Circulatory

14. Overview of the Circulation; Medical Physics of Pressure, Flow, and Resistance

15. Vascular Distensibility and Functions of the Arterial and Venous Systems

16. The Microcirculation and the Lymphatic System: Capillary Fluid Exchange, Interstitial Fluid, and Lymph Flow

18. Nervous Regulation of the Circulation, and Rapid Control of Arterial Pressure

20. Cardiac Output, Venous Return, and Their Regulation

14. Overview of the Circulation; Medical Physics of Pressure, Flow, and Resistance

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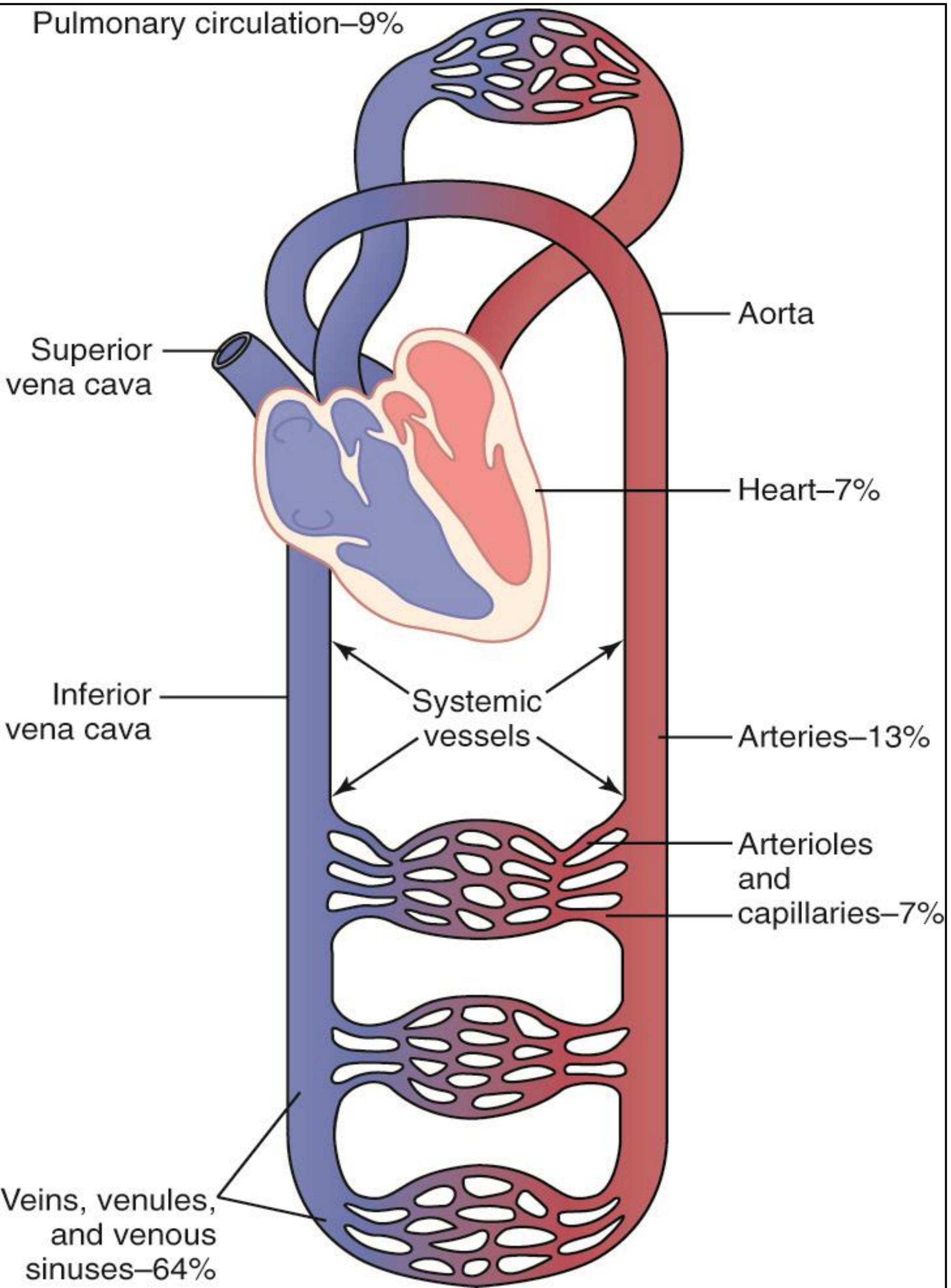
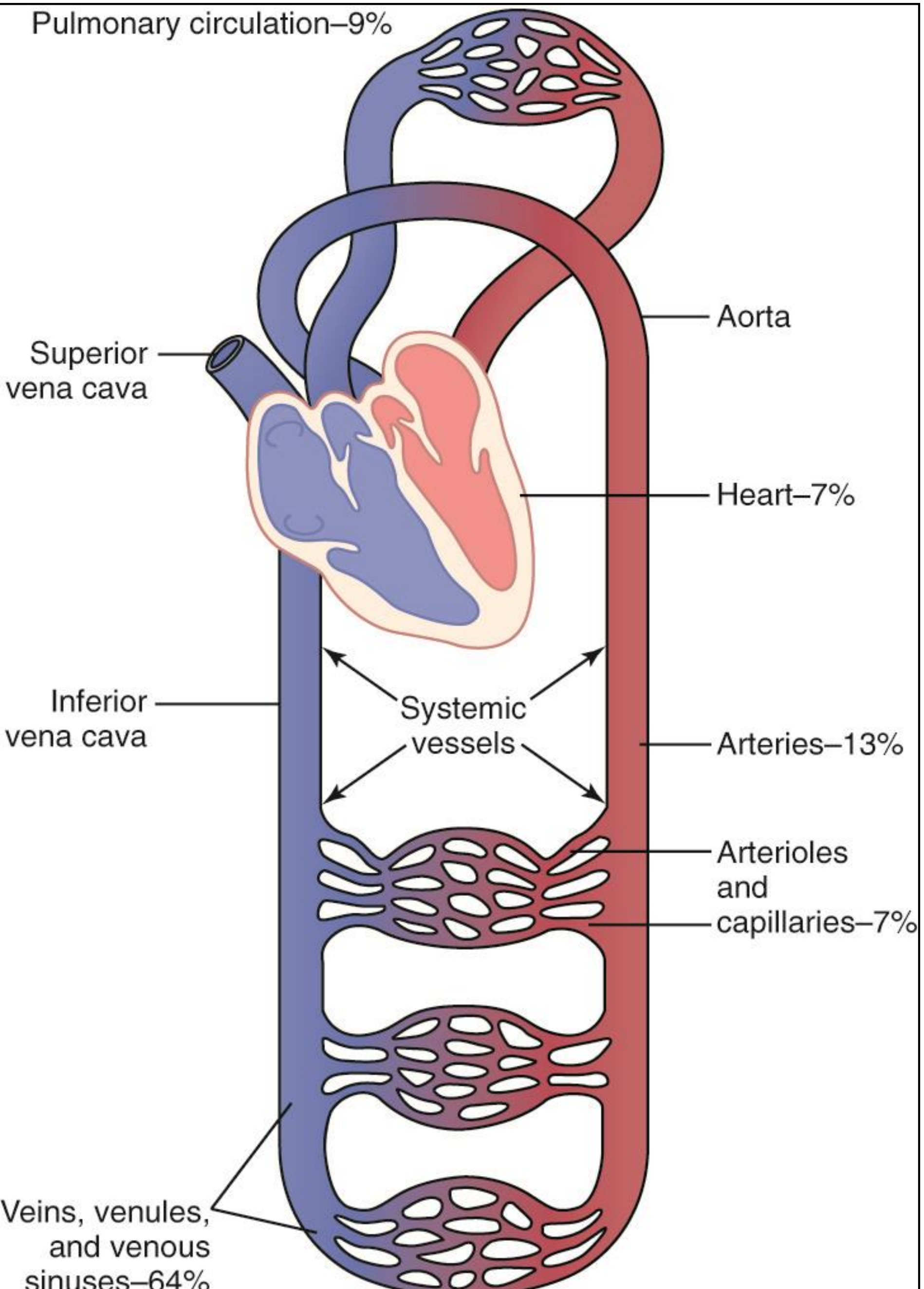
Physical Characteristics of the Circulation



The circulation, shown in Figure 14–1, is divided into the *systemic circulation* and *the pulmonary circulation*.

- systemic circulation is the part of the cardiovascular system which carries oxygenated blood away from the heart to the body, and returns deoxygenated blood back to the heart
- Pulminary circulation is the portion of the cardiovascular system which carries deoxygenated blood away from the heart, to the lungs, and returns oxygenated (oxygen-rich) blood back to the heart

Figure 14-1; Distribution of blood (in percentage of total blood) in the different parts of the circulatory system.



- The function of the arteries is to transport blood under high pressure to the tissues. For this reason, the arteries have strong vascular walls, and blood flows at a high velocity in the arteries.
- The arterioles are the last small branches of the arterial system; they act as control conduits through which blood is released into the capillaries.
- The function of the capillaries is to exchange fluid, nutrients, electrolytes, hormones, and other substances between the blood and the interstitial fluid. To serve this role, the capillary walls are very thin and have numerous minute capillary pores permeable to water and other small molecular substances.
- The venules collect blood from the capillaries, and they gradually coalesce into progressively larger veins.
- The veins function as conduits for transport of blood from the venules back to the heart; equally important, they serve as a major reservoir of extra blood.

- The Capillaries Have the Largest Total Cross-sectional Area of the Circulation

	cm^2
Aorta	**2.5**
Small Arteries	**20**
Arterioles	**40**
Capillaries	**2500**
Venules	**250**
Small Veins	**80**
Venae Cavae	**8**

▪ Velocity of Blood Flow is Greatest in the Aorta

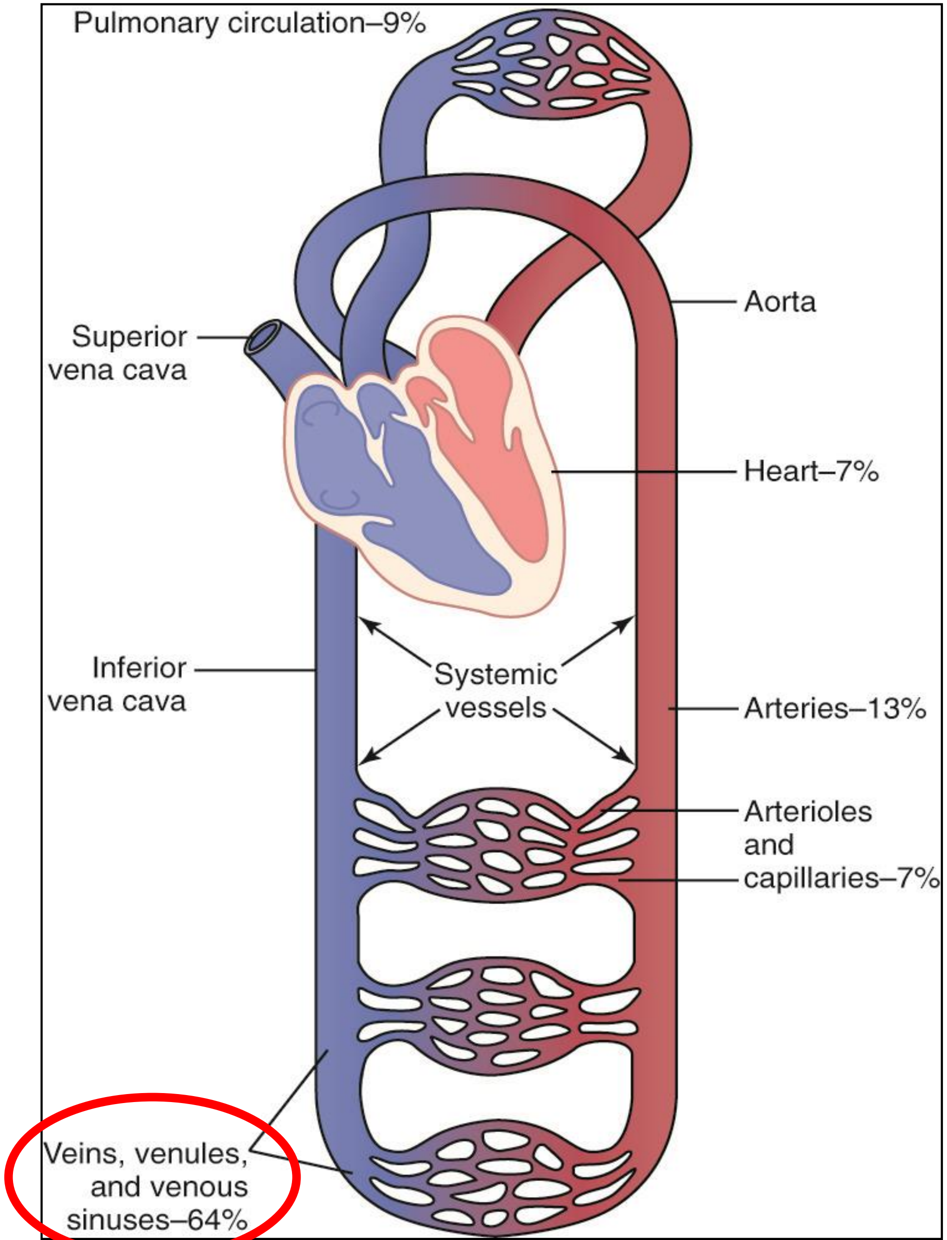
- Because the same volume of blood must flow through each segment of the circulation each minute, the velocity of blood flow is inversely proportional to vascular cross-sectional area.

$$\textit{Velocity}\ \textbf{of Blood Flow} = \frac{\textbf{Blood Flow}}{\textbf{Cross sectional area}}$$

Aorta >Arterioles> Small veins >Capillaries

under resting conditions, the velocity averages about 33 cm/sec in the aorta and 0.3 mm/sec in the capillaries.

▪ The Majority of Blood Volume is in the Veins



<u>Note particularly the much larger cross-sectional areas of the veins than of the arteries, averaging about four times those of the corresponding arteries</u>. This explains the large storage of blood in the venous system in comparison with the arterial system.

