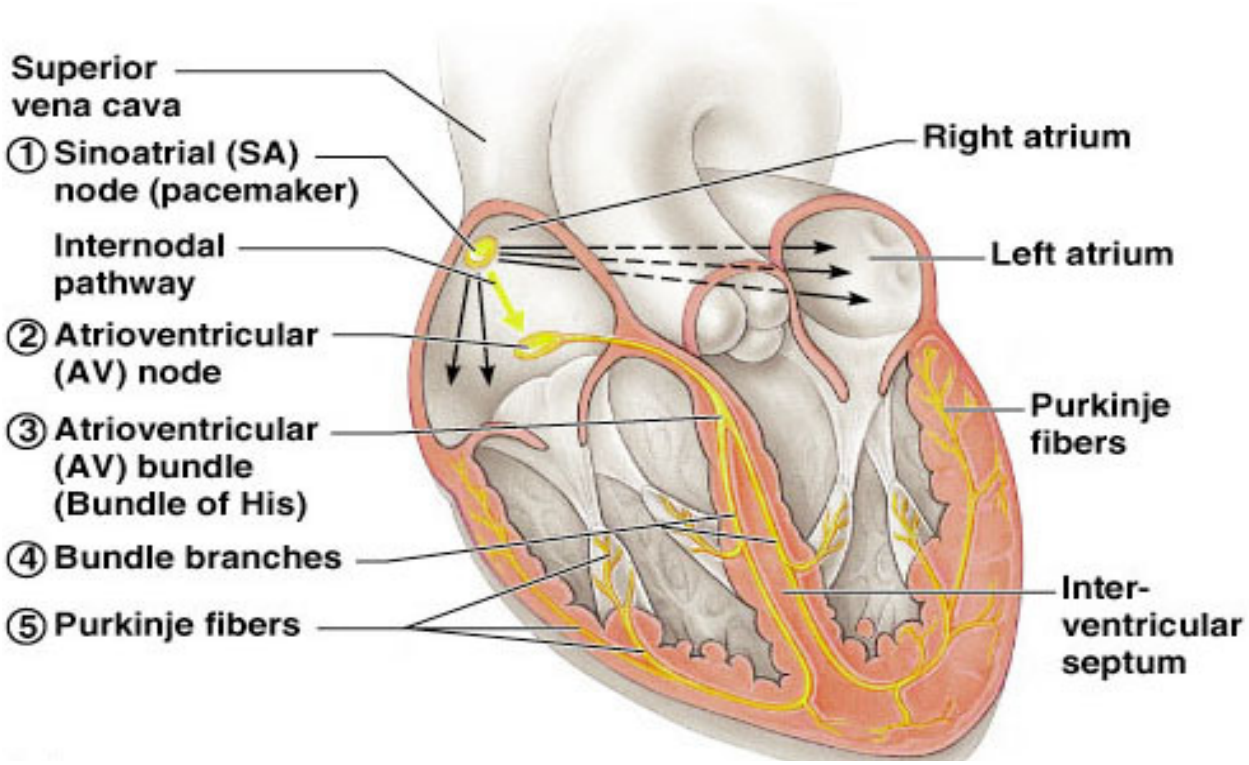
Electrical Conduction System of the Heart

- Consists of specialized myocardial tissue that acts to generate and conduct action potentials rapidly through the heart.
- **Sino-Atrial (SA) Node**
  - Located in the wall of the right superior atrium, near the entrance of the SVC.
  - Functions as the normal heart pacemaker.
  - Innervated by autonomic motor neurons that influence the rate at which action potentials spontaneously generate.
- **Atrio-Ventricuar (AV) Node**
  - Located in the lower part of the interatrial septum of the right atrium.
  - Functions as the only link between the atria and the ventricles.
    - The AV node is like an electrical "bottle-neck".
    - AP (action potentials) are transmitted through the AV node at a slow velocity.
    - Myocardial ischemia in the AV node results in AV Nodal Block.
  - Also innervated by autonomic motor neurons that influences the velocity of the action potential through the AV node.
  - **If the SA node stops functioning, the AV node becomes the pacemaker of the heart.**

Parasympathetic Innervation of the Heart



- **Common Atrio-Ventricular (AV) Bundle (of His)**
    - Extends down the interventricular septum branching into the right and left bundle branches.
    - Functions to conduct AP (action potentials) rapidly from the AV node down to the right and left ventricles.
    - Myocardial ischemia in a bundle branch results in “Bundle Branch Block”.
- **Purkinje Fibers**
    - Branches off the right and left bundle branches
    - Functions to conduct the AP (action potentials) through the ventricular myocardium.



