Physics Applicable to Circulatory System

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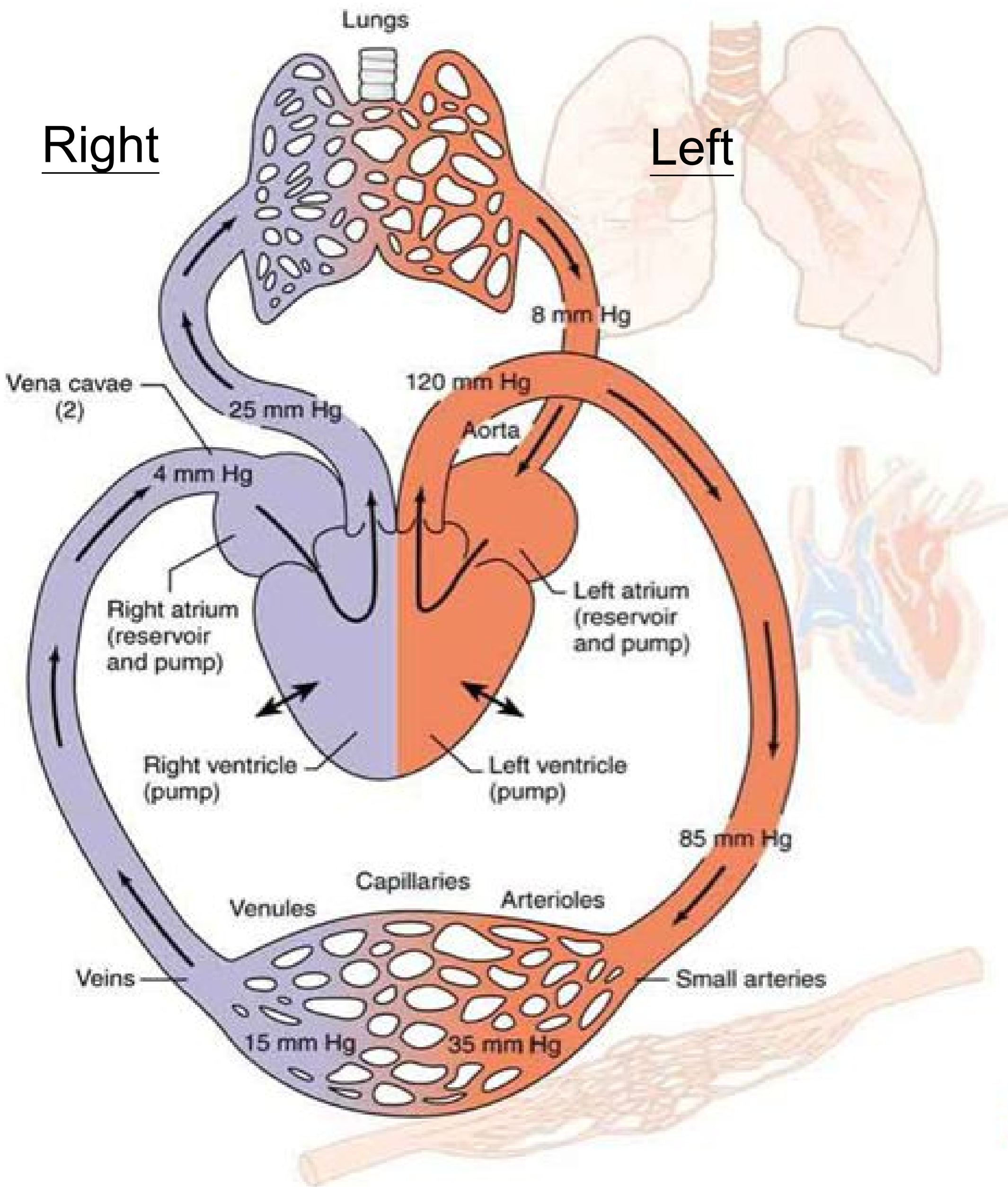
Cardiovascular System

Composed of:

1. Heart:
Pumps blood

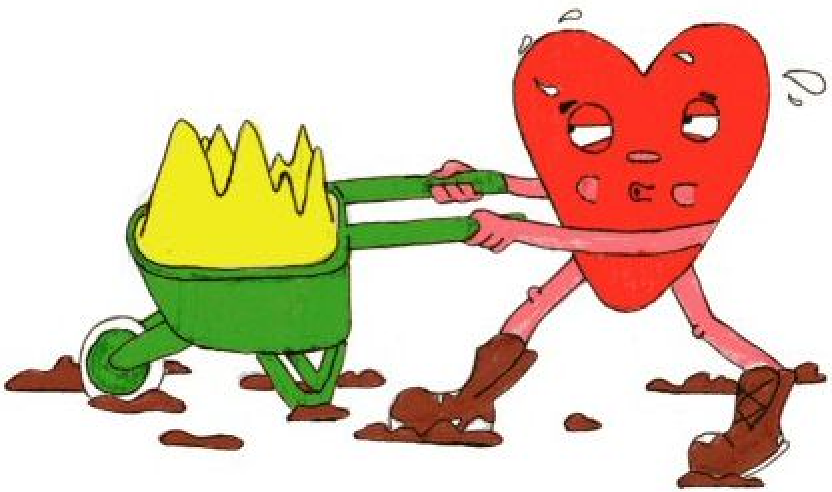
2. Blood vessels:
Transport blood throughout the body



Hemodynamics

Study of blood flow

(involving physical properties of blood, blood vessels & the heart and their interactions)



Cardiac Output (CO)

- Amount of blood pumped by each ventricle in 1 minute
- Product of heart rate (HR) & stroke volume (SV)
  - **HR**: number of heart beats per minute
  - **SV**: volume of blood pumped out by a ventricle with each beat

Trained athletes have higher SV (e.g. 100 mL)

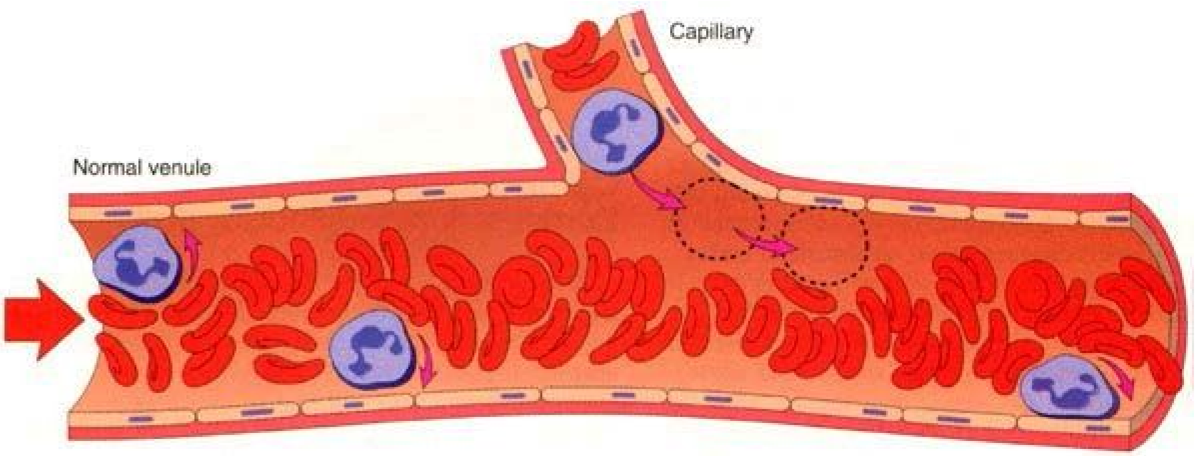
CO (mL/min) = **HR** (75 beats/min) x **SV** (70 mL/beat)
= 5,250 mL/min
= 5.25 L/min

Blood Flow (Q)

Volume of blood flowing through a vessel, an organ, or the entire circulation in a given period (e.g. L/min)

Equivalent to cardiac output (CO)

