Cardiovascular Engineering

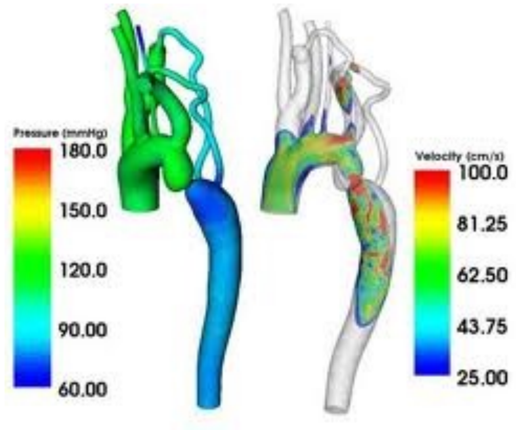
Leo Hwa Liang

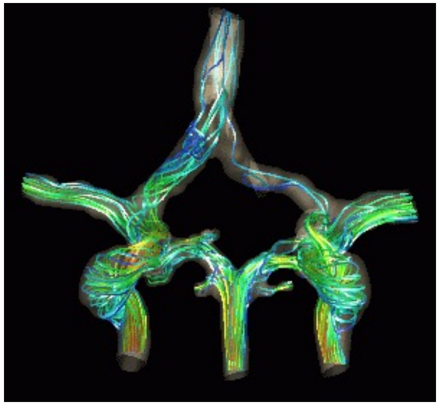
Important flow concepts

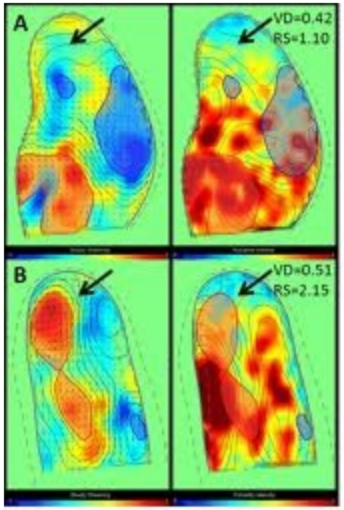
- Pressure
- Boundary layer flow
- Flow separations
- Shear stresses
- Streamlines
- Stagnation points
- Characteristics of Turbulence and Laminar
- Cavitation

Hemodynamics

- The physics of blood/fluid through the vasculature
- Understanding the interrelationships among velocity of blood flow, blood pressure, and the dimensions of the various components of the systemic circulation







Parametric representation of steady streaming field and pulsatile strength in dilated cardiomyopathy with apical thrombus (A) and in dilated cardiomyopathy without apical thrombus (B)

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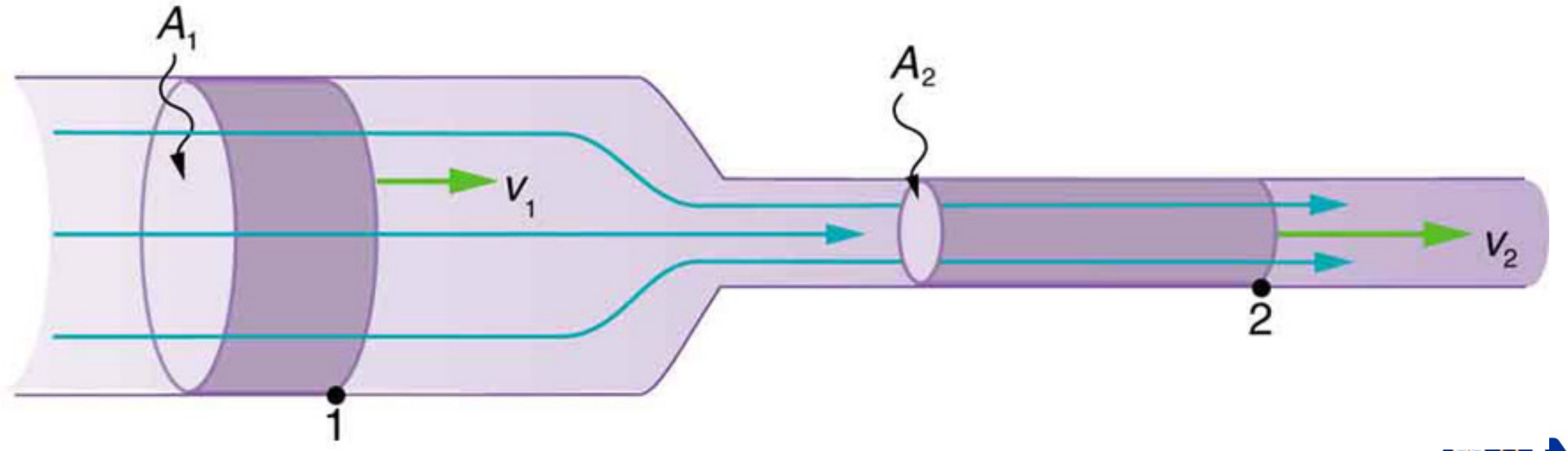
Hemodynamics: Velocity of the bloodstream

- Velocity, as relates to fluid movement, is the distance that a particle of fluid travels with respect to time, and it is expressed in units of distance per unit time (e.g., cm/sec)
- In a rigid tube, velocity (v) and flow (Q) are related to one another by the cross-sectional area (A) of the tube:

Equation 17-1

$$v = Q/A$$



www.boundless.com

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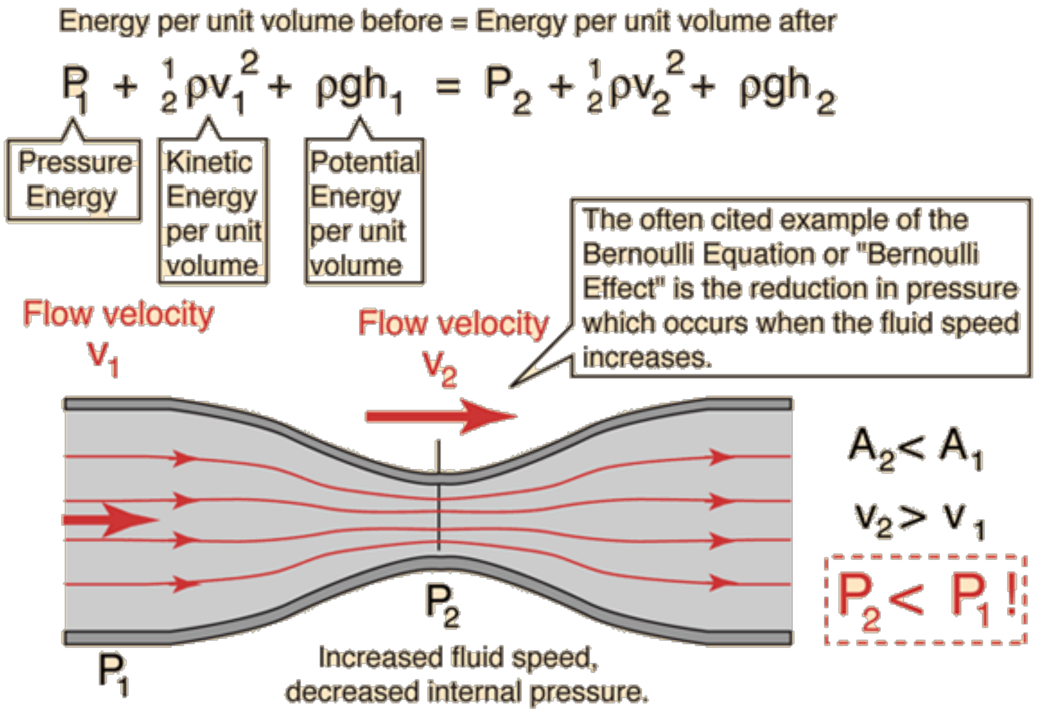
Hemodynamics: Relationship between velocity and pressure

- The total energy in a hydraulic system consists of three components: pressure, gravity, and velocity

Equation 17-2

$$P_{dyn} = \rho v^2/2$$

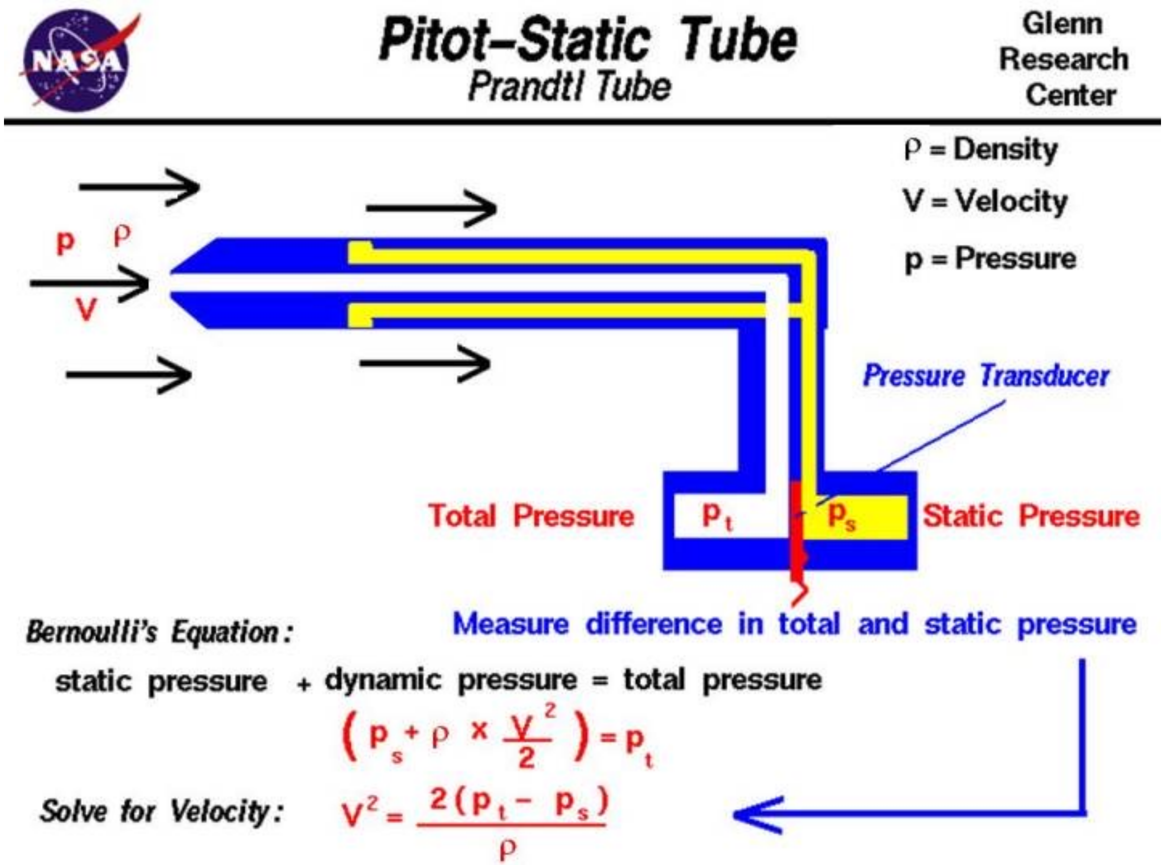
- where ρ is the density of the fluid (g/cm³) and v is velocity (cm/sec)



hyperphysics.phy-astr.gsu.edu

The Bernoulli equation

- Assumptions:
  - 1) Streamline, 2) Incompressible fluid, 3) steady flow, 4) laminar



www.consultkeithyoung.com

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Hemodynamics: Relationship between pressure and flow

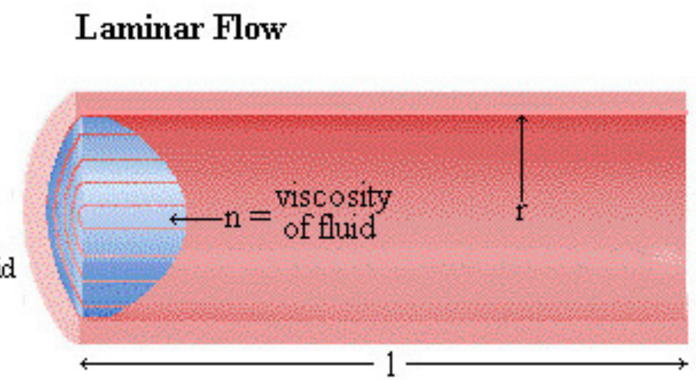
- Poiseuille's law applies to the steady (i.e., nonpulsatile) laminar flow of Newtonian fluids through rigid cylindrical tubes

Equation 17-3

$$Q = \frac{\pi (P_i - P_o) r^4}{8 \eta l}$$

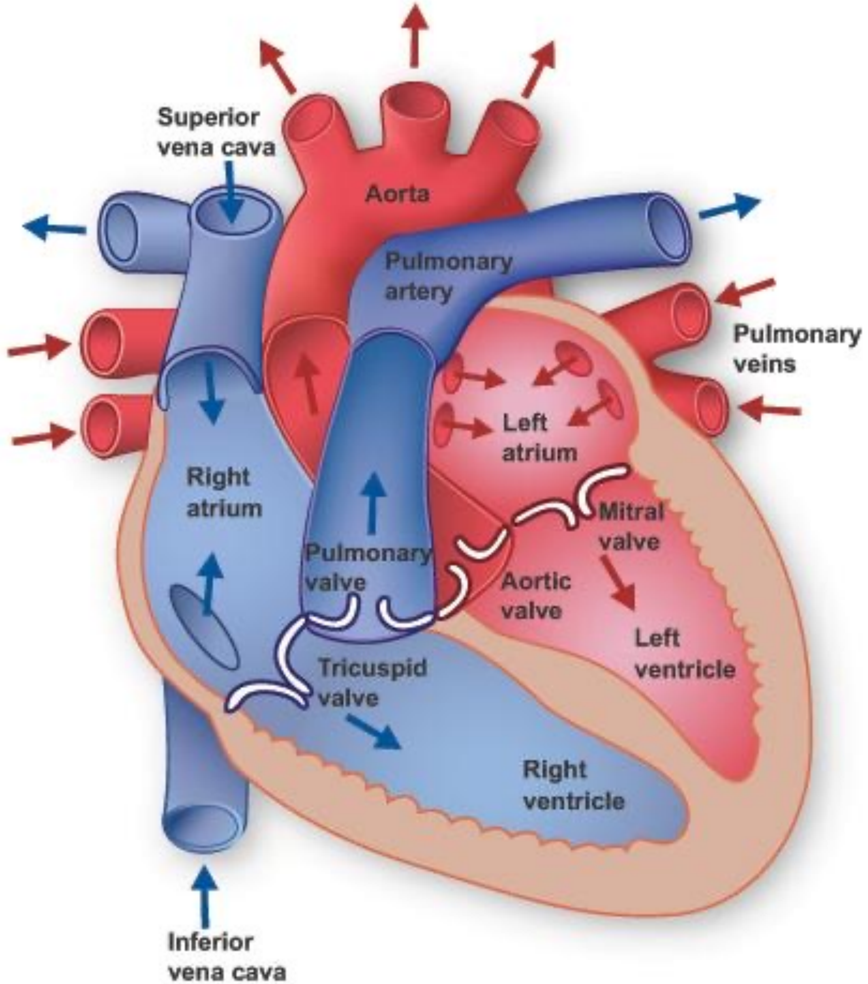
$$R = \frac{8nl}{\pi r^4}$$

where **r** = radius of tube
n = viscosity of fluid
l = length of tube



- Poiseuille's law describes the flow of fluids through cylindrical tubes in terms of flow, pressure, the dimensions of the tube, and the viscosity of liquid where
- Q = flow, Pi - Po = pressure gradient from the inlet (i) of the tube to the outlet (o), r = radius of the tube, l = length of the tube, η = viscosity of the fluid

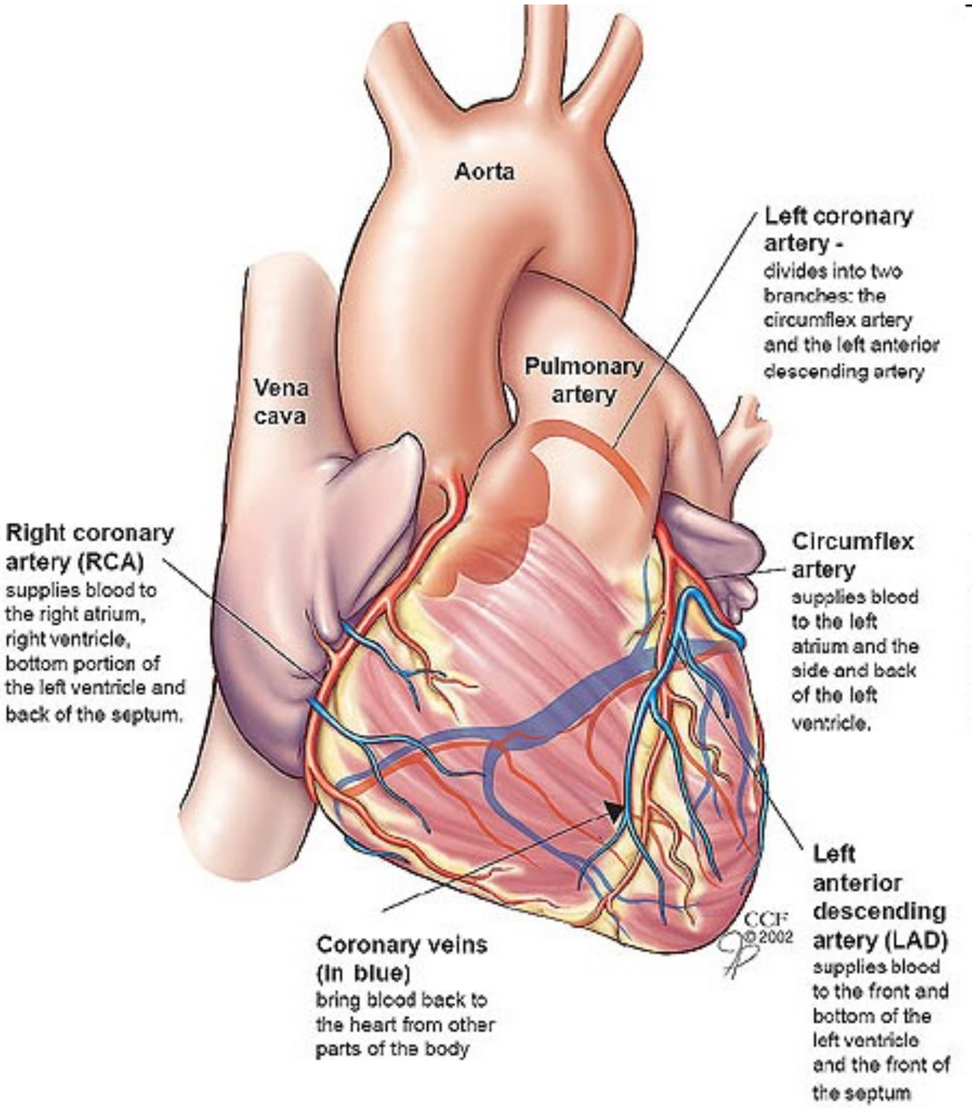
Anatomy of Heart

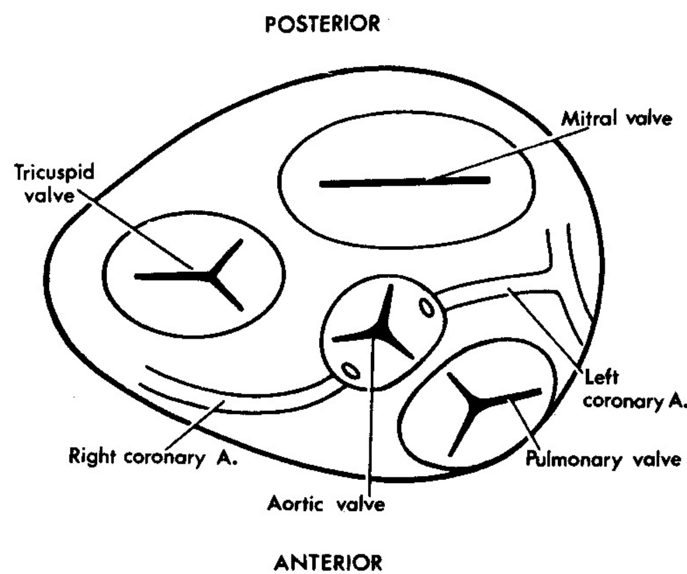


www.cardinalglennon.com

- Two pumps
- Four chambers
- 70 bpm and 4900 ml/min or 5 litre/min
- C.O. = H.R. x S.V.
  - 4900 = 70 x 70, at rest
  - 30,000 = 200 x 150, exercise

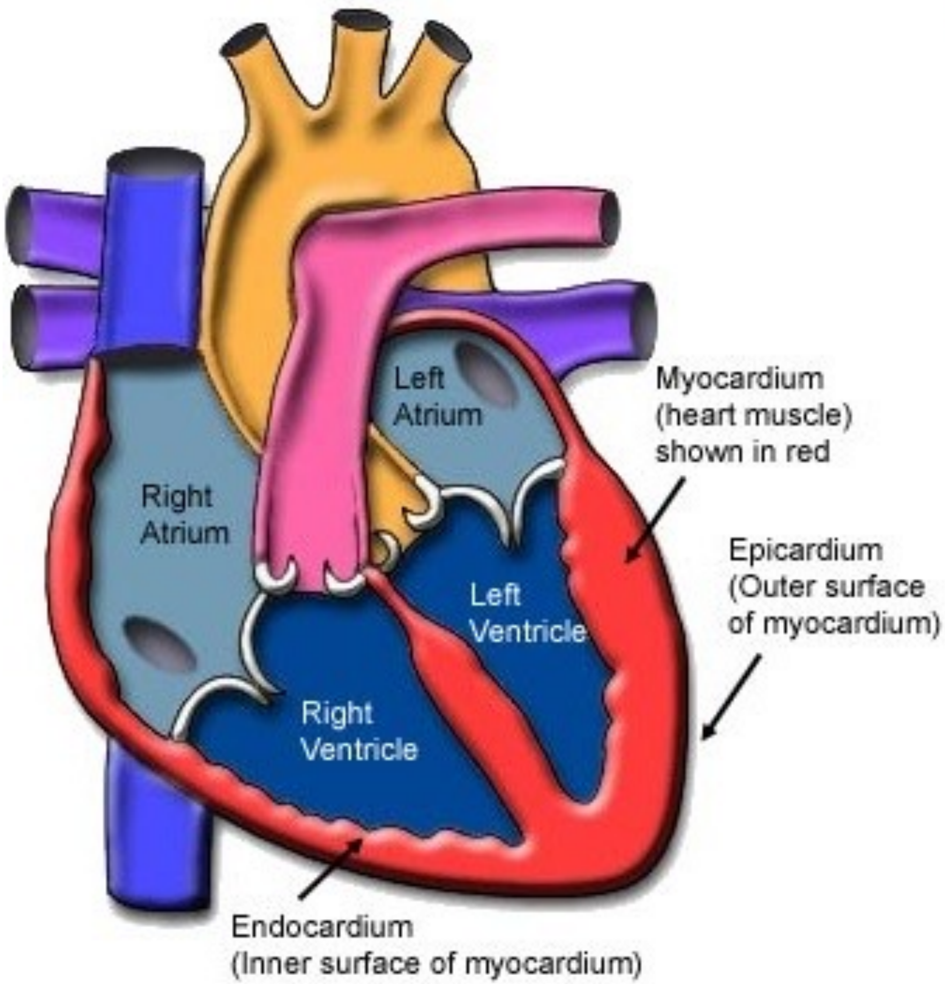
Blood supply to Heart





Content.revolutionhealth.com

Anatomy of Heart



Texas Heart

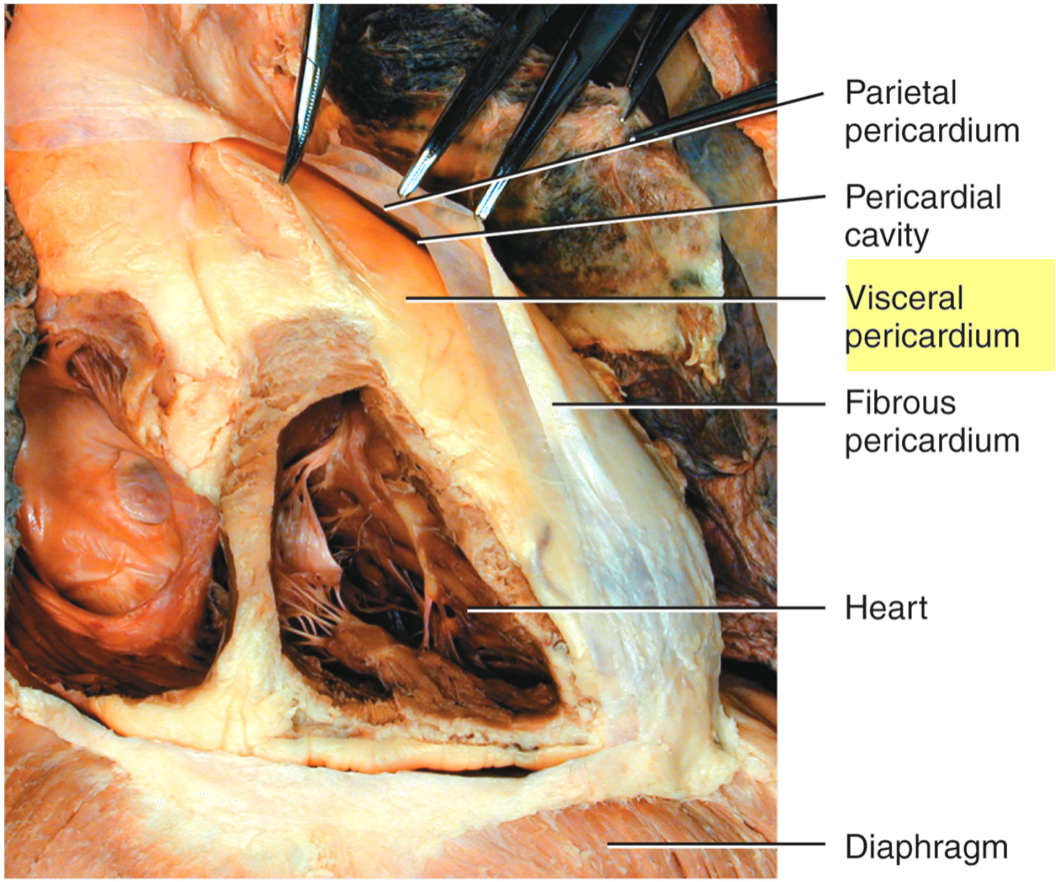
- Muscle orientation of heart changes throughout the thickness of the chamber
- Pericardium – collagen membrane that encloses the heart
  - Contains small amount pericardial fluid that serves as lubricant and limits the excursion of the heart

Layers of the Heart Wall

- The **epicardium**, the thin, transparent outer layer of the heart wall, is also called the visceral layer of the serous pericardium.
- The **myocardium**, the thick middle layer, is composed of cardiac muscle.
- The **endocardium** is a simple squamous epithelium (known throughout the circulatory system as "endothelium”).