Neural Innervation of the Heart

- Autonomic motor neurons
    - Innervates the SA node and AV node
    - Parasympathetic innervation
        - Via the Vagus nerve (X)
        - Causes bradycardia (< 60 BPM) during normal relaxed states
        - Also slows transmission of Aps through the AV node.
        - Mechanism of action:

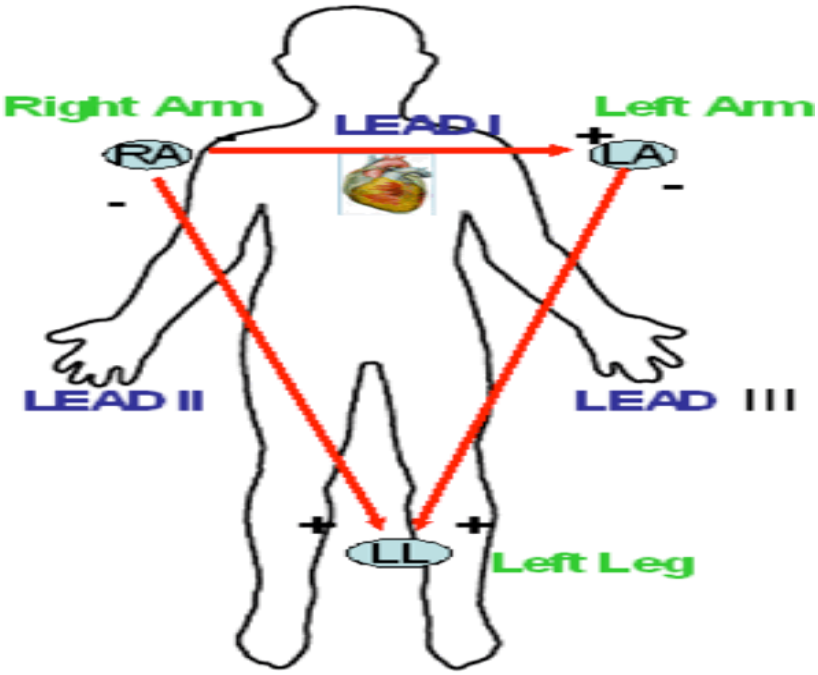
AcH >>>>>> Increases permeability of potassium >>>>>> potassium rushes OUT of the cell >>>>>> hyperpolarization >>>>>> slows the rate of intrinsic activity

- Sympathetic innervation
  - Stimulates 3 changes during states of stress
    - Tachycardia (> 100 BPM)
    - Increased velocity of AP transmission through the AV node >>>>>>
    - Increased myocardial contractility = increased force of contraction
    - Mechanism of action:

Catecholamines >>>>>> increased permeability of sodium >>>>>> sodium rushes INTO cells >>>>>> depolarization >>>>>> increased rate of activity

The Electrocardiogram (EKG)

- The 1924 Nobel Prize in Physiology and Medicine was awarded to William Einthoven (Holland) for first using a galvanometer to record the change in electrical activity of the heart.
- Clinical uses of EKG
  - Used to diagnosis MI and CAD
  - Used to identify cardiac arrhythmias
  - Used to identify cardiomegaly
  - Used to identify electrolyte abnormalities (especially calcium & potassium)
- Surface electrodes are used to record the direction of electrical current (AP) through the heart.
- Bipolar Limb Leads
  - Records the differences in voltages between two limbs
  - Einthoven's Triangle
    - Lead 1 – measures electrical activity from right arm to left arm
    - Lead 2 – measures electrical activity from right arm to left leg.
      THE MOST IMPORTANT LEAD.
      This gives the information from the electrical flow from the SA node to the AV node.
    - Lead 3 – measures the electrical activity between the left arm and the left leg