Blood Pressure Profile in the Circulatory System

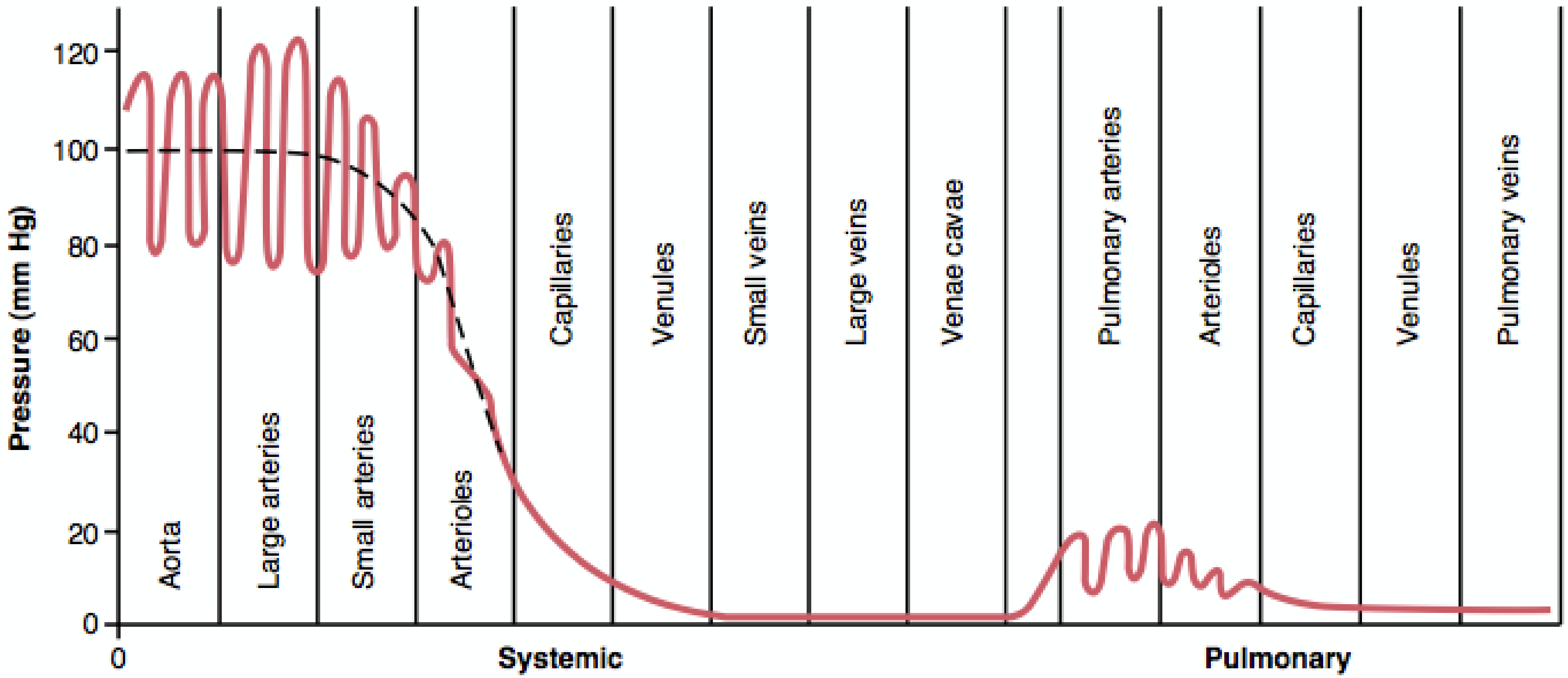


Figure 14-2: Normal blood pressures in the different portions of the circulatory system when a person is lying in the horizontal position.

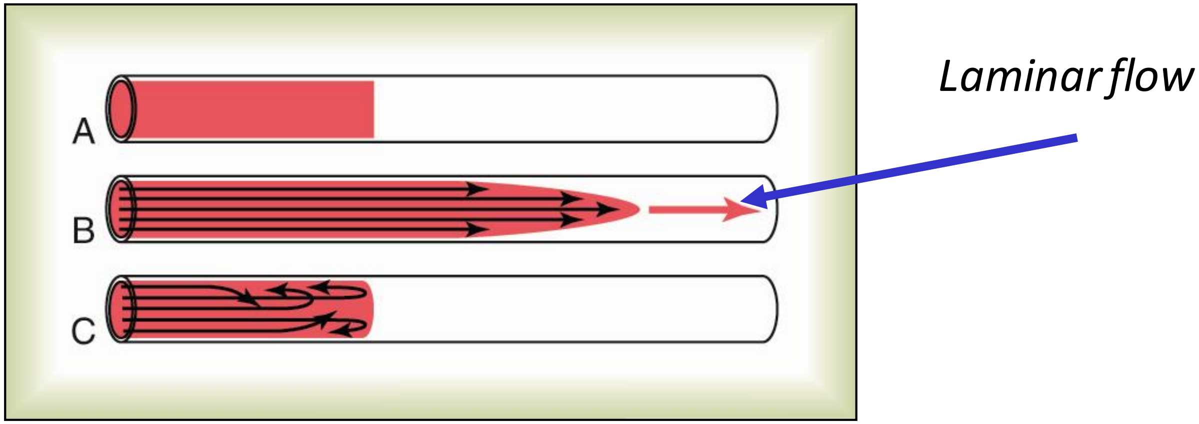
- **High pressures in the arterial tree**
- **Low pressures in the venous side of the circulation**
- **Large pressure drop across the arteriolar-capillary junction**

Variations in Tissue Blood Flow

	Percent	ml/min
Brain	14	700
Heart	4	200
Bronchi	2	100
Kidneys	22	1100
Liver	27	1350
Portal	(21)	(1050)
Arterial	(6)	(300)
Muscle (inactive state)	15	750
Bone	5	250
Skin (cool weather)	6	300
Thyroid gland	1	50
Adrenal glands	0.5	25
Other tissues	3.5	175
Total	100.0	5000

Characteristics of Blood Flow

A, Two fluids (one dyed red, and the other clear) before flow begins;
B, the same fluids 1 second after flow begins;
C, turbulent flow, with elements of the fluid moving in a disorderly pattern

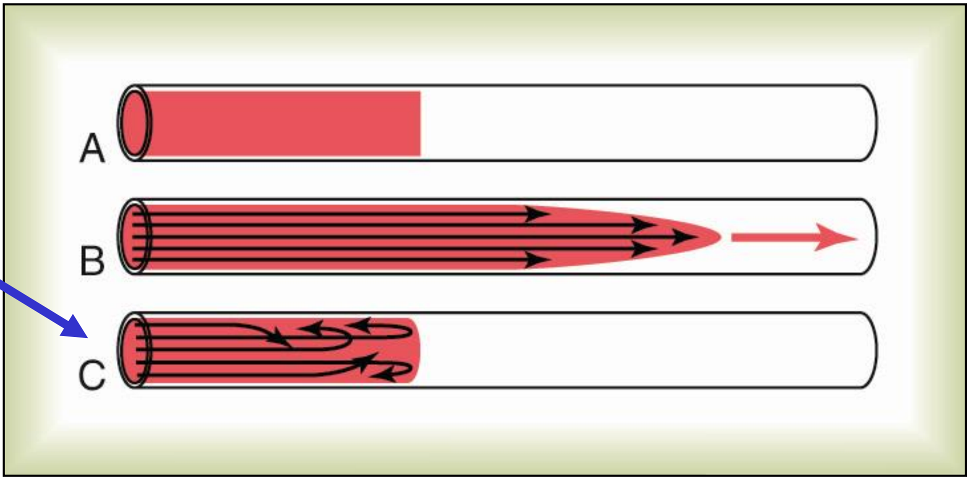


Blood Vessel

– When laminar flow occurs, the velocity of blood in the center of the vessel is greater than that toward the outer edge creating a parabolic profile.

▪ Laminar vs. Turbulent Blood Flow

Turbulent flow

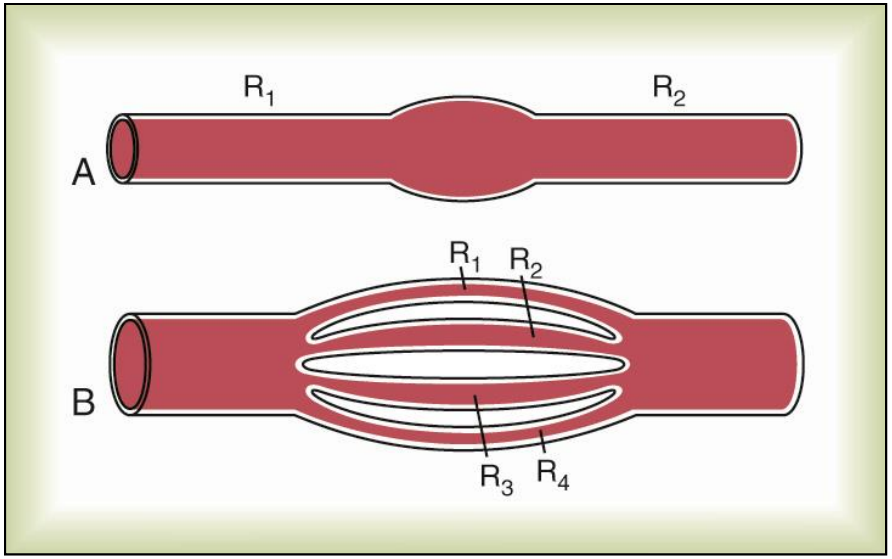


- Laminar flow is silent, whereas turbulent flow tend to cause *murmurs*.
- Murmurs are important in diagnosing vessels stenosis, vessel shunts, and cardiac valvular lesions.

Parallel and Serial Resistance Sites in the Circulation

The arteries, arterioles, capillaries, venules, and veins are collectively arranged in series. When blood vessels are arranged in series, flow through each blood vessel is the same and the total resistance to blood flow

$$R_{total} = R_1 + R_2 + R_3 + R_4 \ldots$$



Vascular resistances: A, in series and B, in parallel.

Blood vessels branch extensively to form parallel circuits that supply blood to the many organs and tissues of the body. This parallel arrangement permits each tissue to regulate its own blood flow, to a great extent, independently of flow to other tissues. total resistance to blood flow is expressed

$$\frac{1}{R_{total}} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \frac{1}{R_4} \ldots$$

Effect of Vessel Diameter on Blood Flow

- Conductance is very sensitive to change in *diameter* of vessel.
- The conductance of a vessel increases in proportion to the *fourth power of the radius.*

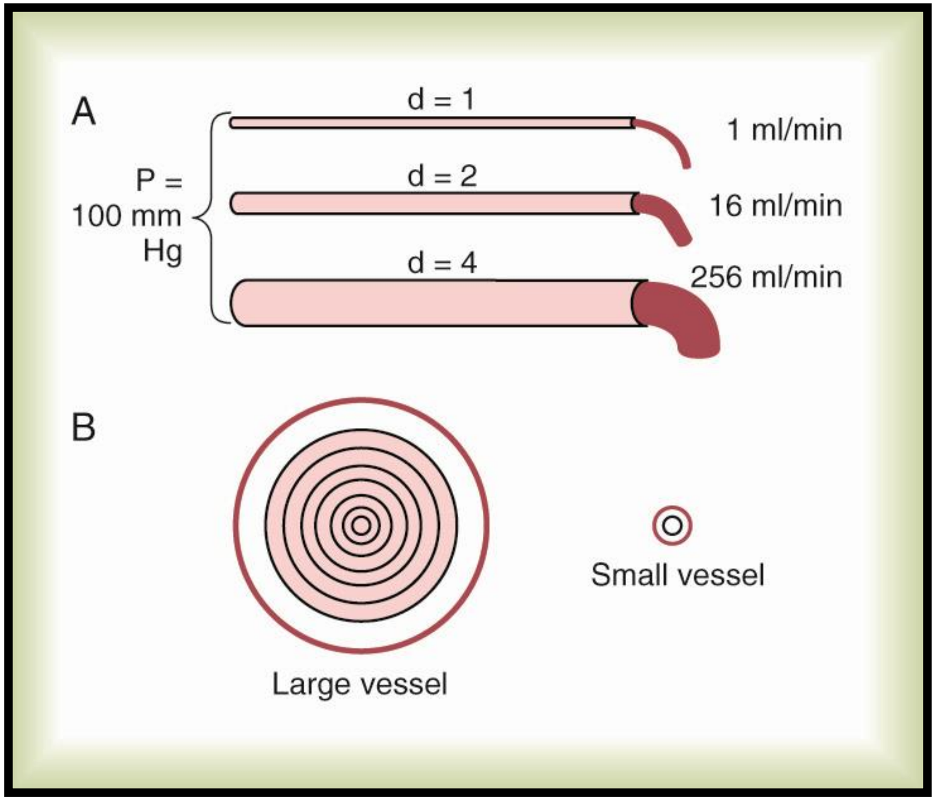
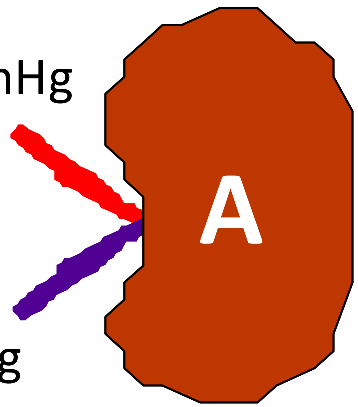


Figure 14-9; A, Demonstration of the effect of vessel diameter on blood flow. B, **Concentric rings of blood flowing at different velocities; the farther away from the vessel wall, the faster the flow.**

Determinants of Blood Flow

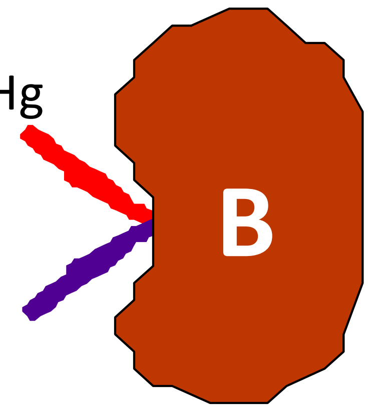
$$\text{FLOW} = \frac{\text{arterial pressure} - \text{venous pressure } (\Delta P)}{\text{resistance (R)}}$$



R = .1mmHg/ml/min

$$\text{FLOW} = \frac{100 - 0 \text{ mmHg}}{.1 \text{ mmHg/ml/min}}$$

FLOW = 1000 ml/min



R = .1mmHg/ml/min

$$\text{FLOW} = \frac{100 - 20 \text{ mmHg}}{.1 \text{ mmHg/ml/min}}$$

FLOW = 800 ml/min

▪ How Would a Decrease in Vascular Resistance Affect Blood Flow?

Vascular resistance refers to the resistance that must be overcome to push blood through the circulatory system and create flow.

$$\uparrow \textbf{FLOW} = \frac{\Delta \textbf{P}}{\downarrow \textbf{RESISTANCE}}$$

Conversely,

$$\downarrow \textbf{FLOW} = \frac{\Delta \textbf{P}}{\uparrow \textbf{RESISTANCE}}$$

▪ Hematocrit and Viscosity Effects on Blood Flow

- The percentage of the blood that is cells is called the hematocrit. Thus, if a person has a hematocrit of 40, this means that 40 per cent of the blood volume is cells and the remainder is plasma. The hematocrit of men averages about 42, while that of women averages about 38.