The Pericardium

- The **pericardium** is the membrane that surrounds and protects the heart and retains its position in the mediastinum (while allowing for some freedom of movement).
- Contains small amount pericardial fluid that serves as lubricant and limits the excursion of the heart



(f) Layers of the pericardium

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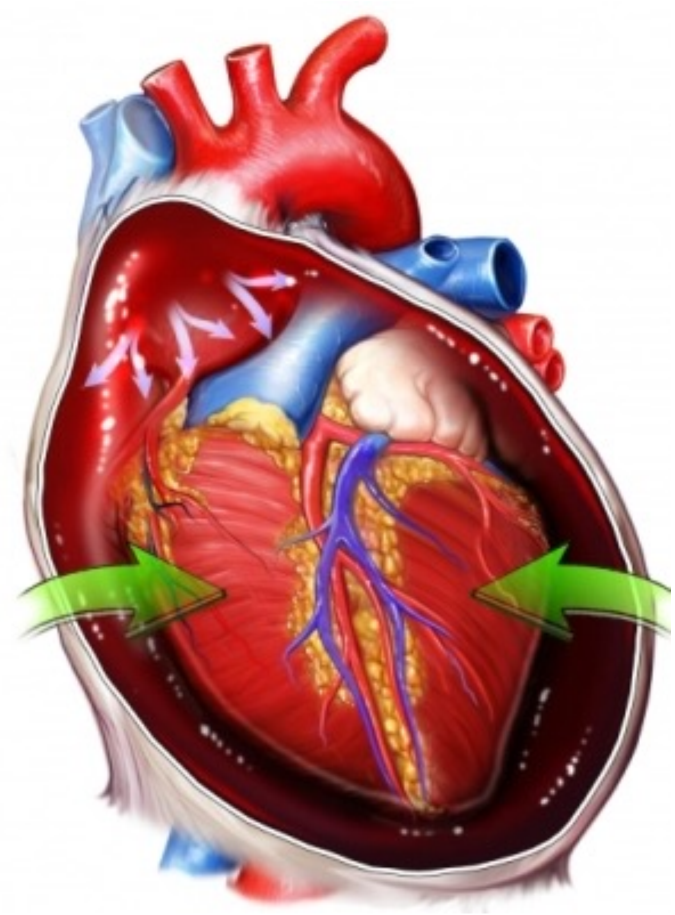
Cardiac Tamponade

- Cardiac tamponade is the pathologic compression of the heart by fluid accumulating in the pericardial sac
  - Gunshot or stab wounds
  - Trauma to the chest in accidents
  - Ruptured aortic aneurysm
  - Inflammation of pericardium

  https://www.youtube.com/watch?v=QwgfuDegC5Y



www.lifescript.com

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Heart Valves

- Blood always flows from an area of high pressure to an area of low pressure.
- The flow of blood (dictated by differences in pressure, not muscles), operates the valves of the heart.
- Valves operate in pairs:
  - **Atrioventricular valves** open to allow blood to flow from the atria into the ventricles.
  - **Outflow (semilunar) valves** open to allow blood to flow from the ventricles, into the outflow vessels.

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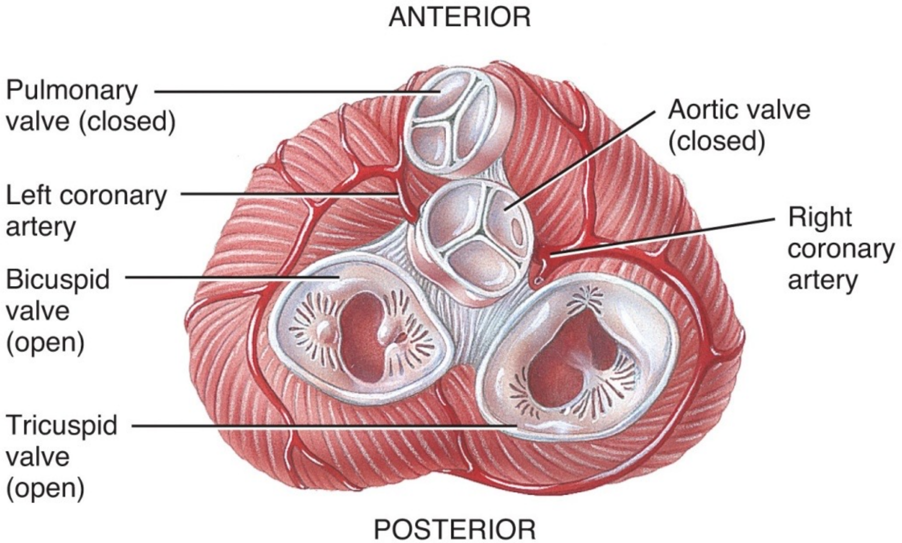
Heart Valves

- Atrioventricular **(AV)** valves are positioned at the entrance to the ventricles:
  - The right AV valve (also called the **tricuspid valve** because of its three leaflets or cusps) opens into the right ventricle.
  - The left AV valve (also called the bicuspid or **mitral valve**) opens into the right ventricle.



(d) Superior view with atria removed: pulmonary and aortic valves closed, bicuspid and tricuspid valves open

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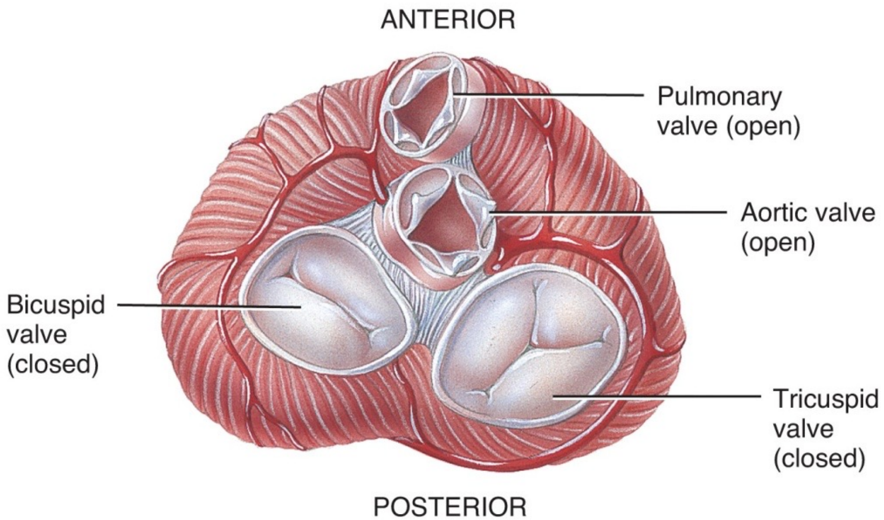
Heart Valves

- The outflow valves are positioned at the entrance to the outflow vessels leading into the pulmonary and systemic circulation:
  - The right outflow valve (also called the **pulmonary valve**) opens into the pulmonary trunk.
  - The left outflow valve (also called the **aortic valve**) opens into the aortic arch.



(e) Superior view with atria removed: pulmonary and aortic valves open, bicuspid and tricuspid valves closed

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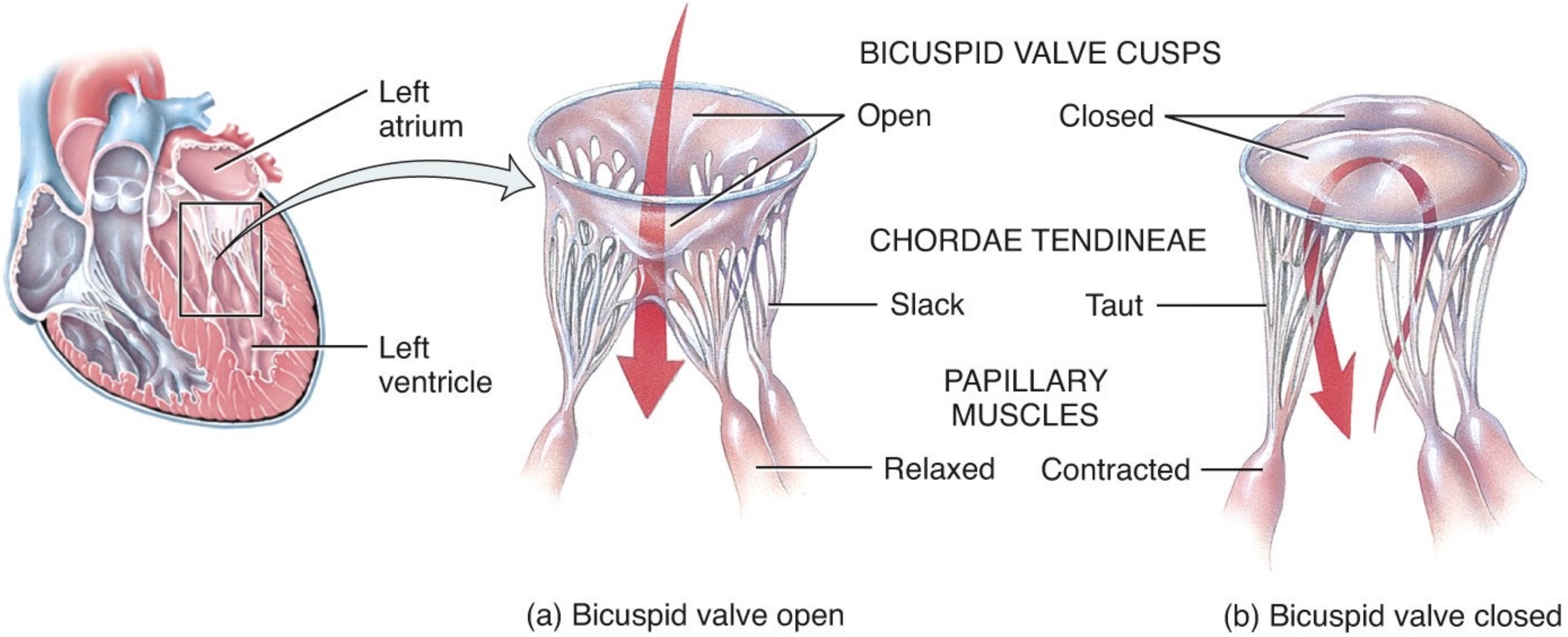
Heart Valves



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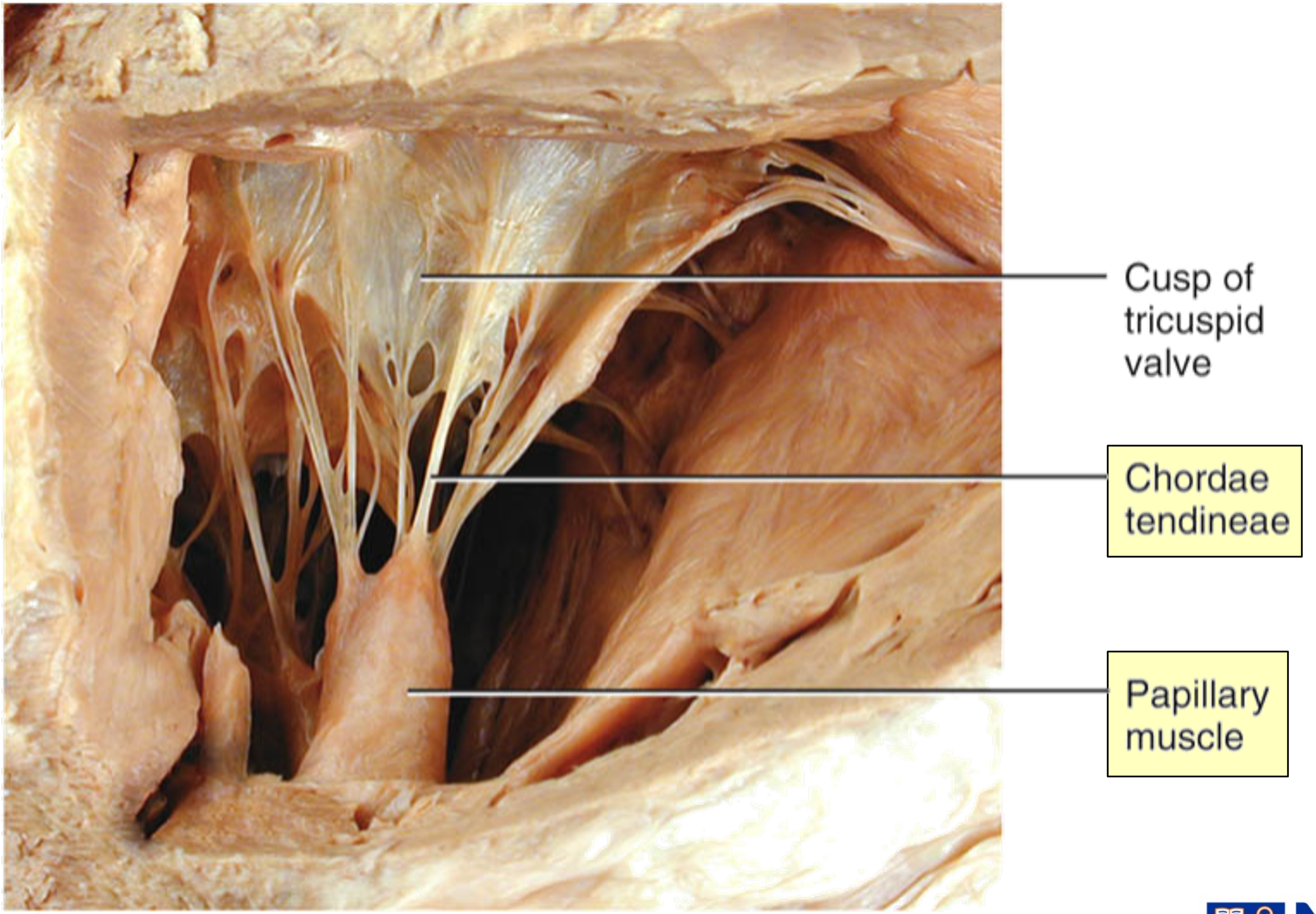
Heart Valves



(c) Tricuspid valve open

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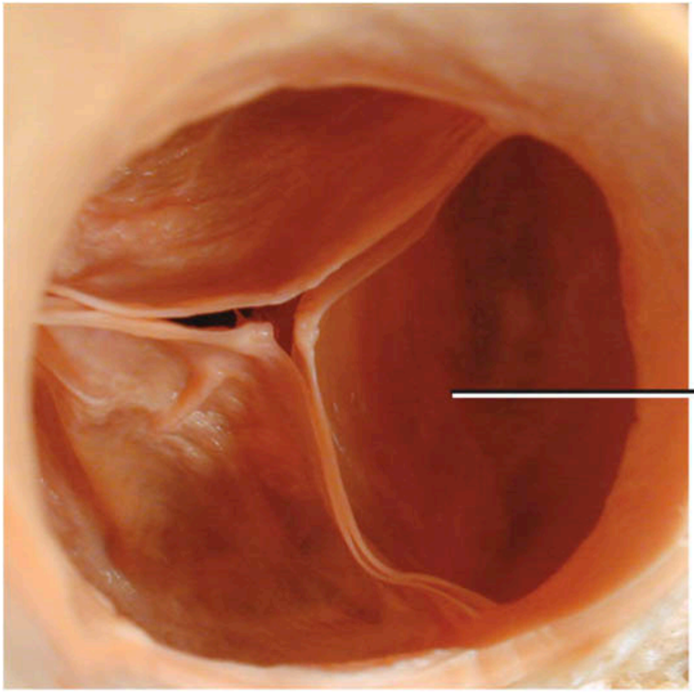
Valves

- In contrast to the delicate, leafy folds of the AV valves, the Outflow valves have rather firm cusps that each look like a semi-full moon (semilunar).
  - Each cusp makes up about a third of the valve.



(g) Superior view of aortic valve

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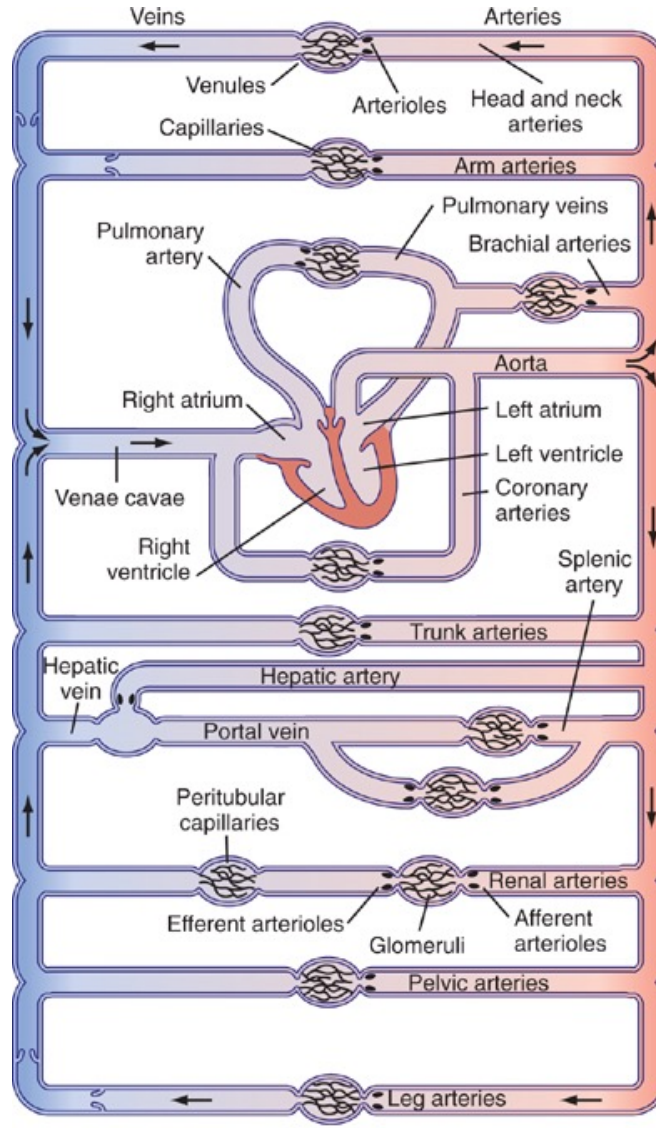
Arterial and venous systems

Vasculature system

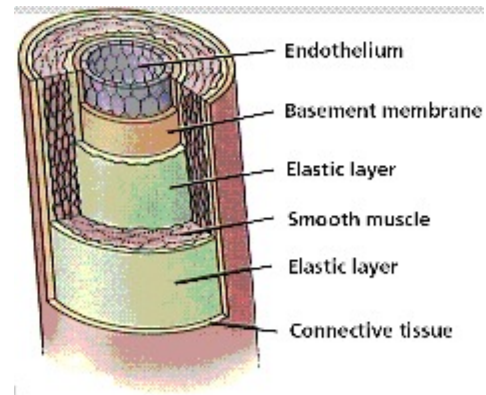
- Arterial system, venous system and the microcirculation
- Vessel types: Aorta → arteries → arterioles → capillaries → venules → veins → vena cava (~60000 miles of blood vessels in an adult)
- Arterial: distributing tubes
- Capillaries: rapid exchange
- Venous: collecting tubes



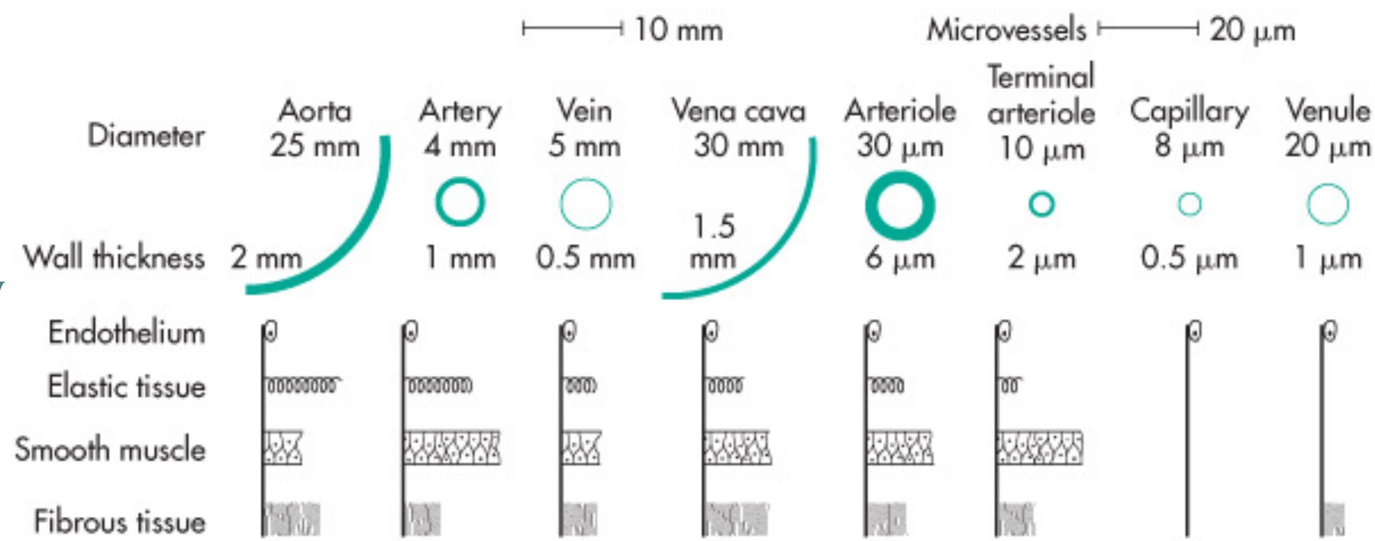
Koeppen and Stanton: Berne & Levy Physiology, 6th Edition.

Blood vessels

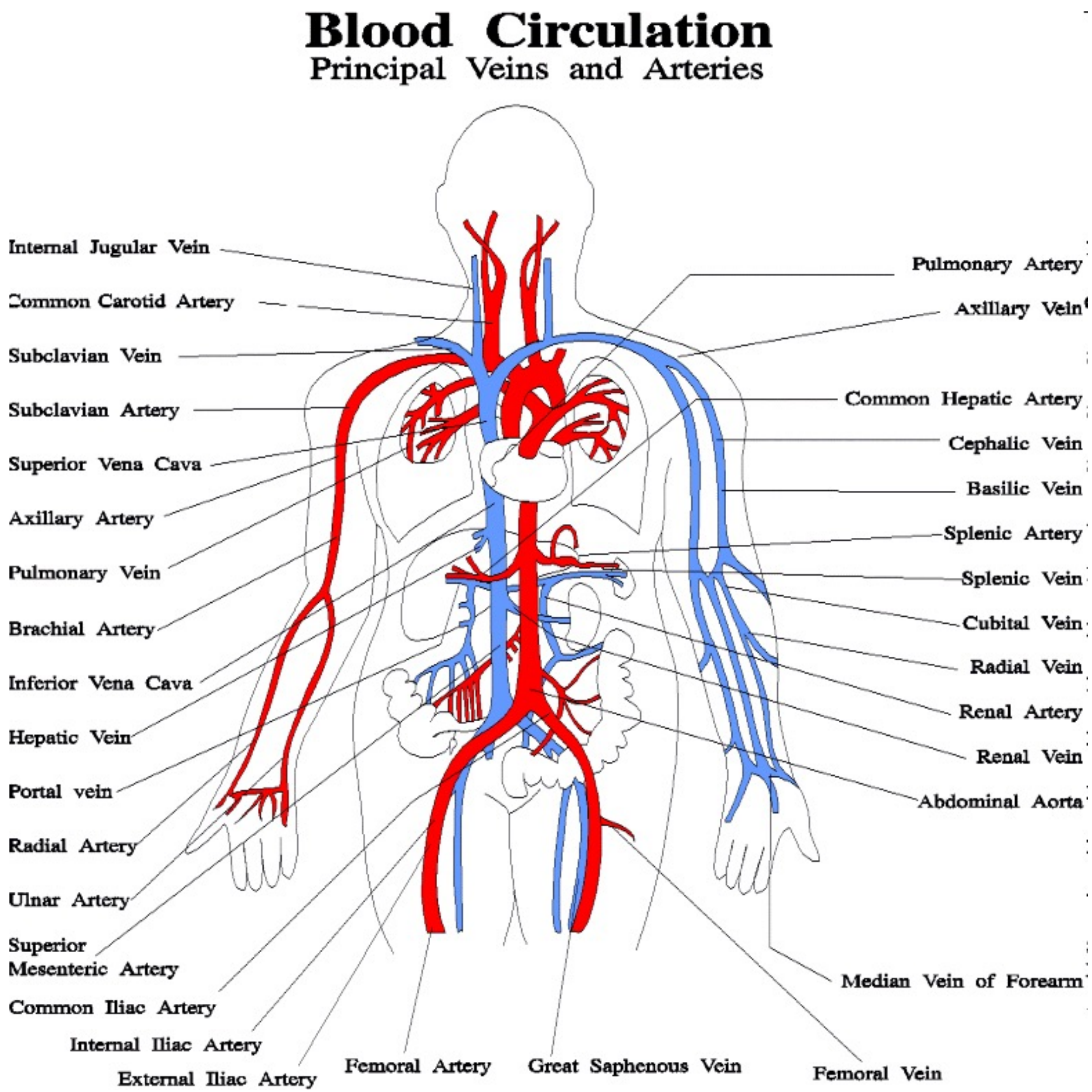
- Walls of arteries and veins have three layers
  - Tunica externa: longitudinal smooth muscle
  - Tunica media: circular smooth muscle
  - Tunica intima: single layer of endothelial cells
- Veins: one-way valves
- Arteries and veins contain different ECM
  - Elastin: stretch
  - Collagen: stiffness
  - Influence the vessel compliance
    - Arterial walls have more collagen: less compliant than veins
- A wide range in the cross-sectional areas and the number of different blood vessels



- **67% volume in veins and venules**
- **12% in pulmonary circulation**



Cardiovascular System



Medical Pictures.com

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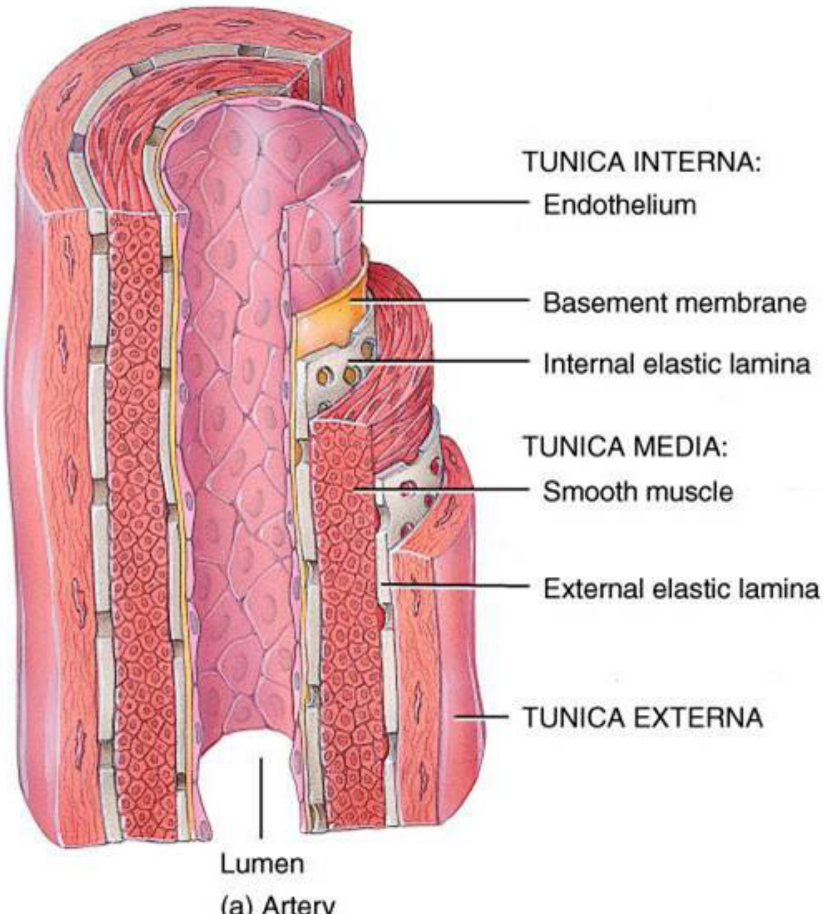
Arteries and Veins

- **Arteries** are vessels that always conduct blood away from the heart – with just a few exceptions, arteries contain **oxygenated** blood.
- Most arteries in the body are thick-walled and exposed to high pressures and friction forces.