Flow



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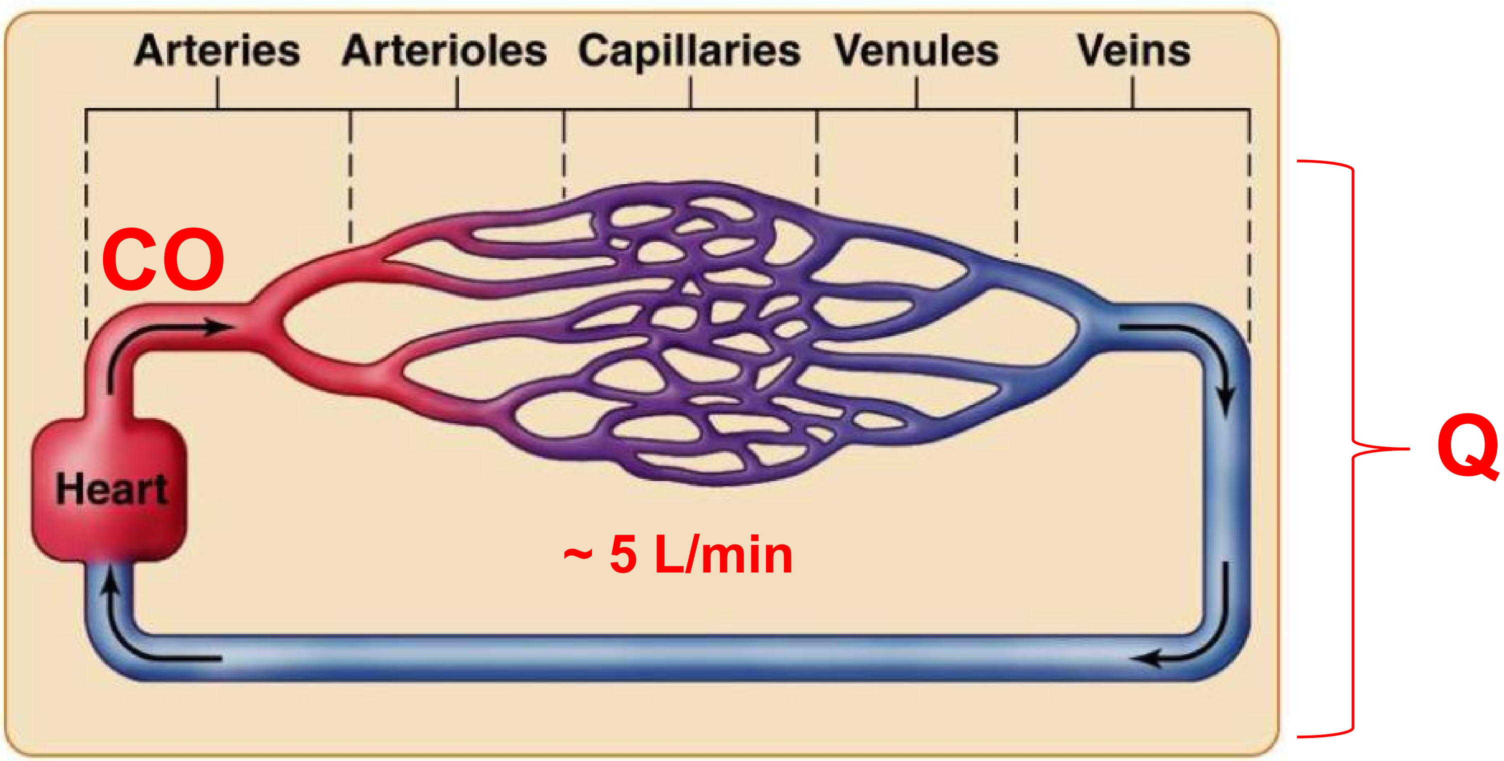
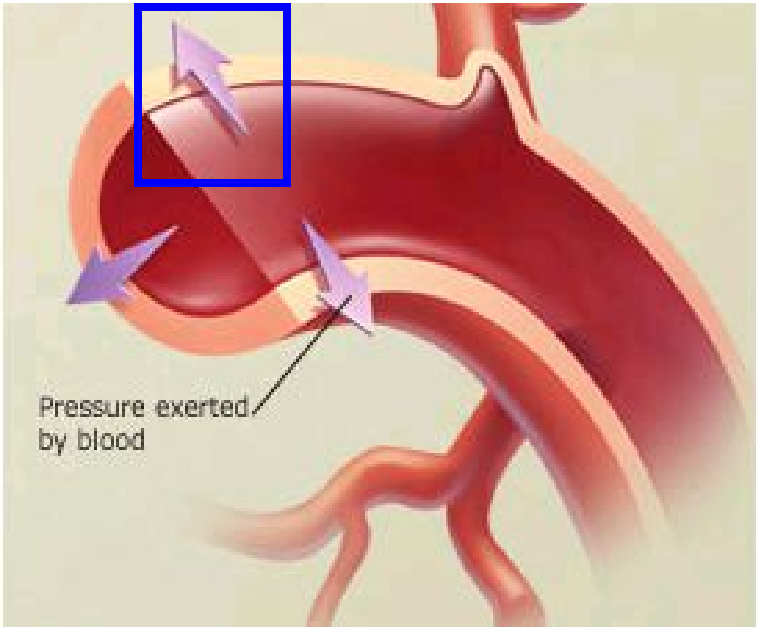