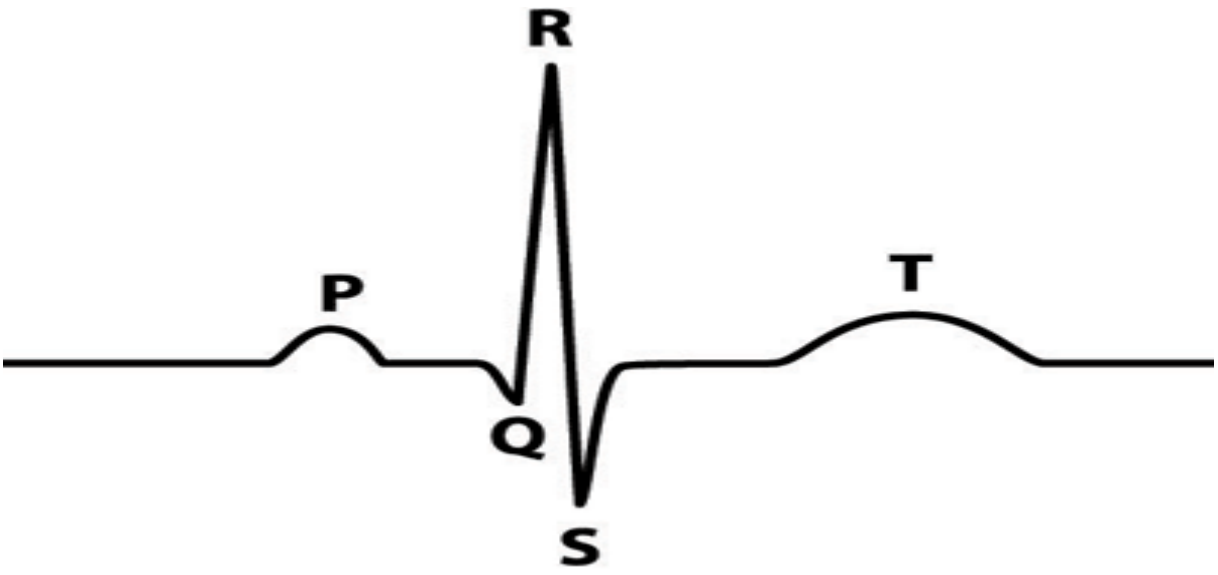


The Electrocardiogram (EKG)

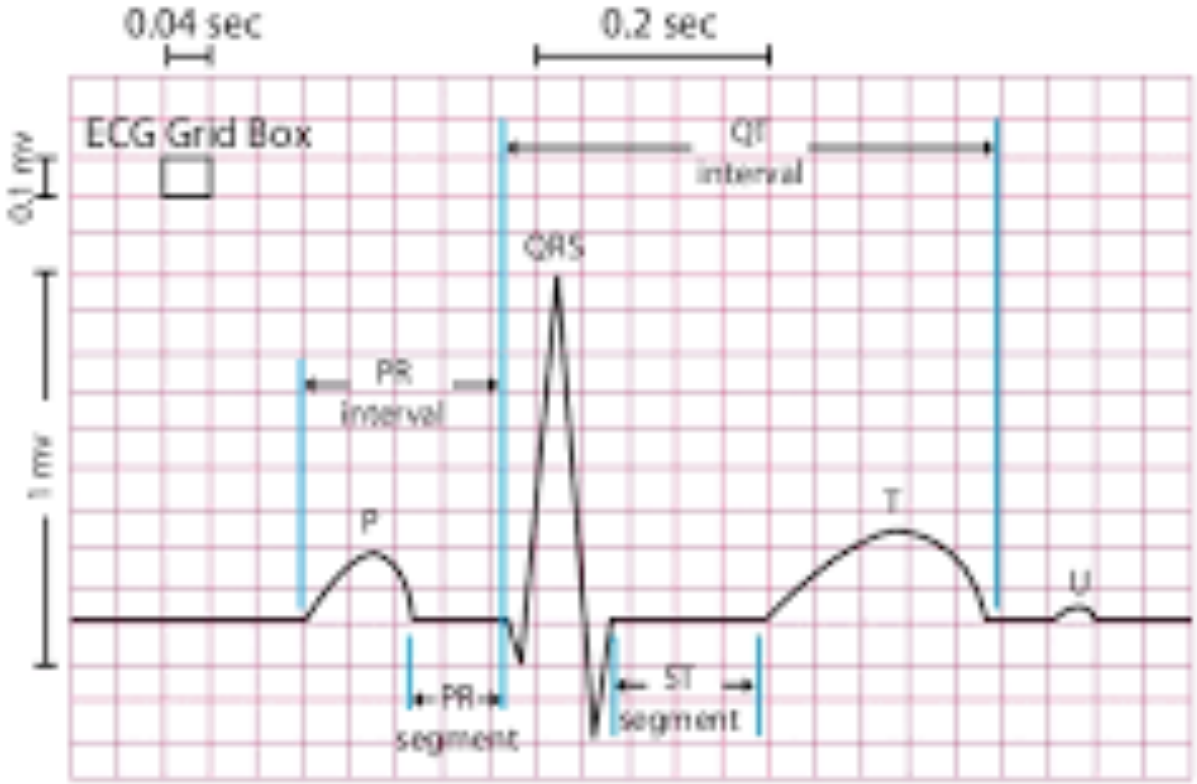
- . Unipolar (Augmented)
    - 9 more leads that are used
    - Records the difference in voltage between one limb (unipolar) and a ground electrode.
    - Unipolar leads slow larger (augmented) pen deflectors than bipolar leads.
    - Examples:
        - AVR – electrodes on right arm
        - AVL – electrode on left arm
        - AVF – electrode on left leg
- Unipolar Chest (Precordial) Leads
    - V1 – V6
    - Records the difference in voltage between one state on the chest and a ground electrode.

