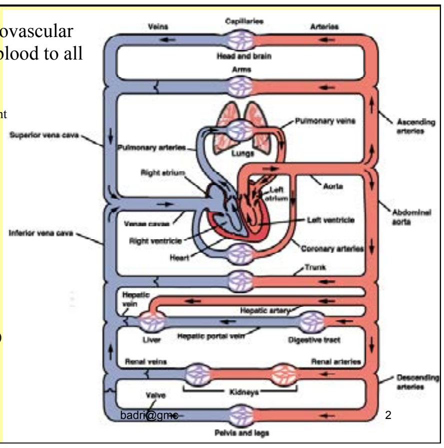
The Cardiovascular System: Blood Vessels and Hemodynamics

Dr Badri Paudel
GMC

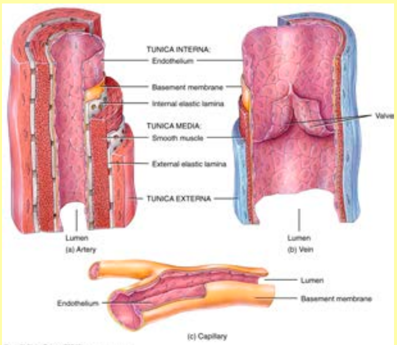
Goal of the Cardiovascular System: deliver blood to all parts of the body

- Does so by using different types of tubing, attached to a pulsatile pump
  - Elastic arteries
  - Muscular arteries
  - Arterioles
  - Capillaries
  - Venuoles
  - Veins
- Distribution system broken up into areas called vascular beds
  - Skin
  - Digestive (splanchnic)
  - Muscle



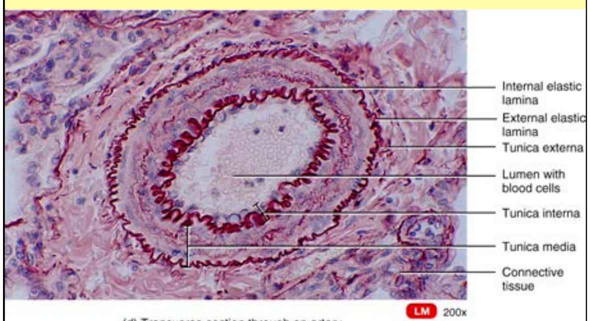
Structure

- **Tunica interna (intima)**
  - Inner lining in direct contact with blood
  - Endothelium continuous with endocardial lining of heart
  - It consists of an inner endothelium (simple squamous epithelium) and a basement membrane.
  - Active role in vessel-related activities
- **Tunica media**
  - Muscular and elastic connective tissue layer
  - Greatest variation among vessel types
  - Smooth muscle regulates diameter of lumen
- **Tunica externa**
  - Elastic and collagen fibers
  - Vasa vasorum: network of small blood vessel that supply large blood vessel.
  - Helps anchor vessel to surrounding tissue
  - forms a protective layer



Arteries

- 3 layers of typical blood vessel
- Thick muscular-to-elastic tunica media
- High compliance – walls stretch and expand in response to pressure without tearing
- The functional properties of arteries are *elasticity* and *contractility*
  1. ***Elasticity***, due to the elastic tissue in the tunica internal and media, allows arteries to accept blood under great pressure from the contraction of the ventricles and to send it on through the system.
  2. ***Contractility***, due to the smooth muscle in the tunica media, allows arteries to increase or decrease lumen
- **Vasoconstriction** – decrease in lumen diameter
- **Vasodilation** – increase in lumen diameter



(d) Transverse section through an artery

1. Elastic Arteries-Windkessel Vessel

- Largest arteries
- Largest diameter but walls relatively thin
- Function **as pressure reservoir**
- Help propel blood forward while ventricles relaxing
- Also known as **conducting arteries** – conduct blood to medium-sized arteries