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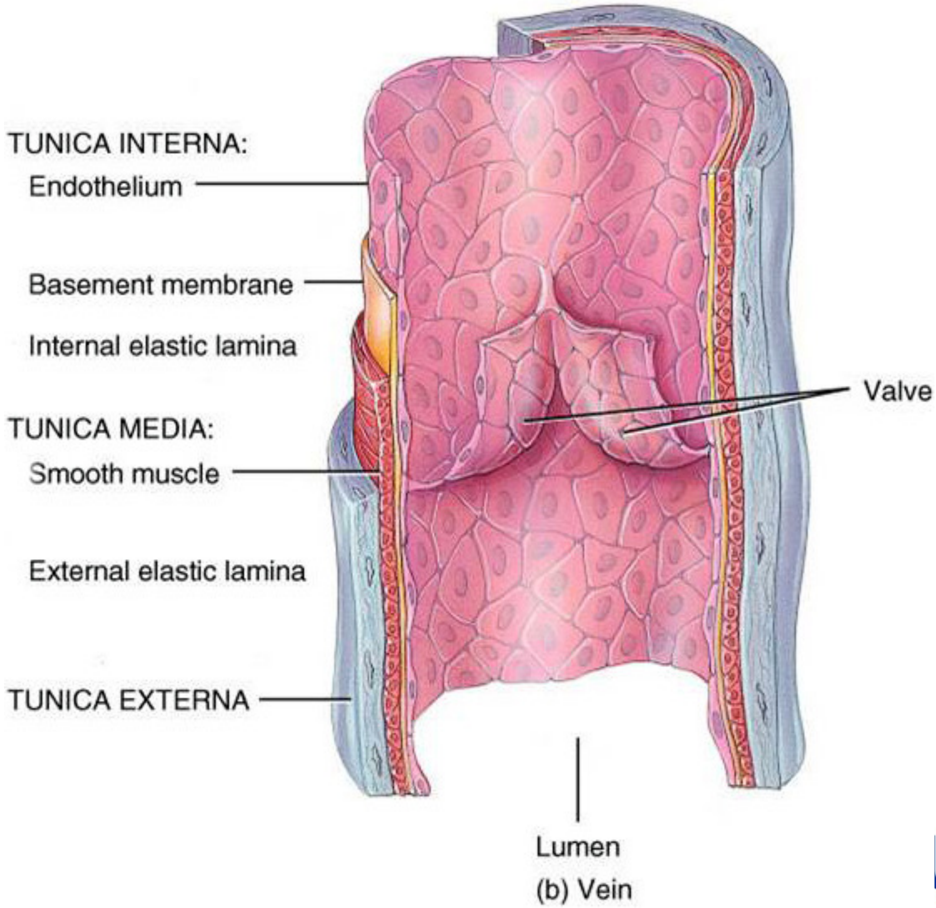
Arteries and Veins

- **Veins** are vessels that always bring blood back to the heart - with just a few exceptions, veins contain **deoxygenated** blood.
- Most veins in the body are thin-walled and exposed to low pressures and minimal friction forces.



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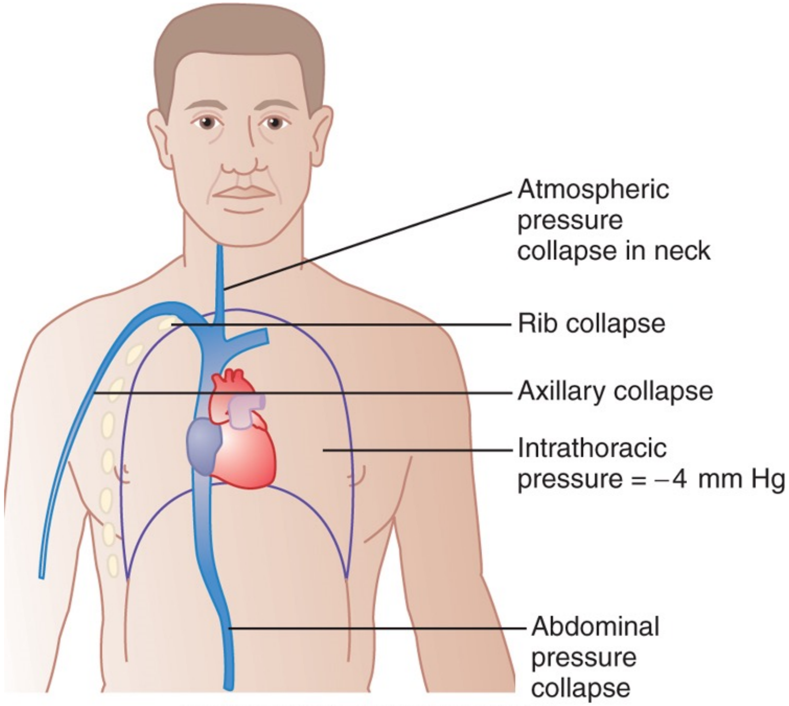
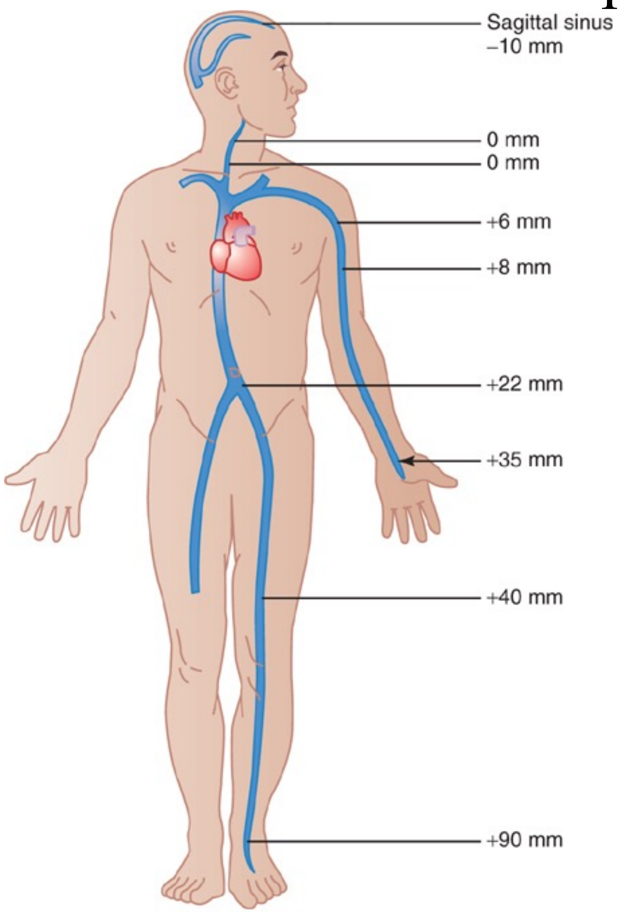
The venous system

- Veins are elements of the circulatory system that return blood to the heart from tissues.
- Veins constitute a very large reservoir that contains up to 70% of the blood in the circulation





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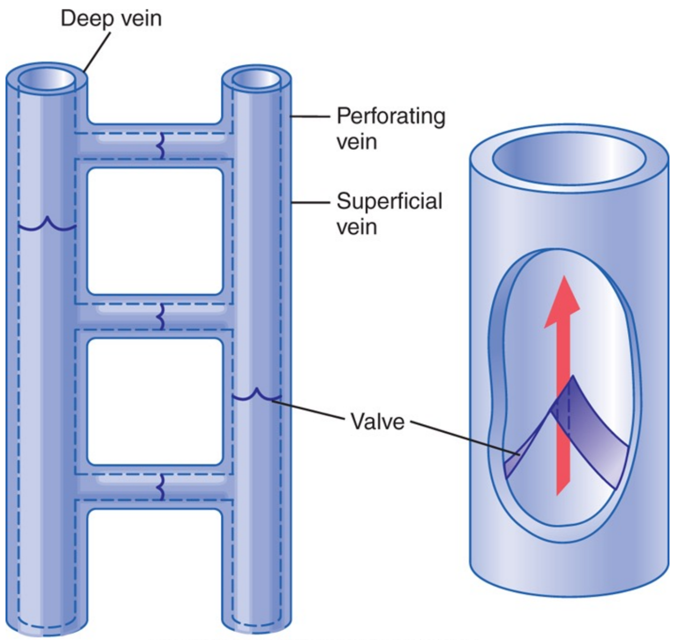
The venous system

- The hydrostatic pressure in postcapillary venules is about 20 mm Hg, and it decreases to around 0 mm Hg in the thoracic venae cavae and right atrium
- Veins control filtration and absorption by adjusting postcapillary resistance and assist in the cardiovascular adjustments that accompany changes in body position

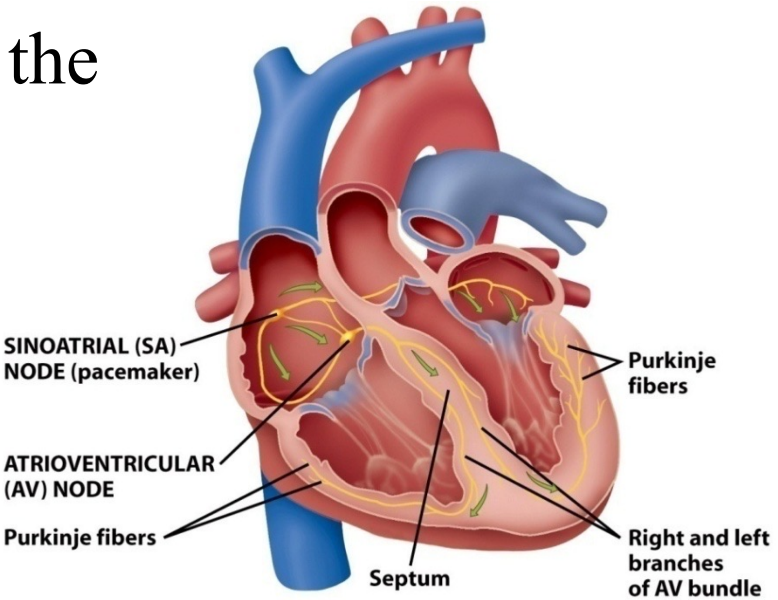


- Venous pump and legs movement as opposed to gravity effect
- http://youtu.be/O2HEwdnF404
- 10-20% of blood volume reduced if standstill for 15-30 mins

Conduction and cardiac phases

Cardiac Conduction

- The self-excitable myocytes that "act like nerves" have the 2 important roles of **forming the conduction system** of the heart and **acting as pacemakers** within that system.
- Because it has the fastest rate of depolarization, the normal pacemaker of the heart is the sinoatrial **(SA) node**, located in the right atrial wall just below where the superior vena cava enters the chamber.



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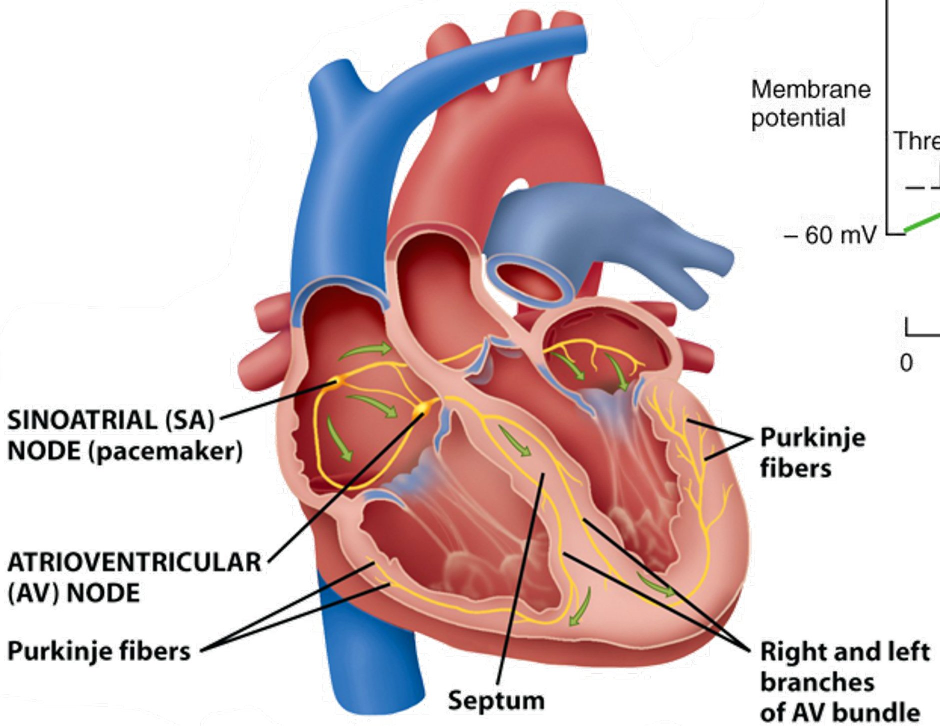
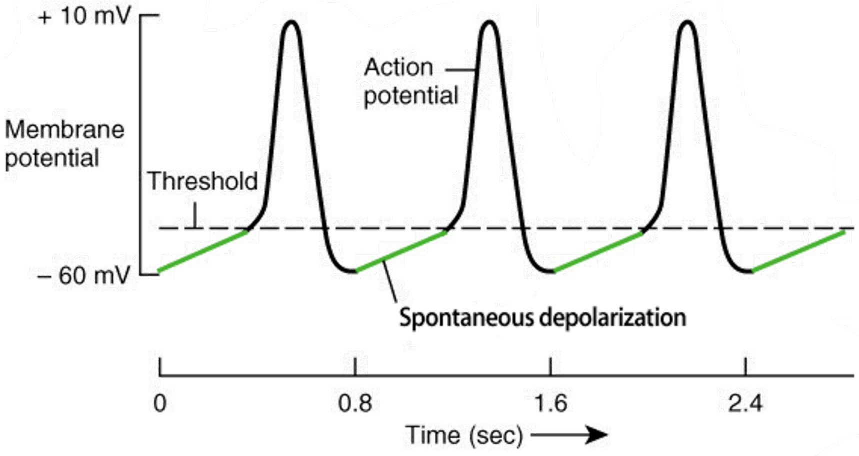
Cardiac Conduction





Spontaneous Depolarization of autorhythmic fibers in the SA node firing about once every 0.8 seconds, or 75 action potentials per minute

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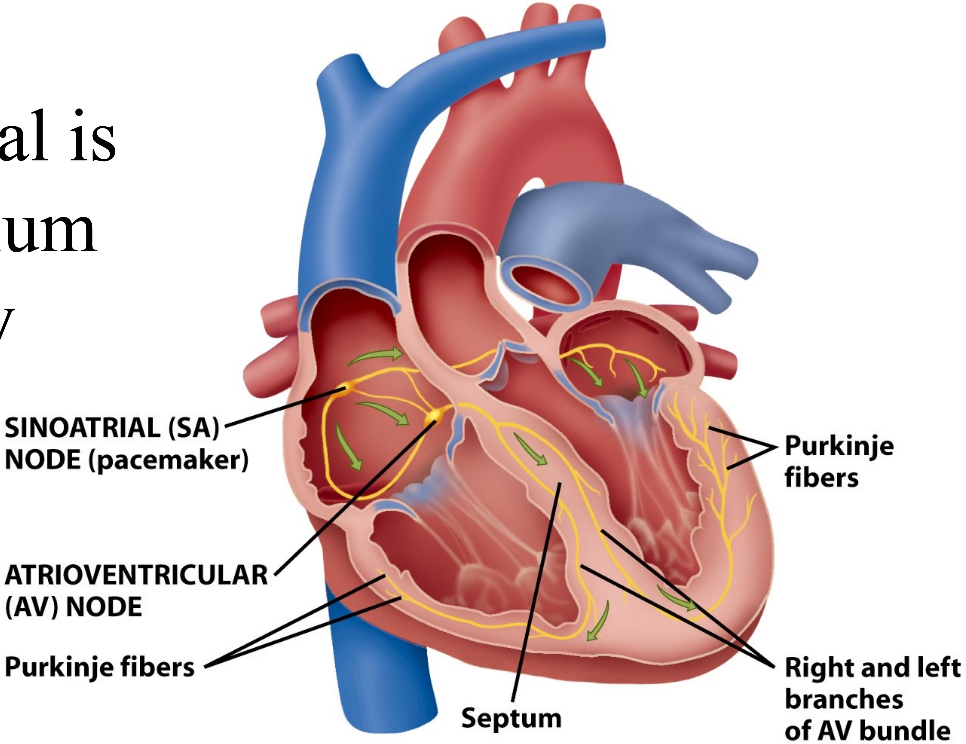
Cardiac Conduction

- The action potential generated from the SA node reaches the next pacemaker by propagating throughout the wall of the atria to the **AV node** in the interatrial septum.
- At the AV node, the signal is slowed, allowing the atrium a chance to mechanically move blood into the ventricles.



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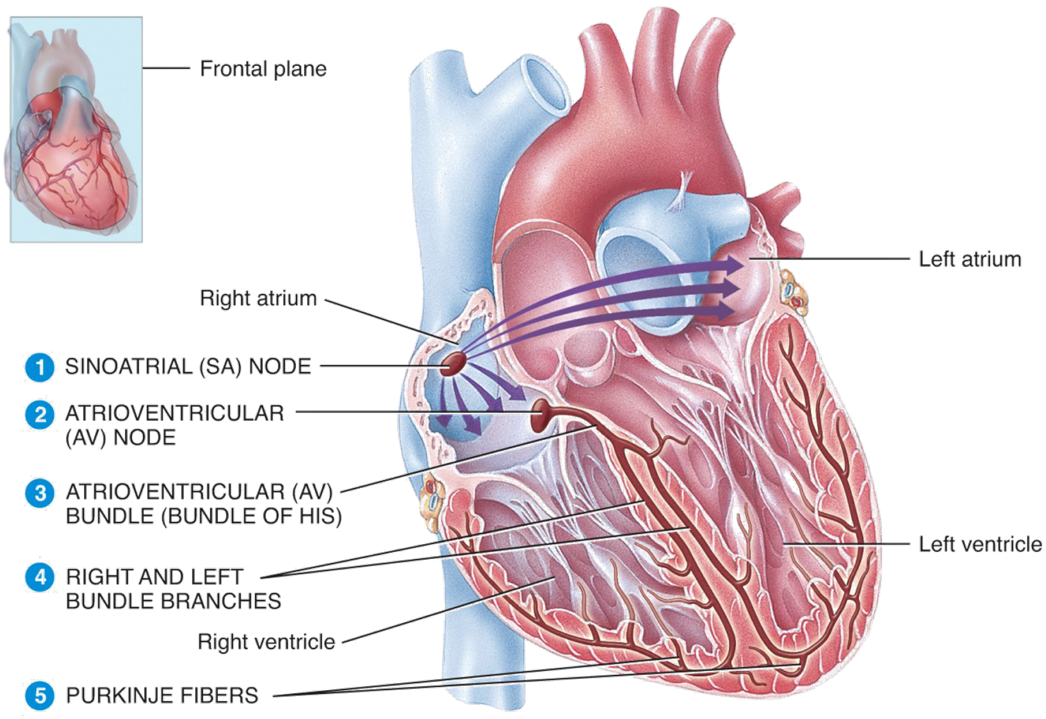
Cardiac Conduction

- From the AV node, the signal passes through the **AV bundle to the left and right bundle branches** in the interventricular septum towards the apex of the heart.
- Finally, the **Purkinje fibers** rapidly conduct the action potential throughout the ventricles (0.2 seconds after atrial contraction).



(a) Anterior view of frontal section

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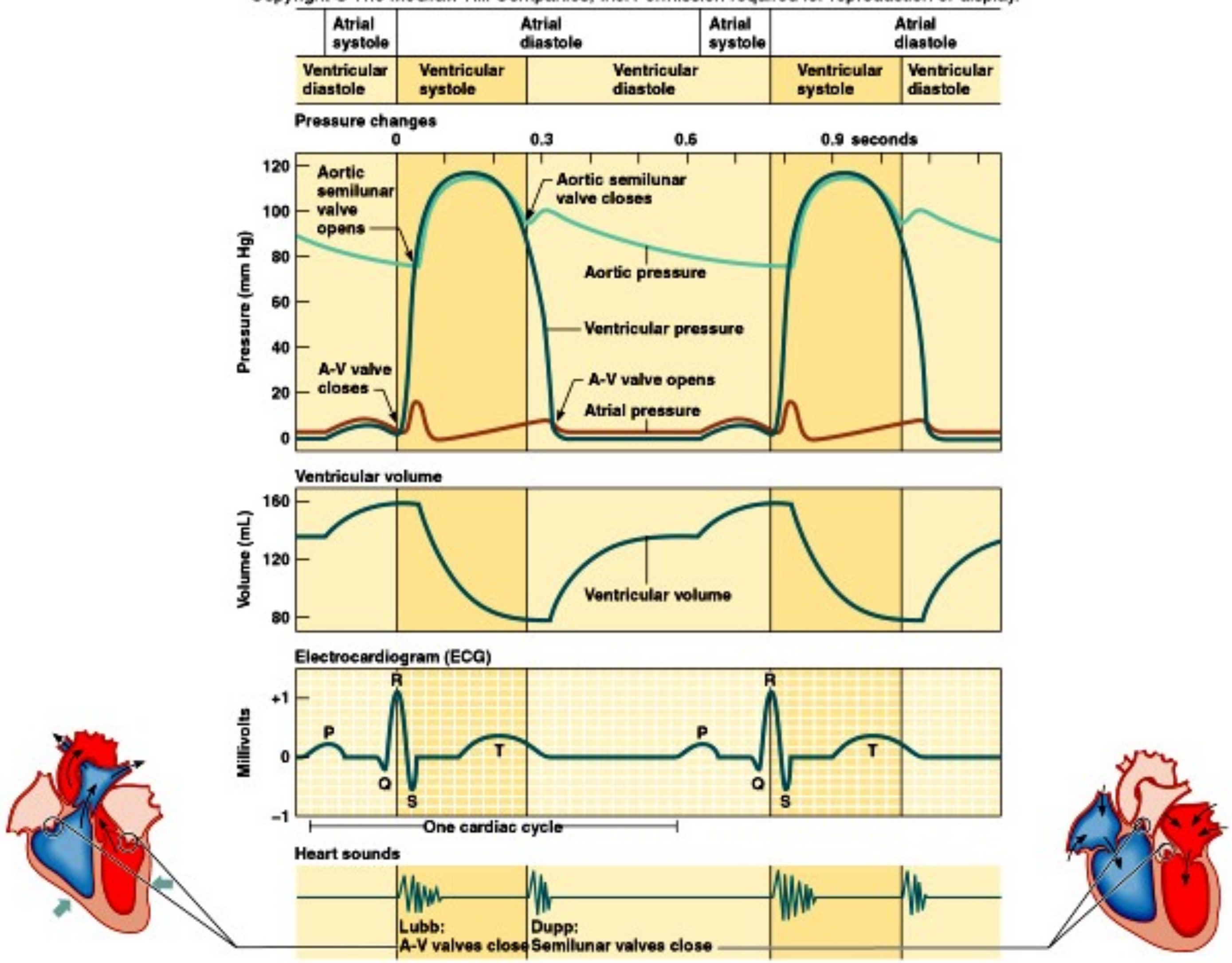
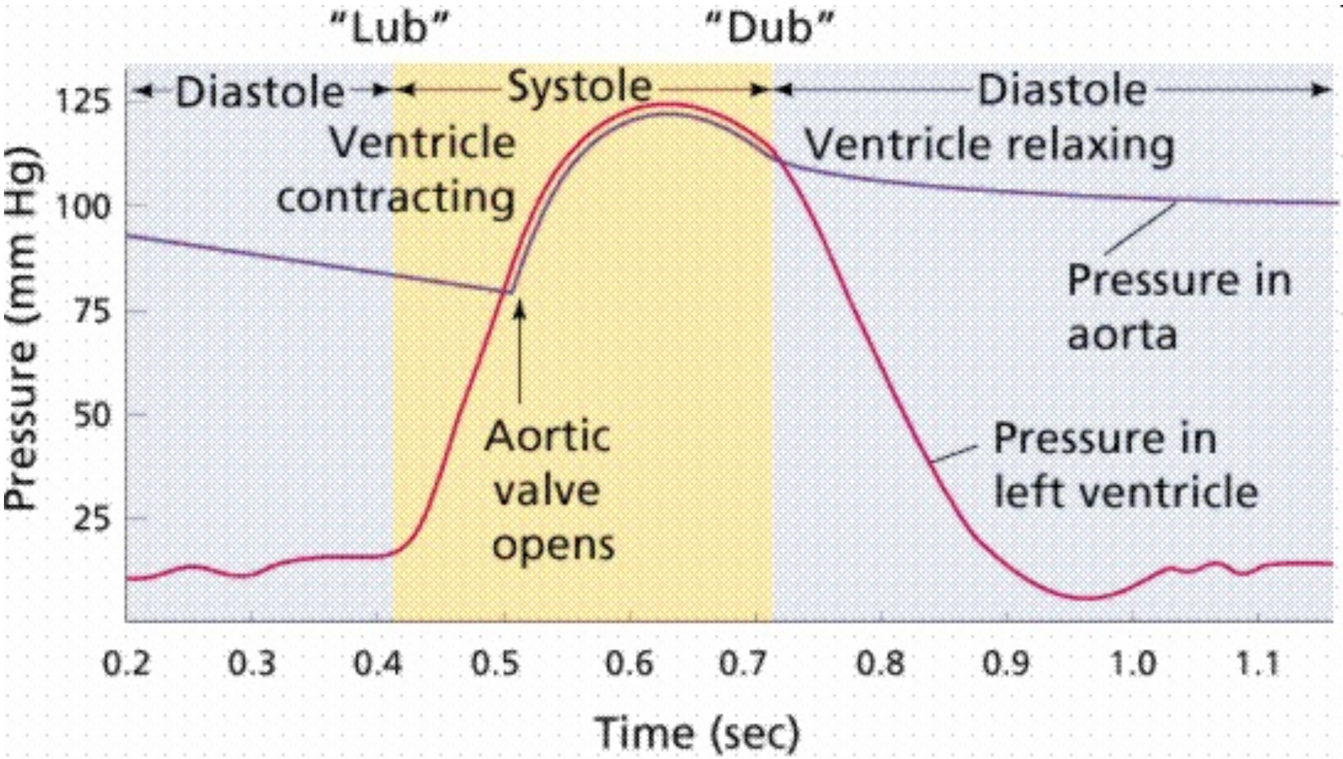
Cardiac Cycle



Bob Ridge, Tokyo

Cardiac Cycle



- Systole – contraction phase, 0.3 seconds
- Diastole – relaxation phase, 0.5 seconds
- Atrial systole lasts only 1/10 of a second

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Shear Stress and Cardiovascular diseases

Hemodynamics Origin of Cardiovascular Diseases

- Pivotal role of hemodynamics in vascular endothelial function and in various pathological conditions
  - Shear stress investigation is of particular importance at molecular and clinical levels
- Pathologic conditions affected by abnormal hemodynamics
  - Atherogenesis
  - Graft – anastomoses
  - Aneurysms
  - In-stent restenosis

Shear stress on vessel wall

- As blood flows through a vessel, it exerts a force on the vessel wall parallel to the wall. This force is called a shear stress (τ). Shear stress is directly proportional to the flow rate and viscosity of the fluid

Equation 17-13

$$\tau = \frac{4\eta Q}{\pi r^3}$$

- The viscous drag on the arterial wall may cause a tear between a normally supported and an unsupported region of the endothelial lining. Aortic dissection or dissecting aneurysm may be resulted from high velocity of blood flow, with associated large shear rate (du/dy) values at the endothelial wall.