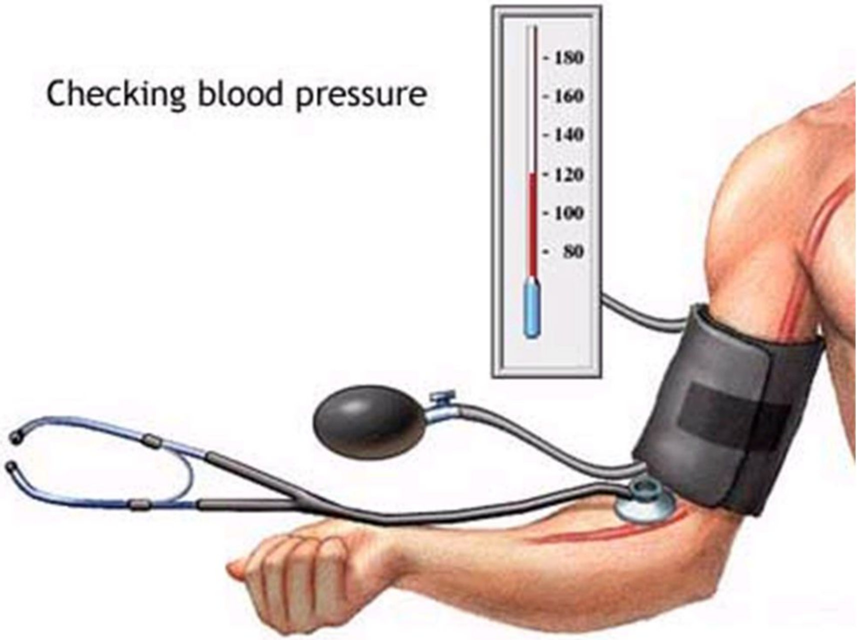
Closed system

Blood Pressure (BP)

- Force per unit area exerted on the wall of a blood vessel by its contained blood   [Pressure = Force / Area]
  - Unit: millimeters of mercury (mmHg)
  - Site of measurement: large arteries near the heart (e.g. brachial artery)