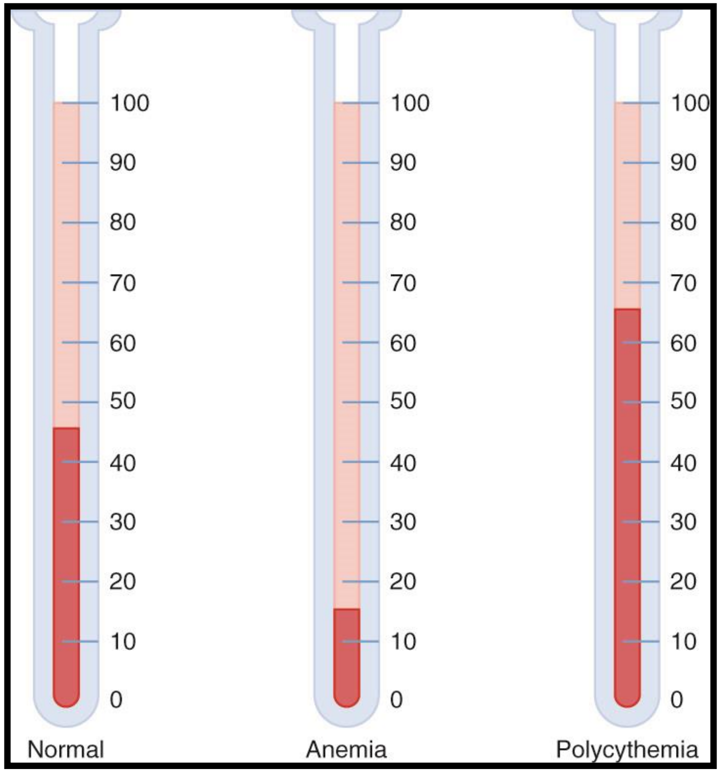


Figure 14-11; Hematocrits in a healthy (normal) person and in patients with anemia and polycythemia.

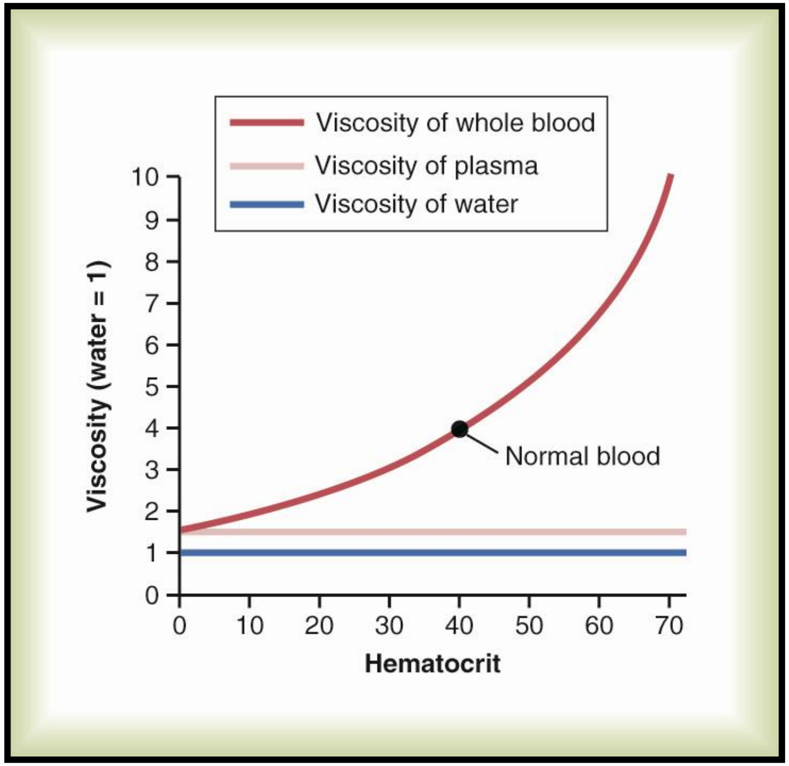


Figure 14-12; Effect of hematocrit on blood viscosity. (Water viscosity = 1.)

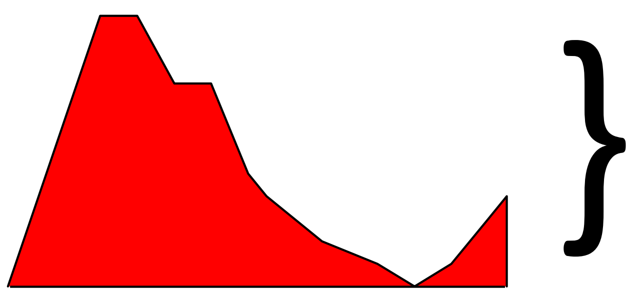
- The viscosity of whole blood at normal hematocrit is about 3; this means that three times as much pressure is required to force whole blood as to force water through the same blood vessel.

▪ Arterial Pulsations

- The height of the pressure pulse is the *systolic pressure* (120mmHg), while the lowest point is the *diastolic pressure* (80mmHg).
- The difference between *systolic* and *diastolic pressure* is called the *pulse pressure* (40mmHg).

Systolic Pressure

Diastolic Pressure



Pulse Pressure

➢ Factors Affecting Pulse Pressure

- *Stroke volume* —increases in stroke volume increase pulse pressure, conversely decreases in stroke volume decrease pulse pressure.

- *Arterial compliance* —decrease in compliance increases pulse pressure; increase in compliance decrease pulse pressure.

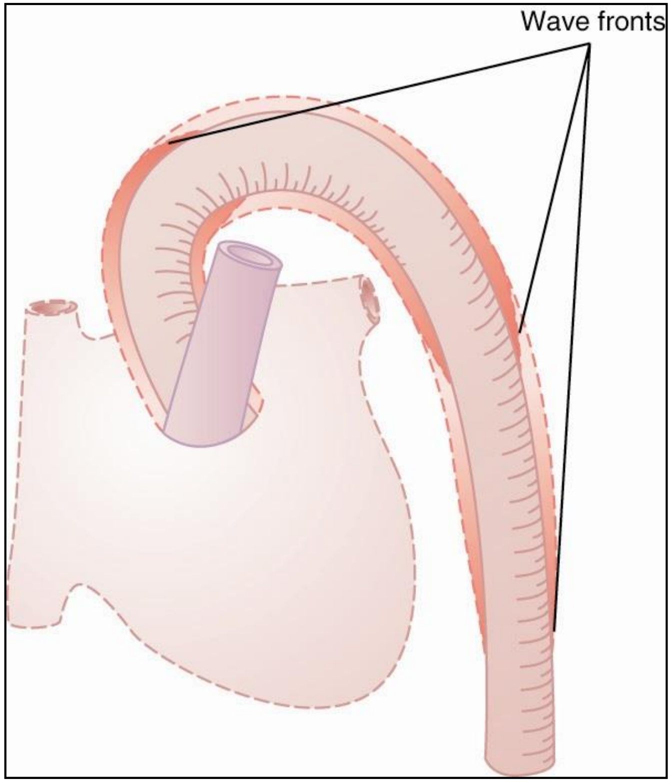


Figure 15-5; Guyton and Hall

- **Transmission of Pressure Pulses to the Peripheral Arteries**

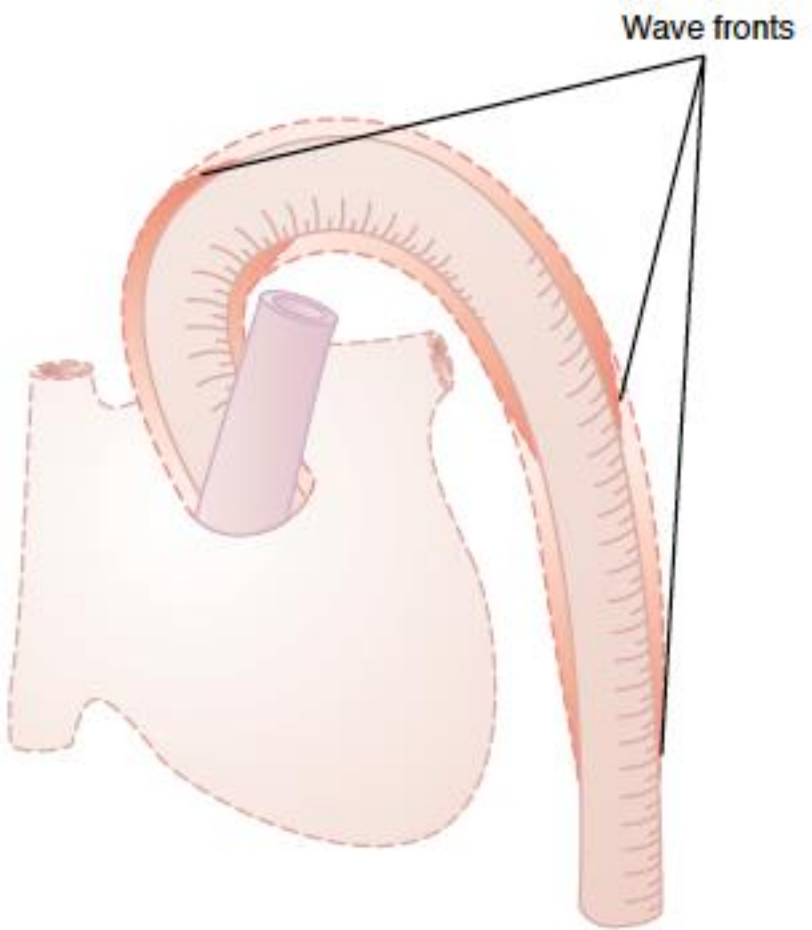
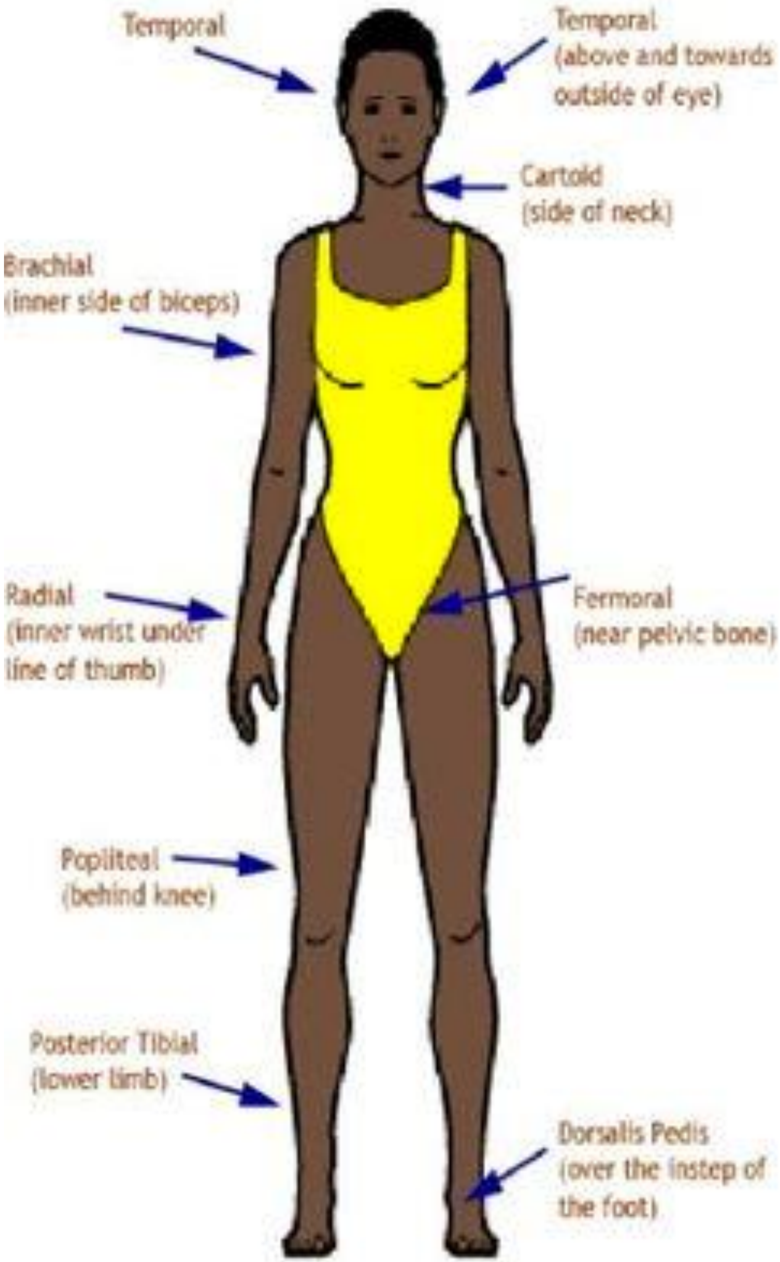
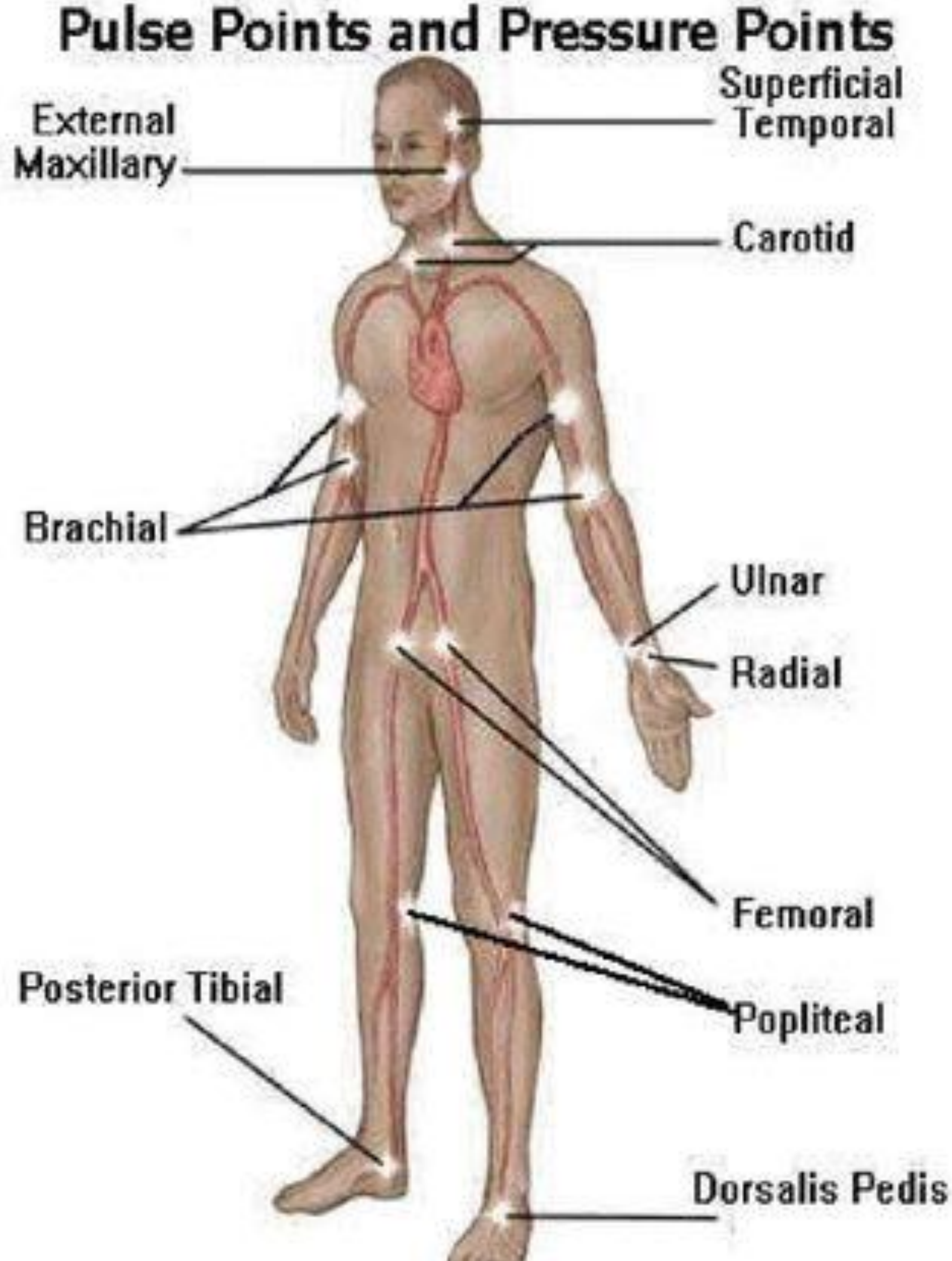