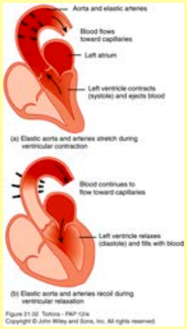
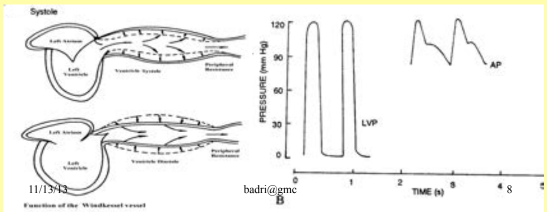
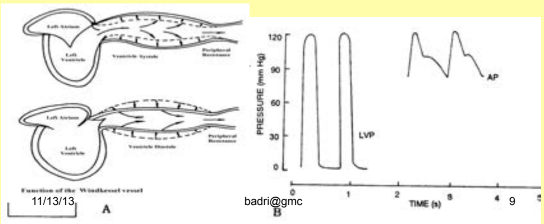


Figure 21.02 Tortora - PAP 12/e

- Contain a large amount of **elastic tissue** besides the smooth muscle.
- Transiently store blood during systole, and then shrink to produce onward blood flow during diastole.



- Convert the **sharp** pressure fluctuations in the left ventricle (0 to 120 mmHg) into much **smaller** pressure fluctuations in the arteries (80 to 120 mmHg).
- Convert the intermittent ventricular ejection into continuous blood blood in the vessels
- This function of large arteries is known as Windkessel effect.



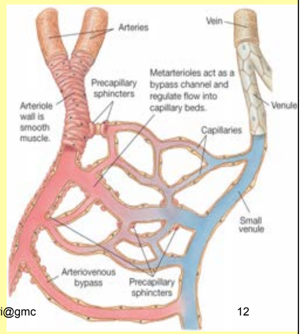
2. Arteries- Distribution vessel

- Muscular arteries
  - Tunica media contains more smooth muscle and fewer elastic fibers than elastic arteries
  - Walls relatively thick
  - Capable of great vasoconstriction/ vasodilatation to adjust rate of blood flow
  - Also called **distributing arteries**
- Anastomoses
  - Union of the branches of 2 or more arteries supplying the same body region
  - Provide alternate routes – collateral circulation

3. Arterioles-Precapillary Resistance Vessels

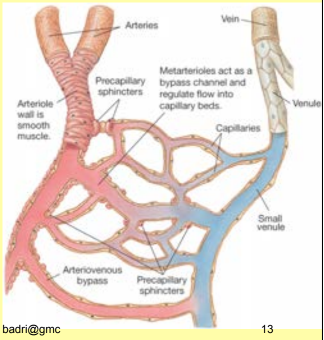
- Abundant microscopic vessels
- **Metarteriole has precapillary sphincter** which monitors blood flow into capillary
- Sympathetic innervation and local chemical mediators can alter diameter and thus blood flow and resistance
- **Resistance vessels** – resistance is opposition to blood flow
- Vasoconstriction can raise blood pressure

- Less elastic than the larger arteries
- Have a thicker layer of smooth muscle.
- Provide the greatest resistance to blood flow through the arterial system
  - since they have narrow lumina.



4. Precapillary Sphincter muscle-

- Partially determines the amount of blood flowing through a particular capillary bed
- Allow only 5% - 10% of the capillary bed in skeletal muscles, for example, to be open at rest.