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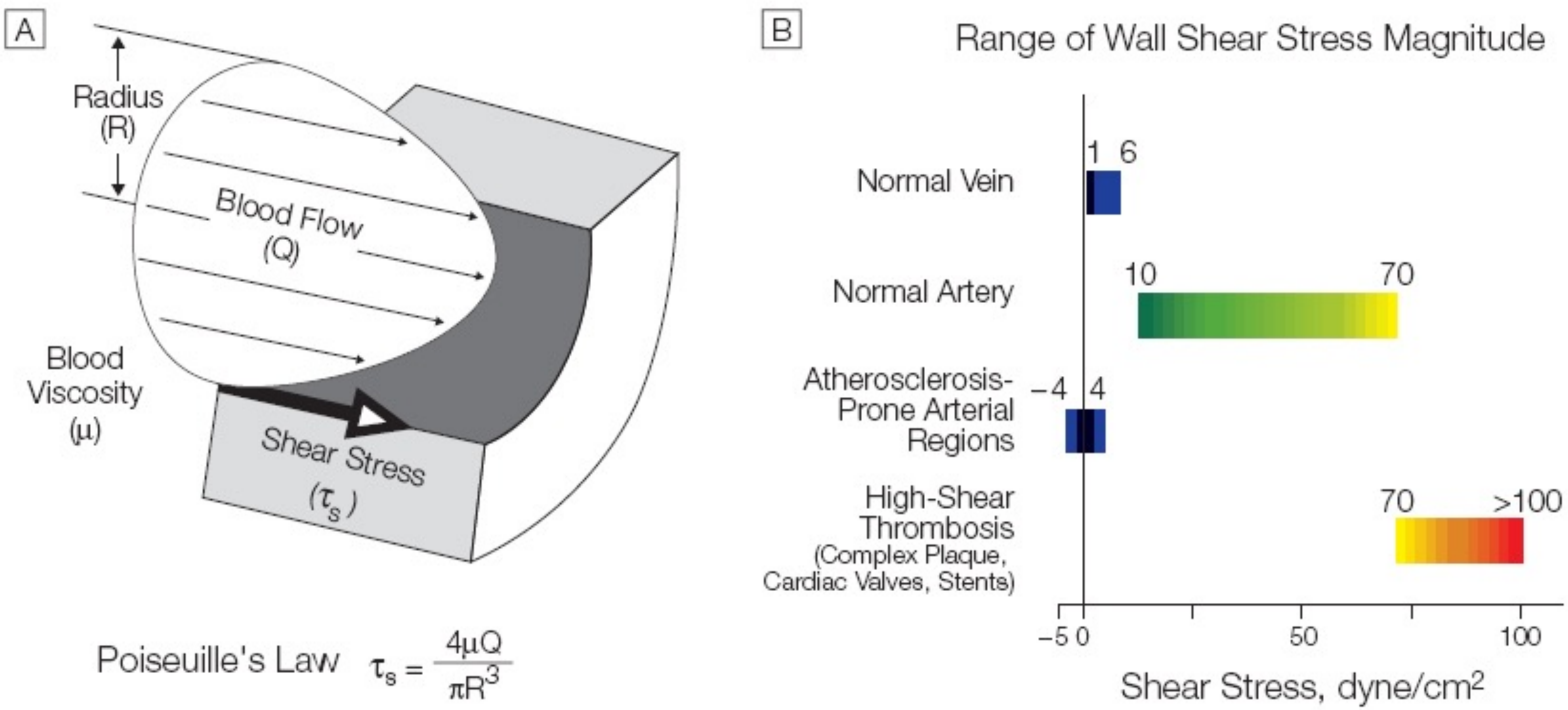
Figure 1. Hemodynamic Shear Stress

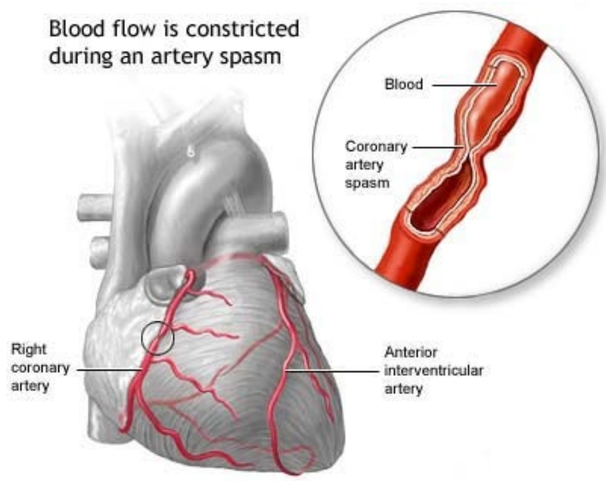


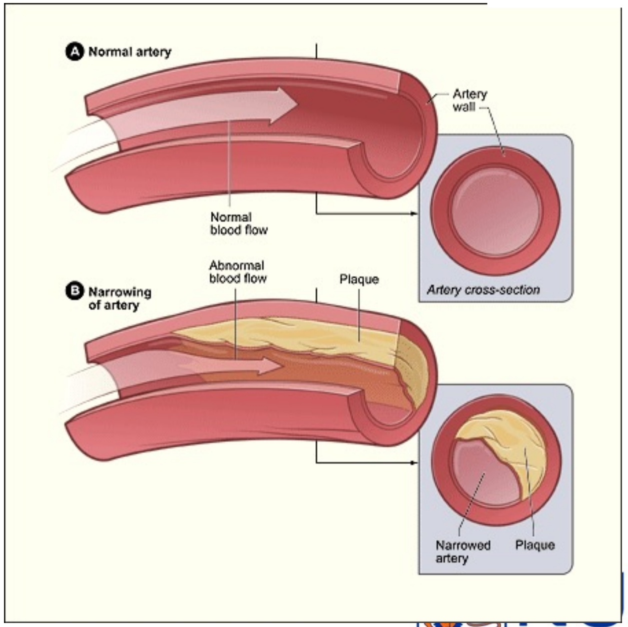
A, Cross-sectional schematic diagram of a blood vessel illustrating hemodynamic shear stress, τ_s, the frictional force per unit area acting on the inner vessel wall and on the luminal surface of the endothelium as a result of the flow of viscous blood. B,Tabular diagram illustrating the range of shear stress magnitudes encountered in veins, arteries, and in low-shear and high-shear pathologic states.

Malek et al. JAMA 1999, p.2035

Coronary atherosclerosis plaques

- Coronary atherosclerosis is a chronic and inflammatory vascular disease characterized by the progressive deposition of arterial plaques or fatty materials along the vascular wall of the coronary arteries.
- The resulted formation of the necrotic core within the lumen of the vascular conduit will eventually lead to the rupture of the plaque responsible for acute coronary syndromes





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Atherosclerosis occurs mostly at bifurcations

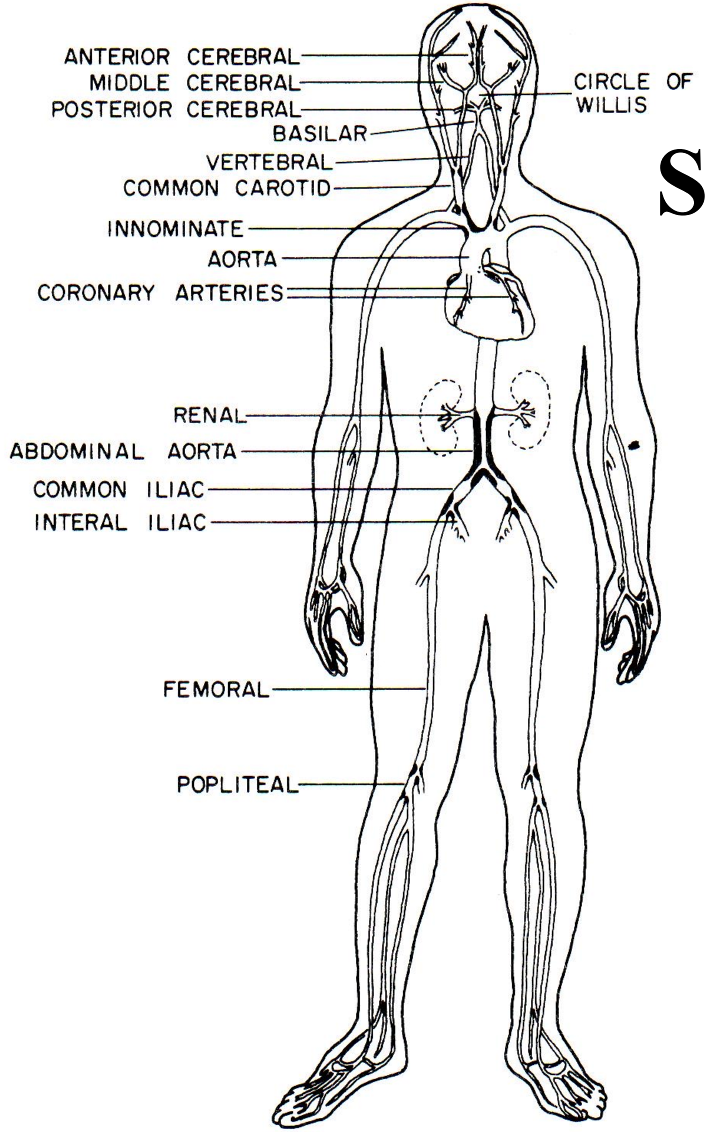
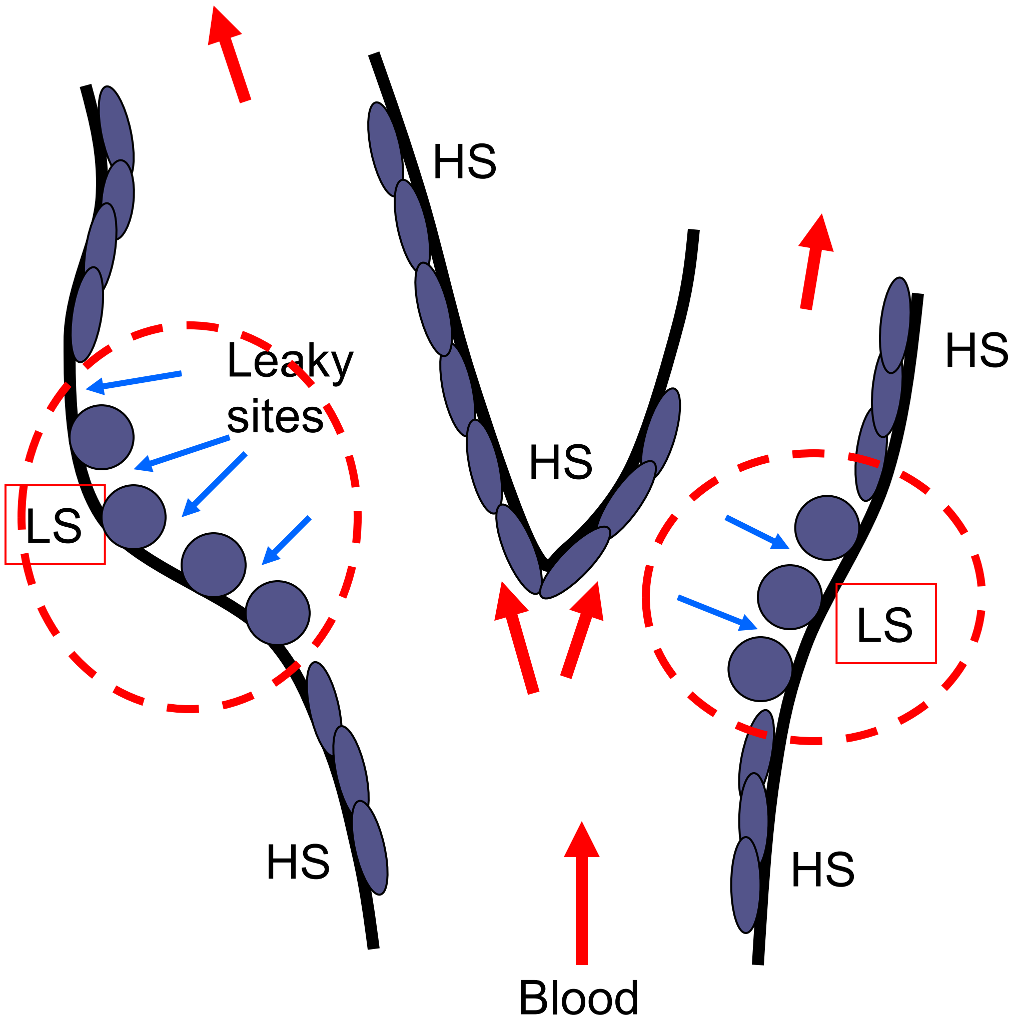


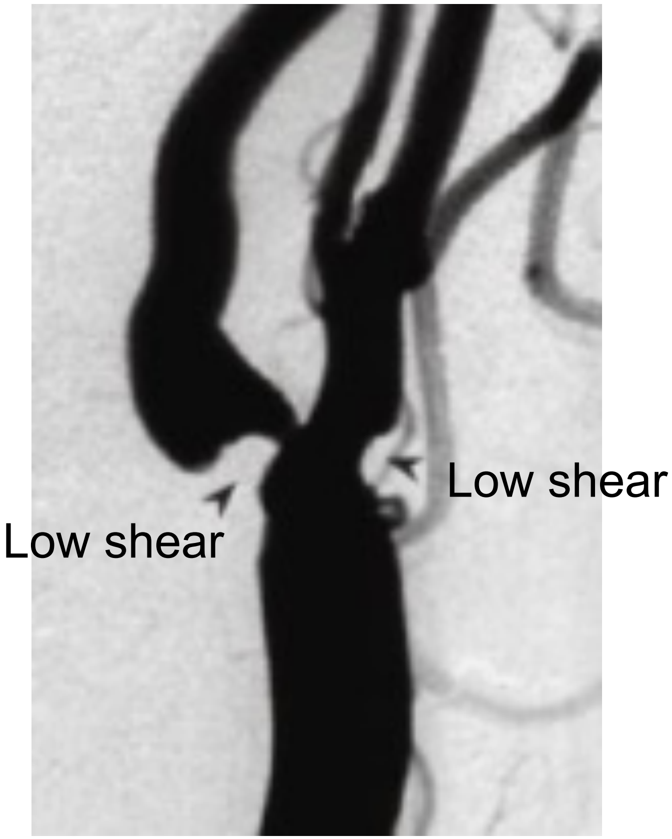
FIG. 21.1 Pattern of atherosclerosis in humans, showing a concentration of disease in the large and medium-sized arteries. (*From Spain [4].*)

Site-specific disease

Handbook of Bioengineering

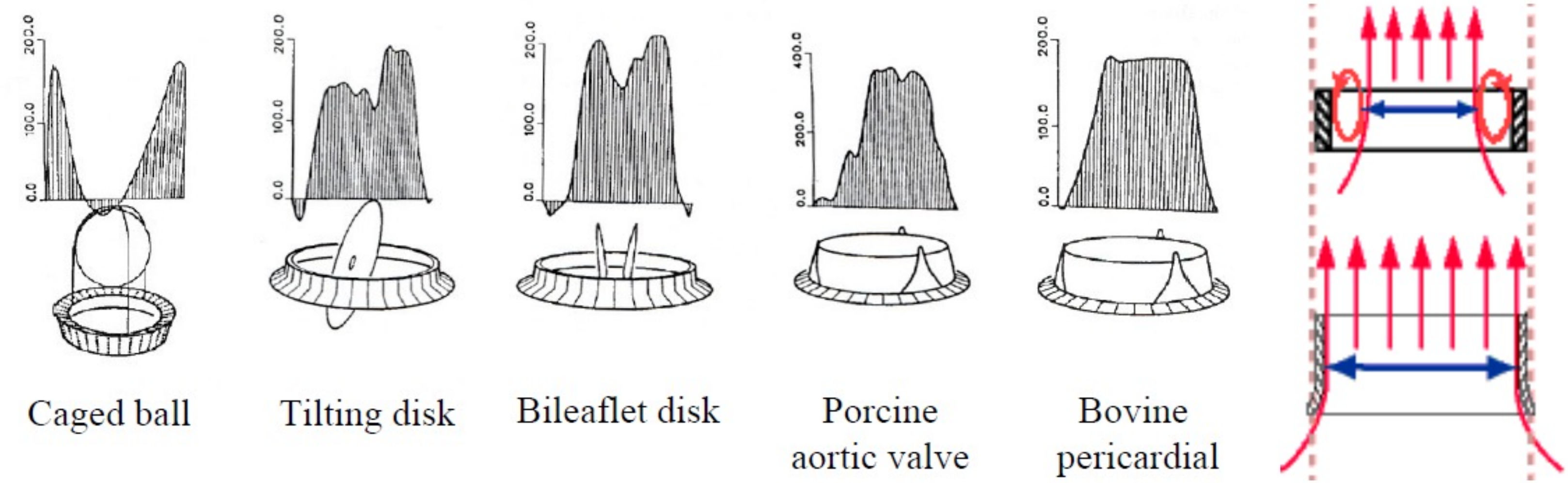
Low shear: dysfunctional E cells (round shape)
Leaky sites (injury) → Inflammation → Plaque growth





Heart Valve Research

- Avoid large pressure drop
  - Minimize flow obstruction
  - Ensure large flow orifice



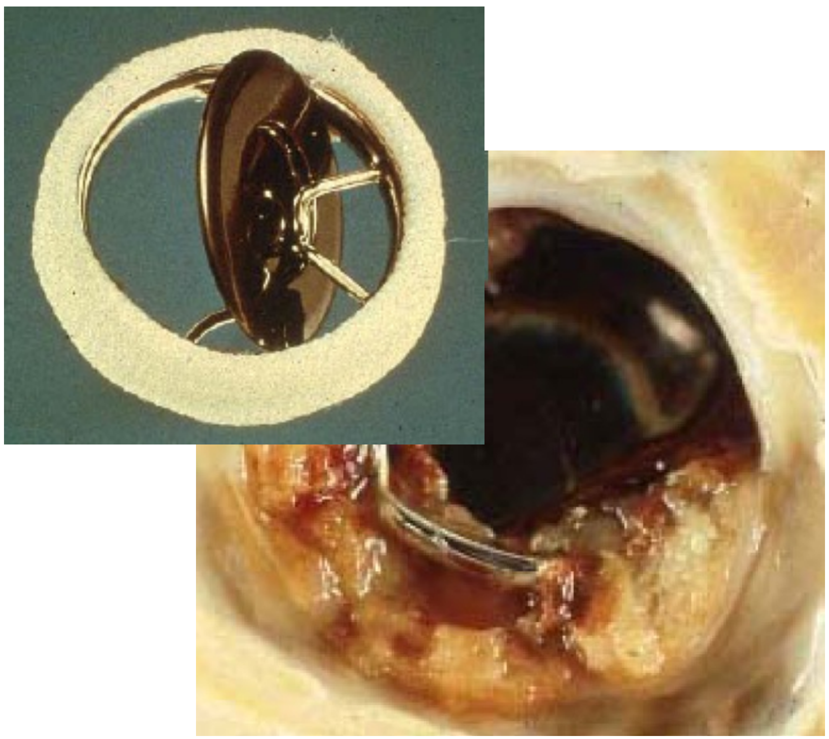
Undesirable flow fields

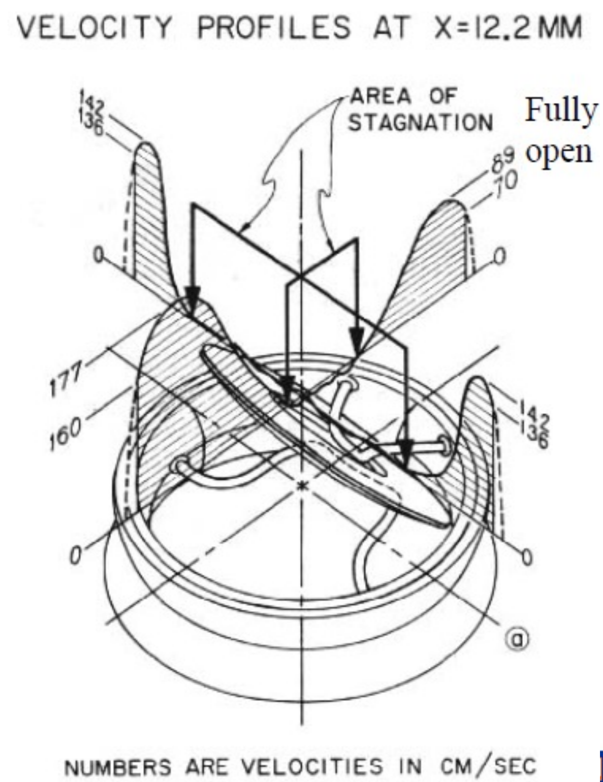
Hemodynamic performance

Hemodynamic performance

Undesirable flow fields

- Areas of Flow Stasis

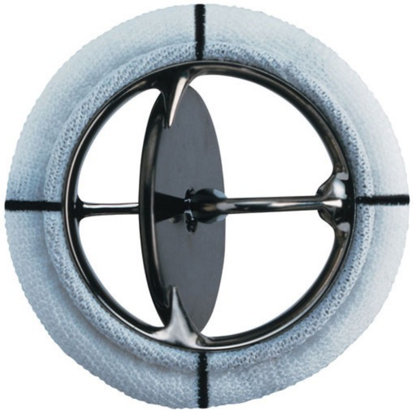


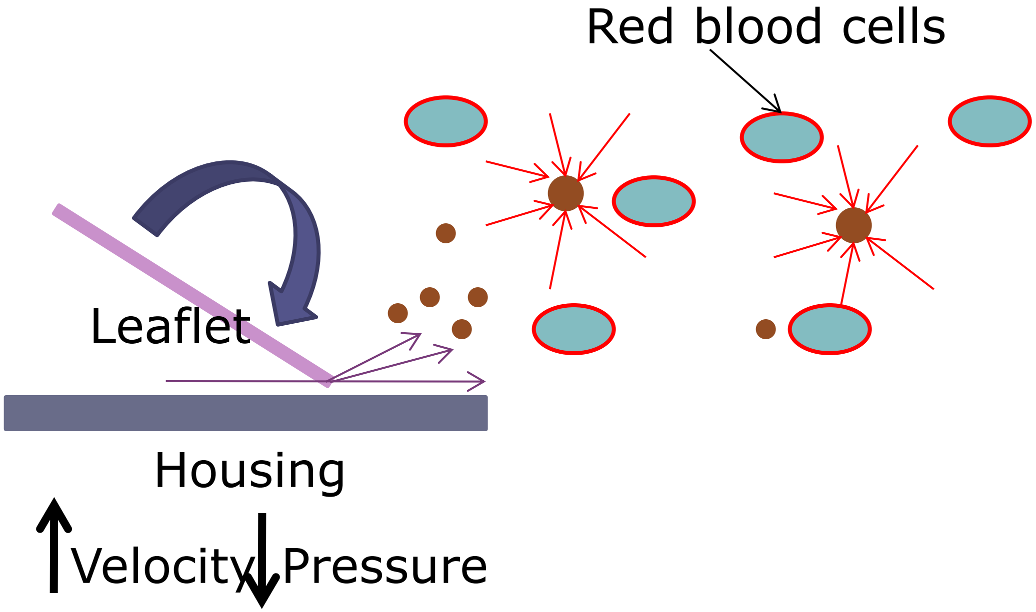


Hemodynamic performance

Undesirable flow fields

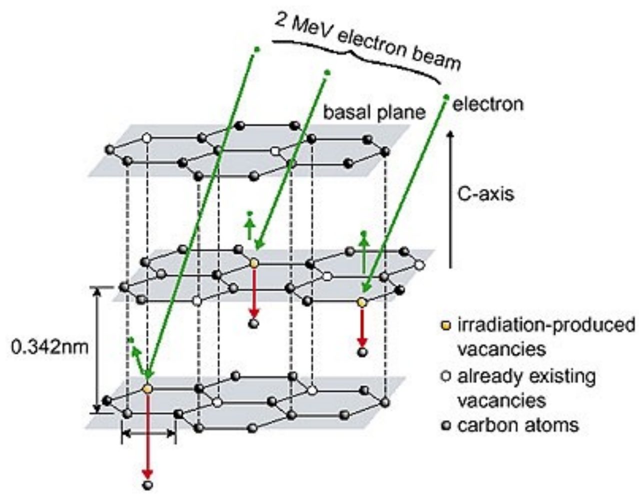
- Cavitation





Biomaterials

Biocompatible, durable, stable, strength

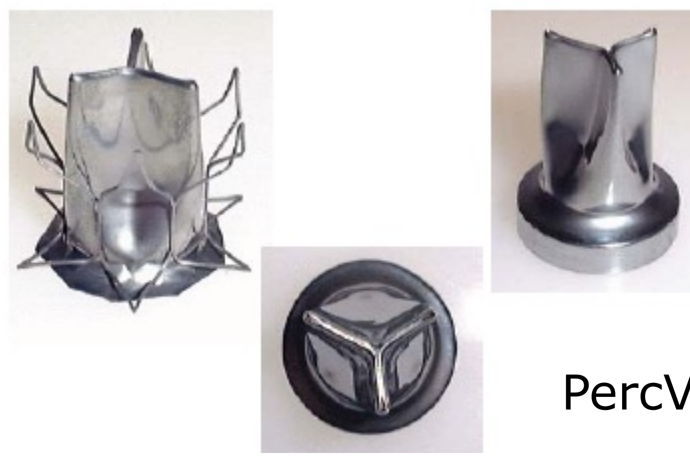


- Mechanical: pyrolytic carbon (antithrombotic)
- Tissue: Porcine or bovine (decellurized pericardial)

Surgical
Percutaneous heart valve

Corevalve

Cribier-Edwards

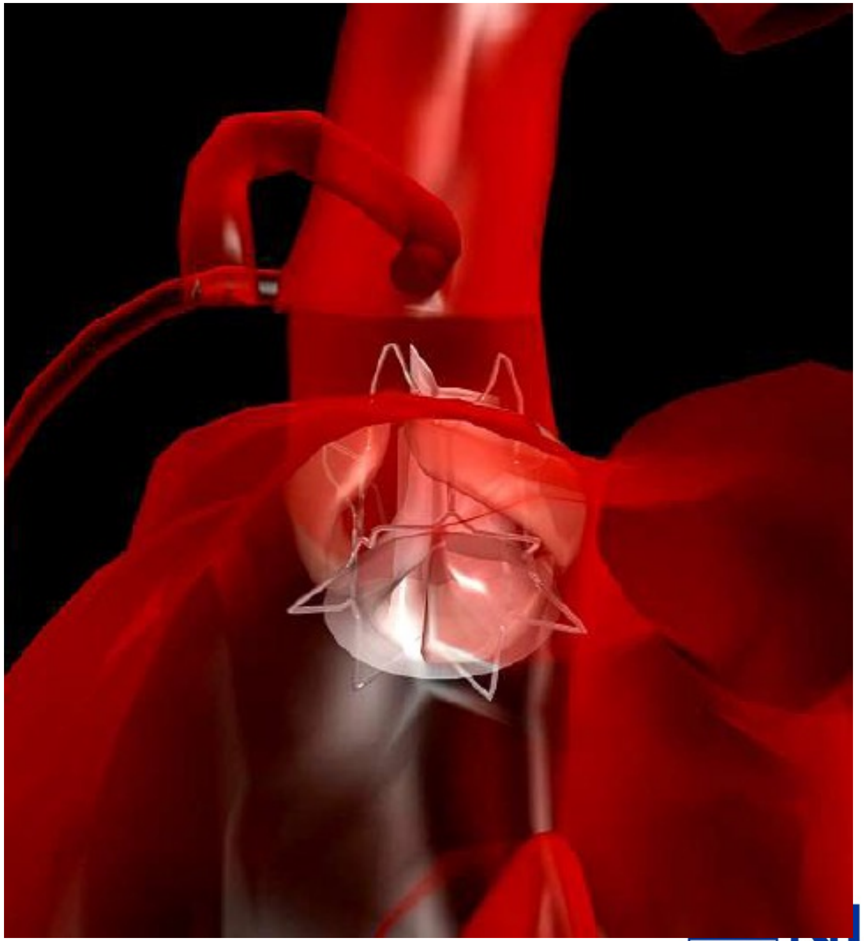


PercValve

Surgical

Percutaneous heart valve

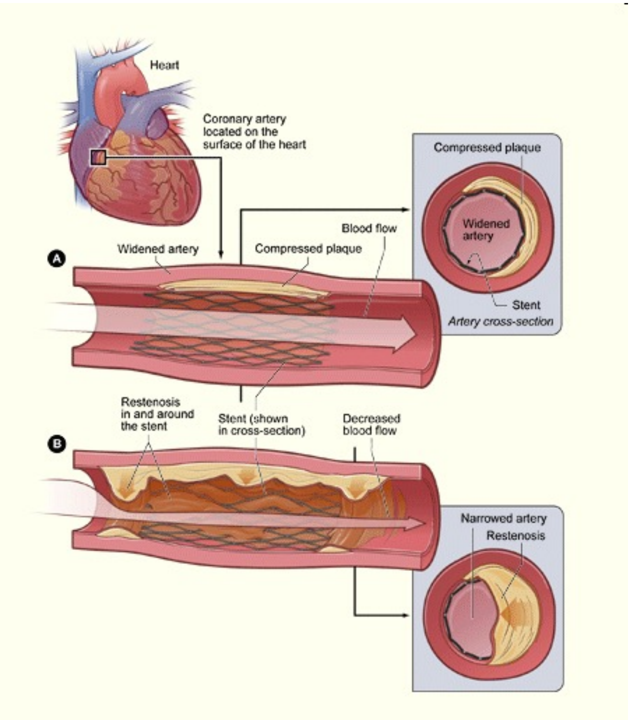
- Minimally invasive
- Reduce surgical time (15-20s)
- Improve survival and recovery rates
- Valve material: nitinol, shape memory and large deformation rate
- Very steep learning curve