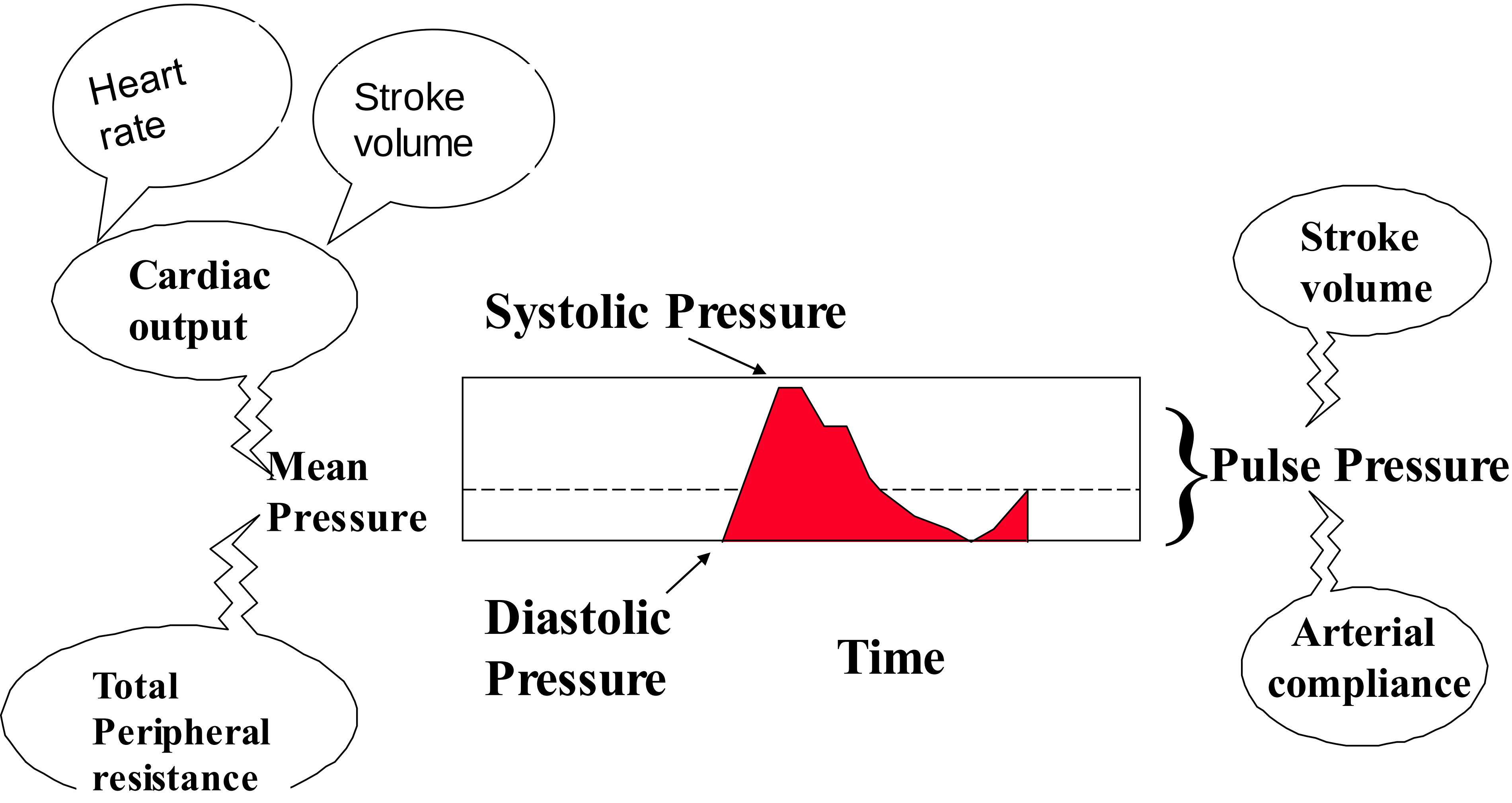
Figure 15–5

Progressive stages in transmission of the pressure pulse along the aorta.

- When the heart ejects blood into the aorta during systole, at first only the proximal portion of the aorta becomes distended because the inertia of the blood prevents sudden blood movement all the way to the periphery. However, the rising pressure in the proximal aorta rapidly overcomes this inertia, and the wave front of distention spreads farther and farther along the aorta, as shown in Figure 15–5. This is called transmission of the pressure pulse in the arteries.


Temporal
Temporal (above and towards outside of eye)
Cartoid (side of neck)
Brachial (inner side of biceps)
Radial (inner wrist under line of thumb)
Fermoral (near pelvic bone)
Popliteal (behind knee)
Posterior Tibial (lower limb)
Dorsalis Pedis (over the instep of the foot)


Pulse Points and Pressure Points
Superficial Temporal
External Maxillary
Carotid
Brachial
Ulnar
Radial
Femoral
Posterior Tibial
Popliteal
Dorsalis Pedis



HR x SV = CO = MAP/ TPR

MAP= (0.4 SP) + (0.6 DP)

PP= SP- DP

▪ Damping of Pulse Pressures in the Peripheral Arteries

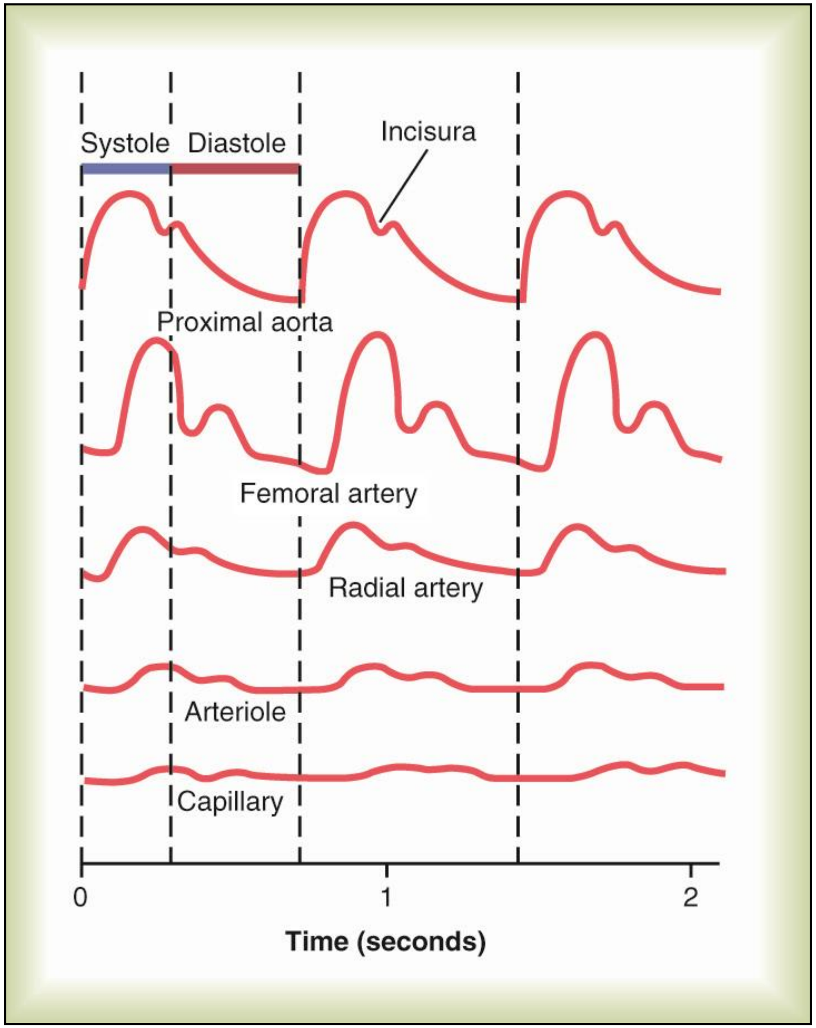
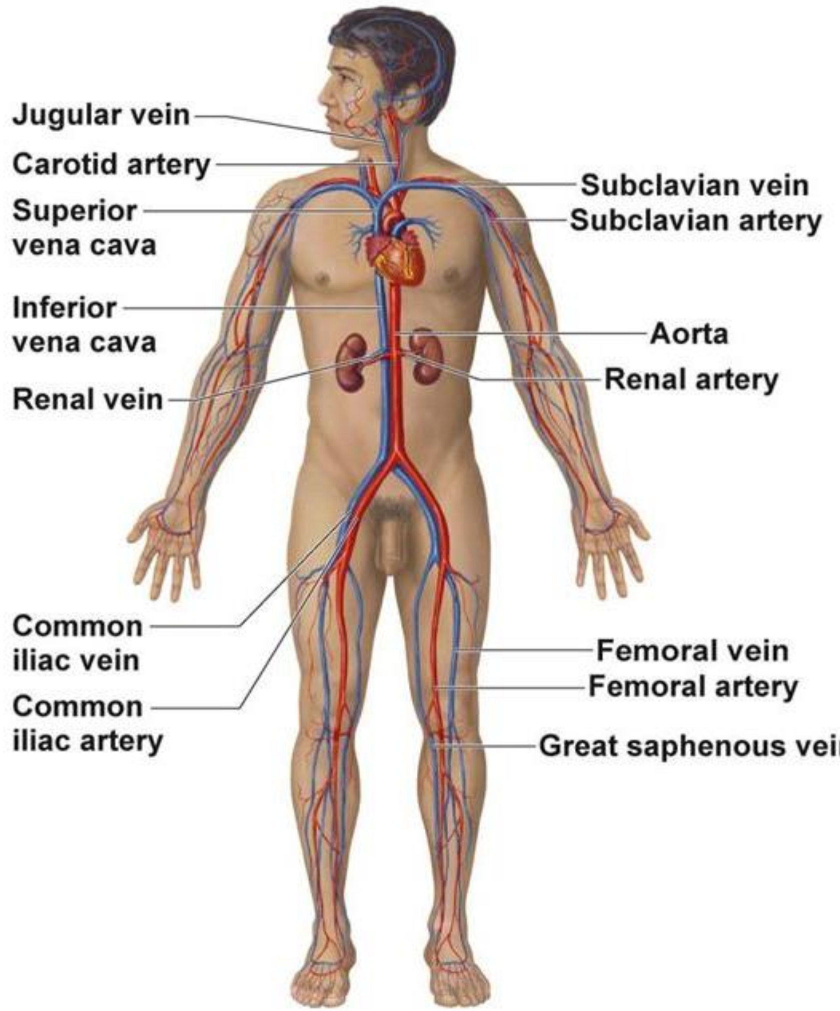
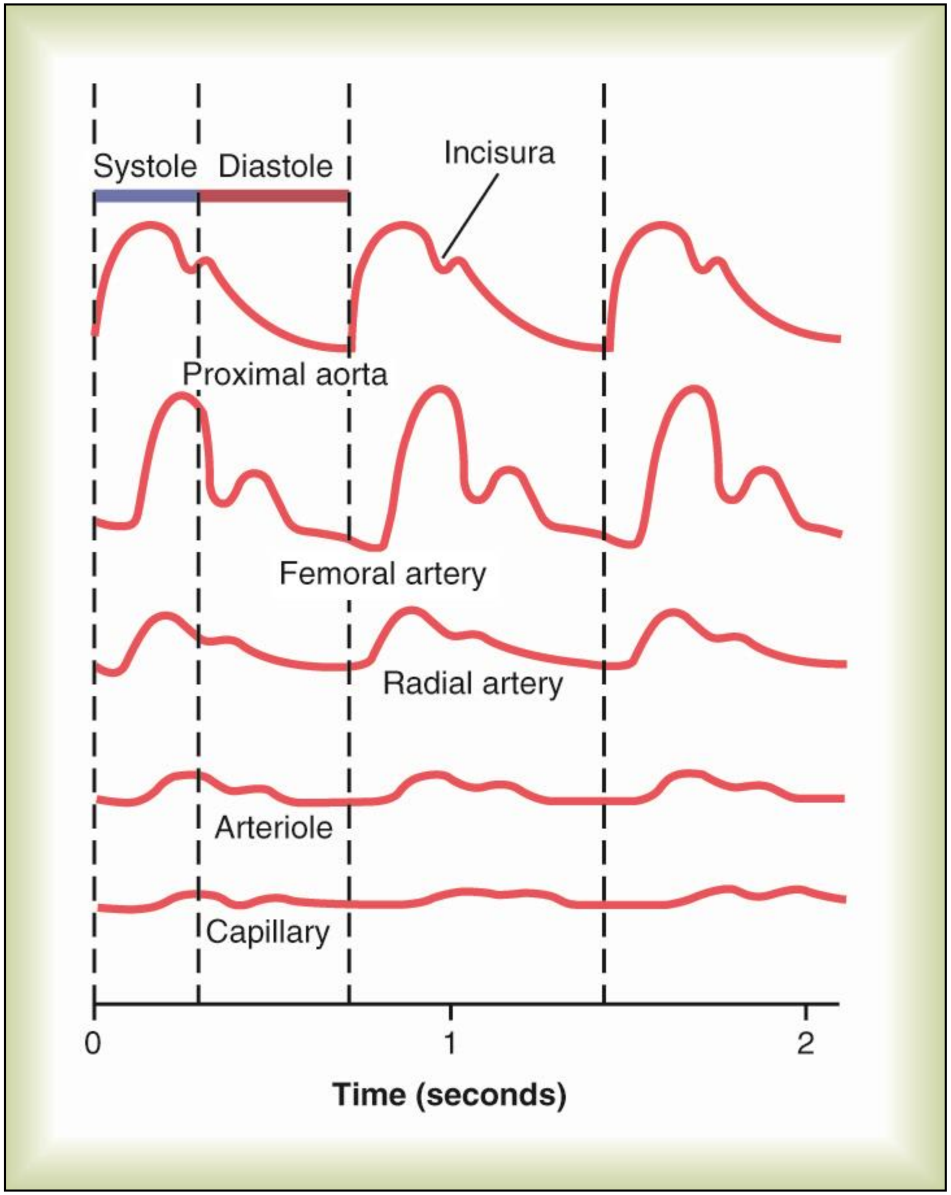


Figure 15-6; Changes in the pulse pressure contour as the pulse wave travels toward the smaller vessels.