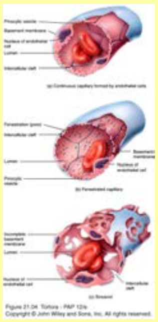


5. Capillaries-Exchange Vessel

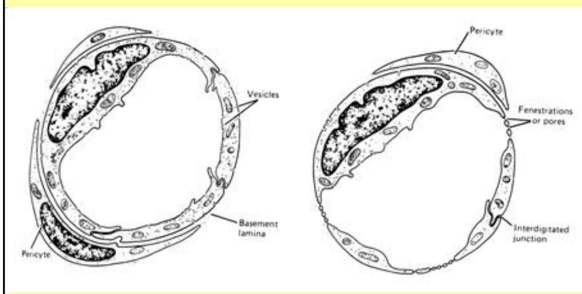
- Capillaries
  - Smallest blood vessels connect arterial outflow and venous return
  - **Microcirculation** – flow from metarteriole through capillaries and into postcapillary venule
  - **Exchange vessels** – primary function is exchange between blood and interstitial fluid
  - **Lack tunica media and tunica externa**
    - Substances pass through just one layer of endothelial cells and basement membrane
  - Capillary beds – arise from single metarteriole
    - Vasomotion – intermittent contraction and relaxation
    - Thoroughfare channel – bypasses capillary bed

Types of Capillaries

- 3 types
1. **Continuous**
   - Endothelial cell membranes form continuous tube
2. **Fenestrated**
   - Have fenestrations or pores
3. **Sinusoids**
   - Wider and more winding
   - Unusually large fenestrations



"pores" in the capillary membrane



A B

A. Continuous Capillaries B. Fenestrated Capillary

Capillary exchange

- Movement of substances between blood and interstitial fluid
- 3 basic methods
  1. **Diffusion**
  2. **Transcytosis**
  3. **Bulk flow**

Diffusion

- Most important method
- **Substances move down their concentration gradient**
  - O_2 and nutrients from blood to interstitial fluid to body cells
  - CO_2 and wastes move from body cells to interstitial fluid to blood
- Can cross capillary wall **through intracellular clefts, fenestrations or through endothelial cells**
  - **Most plasma proteins cannot cross**
  - **Except in sinusoids** – proteins and even blood cells leave
  - **Blood-brain barrier** – tight junctions limit diffusion

Transcytosis

- Small quantity of material
- Substances in blood plasma become enclosed within **pinocytotic vesicles** that enter endothelial cells by endocytosis and leave by exocytosis
- Important mainly for **large, lipid-insoluble** molecules that cannot cross capillary walls any other way

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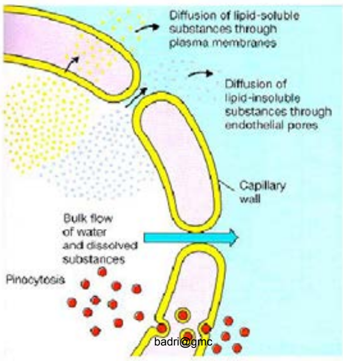
Capillaries



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Bulk Flow

- Passive process in which large numbers of ions, molecules, or particles in a fluid move together in the same direction
- Based on pressure gradient
- **Diffusion** is more important for solute exchange
- **Bulk flow** more important for regulation of relative volumes of blood and interstitial fluid
- **Filtration** – from capillaries into interstitial fluid
- **Reabsorption** – from interstitial fluid into capillaries

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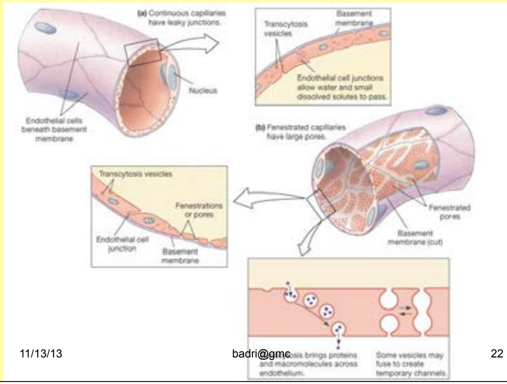
Make Up of Blood Vessels: Capillaries



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6. Venules

- Thinner walls than arterial counterparts
- Postcapillary venule – smallest venule
- Form part of microcirculatory exchange unit with capillaries
- Muscular venules have thicker walls with 1 or 2 layers of smooth muscle