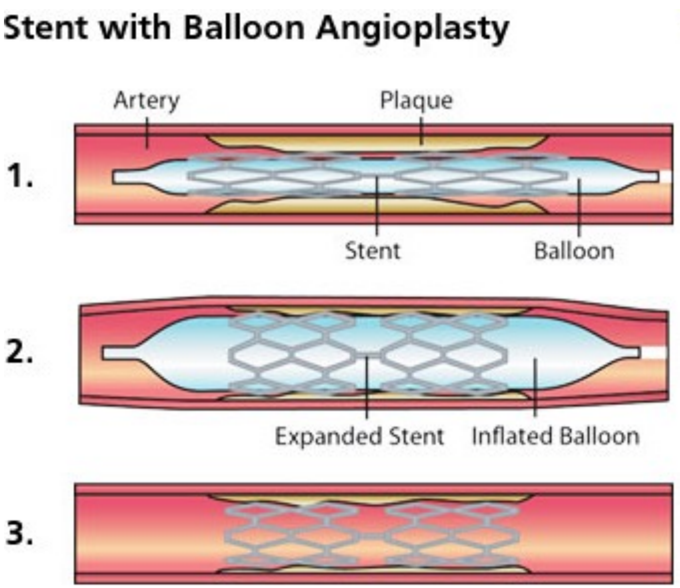


Stents, pacemakers, defibrillators and artificial heart

Stents

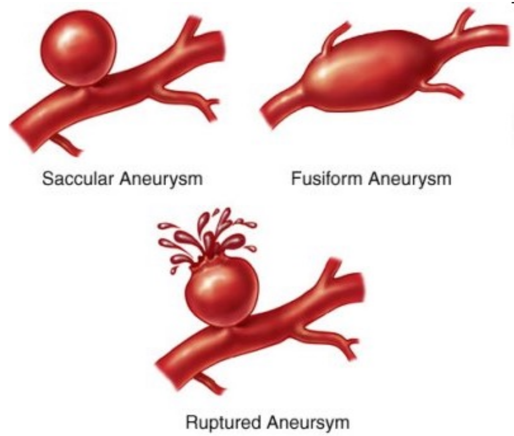
- Stent is a mesh tube used to treat narrowed or weakened arteries in the body
- Through angioplasty to prevent arteries from becoming narrowed or blocked again
- Biomaterials – wire metal or fabric
- Atherosclerosis, peripheral vascular disease, renal vascular hypertension, carotid artery, coronary artery disease, aneurysm

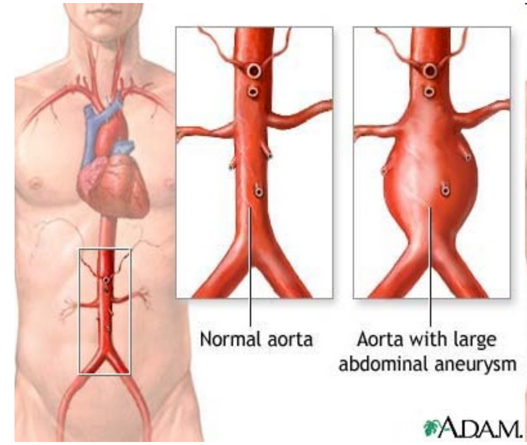


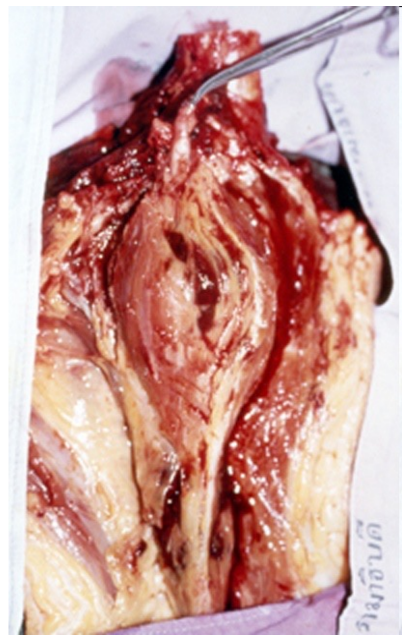


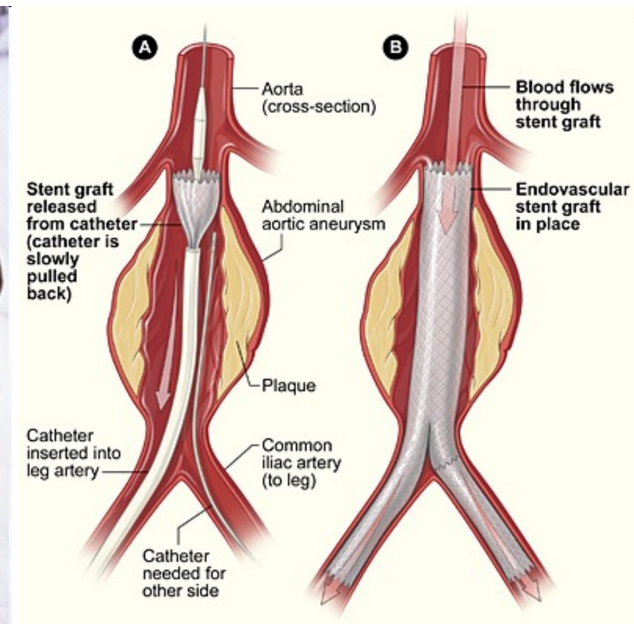
Aneurysm

- Characterized by an abnormal bulge of ballooning in the wall of an artery
- Can grow and become large enough to burst, causing fatal bleeding
- Can occur in arteries in brain, heart, intestine, neck, spleen but most occur in the aorta
- One of the leading cause of death
- Most commonly in patients who smoke and between 65-75
- Treatment – replacement surgeries, medicine to reduce heart rate and blood pressure









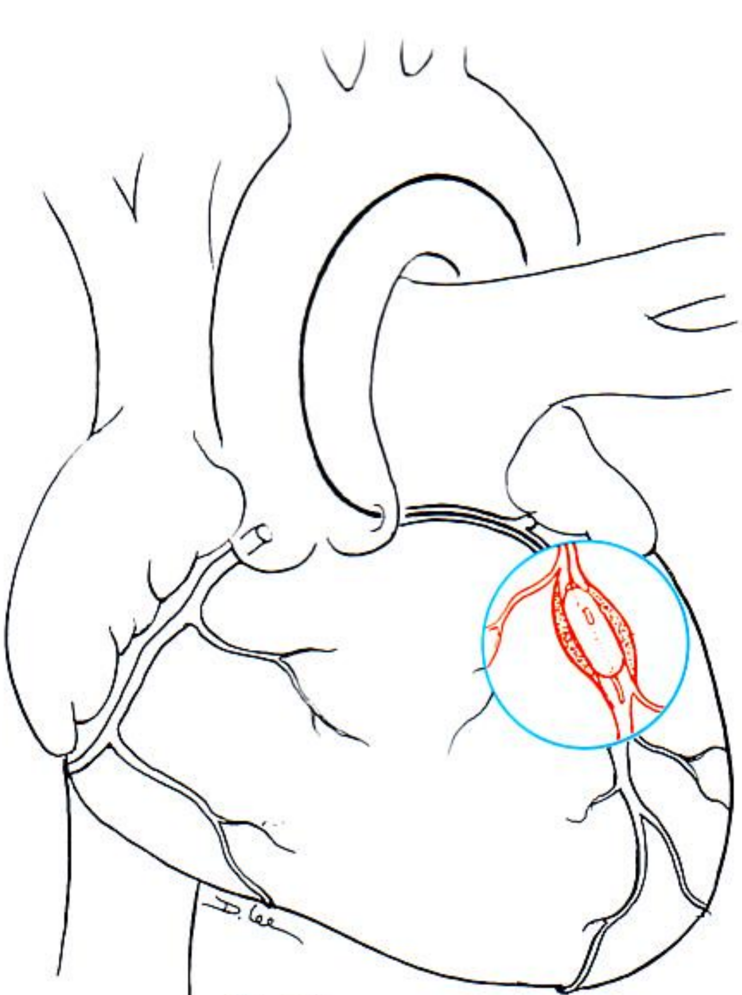


Fig. 8.5

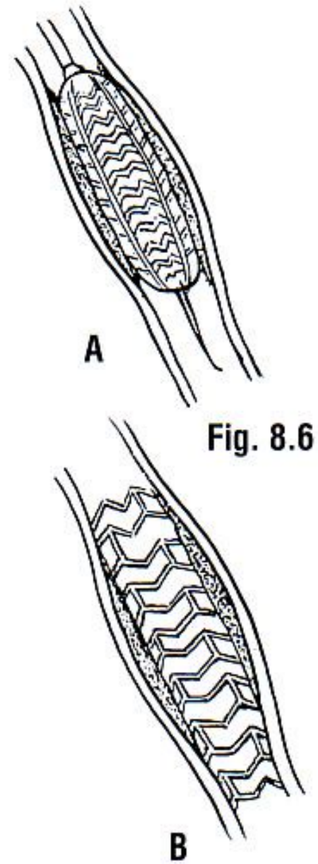
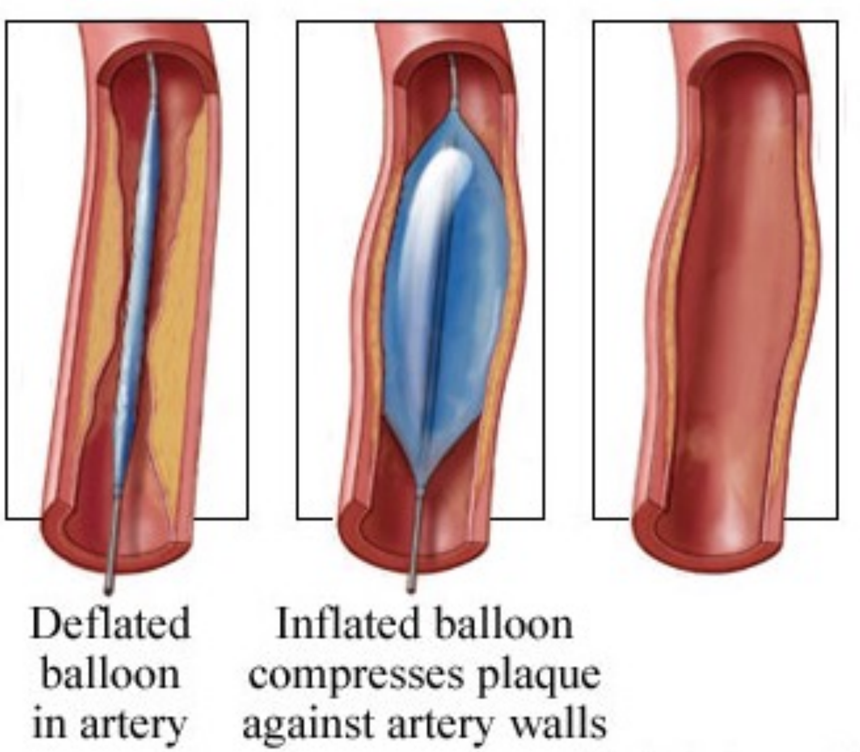


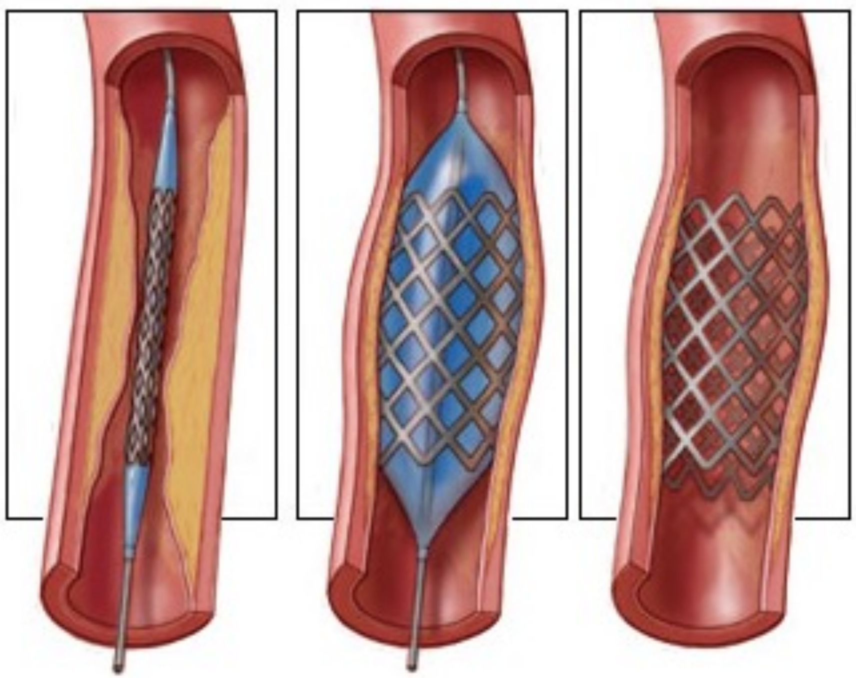
Fig. 8.6

Stephenson LW, State of the Heart, Write Stuff Enterprises, 1999

Angioplasty



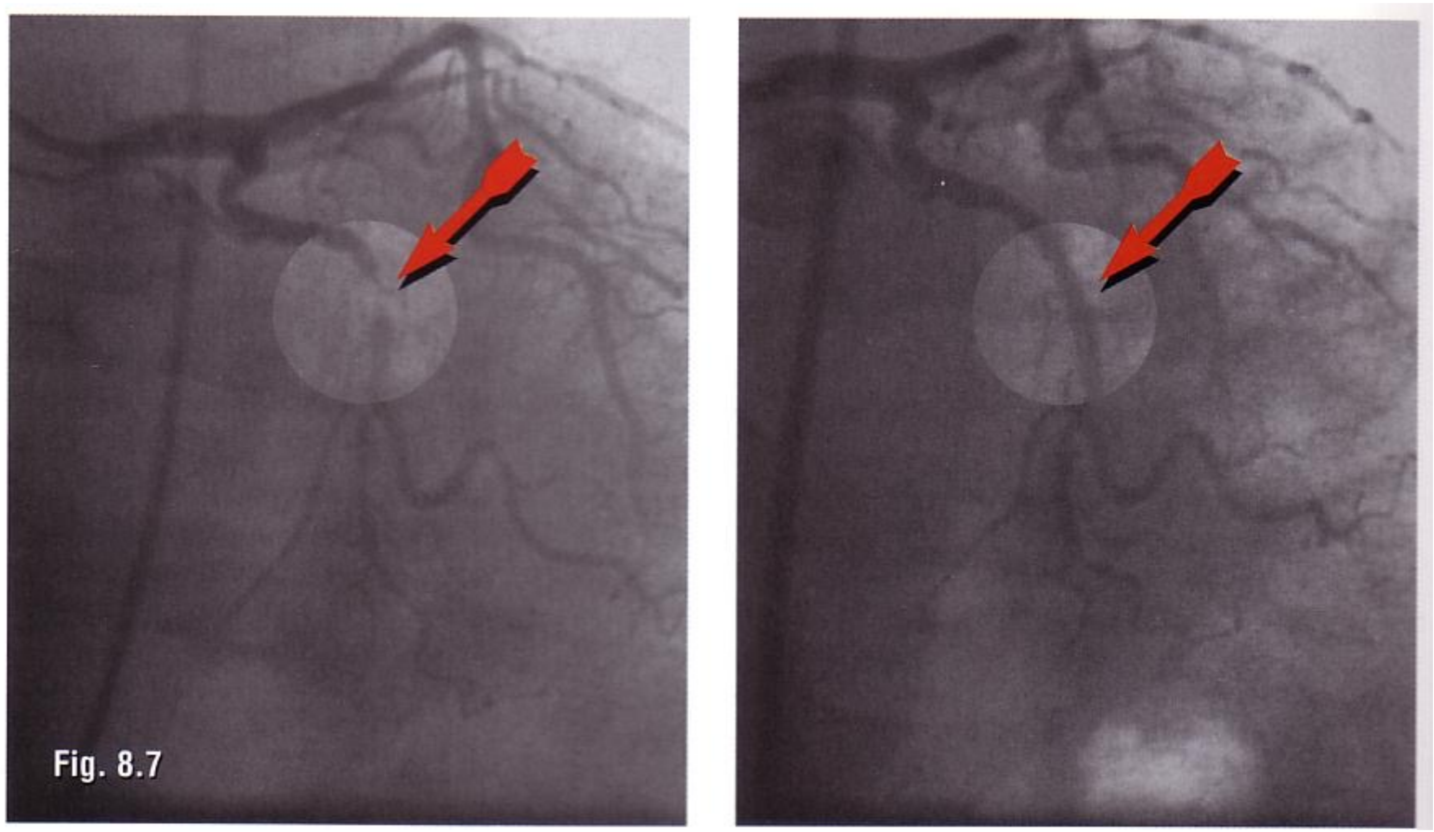
Using inflated balloon



Using a stent

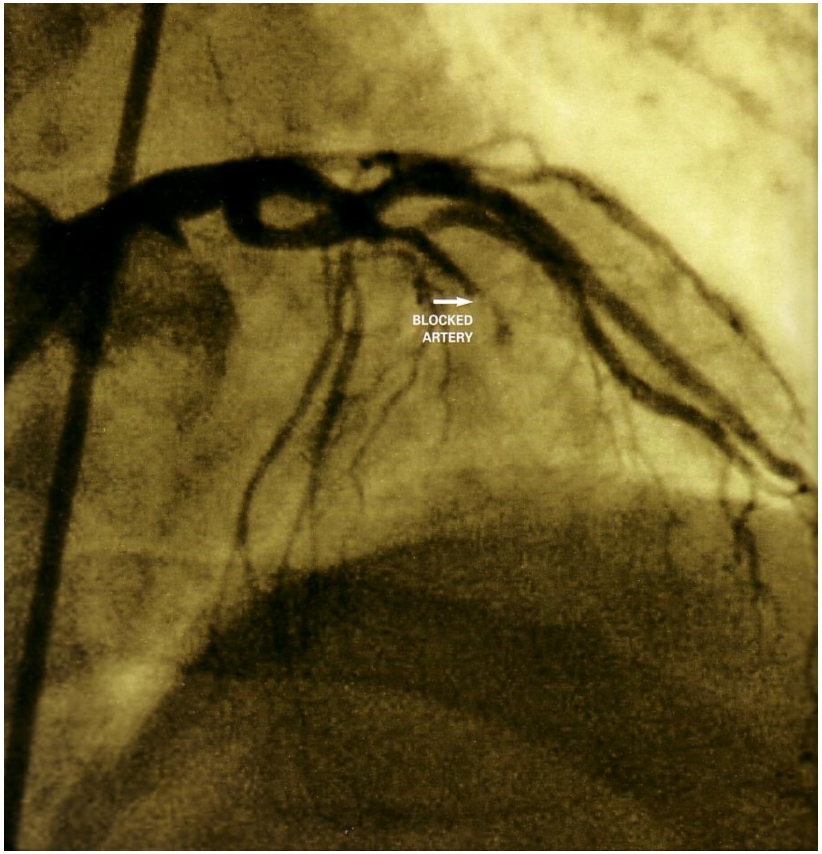
Angiography

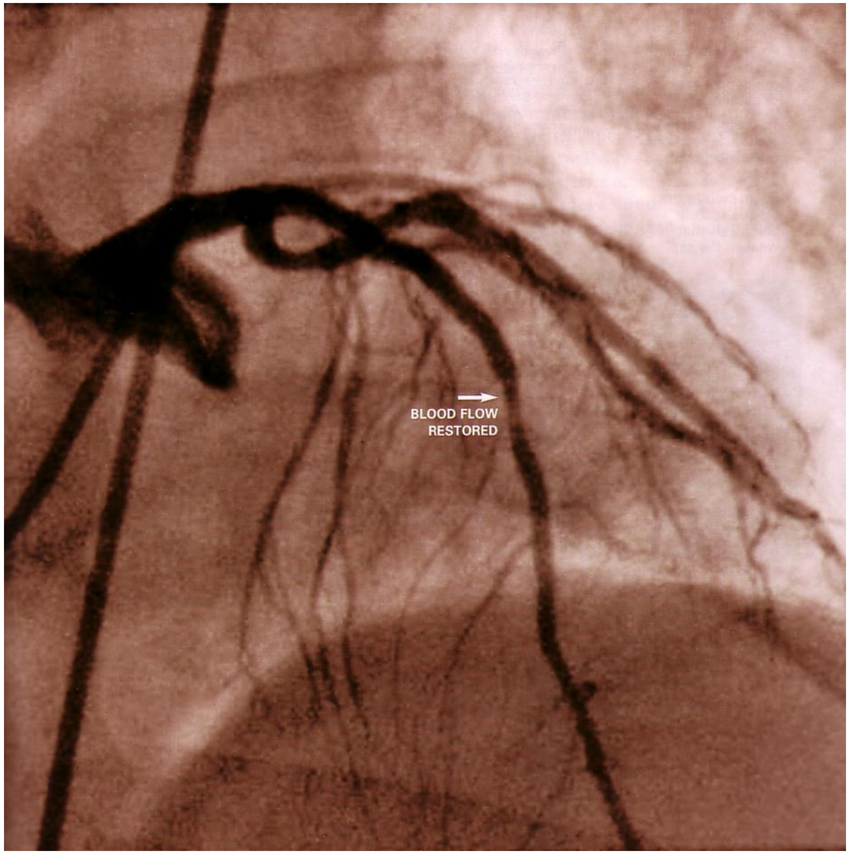
Fig. 8.7: These coronary angiography films were taken before and after a stenting procedure. The blocked artery, left, is contrasted with the open artery, right, after a stent was put in place with a balloon-tipped catheter. Introduced in the early 1990s, coronary stents are designed to hold open a blocked coronary artery after a balloon widening.



Stephenson LW, State of the Heart, Write Stuff Enterprises, 1999

Angiography





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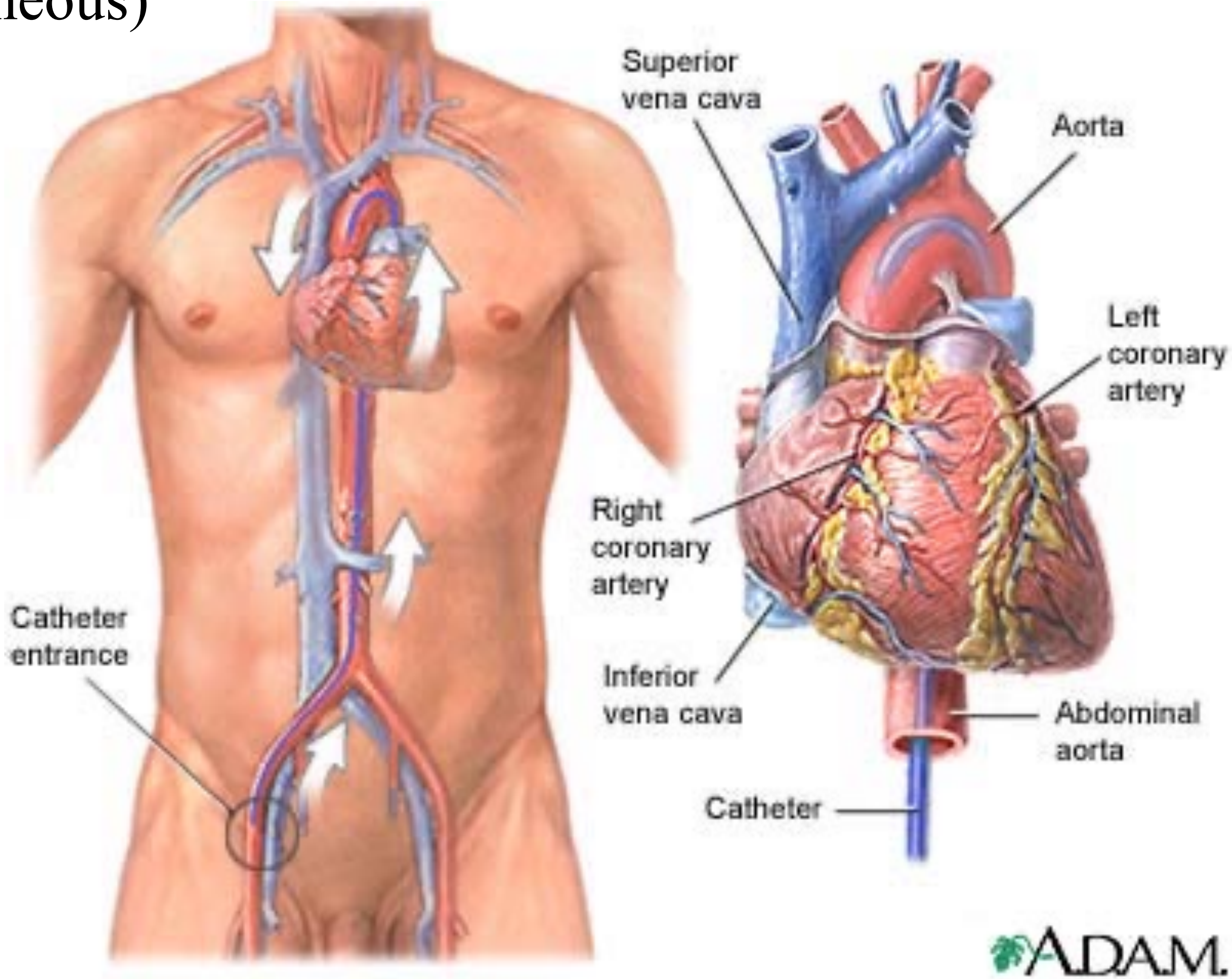
Introduction of catheter through a femoral artery (- percutaneous)



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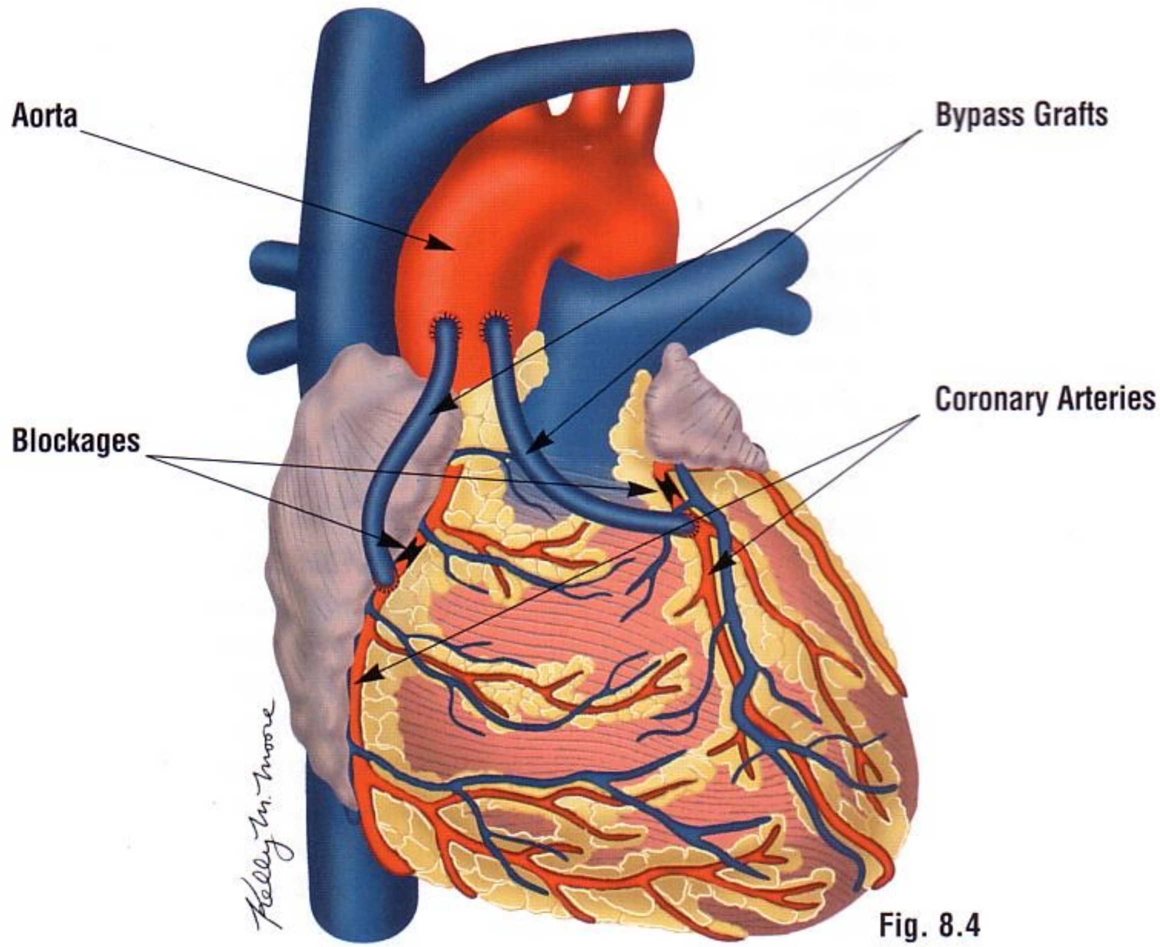
Bypass Graft Surgery