Some of the major arteries and veins in the human body.



Damping of Pulse Pressures in the Peripheral Arteries



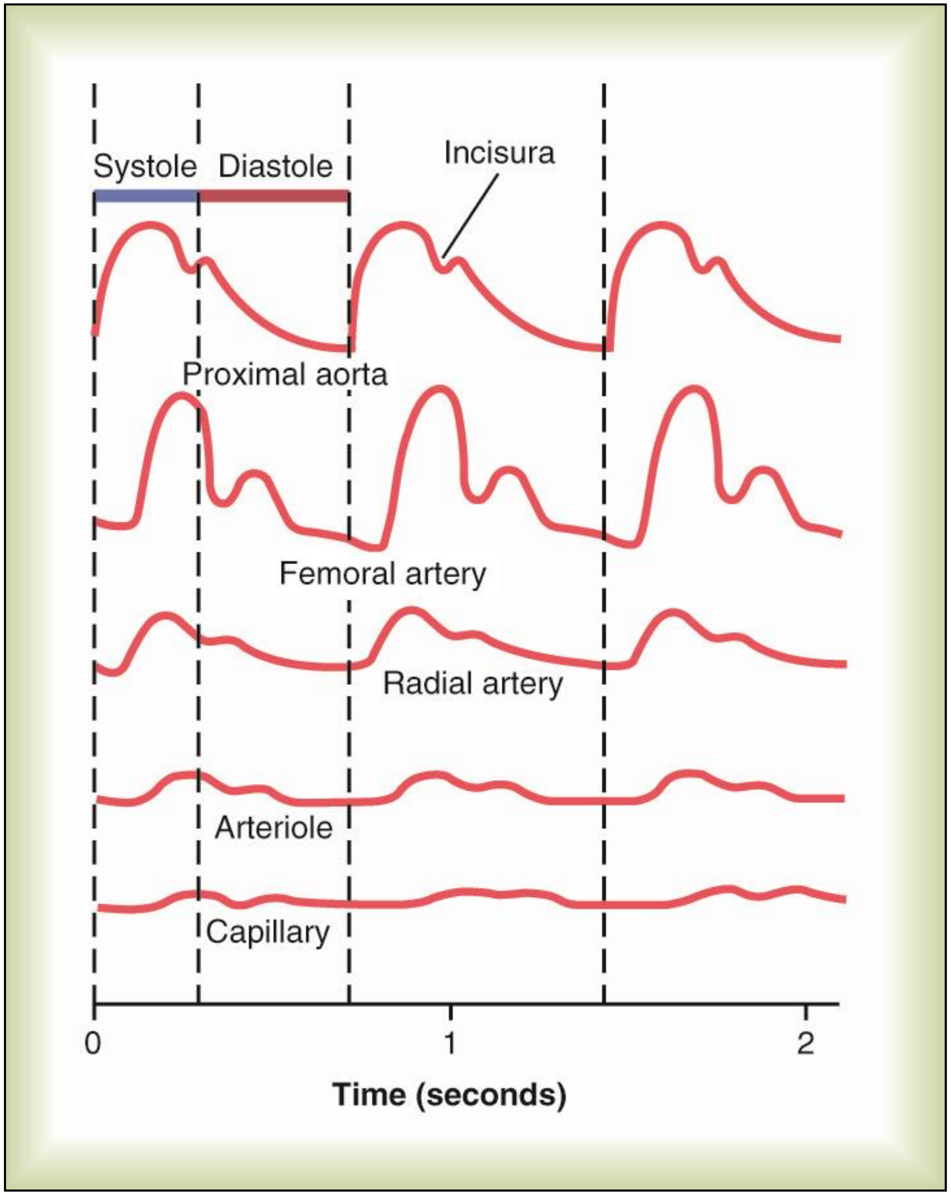
- progressive diminution of the pulsations in the periphery is called damping of the pressure pulses. The cause of this is twofold:

- (1) resistance to blood movement in the vessels

- The resistance damps the pulsations because a small amount of blood must flow forward at the pulse wave front to distend the next segment of the vessel; the greater the resistance, the more difficult it is for this to occur

Figure 15-6; Changes in the pulse pressure contour as the pulse wave travels toward the smaller vessels.

Damping of Pulse Pressures in the Peripheral Arteries



- (2) compliance of the vessels.

> The compliance damps the pulsations because the more compliant a vessel, the greater the quantity of blood required at the pulse wave front to cause an increase in pressure.

the degree of damping is almost directly proportional to the product of resistance times compliance.

Figure 15-6; Changes in the pulse pressure contour as the pulse wave travels toward the smaller vessels.

▪ Abnormal Pressure Pulse Contours ??

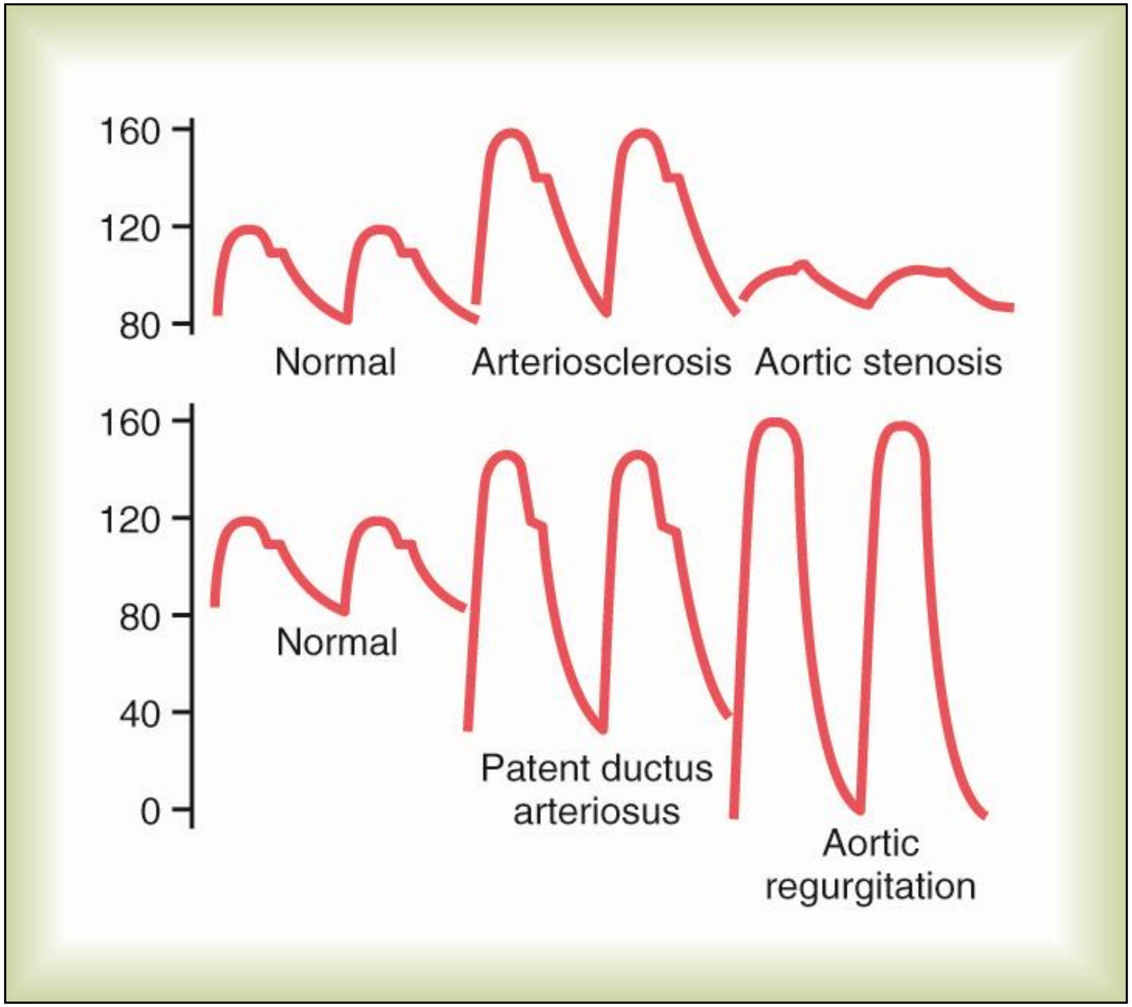


Figure 15– 4, the pulse pressure in old age sometimes rises to as much as twice normal, because the arteries have become hardened with arteriosclerosis and therefore are relatively noncompliant.

Figure 15-4; aortic pressure pulse contours in arteriosclerosis, aortic stenosis, patent ductus arteriosus, and aortic regurgitation.

▪ Pulse Pressure and Age

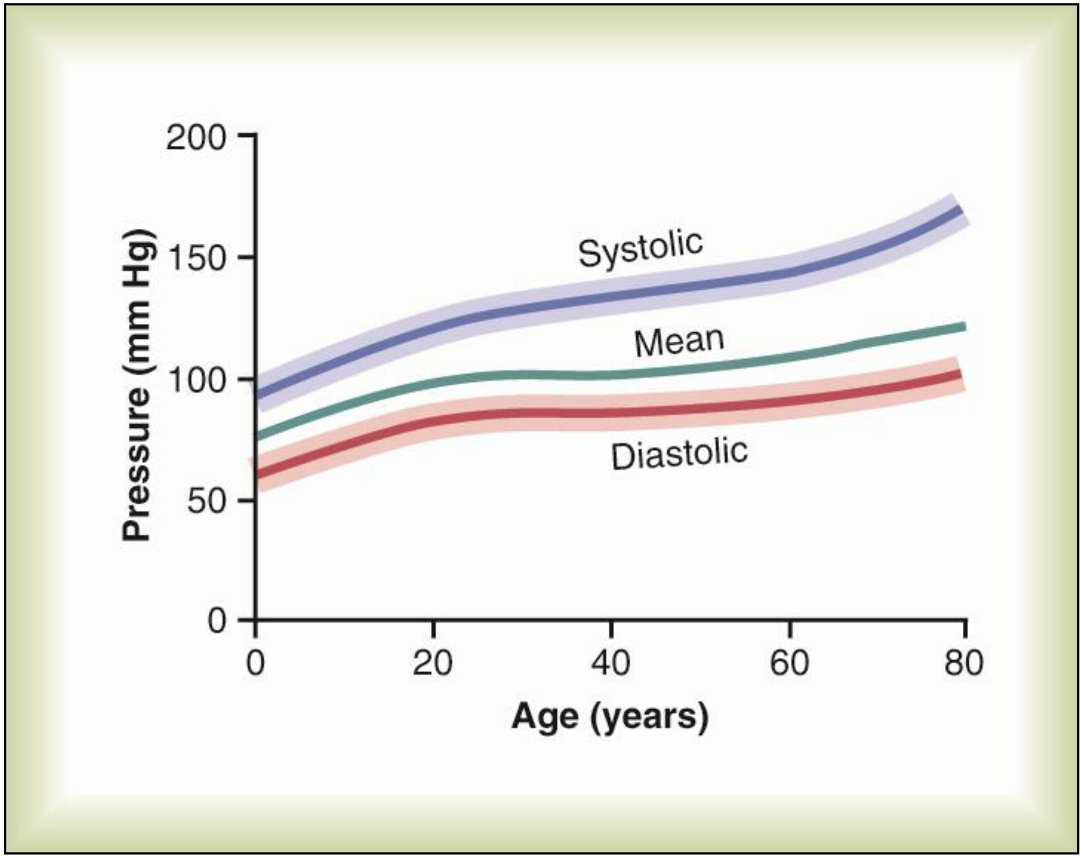
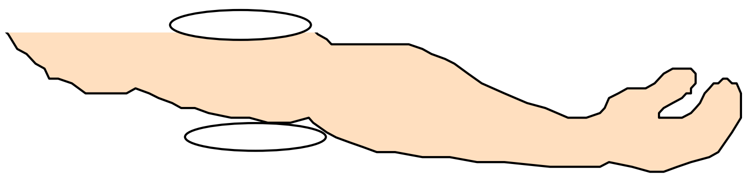


Figure 15-8;
Changes in systolic, diastolic, and mean arterial pressures with age. The shaded areas show the approximate normal ranges.

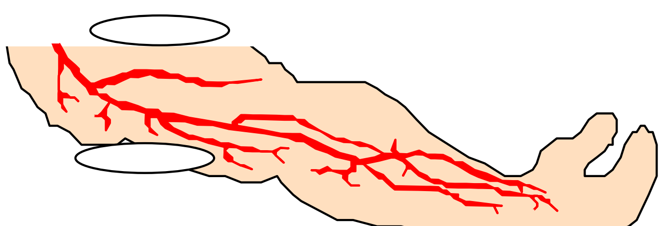
■ Effect of Cuff Pressure on Brachial Blood Flow

Cuff Pressure > 120



NO FLOW

Cuff Pressure < 80



FREE FLOW

- # Measurement of Blood Pressure

Use of Korotkoff Sounds

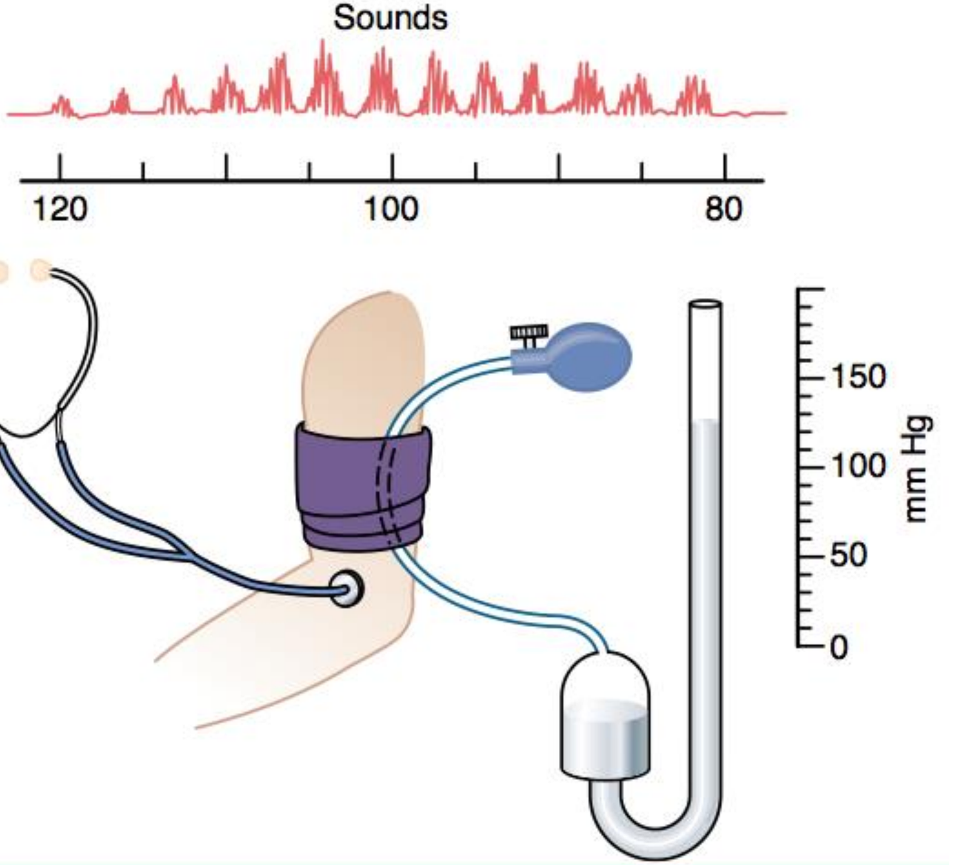


Figure 15–7
Auscultatory method for measuring systolic and diastolic arterial pressures.