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7. Veins

- Structural changes not as distinct as in arteries
- In general, very thin walls in relation to total diameter
- Same 3 layers
  - Tunica interna thinner than arteries
  - Tunica interna thinner with little smooth muscle
  - Tunica externa thickest layer
- Not designed to withstand high pressure
- **Valves** – folds on tunica interna forming cusps
  - Aid in venous return by preventing back flow

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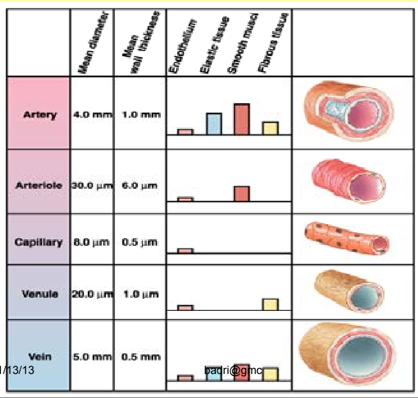
8. Capacitance Vessel – Systemic veins

- Have a large diameter but a thin wall, which includes a thin muscle coat.
- The number is about twice as much as the number of arteries,
  - The large number and cross sectional area gives them an enormous capacity to hold blood.

Capacitance Vessel – Systemic veins

- Most of the time, veins hold more than half the blood volume .
  - are known as capacitance vessels.
- the great distensibility of veins makes their capacity adjustable.
- In times of need, a considerable amount of blood can be squeezed from the veins to areas where it may be needed.

Structure of vasculature changes in response to different needs



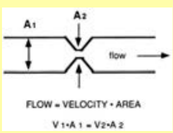
Blood Flow (Q)

- Concept: The quantity of blood that passes a given point in the circulation in a given period of time.
- The overall blood flow in the systemic circulation is identical to the cardiac output

Dynamic Fluid Mechanics

- Blood flowing through circulation follows physical principles of pressure, flow
- Under conditions of constant flow, velocity must increase to allow the same flow through a smaller space

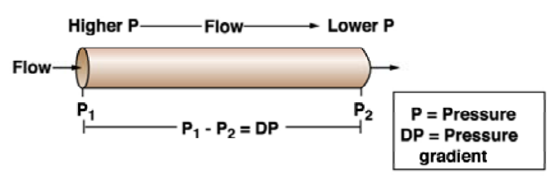
i.e. the continuity equation



How does the flow differ in these two vessels?

Why does blood flow through this closed circuit?

- Blood flows down a pressure gradient
- The absolute value of the pressure is not important to flow, but the difference in pressure (DP or gradient) is important to determining flow.



What happens to pressure if we decrease the volume of a fluid filled compartment (i.e. ventricles during systole)?

P directly proportional to Flow

The resulting pressure is called the *driving pressure* in the vascular system

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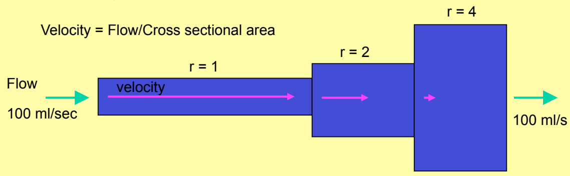
Difference Between Flow and Velocity

Flow is a measure of volume per unit time

Velocity is a measure of distance per second along the axis of movement

Velocity = Flow/Cross sectional area



radius (cm)	1	2	4
area (cm^2) (πr^2)	3.14	12.56	50.24
flow (cm^3/sec)	100	100	100
fluid velocity (cm/sec)	32	8	2

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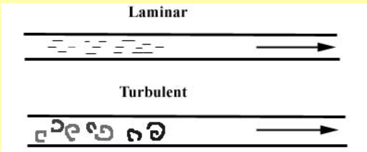
Note: This assumes constant flow and ignores resistance

Types of Blood Flow

- Laminar: When velocity of blood flow is below a critical speed, the flow is orderly and streamlined

  (This is the usual pattern of flow in the vascular system.)