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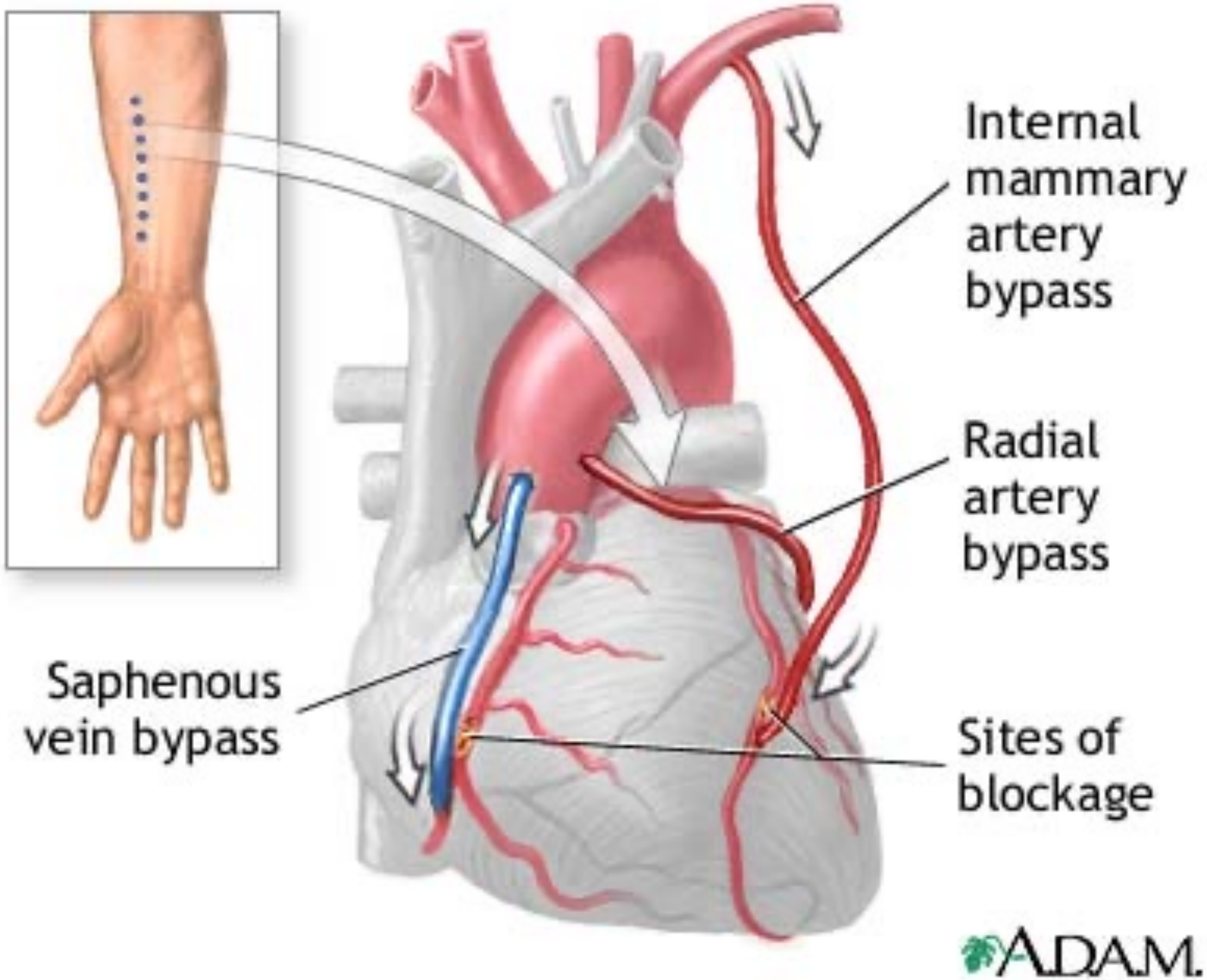
Stephenson LW, State of the Heart, Write Stuff Enterprises, 1999

Coronary artery bypass surgery (double)



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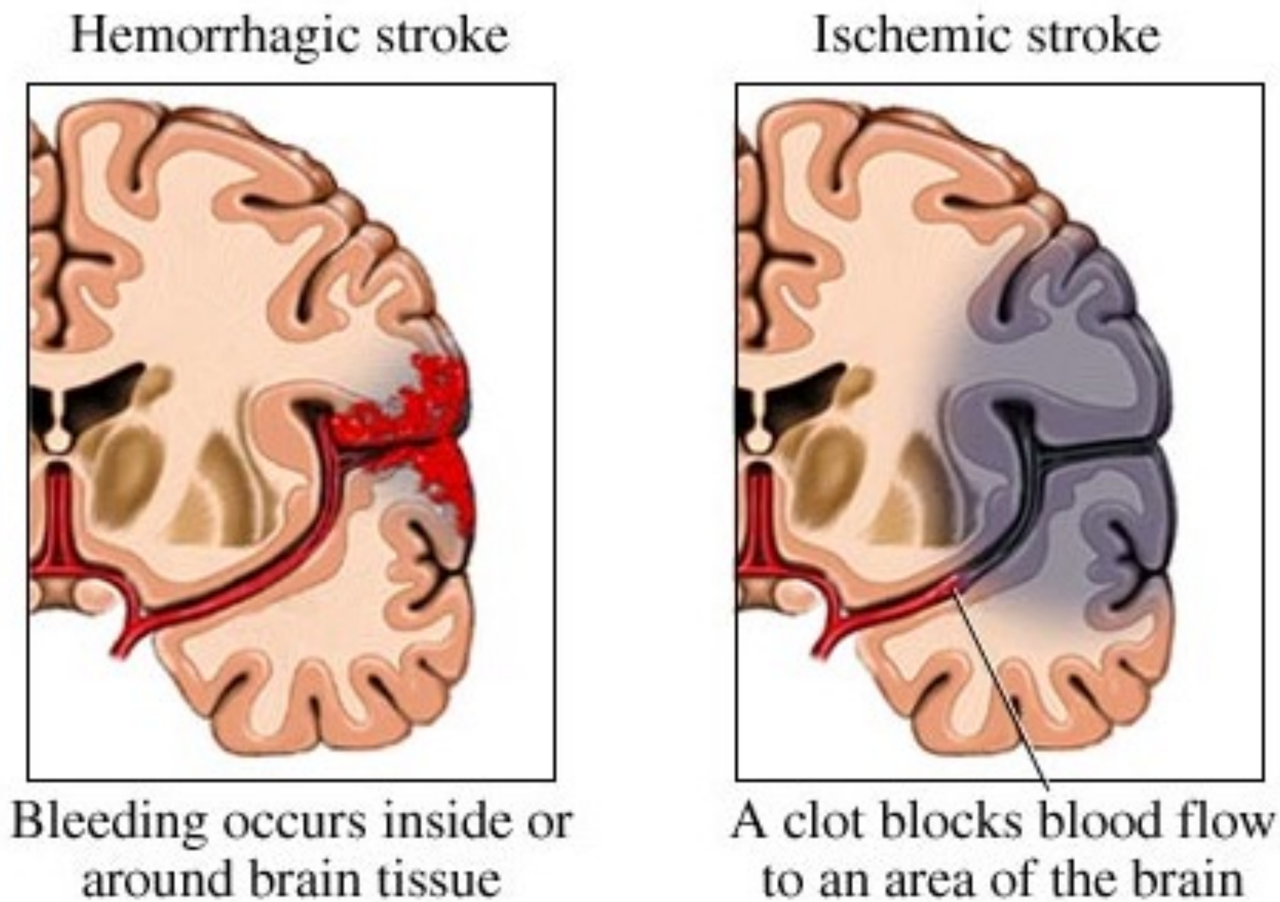
Stroke – cerebral arteries

20%

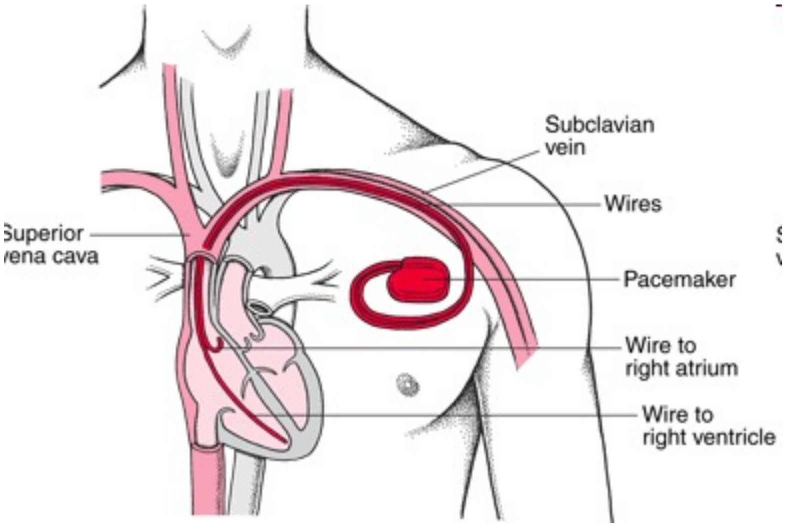


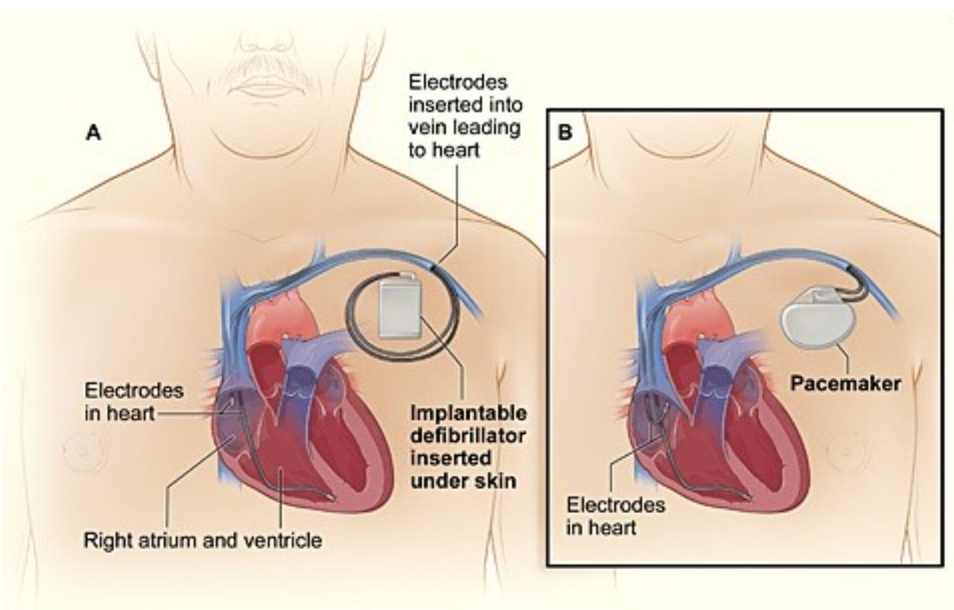
80%

If you are taking aspirin, Hemorrhagic stroke can result in death. Need to stop taking aspirin immediately.

If you are taking aspirin, Ischemic stroke would not have happened.

Pacemakers and defibrillators



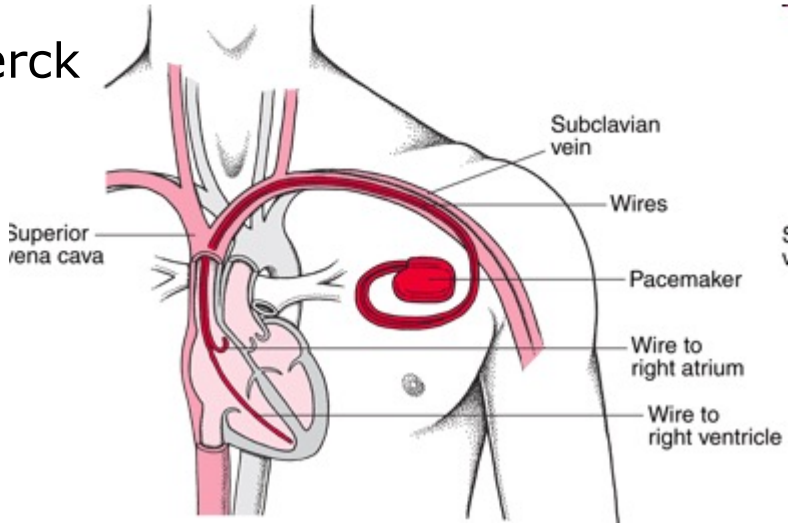


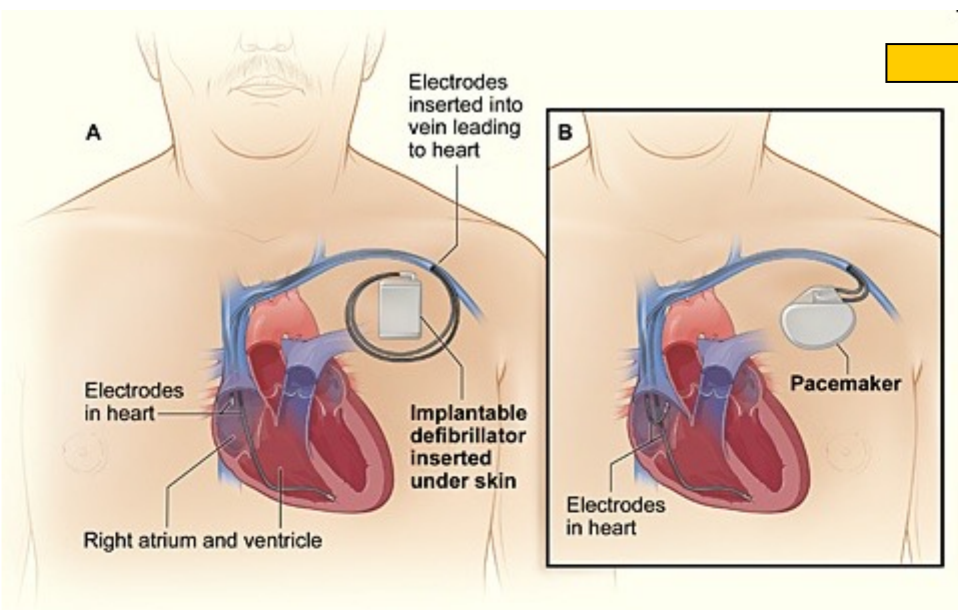
- Pacemaker target patients with heart block – damage AV bundle
  - Low HR of 30 bpm
- Through the left subclavian vein, down the superior vena cava, then through right atrium and tricuspid valve into the right ventricle
- Pacemaker cannot be used near equipments like MRI, electric generator

NHLBI, NIH

Pacemakers and defibrillators

Merck





- Target irregular heart beats or arrhythmias, and sudden cardiac arrest
- Implantable cardioverter defibrillator (ICD)
- Monitor system that send low or high energy pulses to restore normal rhythm
- Similar to pacemakers and can combine purposes

NHLBI, NIH

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Artificial Heart Assist Devices

AbioCor

Jarvik 2000 Heart

Left ventricle assist device

- First clinical implantation of total artificial heart (TAH) in 1969
- TAH or left ventricle assist device
- Minimize moving parts
- Axial flow or centrifugal pump principles
- High fluid shear and biomaterial compatibility

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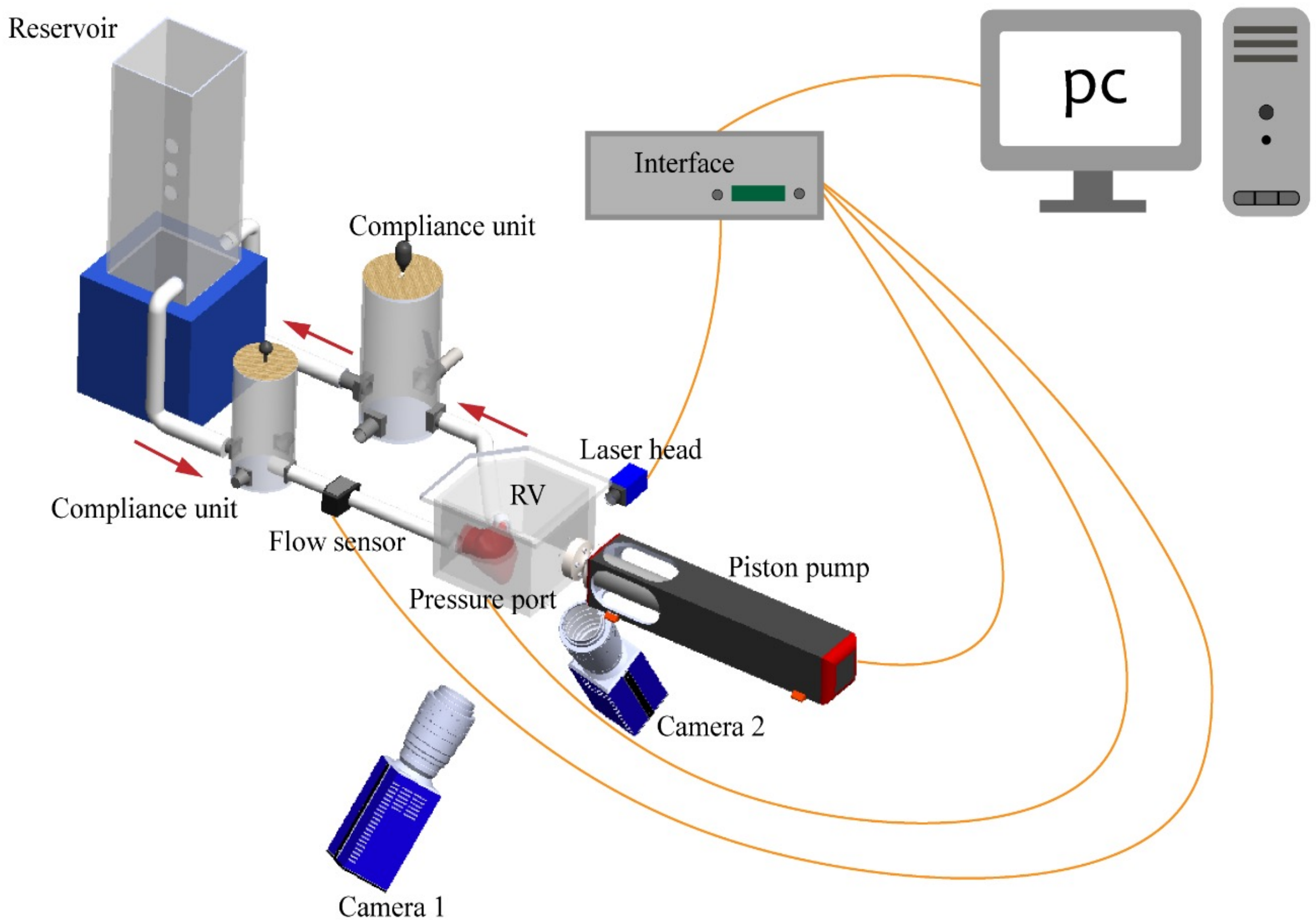
Biofluid Research

Stereo-scopic PIV (3D PIV) setup: Right Heart mock loop



Stroke vol
83.3ml/m
Heart rate
beats/min
Particles o
20μm

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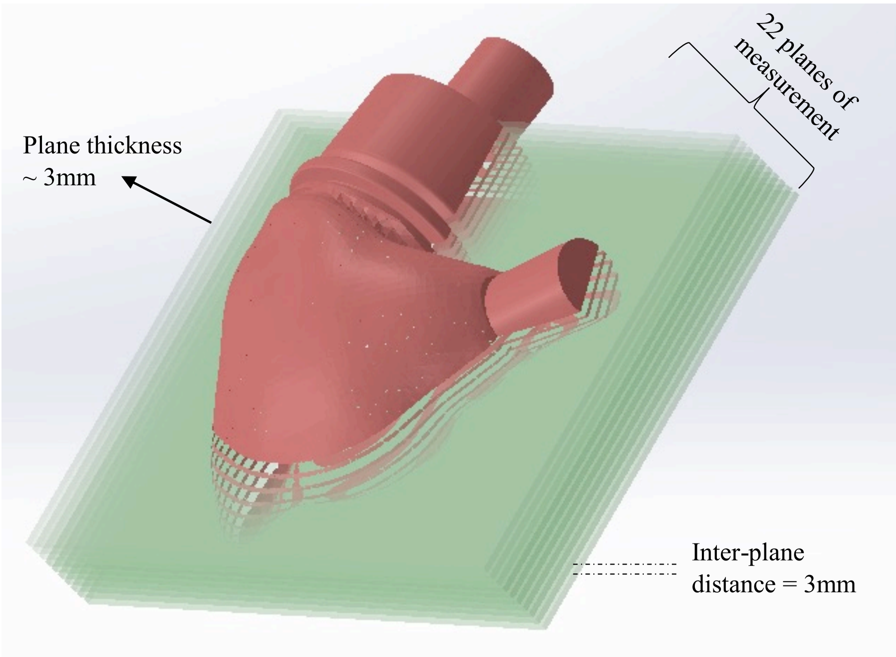
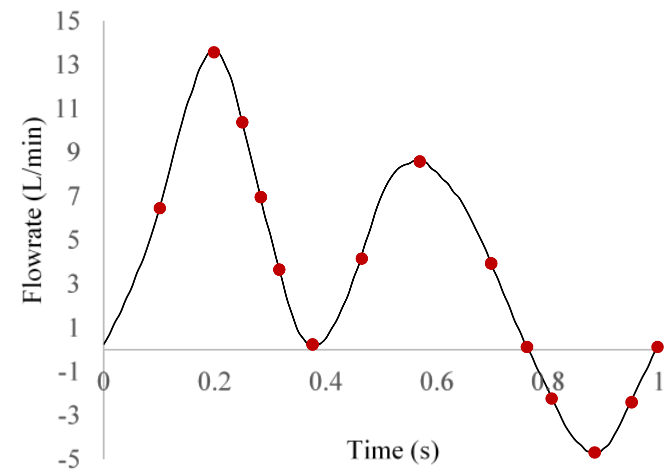
PIV measurement parameters of Right Ventricle

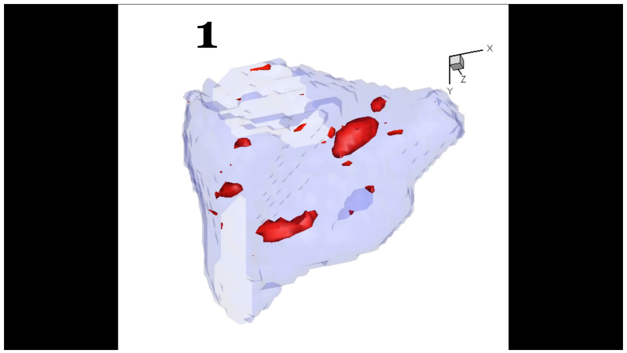


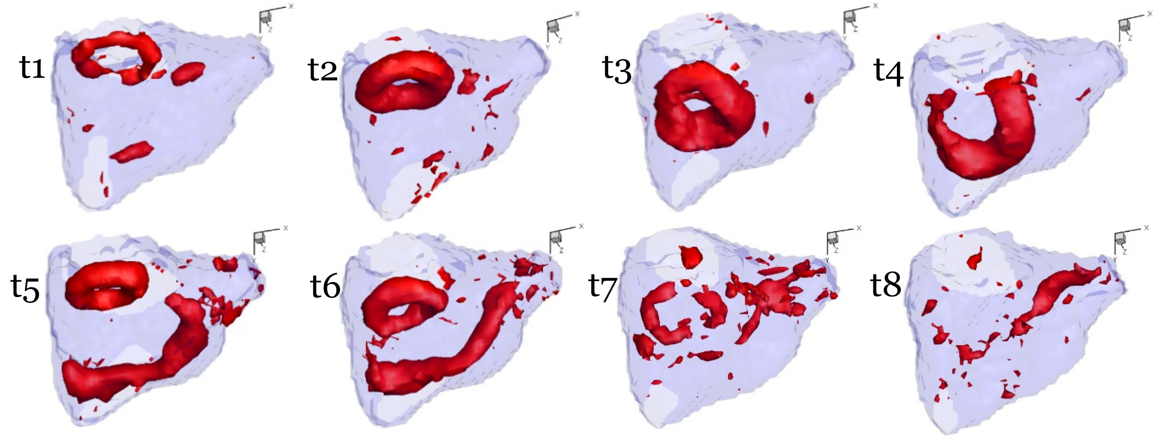


	Cardiac output (L/min)	Peak E-wave flowrate (L/min)	Peak RV pressure (mmHg)
FTR (n=3)	3.90 ± 0.00	13.68 ± 0.17	42.88 ± 1.21
Bicuspidization (n=3)	4.13 ± 0.06	13.41 ± 0.16	44.87 ± 0.78