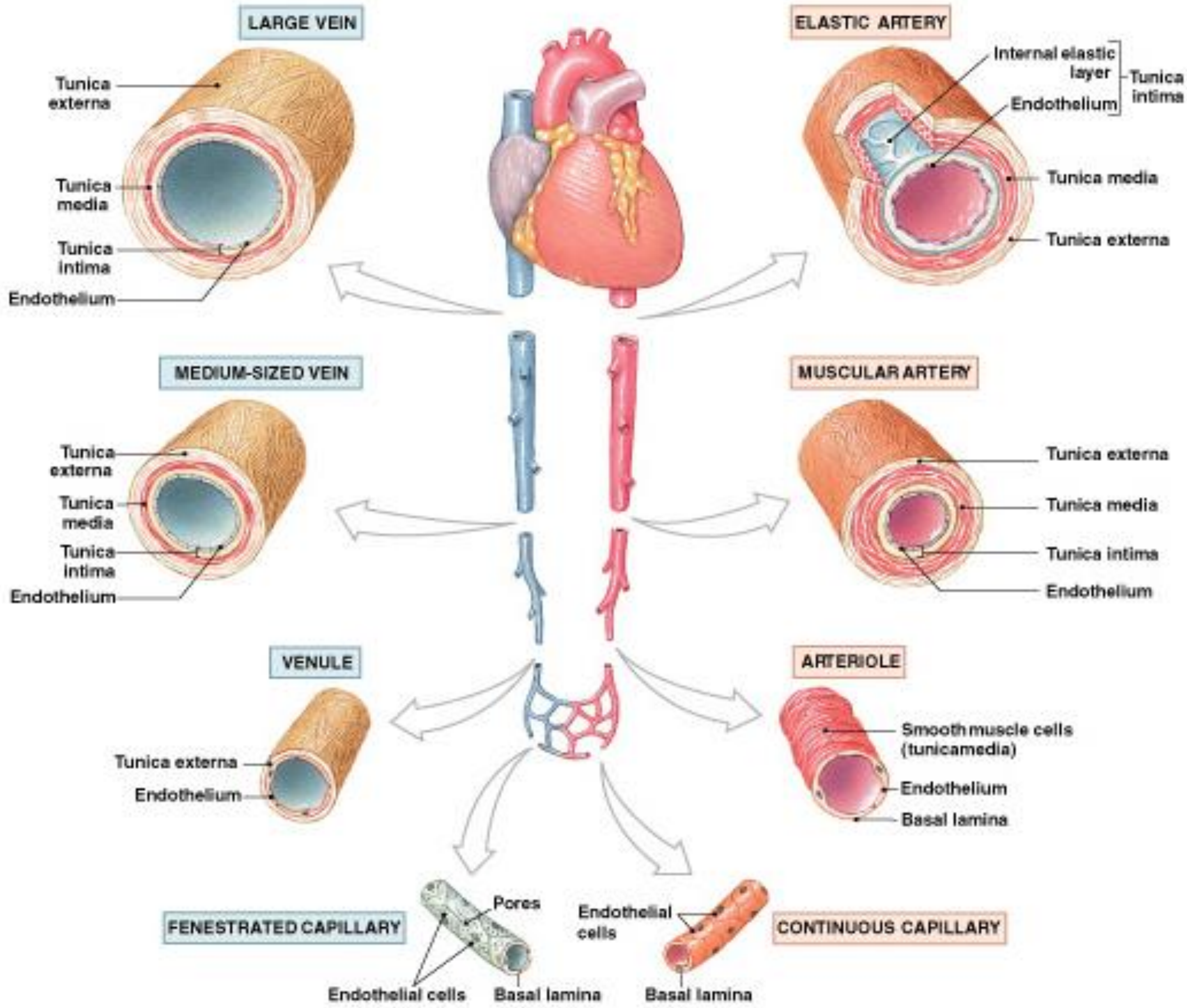
16. The Microcirculation and the Lymphatic System: Capillary Fluid Exchange, Interstitial Fluid, and Lymph Flow

▪ Blood Vessels

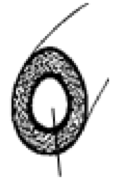
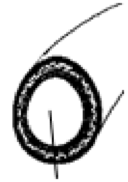
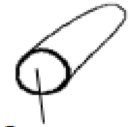
- Blood is carried in a closed system of vessels that begins and ends at the heart
- The three major types of vessels are arteries, capillaries, and veins
- Arteries carry blood away from the heart, veins carry blood toward the heart
- Capillaries contact tissue cells and directly serve cellular needs

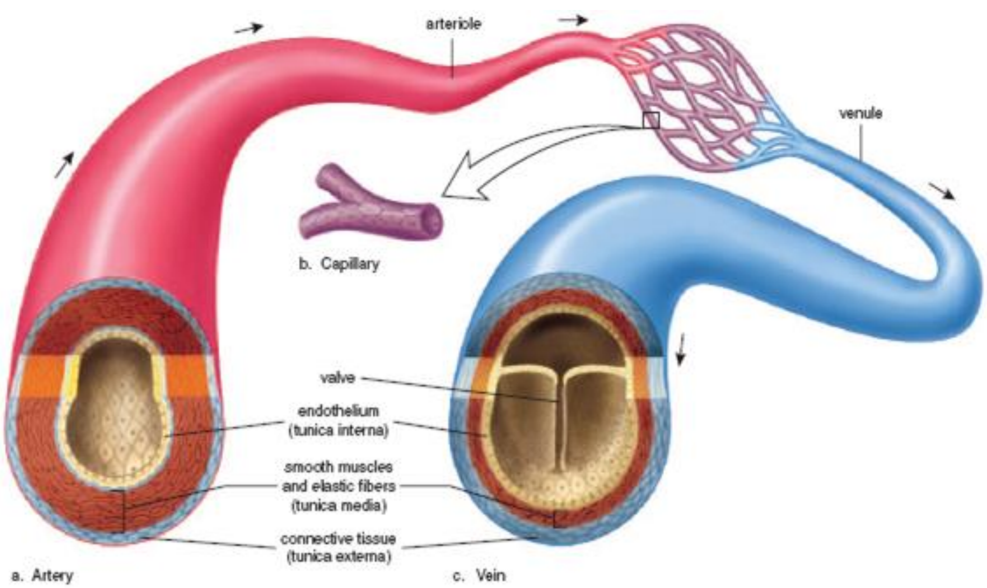
▪ Generalized Structure of Blood Vessels

- Arteries and veins are composed of three tunics – tunica interna, tunica media, and tunica externa
- Lumen – central blood-containing space surrounded by tunics
- Capillaries are composed of endothelium with sparse basal lamina



Generalized Structure of Blood Vessels

Aspect	Artery	Vein	Capillary
Cross section	 Lumen	 Lumen	 Lumen
Function	To carry blood away from the heart to other parts of the body	To carry blood to the heart	To connect the artery and the vein
Size of lumen	Small	Large	Very small
Wall thickness	Thick, elastic and muscular	Thinner and less elastic	Very thin (one-cell thick)
Blood flow	Very fast, high pressure	Slow, low pressure	Very slow, very low pressure
Type of blood carried	Oxygenated blood (except pulmonary artery)	Deoxygenated blood (except pulmonary vein)	Carries oxygenated blood to cell body; bring deoxygenated blood out of cell body
Presence of valve	× (except pulmonary artery)	✓ (except pulmonary vein)	×



Structure of the Microcirculation and Capillary System

• The Microcirculation

- The microcirculation of each organ is organized specifically to serve that organ's needs.
- In general, each nutrient artery entering an organ branches six to eight times before the arteries become small enough to be called arterioles, which generally have internal diameters of only 10 to 15 micrometers.
- Then the arterioles themselves branch two to five times, reaching diameters of 5 to 9 micrometers at their ends where they supply blood to the capillaries.

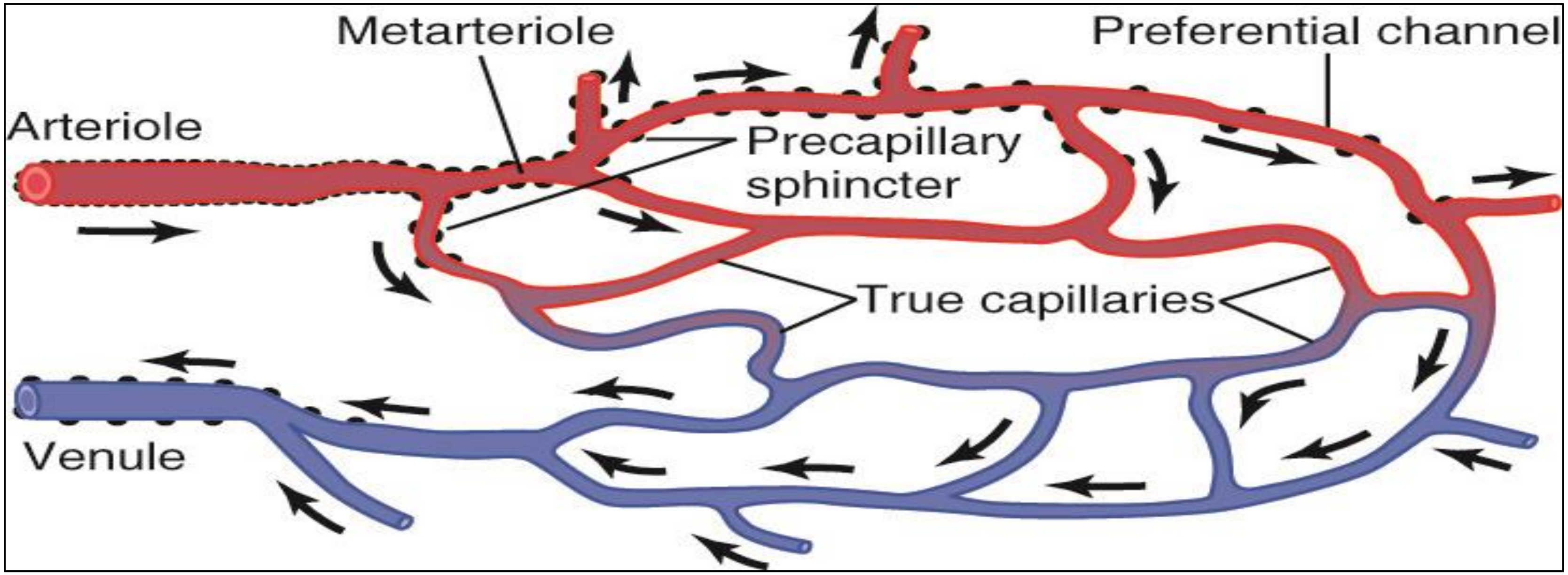


Figure 16-1;
Structure of the mesenteric capillary bed. (Redrawn from Zweifach BW: Factors Regulating Blood Pressure. New York: Josiah Macy, Jr., Foundation, 1950.)

The Microcirculation

- The arterioles are highly muscular. The metarterioles (the terminal arterioles) do not have a continuous muscular coat, but smooth muscle fibers encircle the vessel at intermittent points (black dots).
- At the point where each true capillary originates from a metarteriole, a smooth muscle fiber usually encircles the capillary. This is called the precapillary sphincter. This sphincter can open and close the entrance to the capillary.
- The venules are larger than the arterioles and have a much weaker muscular coat and remember that the pressure in the venules is much less than that in the arterioles

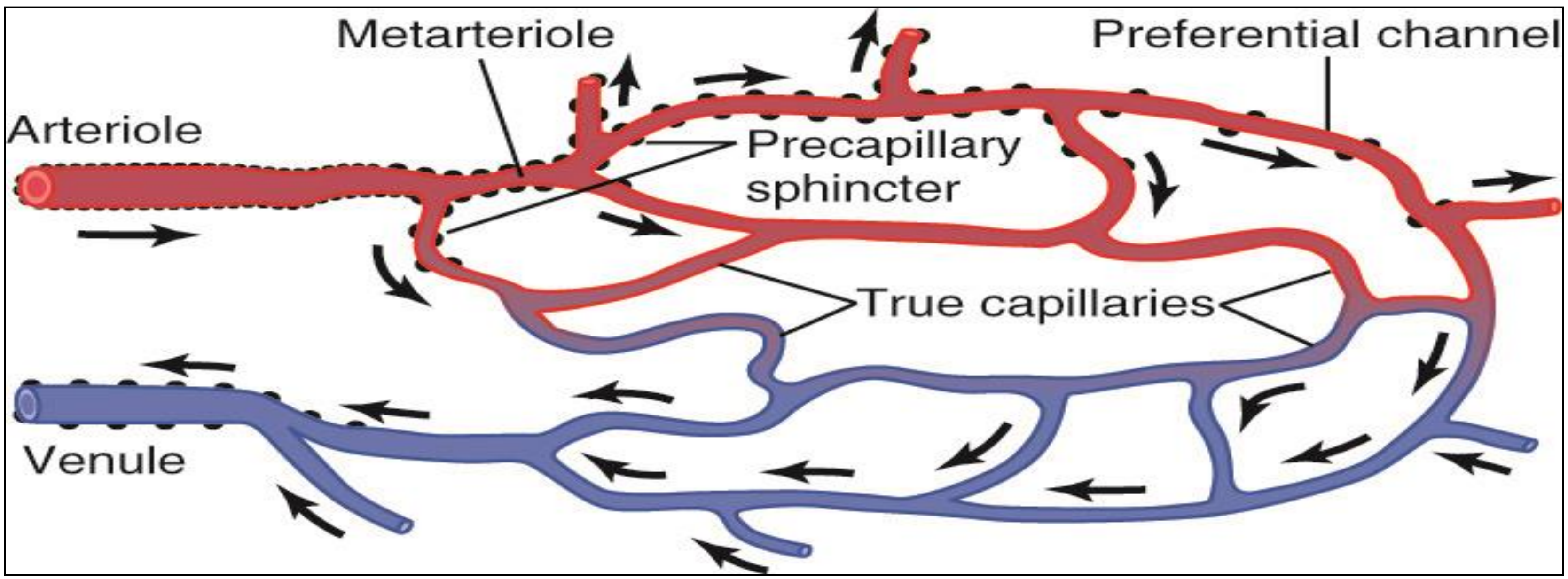
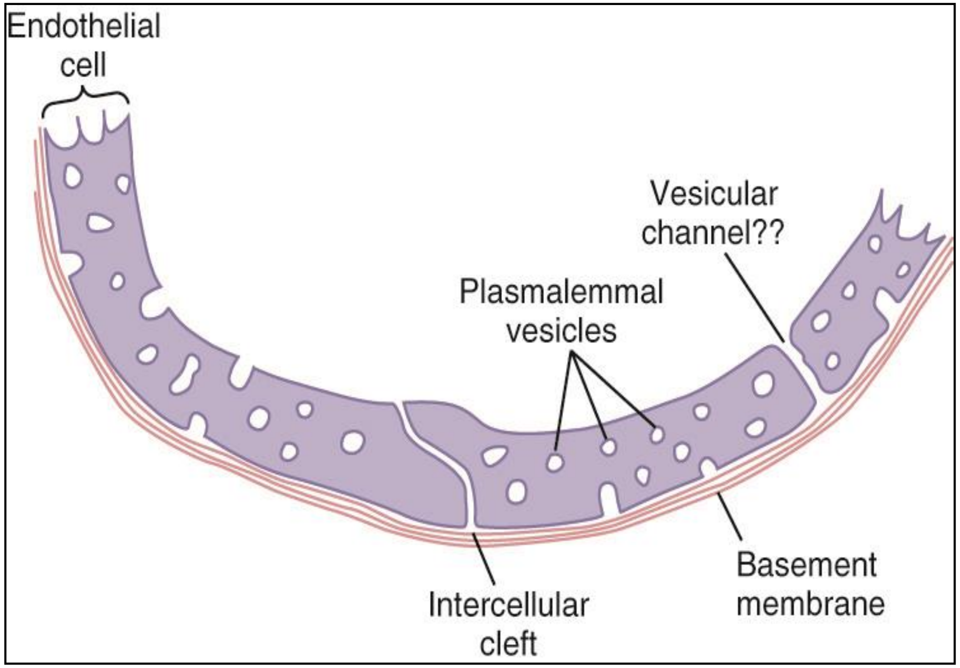


Figure 16-1;
Structure of the mesenteric capillary bed. (Redrawn from Zweifach BW: Factors Regulating Blood Pressure. New York: Josiah Macy, Jr., Foundation, 1950.)