- Turbulent: disorderly flow with eddies & vortices



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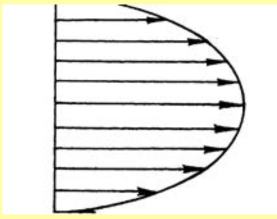
➢ Laminar flow – blood flows in streamlines with each layer of blood remaining the same distance from the wall



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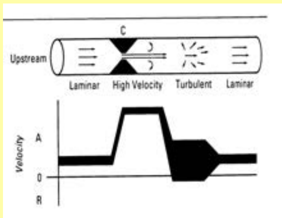
➢ Turbulent flow – blood flow in all directions in the vessel and continually mixes within the vessel.

➢ because of

- ➢ the velocity of blood flow is too great,
- ➢ is passing by an obstruction,
- ➢ making a sharp turn,
- ➢ passing over a rough surface)



C, constriction;

A, anterograde;

R, retrograde

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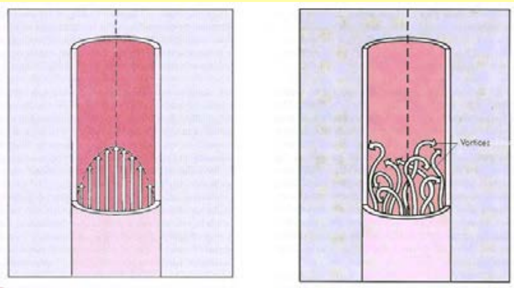
Laminar vs Turbulent Flow



■ Fig. 26-13 In laminar flow all elements of the fluid move in streamlines that are parallel to the axis of the tube; movement does not occur in a radial or circumferential direction. The layer of fluid in contact with the wall is motionless; the fluid that moves along the axis of the tube has the maximal velocity.

■ Fig. 26-14 In turbulent flow the elements of the fluid move irregularly in axial, radial, and circumferential directions. Vortices frequently develop.

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Berne and Levy, Physiology 3rd Ed. p. 447

- Turbulent flow is noisy
- In the vascular system high flow velocities cause turbulent flow and produce sound
- The murmur heard when blood flows through a narrowed heart valve is due to turbulent flow
- To determine whether flow is laminar or turbulent, calculate the Reynolds Number (R) (dimensionless no.)

  R = Velocity * Diameter * Density / Viscosity

  $$R = \frac{\rho V D}{\mu}$$

- Values below 2000 define laminar flow

Bernoulli Equation

- When blood flows through an artery, the total energy of the fluid at any point is assumed to be constant
- i.e. The sum of energy stored in pressure, energy provided by flow and potential energy due to the height of the blood above a reference point is constant

  Energy = [V2/2g] + [P/r] + H = Constant

- In an arterial stenosis, the increase in velocity causes a fall in pressure in the stenosis

Resistance

Pressure = Flow x Resistance

Poiseulle equation:

$$Q = \frac{\Delta p \pi R^4}{8 \mu L}$$

Pressure drop across a length of vessel (Δp); Radius (R); Flow (Q); Length of Vessel (L)

- For a given pressure, there is greater flow when the blood vessel is short
- Since BP is constant most of the time, flow is controlled by small changes in r--the vessel radius
- This is most effective in the arterioles
- Resistance is measured in Wood units
- Pulmonary resistance = (PA pressure - LA pressure) / CO

  e.g. R = (14 mm Hg - 7 mm Hg) / 5 l/min (Pulmonary Artery)

  = 1.4 Wood units

Resistance of Blood Flow

- From Q = ΔP / R (1)
  - we get R = ΔP / Q (2)
- According to Poiseuille's law, Q = πΔP r4/8ηl (3)
- From (3) and (2), we get R = 8 ηl/ π r4 π is constant
- Note that the resistance (R) of a vessel is directly proportional to the blood viscosity (η) and length (l) of the vessel,
  - but inversely proportional to the **fourth power** of the radius (r).
- Normally, L and η have no change or almost no change.
  - Therefore, the diameter of a blood vessel plays by far the greatest role of all factors in determining the resistance (R) of blood flow.