EKG Waves Related to Heart Anatomy

- **NSR = Normal Sinus Rhythm**
    - **Every P, Q, R, S, T Cycle = 1 Heartbeat**
- **P - Wave**
    - Corresponds to electrical depolarization
    - Enlarged P – wave indicates an enlarged atria
        - Example – mitral stenosis
- **P – R Interval**
    - Period of time between the start of the P – wave to the start of the Q – wave.
    - This is measuring the travel time from the SA Node to the AV node.
        - Cardiologist will examine this to see if it to short or to long.
    - P – R Intervals longer than .2 sec indicated some degree of AV Nodal Block.
        - Will need a pacemaker
- **QRS Complex**
    - This is showing the depolarization of the ventricle muscle
    - This corresponds to ventricular muscle depolarization
    - It is examined to see how long or short it is
    - Enlarged R – wave means enlargement of the ventricles
- **ST Segment**
    - This is the refractory or resting time (300 msec)
- **T – Wave**
    - Corresponds to ventricular repolarization of the heart muscle cells
    - If it doesn't look normal, it is interpreted as the ventricles not normally repolarizing
    - A flat T – wave indicates ventricular myocardial ischemia
    - An inverted T – wave indicates Myocardial Infarction
    - A peaked T – wave indicates hyperkalemia (increased potassium)