Structure of Capillary Wall

- Composed of unicellular layer of endothelial cells surrounded by a basement membrane.
- Diameter of capillaries is 4 to 9 microns.
- Solute and water move across capillary wall via *intercellular cleft* (space between cells) or by *plasmalemma vesicles*.



Structure of the capillary wall. Note especially the intercellular cleft at the junction between adjacent endothelial cells; it is believed that most water-soluble substances diffuse through the capillary membrane along the clefts.

▪ Effect of Molecular Size on Passage Through Capillary Pores

- The *width of capillary intercellular slit* pores is 6 to 7 nanometers.
- The *permeability* of the capillary pores for different substances varies according to their *molecular diameters*.
- The capillaries in different tissues have *extreme differences* in their permeabilities.

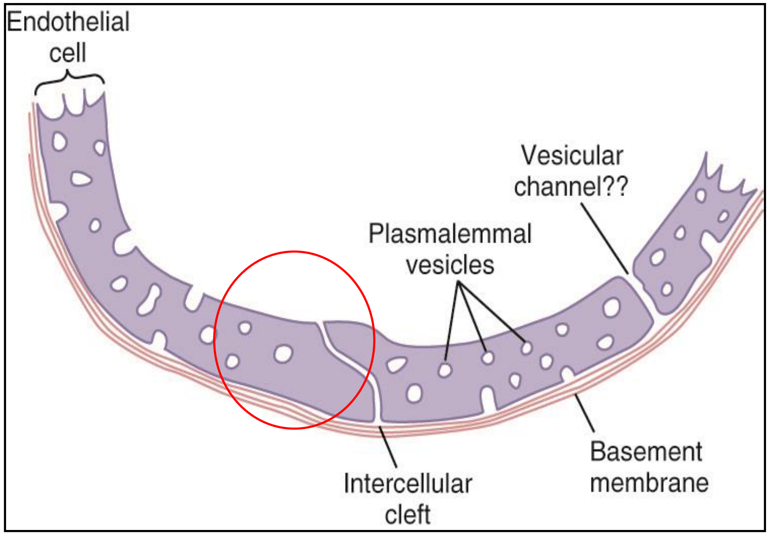


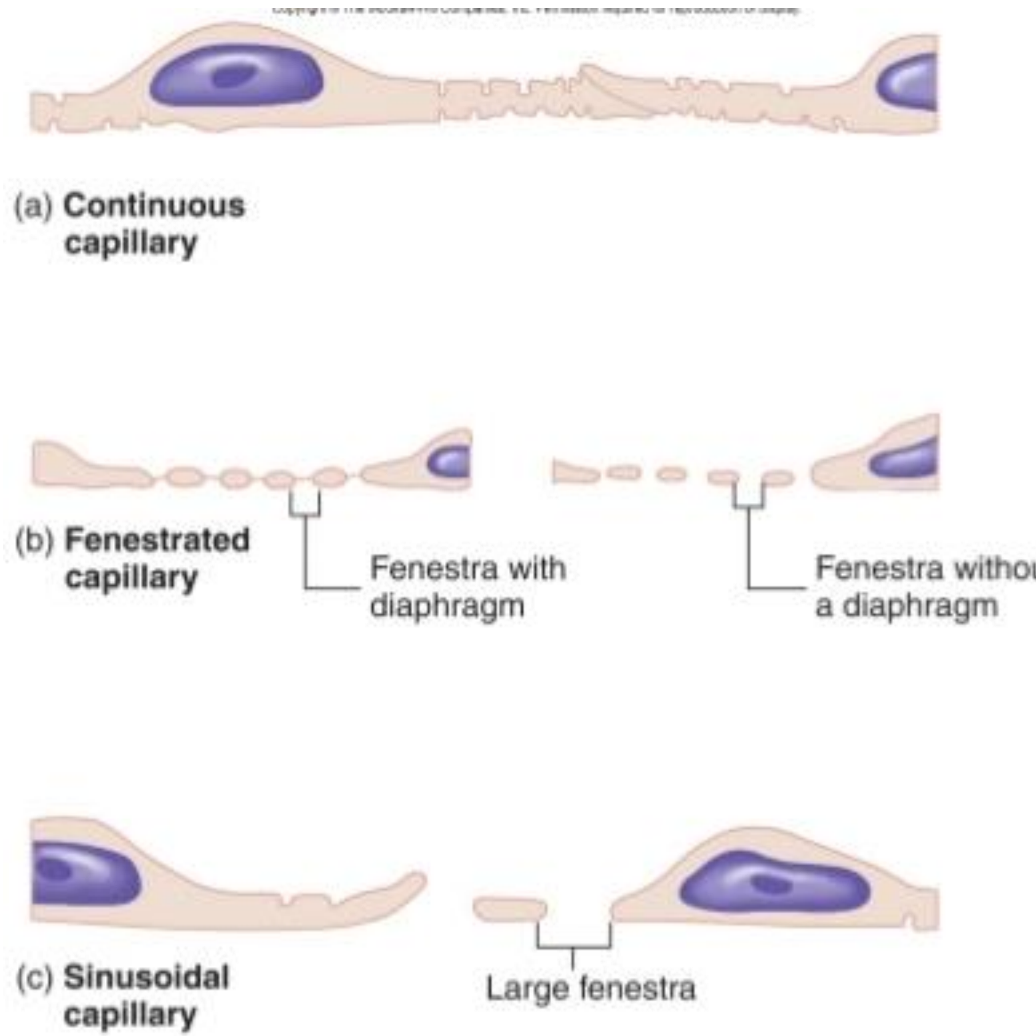
Figure 16-2; Guyton and Hall

Types of Capillaries

- **Continuous.** No gaps between endothelial cells. No fenestrae. Less permeable to large molecules than other capillary types. E.g., muscle, nervous tissue.

- **Fenestrated.** Fenestrae are areas where cytoplasm is absent and plasma membrane is made of a thin, porous diaphragm. Endothelial cells have numerous fenestrae. Highly permeable. E.g., intestinal villi, ciliary process of eye, choroid plexus, glomeruli of kidney

- **Sinusoidal.** Large diameter with large fenestrae. Less basement membrane. E.g., endocrine glands (large molecules cross their walls).



Interstitium and Interstitial Fluid

- About one sixth of the total volume of the body consists of spaces between cells, which collectively are called the *interstitium*. The fluid in these spaces is the *interstitial fluid*.

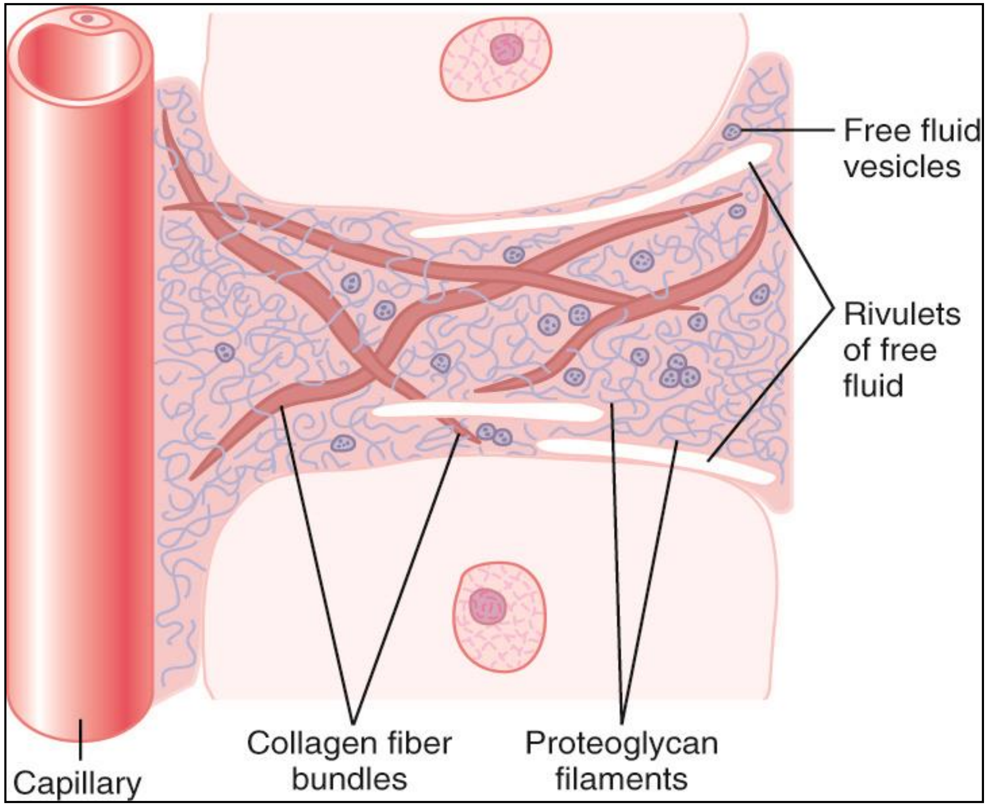


Figure 16-4; Structure of the interstitium. Proteoglycan filaments are every where in the spaces between the collagen fiber bundles. Free fluid vesicles and small amounts of free fluid in the form of rivulets occasionally also occur.

- **two major types of solid structures: (1) collagen fiber bundles and (2) proteoglycan filaments.**
- The collagen fiber bundles extend long distances in the interstitium. They are extremely strong and therefore provide most of the tensional strength of the tissues.
- The proteoglycan filaments form a mat of very fine reticular filaments aptly described as a "brush pile."

Determinants of Net Fluid Movement across Capillaries

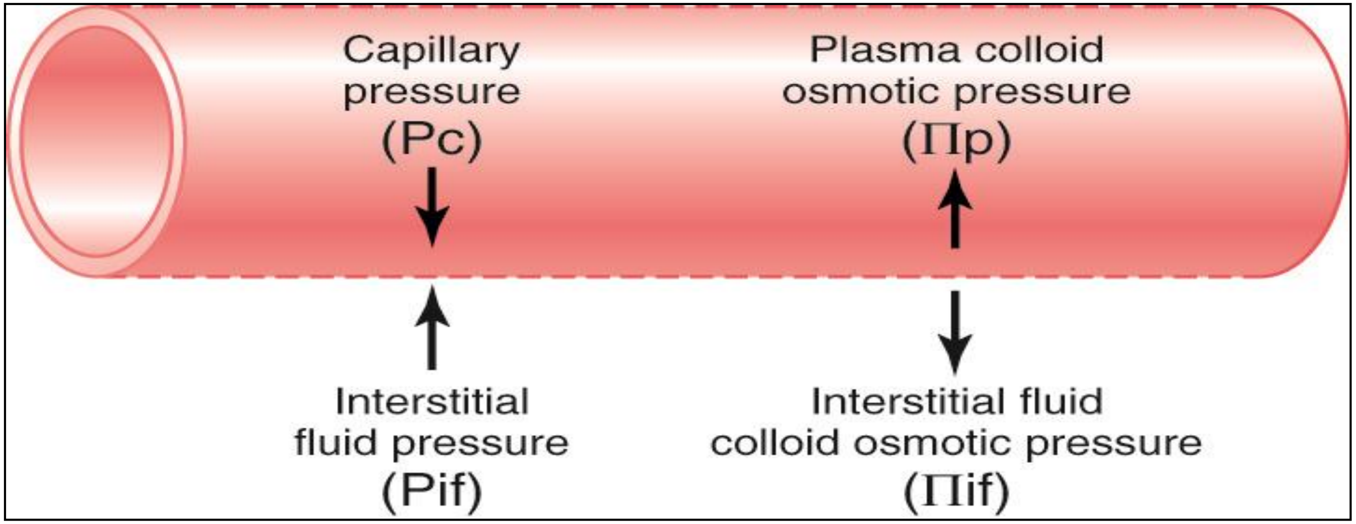


Figure 16-5; Fluid pressure and colloid osmotic pressure forces operate at the capillary membrane, tending to move fluid either outward or inward through the membrane pores.

- *Capillary hydrostatic pressure* (Pc)-tends to force fluid outward through the capillary membrane.
- *Interstitial fluid pressure* (Pif)- opposes filtration when value is positive.

Determinants of Net Fluid Movement across Capillaries- (cont.)