Relationship Between Pressure, Flow and Resistance

Change in Pressure = Flow x Resistance ΔP = QR

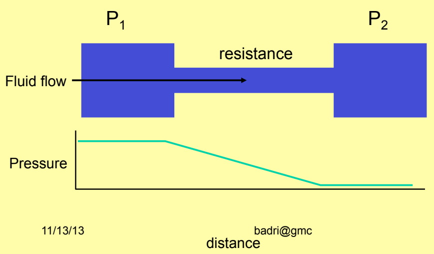
$$\text{Flow} = \frac{\text{Change in Pressure}}{\text{Resistance}} \qquad Q = \frac{\Delta P}{R}$$

Similar to Ohm's Law for electricity $I = \frac{\Delta V}{R}$ or V = IR

Resistance to Fluid Flow

Resistance is important in the Circulatory System.

As fluid passes through a resistance pressure drops.
A resistance dissipates energy, so as the fluid works its way through the resistance it must give up energy. It gives up potential energy in the form of a drop in pressure.



$P_1 > P_2$

$\Delta P = QR$

Origin of Resistance in Laminar Flow

resistance arises due to
1) interactions between the moving fluid and the stationary tube wal
2) interactions between molecules in the fluid (viscosity)

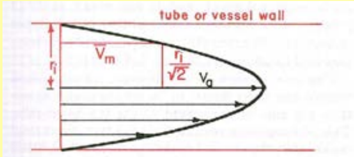
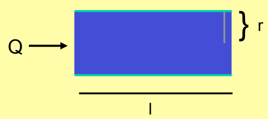


Figure 2.21. Parabolic flow velocity profile plot. The plot represents calculation of flow velocity (V) at various radial distances (r) from the center of the tube to the wall (where flow is assumed to be stationary, V = 0). Flow is fastest in the central axial stream (V_a) and decreases to 0 at the wall. At a distance $r/\sqrt{2}$ from the center of the tube, the flow velocity is half that along the central axis and equals the mean flow velocity (V_m) along the tube. The arrows indicate relative flow velocities at various radial distances (r) from the central axis.

West, Physiological Basis of Medical Practice 11th Ed. p. 133

Determinants of Resistance in Laminar Flow – Poiseuille's Law



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

length
viscosity
radius

$$Q = \frac{\Delta P}{R} = \frac{\pi r^4}{8 \eta l} (\Delta P)$$

π = 3.14159 as always
l = tube length
η= fluid viscosity
r = tube radius

Blood Vessel Diameter and Blood Velocity

Table 2.1
Vessel diameter, blood velocity, and Reynolds number for the systemic circulation of man

Structure	Diameter, cm	Blood Velocity, cm/s	[redacted]
Ascending aorta	2.0–3.2	63[b]	[redacted]
Descending aorta	1.6–2.0	27[b]	
Large arteries	0.2–0.6	20–50[b]	
Capillaries	0.0005–0.001	0.05–0.1[c]	
Large veins	0.5–1.0	15–20[c]	
Venae cavae	2.0	11–16[c]	

From Whitmore (1968). [a] Assuming viscosity of blood is 0.035 poise. [b] Mean peak value. [c] Mean velocity over indefinite period of time.