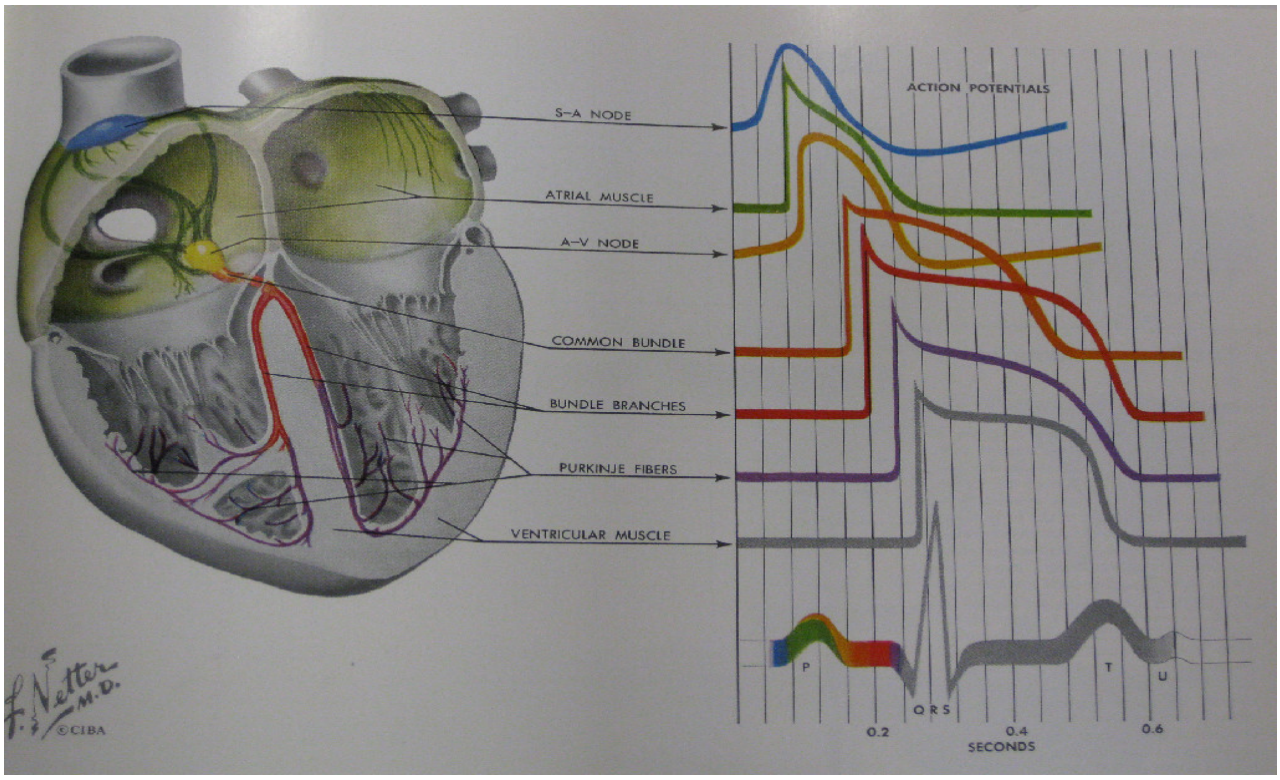


ECG INTERVALS



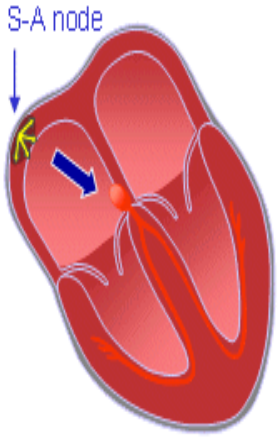
ECG intervals

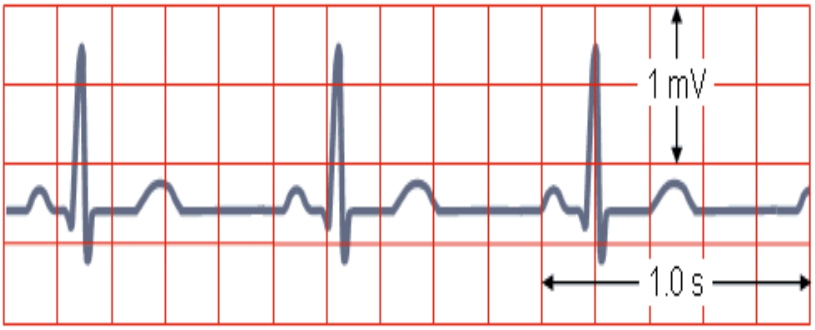
Intervals	Normal Duration(s) Average	Range	Events on the heart during intervals
PR interval[1]	0.18[2]	0.12-0.20	Atrial depolarization and conduction through AV node
QRS duration	0.08	to 0.10	Ventricular depolarization and atrial repolarization
QT interval	0.40	to 0.43	Ventricular depolarization plus ventricular repolarization
ST interval (QT-QRS)	0.32	…	Ventricular repolarization