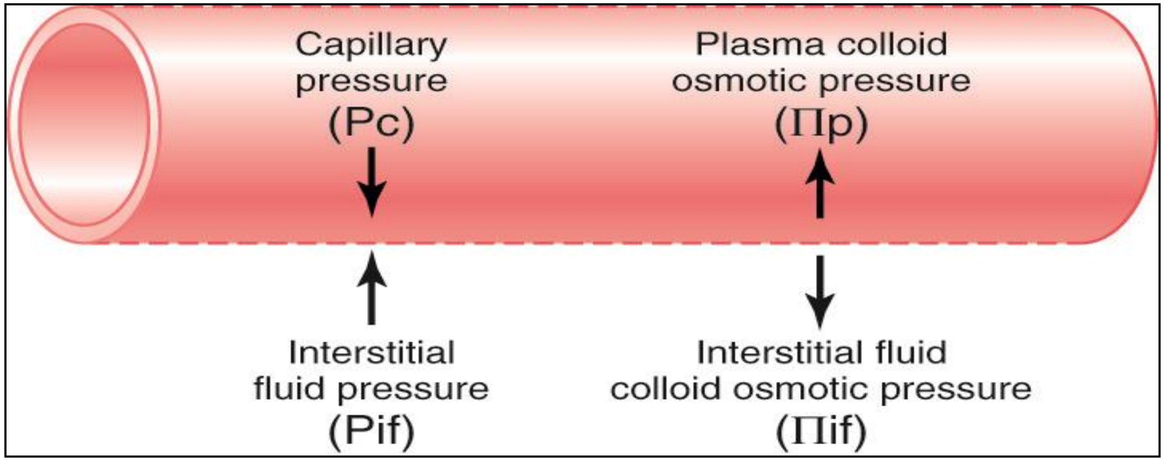


Figure 16-5; Guyton and Hall

- *Plasma colloid osmotic pressure by the plasma proteins* (π p)- opposes filtration causing osmosis of water inward through the membrane
- *Interstitial fluid colloid osmotic pressure* (π if) promotes filtration of fluid outward through the membrane

If the sum of these forces, the net filtration pressure, is positive, there will be a net fluid filtration across the capillaries. If the sum of the Starling forces is negative, there will be a net fluid absorption from the interstitial spaces into the capillaries.

- Forces Causing Filtration <u>at the Arterial End of the Capillary</u>

	mm Hg
Forces tending to move fluid outward:	
Capillary pressure (arterial end of capillary)	30
Negative interstitial free fluid pressure	3
Interstitial fluid colloid osmotic pressure	8
TOTAL OUTWARD FORCE	41
Forces tending to move fluid inward:	
Plasma colloid osmotic pressure	28
TOTAL INWARD FORCE	28
Summation of forces:	
Outward	41
Inward	28
NET OUTWARD FORCE (AT ARTERIAL END)	13

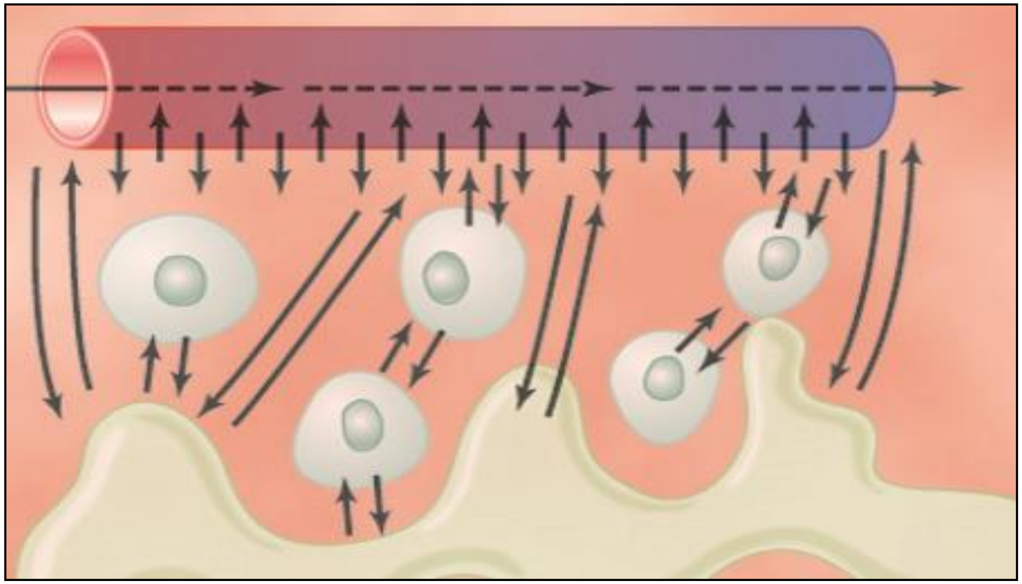
▪ Forces Causing Reabsorption at the Venous End of the Capillary

	mm Hg
Forces tending to move fluid inward:	
Plasma colloid osmotic pressure	28
TOTAL INWARD FORCE	28
Forces tending to move fluid outward:	
Capillary pressure (venous end of capillary)	10
Negative interstitial free fluid pressure	3
Interstitial fluid colloid osmotic pressure	8
TOTAL OUTWARD FORCE	21
Summation of forces:	
Inward	28
Outward	21
NET INWARD FORCE	7

Net Starling Forces in Capillaries

	mm Hg
Mean forces tending to move fluid outward:	
Mean capillary pressure	17.3
Negative interstitial free fluid pressure	3.0
Interstitial fluid colloid osmotic pressure	8.0
TOTAL OUTWARD FORCE	28.3
Mean force tending to move fluid inward:	
Plasma colloid osmotic pressure	28.0
TOTAL INWARD FORCE	28.0
Summation of mean forces:	
Outward	28.3
Inward	28.0
NET OUTWARD FORCE	0.3

- Net Starling Forces in Capillaries



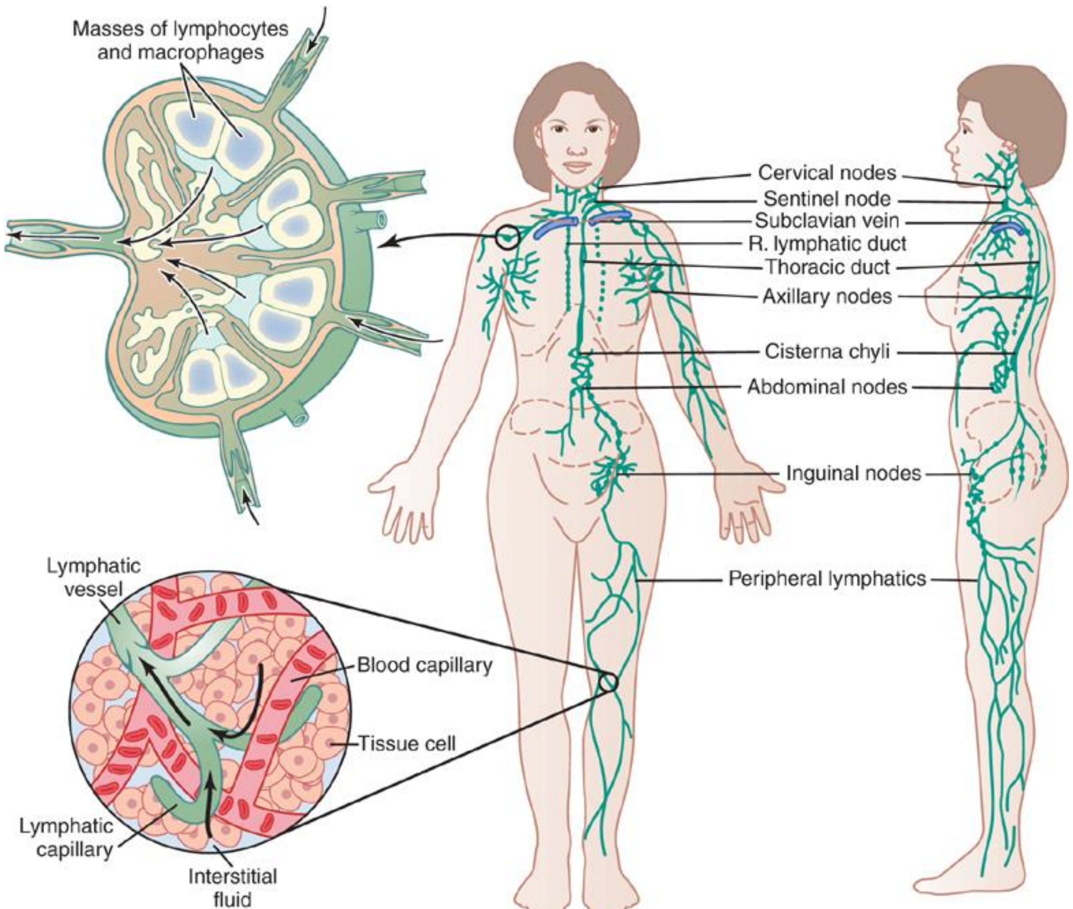
Watch video #15

Figure 16–3 Diffusion of fluid molecules and dissolved substances between the capillary and interstitial fluid spaces.

- *Net filtration pressure* of .3 mmHg which causes a net filtration rate of 2ml/min for entire body.

Lymphatic System

- The lymphatic system represents an accessory route through which fluid can flow from the interstitial spaces into the blood. Most important, the lymphatics can carry proteins and large particulate matter away from the tissue spaces, neither of which can be removed by absorption directly into the blood capillaries.



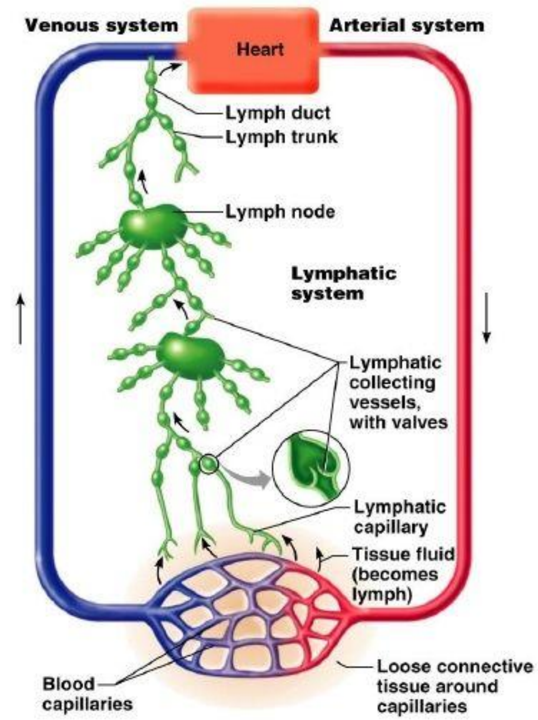


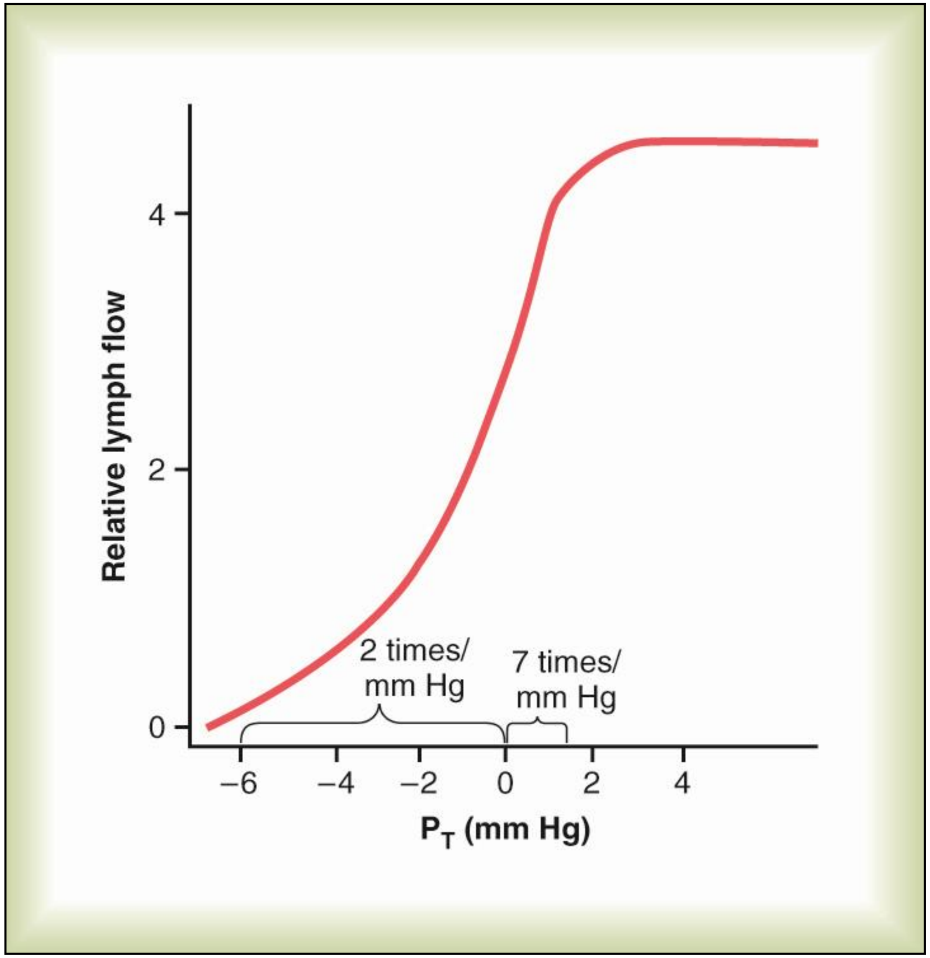
FIGURE 16–8
Lymphatic system.

FUNCTIONS OF THE LYMPHATIC SYSTEM:

1. It carries excess of interstitial fluid from interstitium into the blood. Rate of lymph flow is more than 3 liters/day. So this amount is drained by lymphatic system.
2. It drains proteins and electrolytes from Interstitial space into lymphatic system. Lymphatic system drain 195 grams of blood proteins from interstitium back into the blood.
3. It provides lymphocytes and antibodies into the circulation
4. Removes bacteria and other microorganisms from the tissues.
5. Lacteals (lymphatic vessels of the small intestine) are involved in the absorption and transport of lipids.
6. Many large enzymes which are produced in the tissues get entry into the circulation through lymphatic system like histaminases and lipase.
7. It maintains the negative interstitial fluid hydrostatic pressure.

Determinants of Lymph Flow

↑ Interstitial fluid hydrostatic pressure → ↑ Lymph Flow



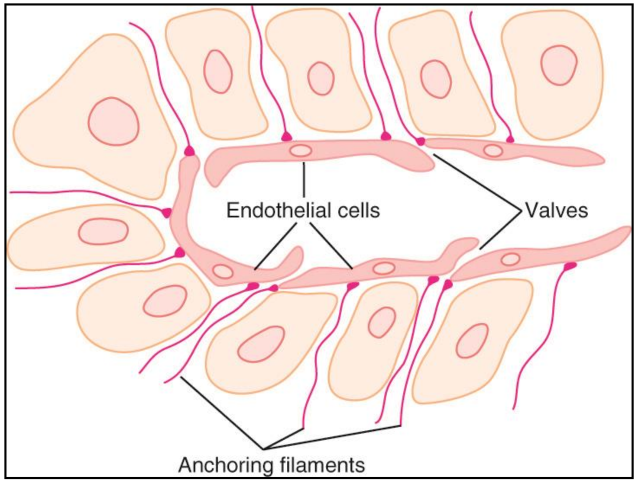


Figure 16-9; Special structure of the lymphatic capillaries that permits passage of substances of high molecular weight into the lymph.

Figure 16-10; Relation between interstitial fluid pressure and lymph flow in the leg of a dog. Note that lymph flow reaches a maximum when the interstitial pressure, P_T, rises slightly above atmospheric pressure (0 mm Hg). (Courtesy Drs. Harry Gibson and Aubrey Taylor.)