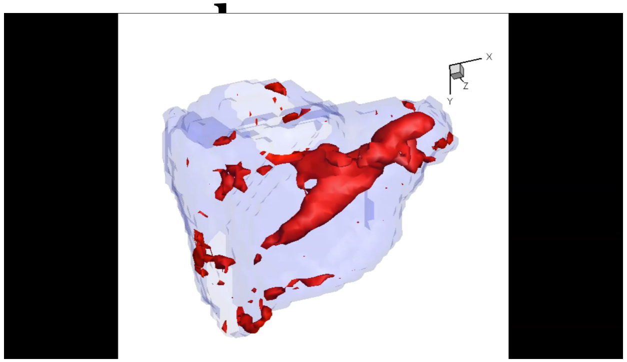
3D vortex assessment – Q-criterion

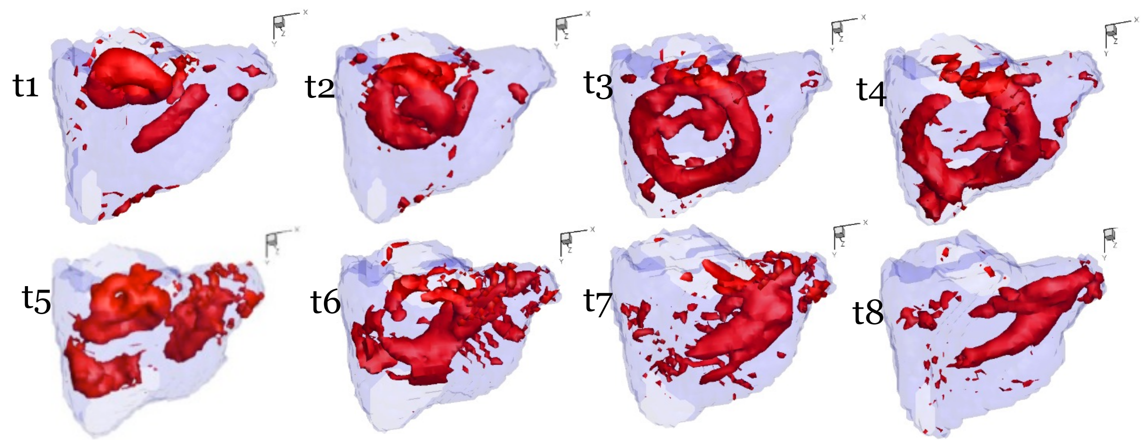
FTR valve 1





Repaired valve



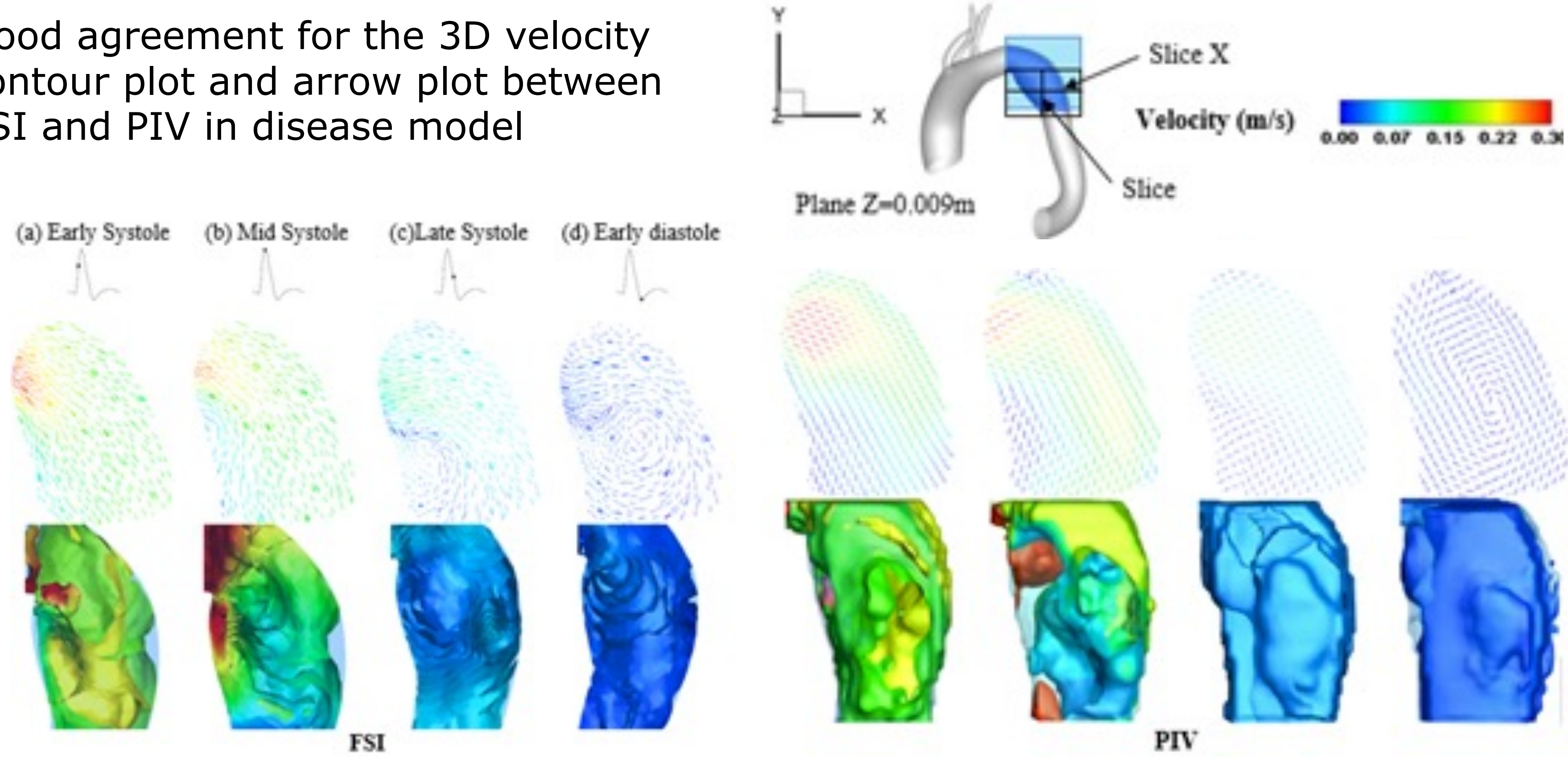


<u>Post-repair:</u> Sum of RV vorticity magnitude (s^{-1}) ↑ 33.72 %

Q-thresholded sum ↑ 92.71 %

Aortic Aneurysm: Experimental Validation of CFD modeling

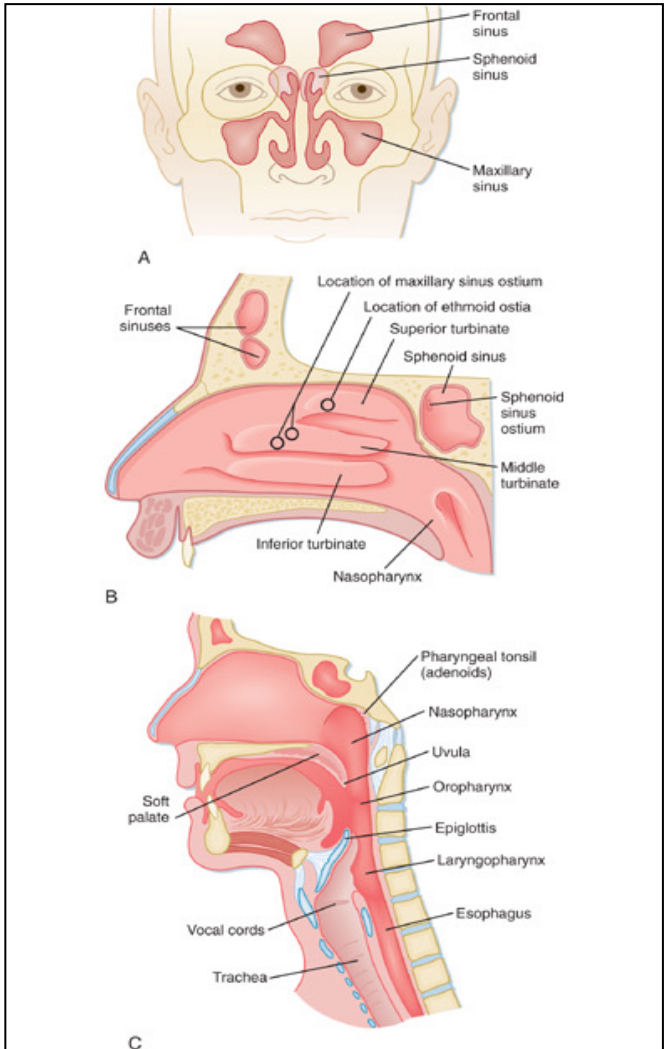
Good agreement for the 3D velocity contour plot and arrow plot between FSI and PIV in disease model



Respiratory System

Leo Hwa Liang

Respiratory System



Koeppen and Stanton: Berne & Levy Physiology, 6th Edition.

1. The lungs are contained in a space with a volume of approximately 4 L, but they have a surface area for gas exchange that is the size of a tennis court (~85 m2)
2. In adults, the lung weighs approximately 1 kg, with lung tissue accounting for 60% of the weight and blood the remainder
3. The respiratory system begins at the nose and ends in the most distal **alveolus**
4. Thus, the **nasal cavity,** the **posterior pharynx,** the **glottis** and **vocal cords,** the **trachea,** and all divisions of the **tracheobronchial tree** are included in the respiratory system
5. Upper and lower airways
6. In humans, the volume of air entering the **nares** each day is on the order of 10,000 to 15,000 L
7. Resistance to airflow in the nose during quiet breathing accounts for approximately 50% of the total resistance of the respiratory system, which is about 8 cm H_2O/L/sec

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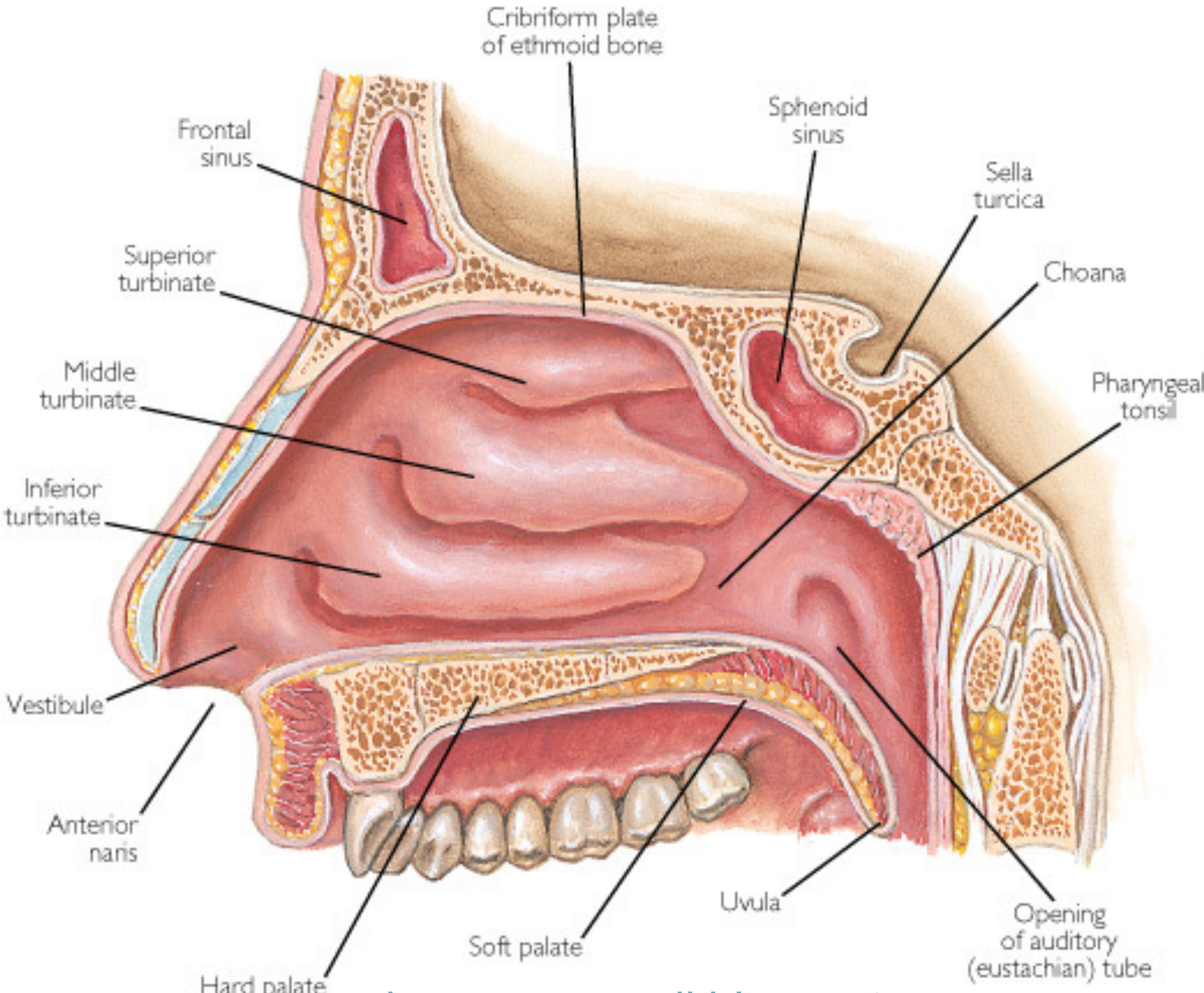
Turbinates



myjawsurgeryandi.blogspot.com

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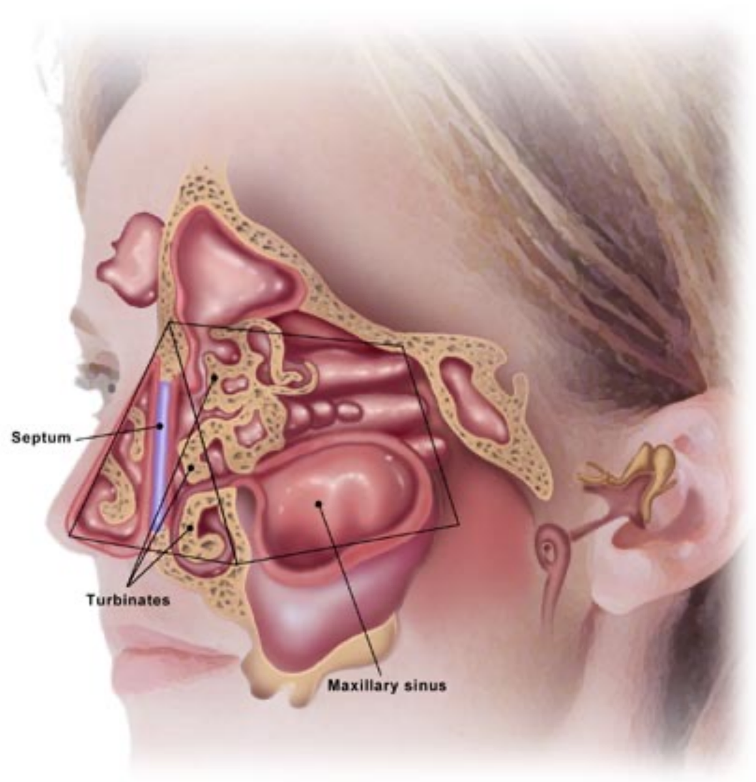
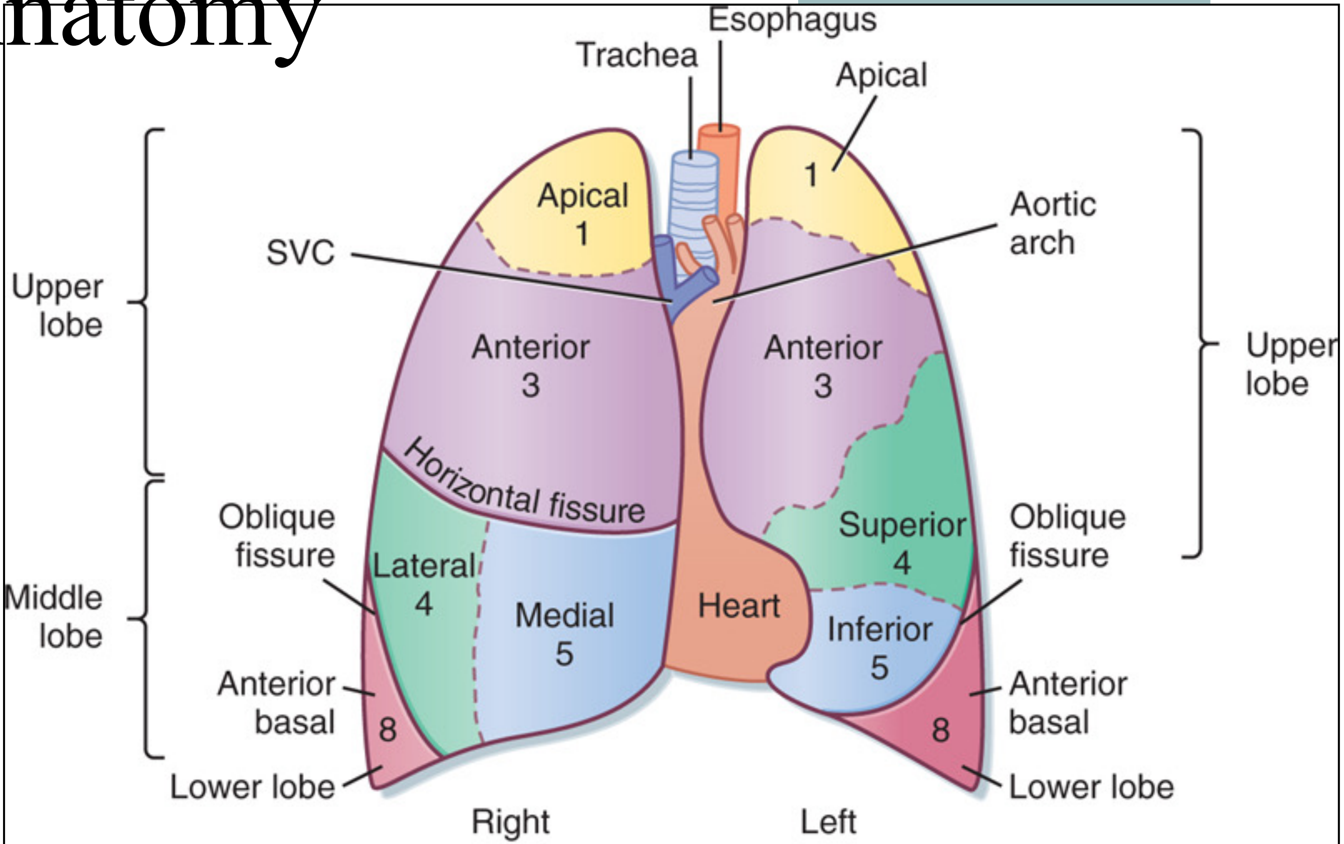
Turbinates

1. Divide airway into four passages
2. Pseudostratified columnar, ciliated respiratory epithelium with a thick, **vascular**, and erectile glandular tissue layer
3. Airflow direction, humidification, heating, and filtration
4. Sensors: airflow pressure and temperature-sensing nerve receptors
5. Superior turbinates are smaller structures, connected to the middle turbinates by nerve-endings, and serve to protect the olfactory bulb



Lung Anatomy



1. The right lung is wider than left lung because the heart is located at the located at the left thoracic cavity space. And the right lung is shorter than the left lung to accommodate the liver
2. **Visceral pleura** and **parietal pleura**. Former is cover the lungs and the latter is attached to the thoracic wall, the diaphragm and the ribs
3. Fluid between the two membrane is termed pleural fluid

Figure 20-2 Topography of the lung demonstrating the lobes, segments, and fissures. The fissures (or chasms) demarcate the lobes in each lung. Numbers refer to specific bronchopulmonary segments, as presented in Figure 20-3. SVC, superior vena cava.

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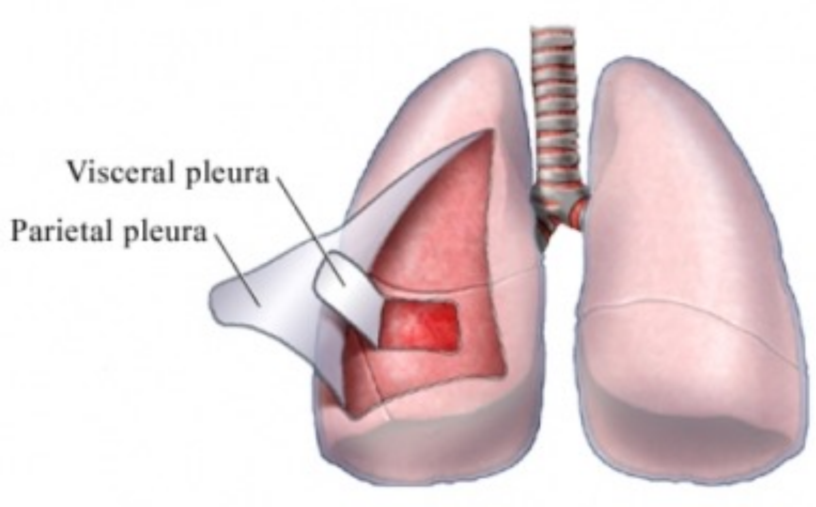
Lung Anatomy



www.knowyourbody.net

academic.amc.edu

1. The pleural membrane is a single membrane folding back upon itself
2. **Visceral pleura** and **parietal pleura**. Former is cover the lungs and the latter is attached to the thoracic wall, the diaphragm and the ribs
3. Fluid between the two membrane is termed pleural fluid

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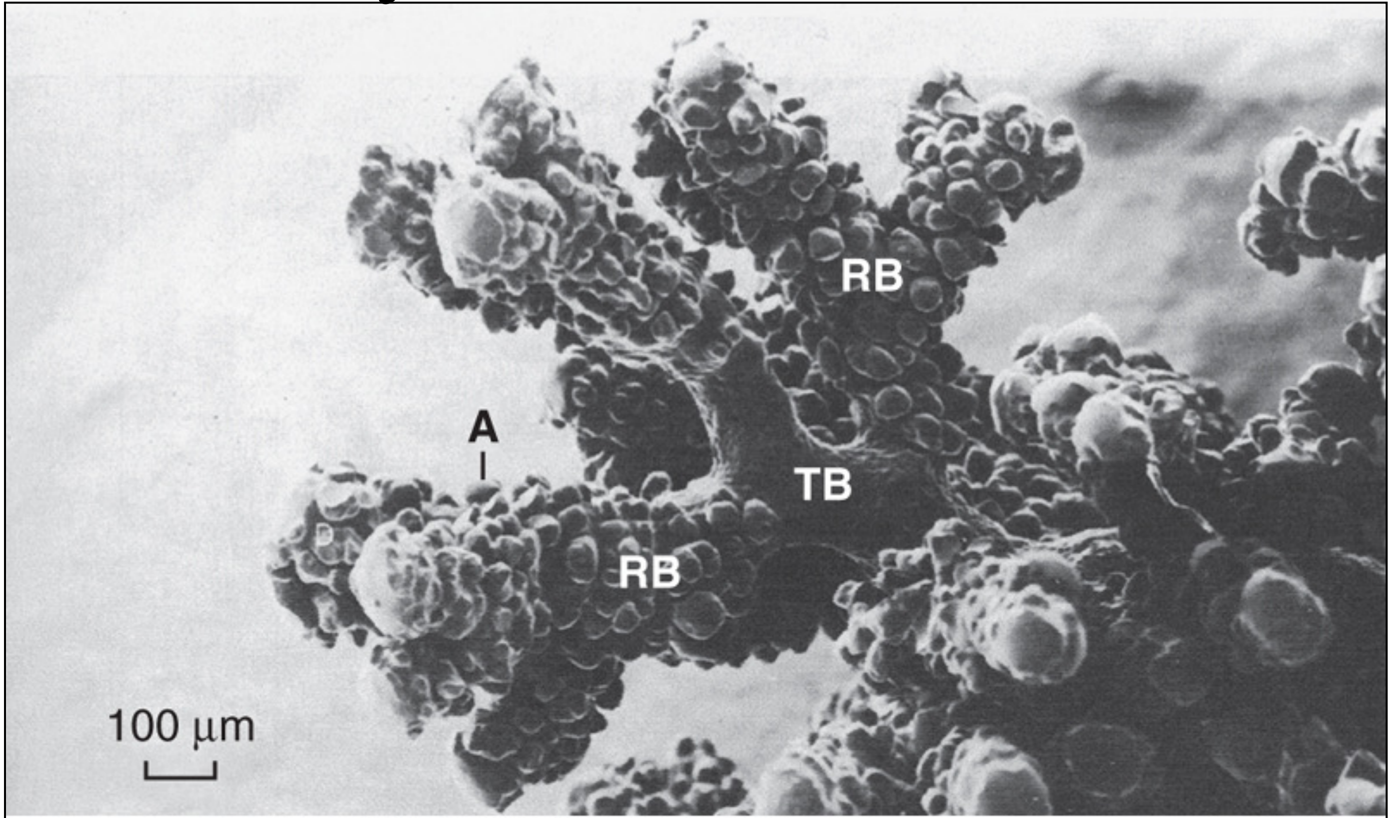
Lung Anatomy



The basic physiological unit of the lung is the respiratory or gas-exchanging unit (respiratory unit), which consists of the respiratory bronchioles, the alveolar ducts, and the alveoli

Figure 20-5 The airway from the terminal bronchiole to the alveolus. A, alveolus; RB, respiratory bronchiole; TB, terminal bronchiole. Note the absence of alveoli in the terminal bronchiole.

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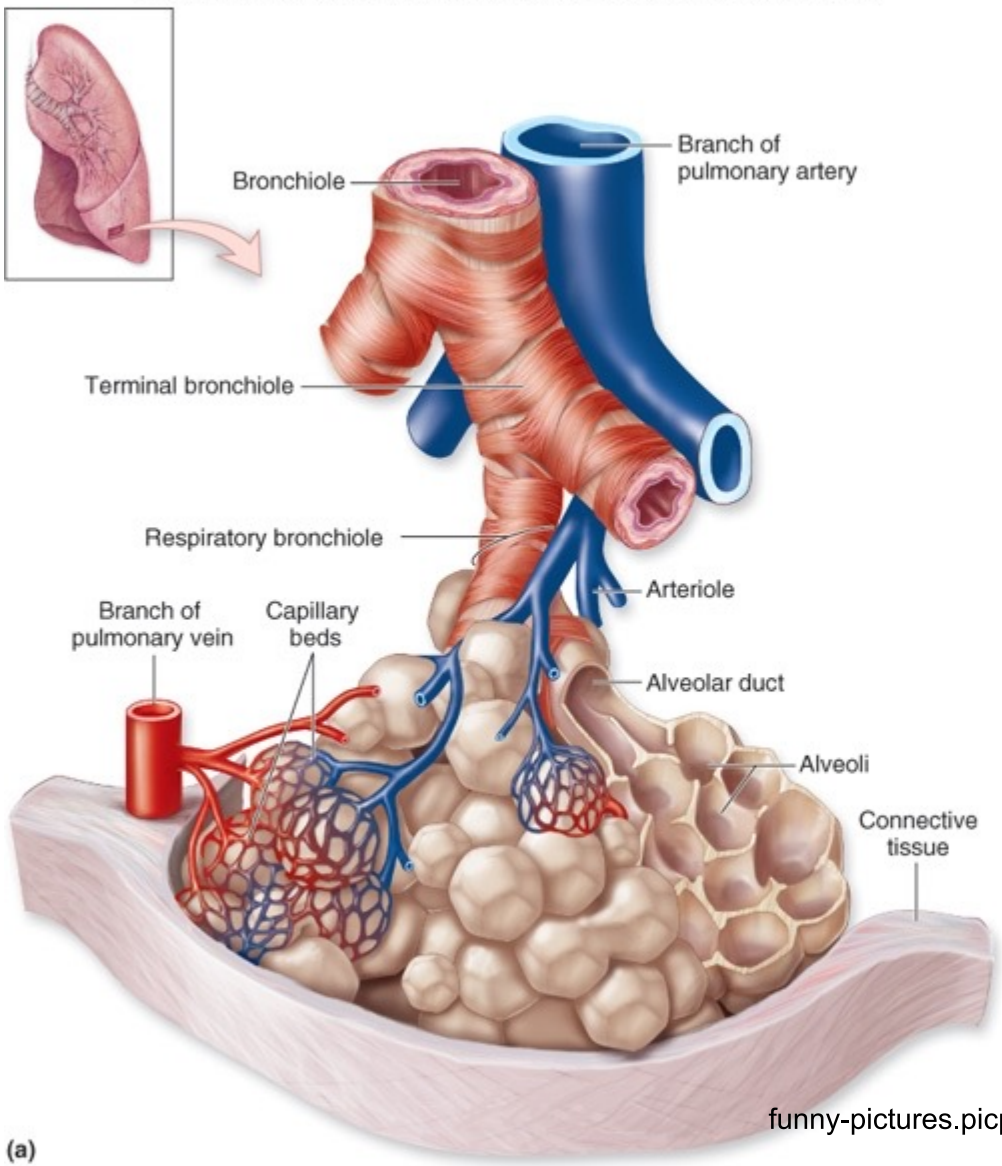
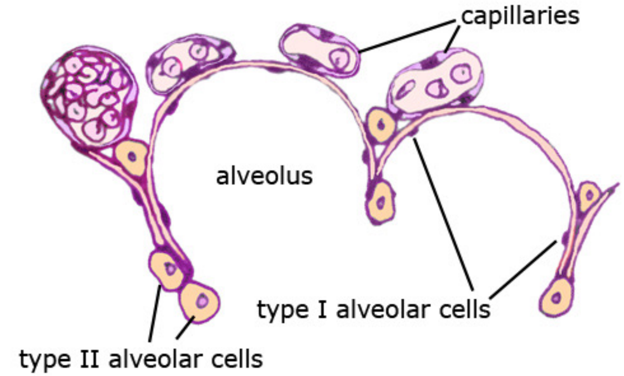
Lung Anatomy