Introduction to Cardiac Arrhythmias

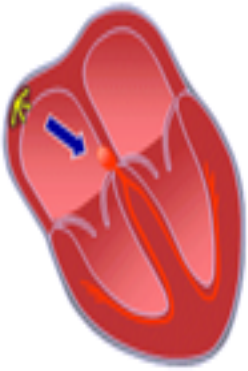
- **Normal Sinus Rhythm**

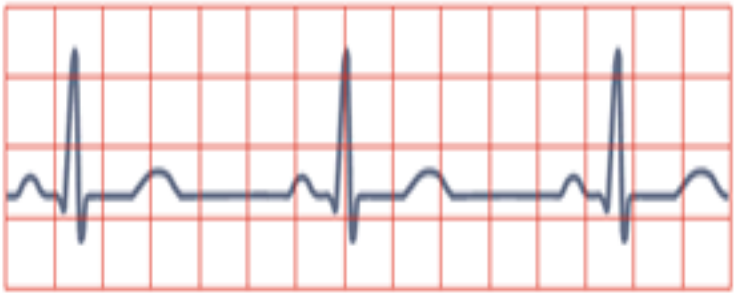




All complexes normal, evenly spaced. Rate 60 – 100/min.

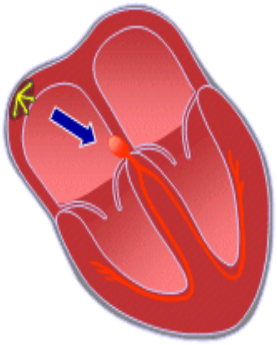
- **Sinus Bradycardia**

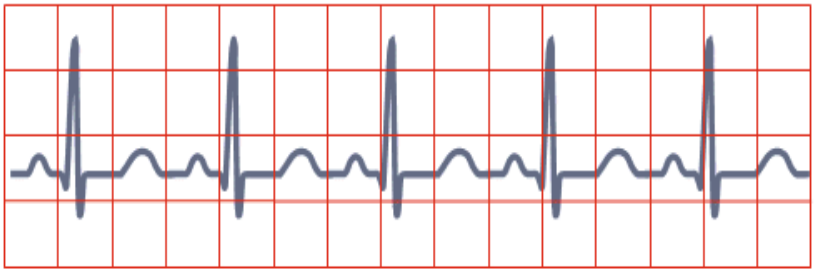




All complexes normal, evenly spaced. Rate < 60/min.

- **Sinus Tachycardia**





All complexes normal, evenly spaced. Rate >100/min.

Cardiac Arrhythmias

- Premature atrial contractions (PAC)
    - Seen in normal people with to much caffeine, anxiety, alcohol, electrolytes, vomiting or diarrhea
- Premature ventricular contractions (PVC)
    - Often seen in middle age and of no concern
    - Can also occur with MI, CHF, hypoxia
- Paroxysmal atrial tachycardia (PAT)
    - Usually in women 20-25
    - May be congenital and start in first year of life
        - Called Wolf Parkinson White Syndrome which requires a catheter radio-ablation
- Atrial fibrillation and flutter (AF)
    - Not life-threatening, yet it is a common cause of hospitalization
    - Causes the heart to be sporadically with no rhythmic pattern
    - May be caused by COPD, alcohol, cardiac surgery, hyperthyroidism, or idiopathic
    - The inefficiency of the atrial contraction leads to a potential buildup of clots in the wall of the atria
    - Treated with electrical cardioversion with anticoagulation meds
    - Some are resistant to cardioversion which puts them at risk for strokes, ventricular fibrillation and sudden death
- Ventricular tachycardia (VT)
    - A normal response to exercise, stress reactions and sexual activity causing the heart to elevate up to 200/minute
    - In patient's with structural heart disease, VT can occur without provocation
    - S & S – pounding heart and lightheadedness
    - Treated with electrical cardioversion and beta blockers
- Bradycardia
    - Pulse less than 60/min or 46/min for athletes
    - Extrinsic causes by drugs, hypothyroidism, CNS disorders
    - Intrinsic causes by SA or AV node dysfunction
    - Treat the cause, such as a pacemaker

Cardiac Arrhythmias

- Heart block
    - Often caused by ischemia due to CAD or may be idiopathic
    - Three degrees possible
        - 1st degree – impulses reach the ventricles and slow in the AV node – no treatment needed
        - 2nd degree – impulse slows so that not all beats get through the ventricle, causing bradycardia – may or may not need a pacemaker
        - 3rd degree (complete) – all impulses from the atria to the ventricles are blocked at the AV node – all need external pacemaker
    - Sick sinus syndrome - a wide variety of alternate bradycardia and tachycardia

A Schematic Heart