West, Physiological Basis of Medical Practice 11th Ed. p. 120

What Can the Body Regulate to Alter Blood Flow and Specific Tissue Perfusion?

$$Q = \frac{\Delta P}{R} = \frac{\pi r^4}{8 \eta l} (\Delta P)$$

ΔP = Mean Arterial Pressure – Mean Venous Pressure

ΔP, not subject to significant short term regulation

R = Resistance $R = \frac{8 \eta l}{\pi r^4}$

8, η, l, π are not subject to significant regulation by body
r^4 can be regulated especially in arterioles, resistance vessels

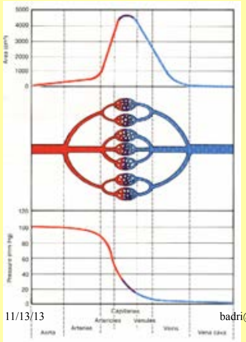
Physiological Basis of Exertional Angina: Why Atherosclerotic Narrowing of Coronary Arteries Reduces Blood Flow: Implications of Poiseuille's Law

$$Q = \frac{\Delta P}{R} = \frac{\pi r^4}{8 \eta l} (\Delta P) = \left(\frac{\pi (\Delta P)}{8 \eta l}\right) r^4$$

If ΔP is constant, flow is very sensitive to tube radius

r	% decrease in radius (1 - r/10)*100	r^4	% decrease in flow [1 - (Q/$Q_{r=10}$)]*100
10	0%	10,000	0%
9	10%	6,561	35%
5	50%	625	94%
1	90%	1	99.99%

Physical Characteristics of the Systemic Circulation



- (1)The velocity of blood flow in each segment of the circulation is inversely proportional to its cross-sectional area.

Physical Characteristics of the Systemic Circulation

- (2) Pressure and resistance in the various portion of the systemic circulations.
  - The decrease in pressure in each part of the systemic circulation is directly proportional to the vascular resistance.

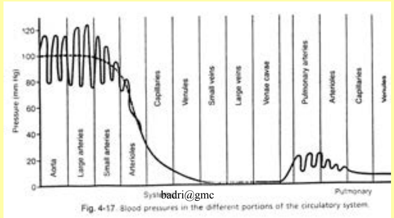


Fig. 4-17. Blood pressures in the different portions of the circulatory system.

Formation of the blood pressure:

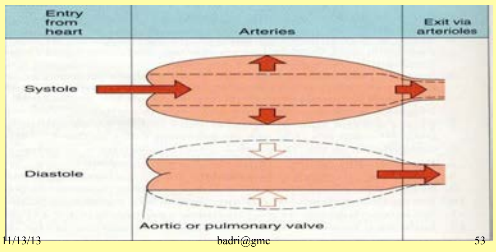
- (1) Mean circulatory filing pressure (MCFP):
  - when heart beat is stopped, the pressure in any point of cardiovascular system is equal. This pressure is called MCFP
  - systemic circulation, 7 mmHg;
  - pulmonary circulation, 10 mmHg.
- (2) Total peripheral resistance.

Formation of the blood pressure:

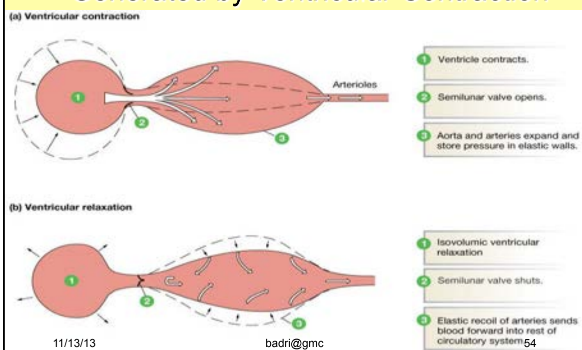
- (3) Cardiac pumping
  - Energy released from heart contraction is transferred into parts,
    - 1) kinetic energy (1% of the total),
    - 2) potential energy (pressure) (99% of the total).
  - That means most part of energy used to create the blood pressure

Formation of the blood pressure:

- **(4) Elasticity of Windkessel vessel**
  - **① diastolic blood pressure**
  - **② continuous blood flow in diastole**
  - **③ buffering blood pressure**



Blood Pressure: Generated by Ventricular Contraction

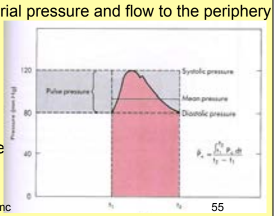


Converting Intermittent Pumping to Continuous Flow

The heart is the pump that keeps the fluid circulating.
The heart is a pulsatile, intermittent pump.
During each pump cycle blood flows out of the heart for only 1/3 of the time.
THE PROBLEM: To maintain continuous flow during diastole.