1. Conducting airway makes up 30% in volume while respiratory airway 70%
2. An adult has around 5×10^8 alveoli, which are composed of type I and type II epithelial cells. Under normal conditions **type I** and **type II** cells exist in a 1 : 1 ratio



medicineisnotmerchandise.tumblr.com

funny-pictures.picphotos.net

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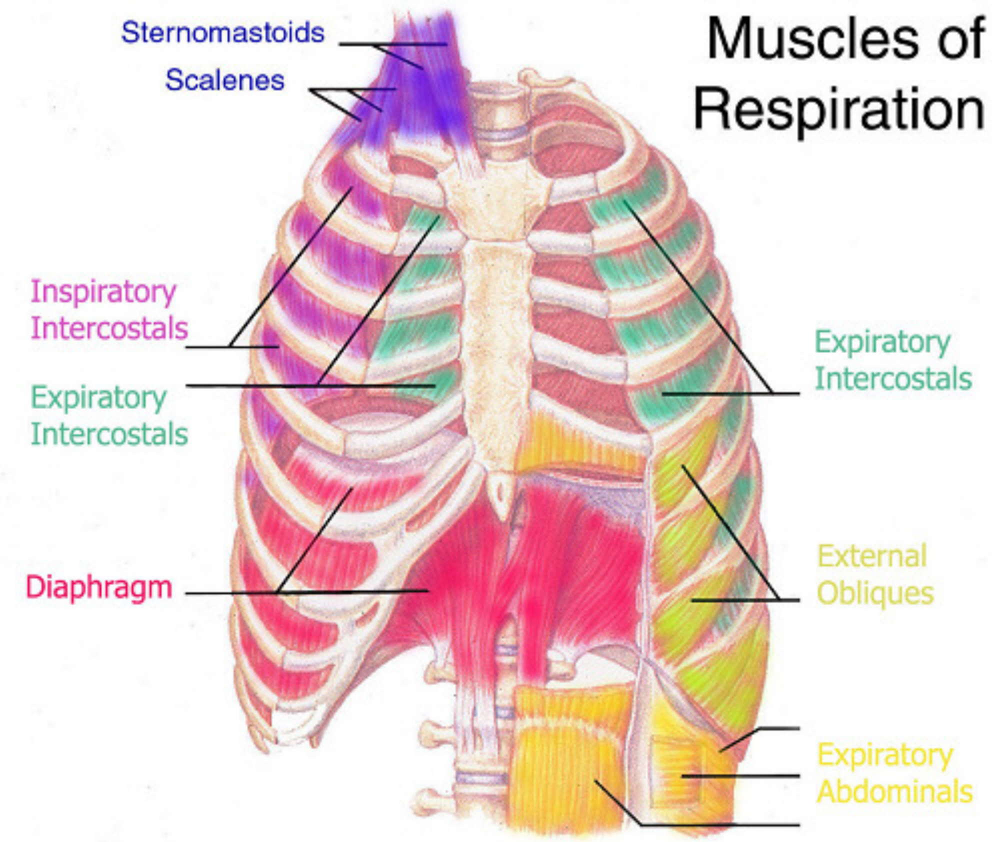
Major respiratory muscles



ankiweb.net

1. The major muscles of respiration include the diaphragm, the external intercostals, and the scalene
2. Diaphragm is the major muscle of respiration and it divides the thoracic cavity from the abdominal cavity
3. Contraction of the diaphragm forces the abdominal contents downward and forward
4. External intercostal muscles pull the ribs upward and forward during inspiration

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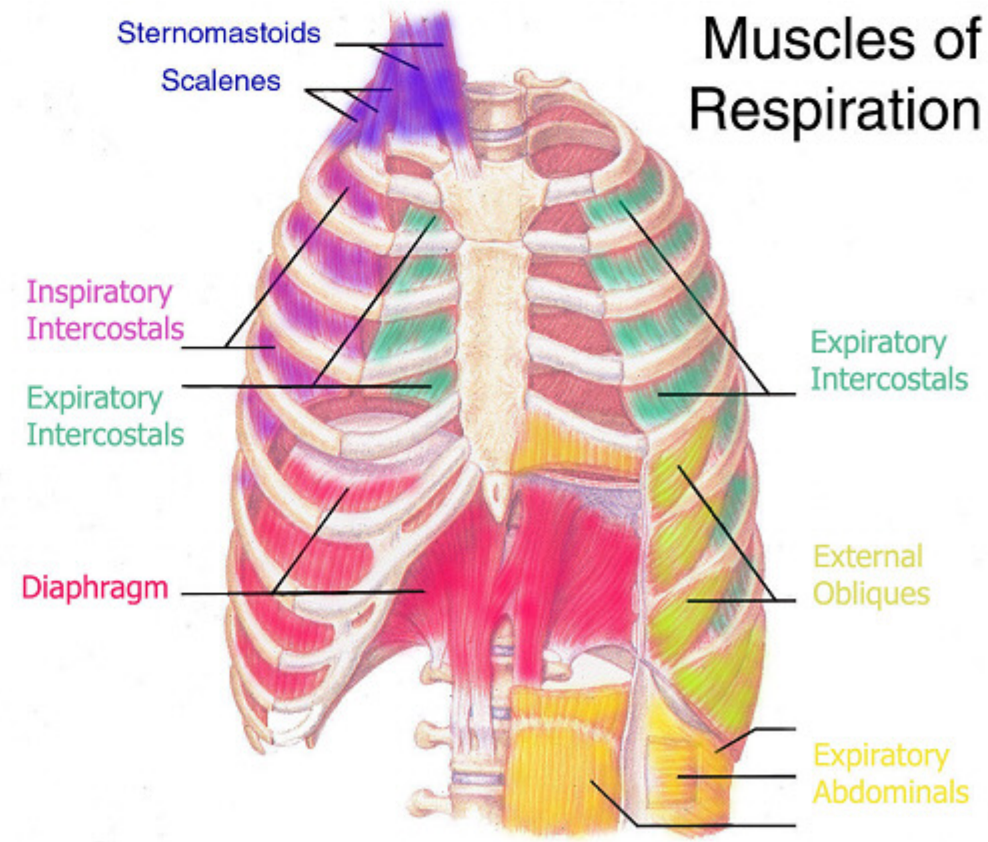
Major respiratory muscles



ankiweb.net

1. Exhalation during normal breathing is passive, but it becomes active during exercise and hyperventilation
2. important muscles of exhalation are those of the abdominal wall and the internal intercostal muscles

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Compliance of lung

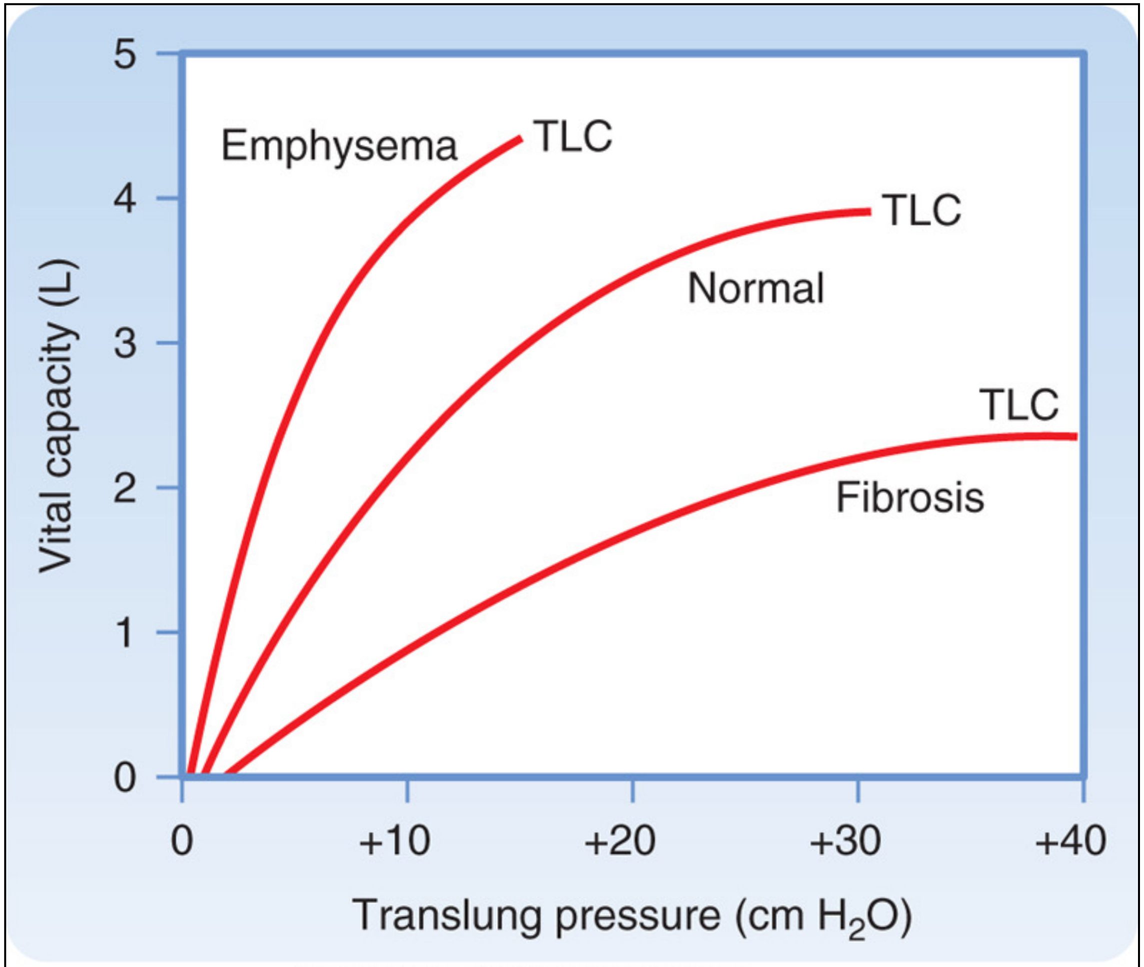

Figure 21-6 Fibrosis/emphysema pressure-volume curve.

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Airflow in airway

1. There are two major patterns of gas flow in the airways-laminar and turbulent flow
2. Laminar flow is parallel to the airway walls and is present at low flow rates. As the flow rate increases and particularly as the airways divide, the flow stream becomes unsteady and small eddies occur
3. At higher flow rates, the flow stream is disorganized and turbulence occurs
4. Turbulence is also promoted by the glottis and vocal cords, which produce some irregularity and obstruction in the airways
5. Overall, the gas flow in the larger airways (nose, mouth, glottis, and bronchi) is turbulent, whereas the gas flow in the smaller airways is laminar

Equation 21-7

$$\dot{V} = \frac{P\pi r^4}{8\eta l}$$

Equation 21-8

$$R = \frac{\Delta P}{\dot{V}} = \frac{8\eta l}{\pi r^4}$$

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Airway resistance as a function of the airway generation

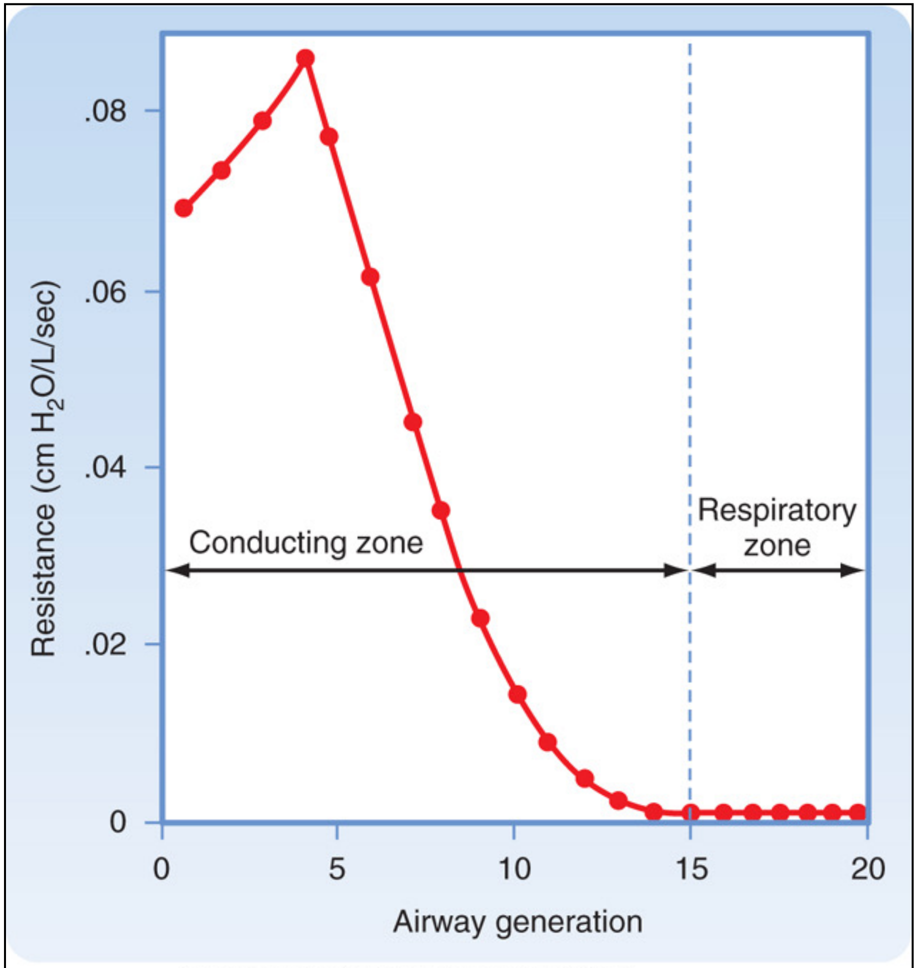

Figure 21-10 Airway resistance as a function of the airway generation. In a normal lung, most of the resistance to airflow occurs in the first eight airway generations.

1. The major site of resistance along the bronchial tree is the large bronchi. The smallest airways contribute very little to the overall total resistance of the bronchial tree
2. First, airflow velocity decreases substantially as the effective cross-sectional area increases (i.e., flow becomes laminar)
3. Second and most important, the airway generations exist in parallel rather than in series
4. During normal breathing, approximately 80% of the resistance to airflow at FRC occurs in airways with diameters greater than 2 mm

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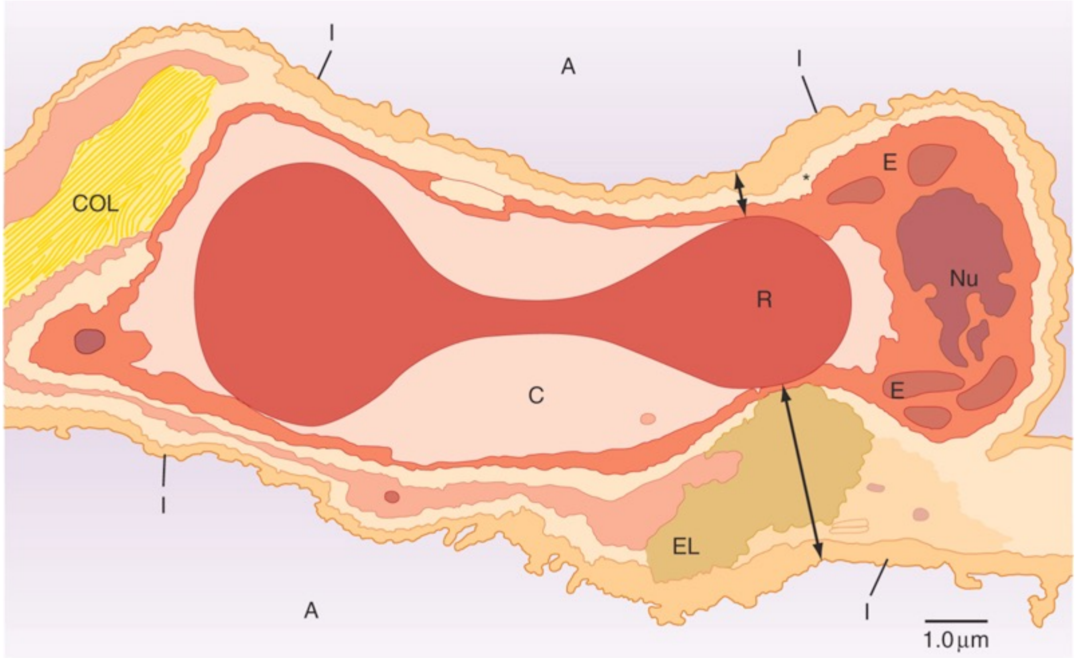
Perfusion and pulmonary circulation



Cross section of an alveolar wall showing the path for diffusion of O2 and CO2. The thin side of the alveolar wall barrier (short double arrow) consists of type I epithelium (I), interstitium (*) formed by the fused basal laminae of the epithelial and endothelial cells, capillary endothelium (E), plasma in the alveolar capillary (C), and finally the cytoplasm of the red blood cell (R). The thick side of the gas exchange barrier (long double arrow) has an accumulation of elastin (EL), collagen (COL), and matrix that jointly separate the alveolar epithelium from the alveolar capillary endothelium. As long as the red blood cells are flowing, O2 and CO2 diffusion probably occurs across both sides of the air-blood barrier. A, alveolus; Nu, nucleus of the capillary endothelial cell.

1. Perfusion is the process by which deoxygenated blood passes through the lung and becomes reoxygenated
2. **The arteries of the pulmonary circulation are the only arteries in the body that carry deoxygenated blood**
3. The arteries of the pulmonary circulation are thin walled, with minimal smooth muscle. They are seven times more compliant than systemic vessels, and they are easily distensible

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Perfusion and pulmonary circulation

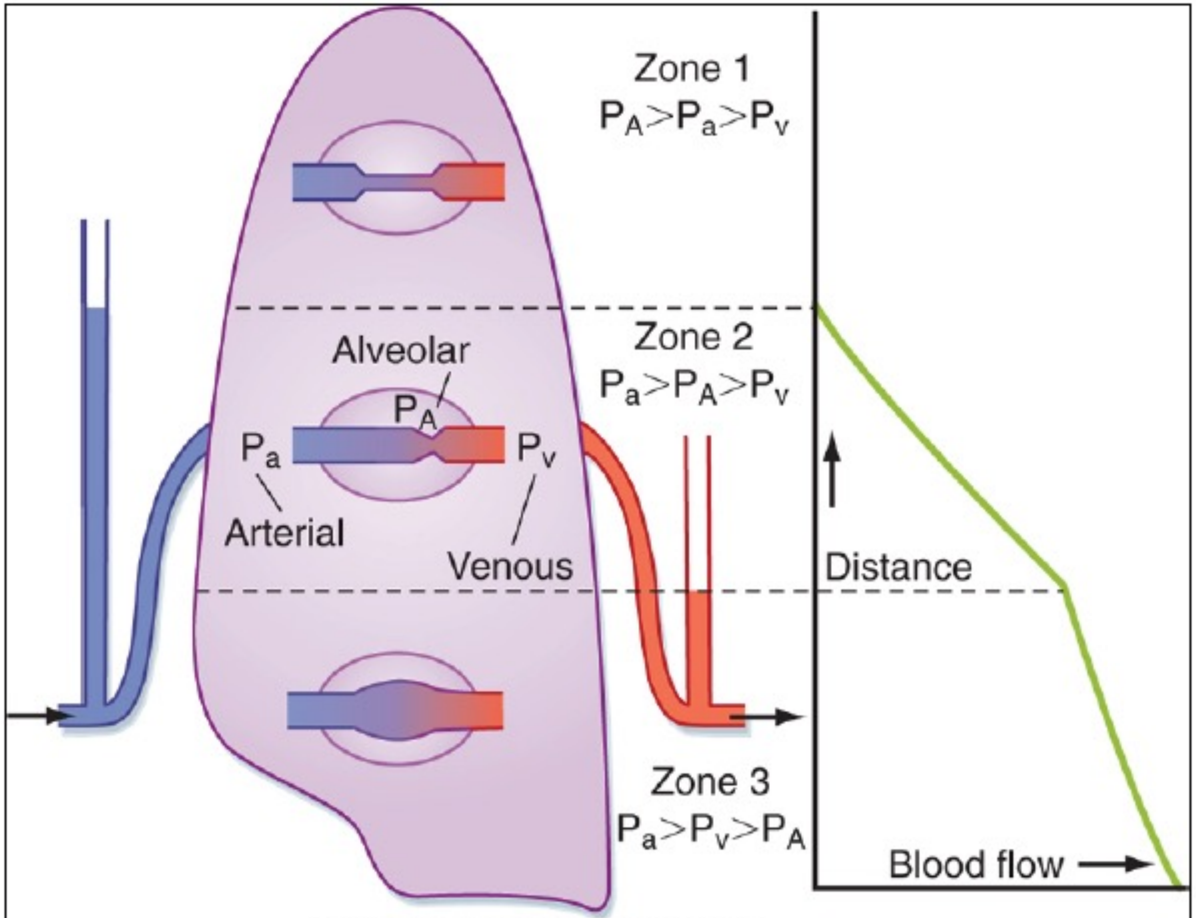
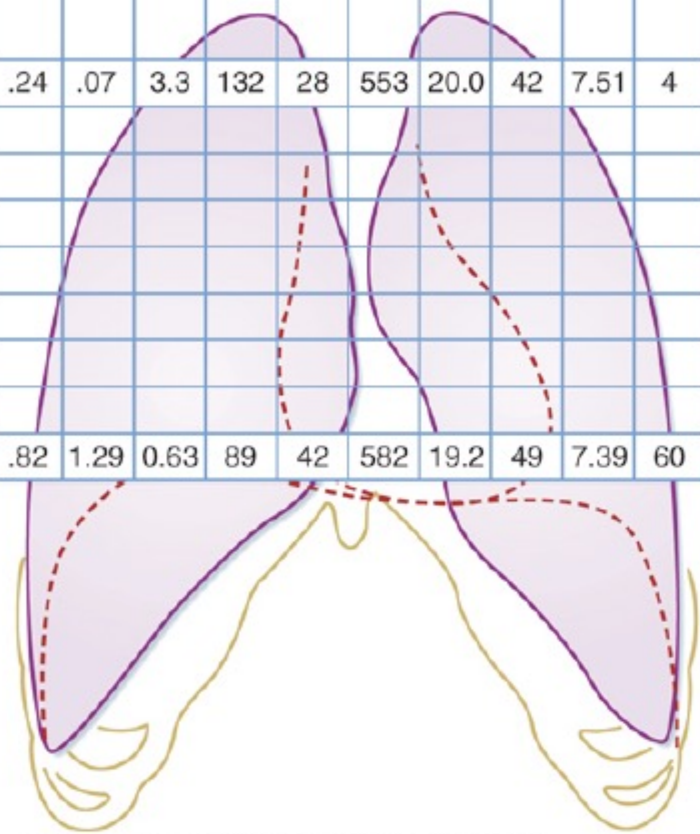


Figure 22-9 Model to explain the uneven distribution of blood flow in the lung based on the pressures affecting the capillaries. (From West JB et al: J Appl Physiol 19:713, 1964.)

Ventilation-Perfusion Relationships

Vol (%)	$\dot{V}_A$ (L/min)	$\dot{Q}$ (L/min)	$\dot{V}_A/\dot{Q}$	P_{O_2} (mm Hg)	P_{CO_2} (mm Hg)	P_{N_2} (mm Hg)	O_2 content (mL/100 mL)	CO_2 content (mL/100 mL)	pH	O_2 in (mL/min)	CO_2 out (mL/min)
7	.24	.07	3.3	132	28	553	20.0	42	7.51	4	8
13	.82	1.29	0.63	89	42	582	19.2	49	7.39	60	39



Regional differences in gas exchange in a normal lung. Only the apical and basal values are shown for clarity

Oxygen and carbon dioxide transport

Table 23.2 Partial Pressures of Gases at Sea Level

	Dry Air		Humidified Air		Alveolar Air		Expired Air	
Gases	**mm Hg**	**%**	**mm Hg**	**%**	**mm Hg**	**%**	**mm Hg**	**%**
Nitrogen	597.5	78.62	563.4	74.09	569.0	74.9	566.0	74.5
Oxygen	158.4	20.84	149.3	19.67	104.0	13.6	120.0	15.7
Carbon dioxide	0.3	0.04	0.3	0.04	40.0	5.3	27.0	3.6
Water vapor	0.0	0.0	47.0	6.20	47.0	6.2	47.0	6.2

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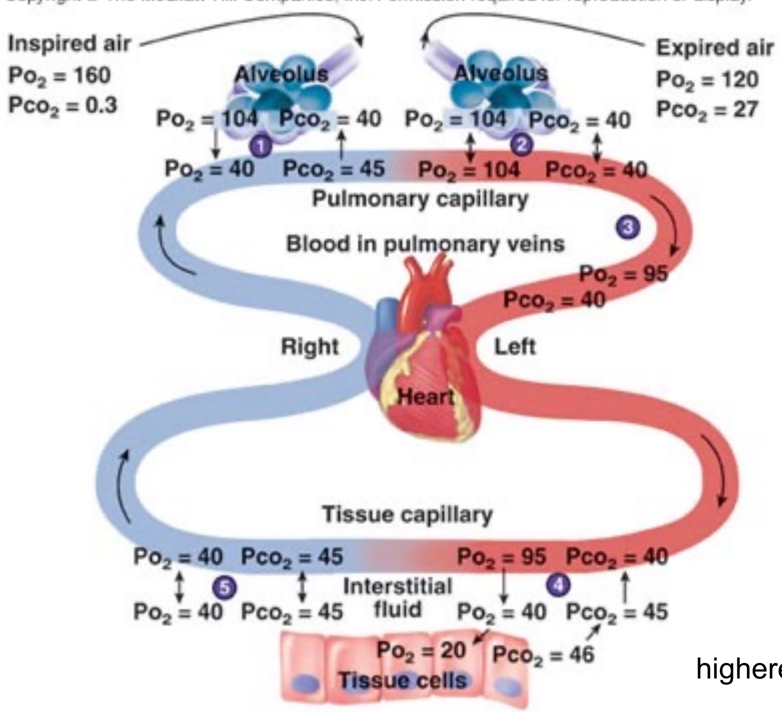

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The Oxyhemoglobin dissociation curve

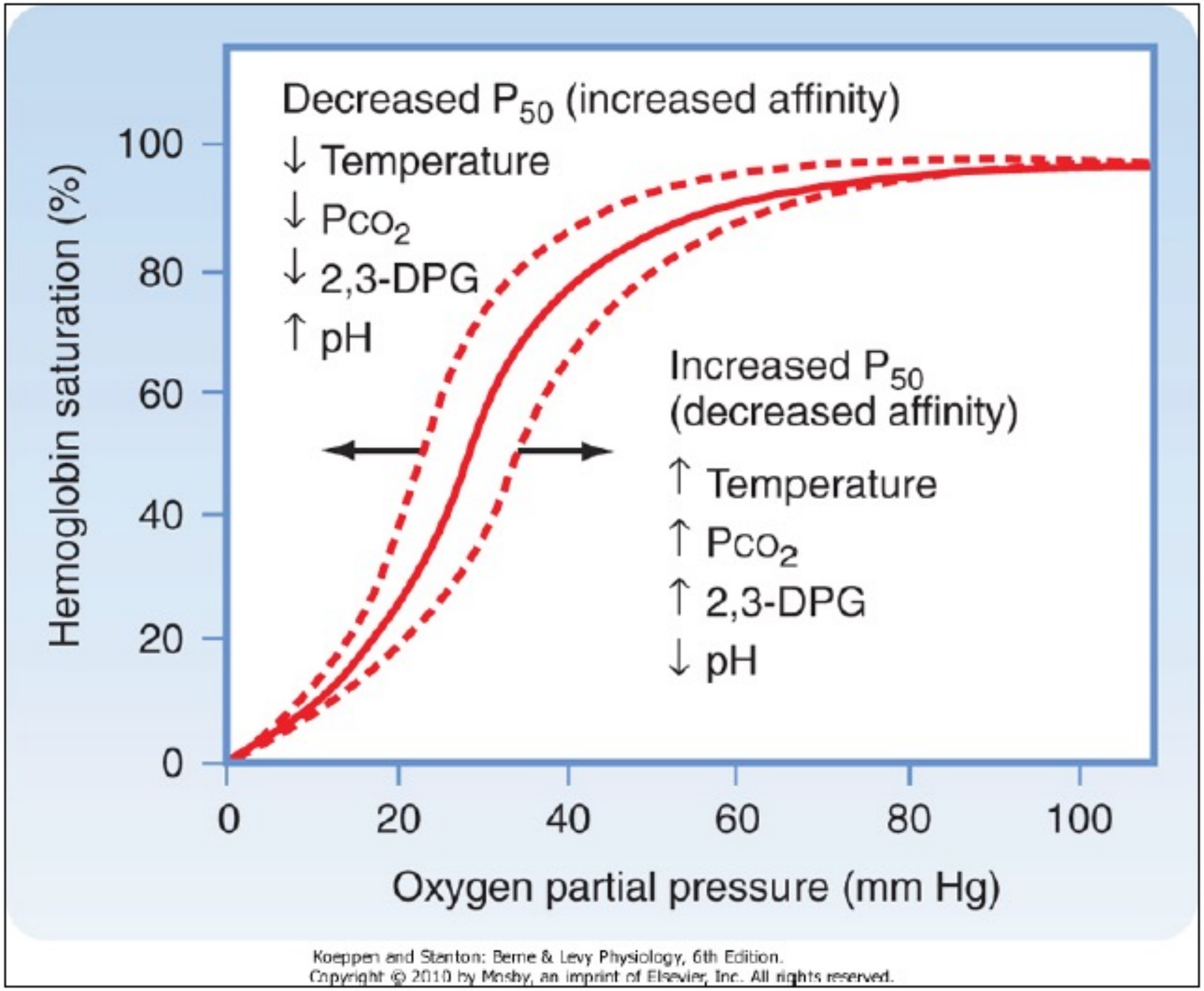

Figure 23-5 Factors that shift the oxyhemoglobin dissociation curve.