THE SOLUTION: Large elastic arteries
- distend during systole to absorb ejected volume pulse
- relax during diastole maintaining arterial pressure and flow to the periphery

volume ejected
↓
large elastic arteries distend
↓
aortic valve closes
↓
blood flows into periphery under pressure created by elastic recoil of arteries while the heart fills during diastole



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Berne and Levy, Physiology 3rd Ed. p. 457

Hemodynamics: Factors affecting blood flow

- Blood flow – volume of blood that flows through any tissue in a given period of time (in mL/min)
- Total blood flow is cardiac output (CO)
  - Volume of blood that circulates through systemic (or pulmonary) blood vessels each minute
- CO = heart rate (HR) x stroke volume (SV)
- Distribution of CO depends on
  - Pressure differences that drive blood through tissue
    - Flows from higher to lower pressure
  - Resistance to blood flow in specific blood vessels
    - Higher resistance means smaller blood flow

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Cardiac Output

- Flow of blood is usually measured in l/min
- Total amount of blood flowing through the circulation = *Cardiac Output (CO)*

Cardiac Ouput = Stroke Vol. x *Heart Rate*

= 5 l/min

Influenced by **Blood Pressure** & Resistance

Force of blood against vessel wall
↑ with water retention
↓ with dehydration, hemorrhage

•Blood viscosity
•Vessel Length
•Vessel Elasticity
•Vasconstriction / Vasodilation

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Vascular resistance

– Opposition to blood flow due to friction between blood and walls of blood vessels
– Depends on
  1. **Size of lumen** – vasoconstriction males lumen smaller meaning greater resistance
  2. **Blood viscosity** – ratio of RBCs to plasma and protein concentration, higher viscosity means higher resistance
  3. **Total blood vessel length** – resistance directly proportional to length of vessel

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Determinants of Vascular Resistance

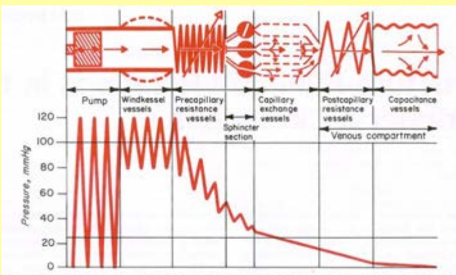

Figure 2.9. Functionally differentiated segments of the vascular bed. [From Mellander and Johansson (1968).]

Arterial blood pressure – systole vs diastole
Perfusion pressure largely determined by arterial blood pressure
Major site of pressure drop is in arterioles

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West, Physiological Basis of Medical Practice 11th Ed. p. 120

Velocity of blood flow

– Speed in cm/sec in inversely related to **cross-sectional** area
– Velocity is slowest where total cross sectional area is greatest
– Blood flow becomes slower farther from the heart
– **Slowest in capillaries**
– **Aids in exchange**
– Circulation time – time required for a drop of blood to pass from right atrium, through pulmonary and systemic circulation and back to right atrium
  - Normally 1 minute at rest

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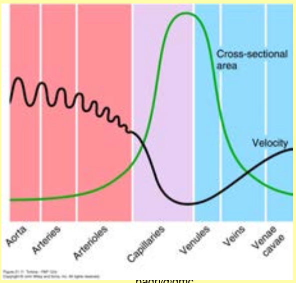
Relationship between Velocity of Blood Flow and Total Cross-sectioned area in Different Types of Blood Vessels



A doctor taking the pulse of a skeleton sitting on an examination table.