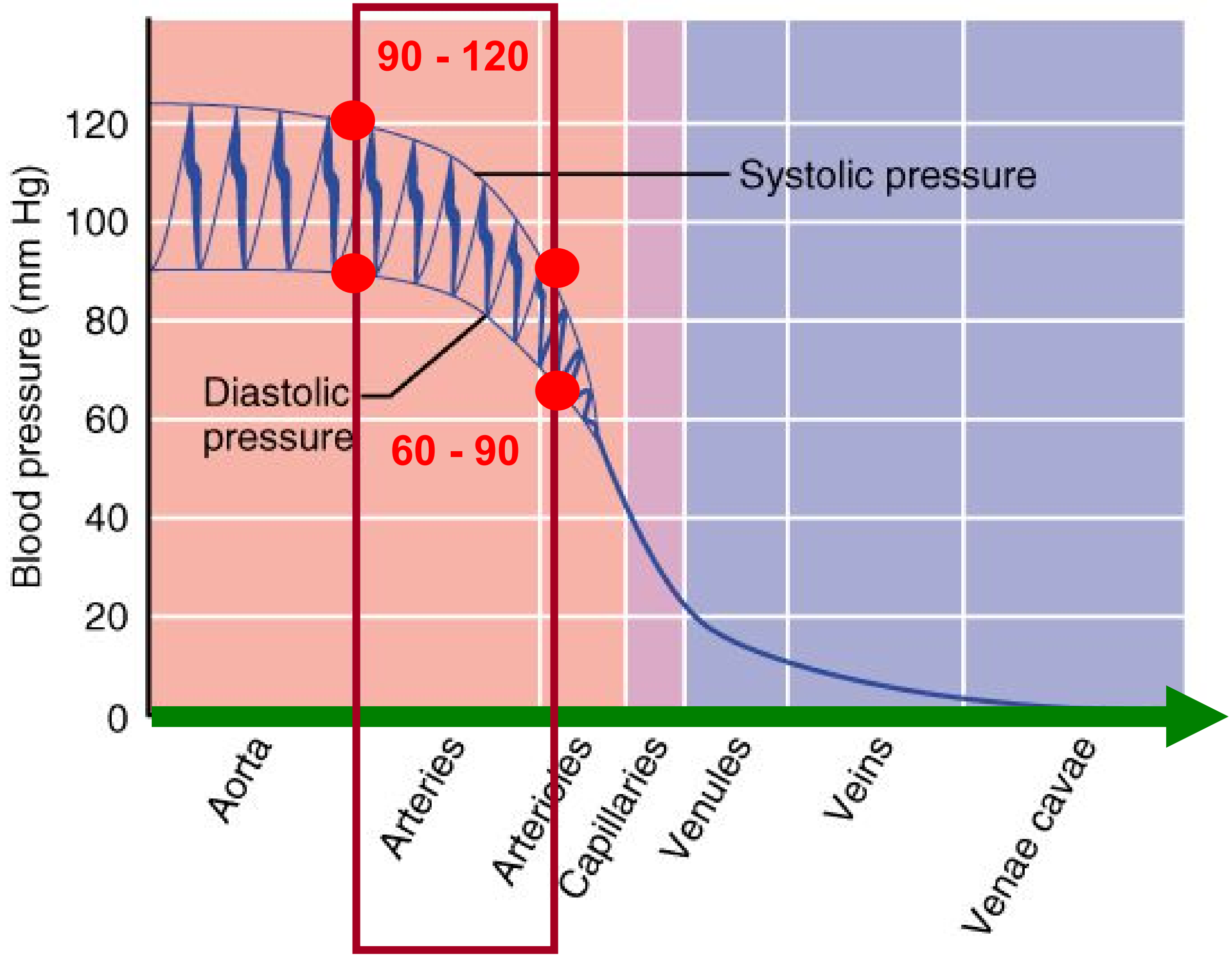


Blood pressure is the measurement of force applied to artery walls



Blood Pressure (BP)

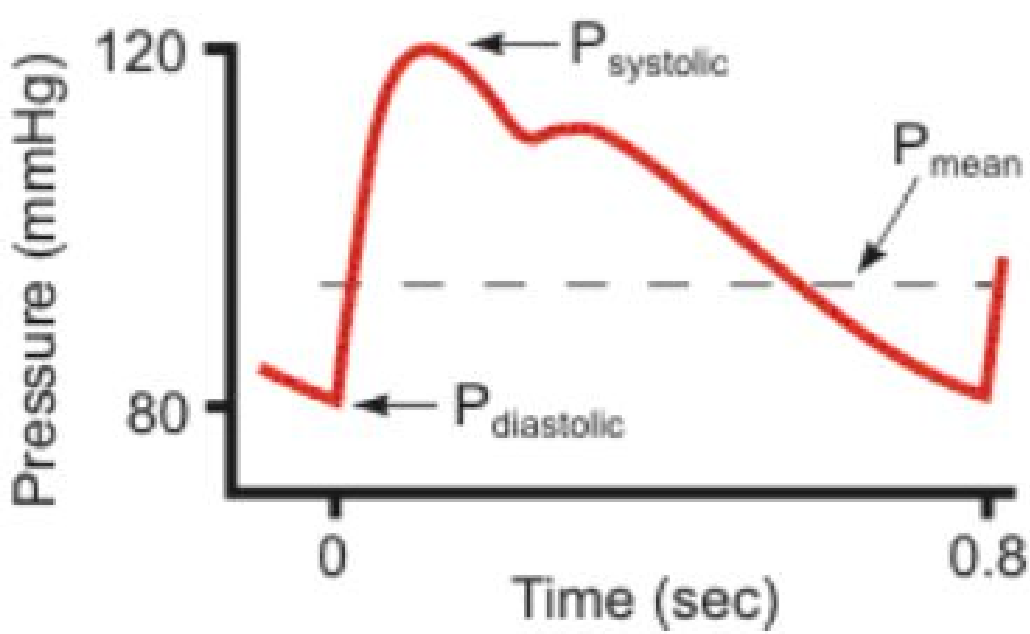
Differences in BP within vascular system provide driving force that keeps blood moving (from higher to lower pressure areas)



Arterial Blood Pressure

- **Systolic pressure** : arterial pressure <u>during ventricular contraction</u>
  (highest level in a cardiac cycle)
- **Diastolic pressure** : arterial pressure during ventricular filling
  (lowest level in a cardiac cycle)
- **Pulse pressure** = <u>difference</u> between systolic & diastolic pressure
- **Mean arterial pressure (MAP)**

= Average arterial pressure during a single cardiac cycle



Relationship between BP & CO

Entire circulation:

Blood pressure (BP) = Cardiac output (CO) x Total peripheral resistance (TPR)

(Opposition to flow)

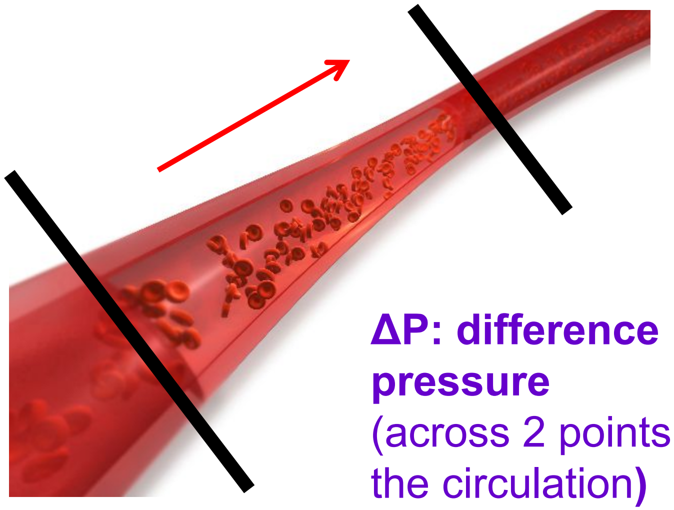
$BP = CO \times TPR$

$CO = BP / TPR$

Between 2 points in the circulation:

$Q = \Delta P / R$

$$\boxed{\text{Flow} = \frac{\text{Pressure Difference}}{\text{Resistance}}}$$



ΔP: difference in pressure
(across 2 points in the circulation)

Relationship between BP & CO

Entire circulation:

Blood pressure (BP) = Cardiac output (CO) x Total peripheral resistance (TPR)

(Opposition to flow)

BP = CO x TPR

CO = BP / TPR

Blood circulation

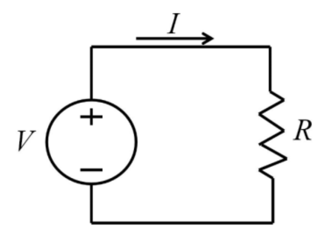
Q = ΔP / R

$$\text{Flow} = \frac{\text{Pressure Difference}}{\text{Resistance}}$$

Electric circuit

Ohm's Law:

I = V / R



$$\text{Current} = \frac{\text{Potential Difference}}{\text{Resistance}}$$

Velocity of Blood Flow

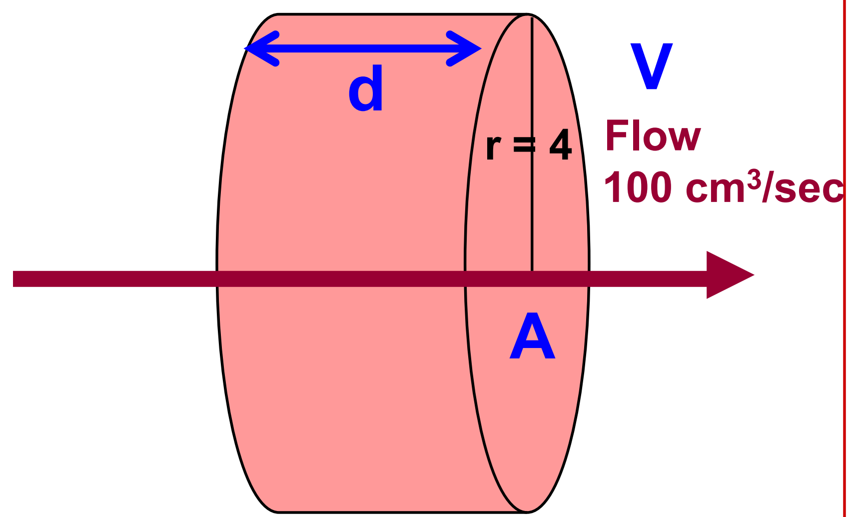
- Flow (Q): measure of volume per unit time (e.g. mL/sec → cm^3/sec)
- Velocity (v): measure of displacement per unit time (e.g. cm/sec)

[distance per unit time in a specific direction]

$$V = A \times d$$

$$d = V / A$$

÷ sec ÷ sec



Velocity = Flow / Cross sectional area

Velocity of Blood Flow

- Flow (Q): measure of volume per unit time (e.g. mL/sec → cm^3/sec)
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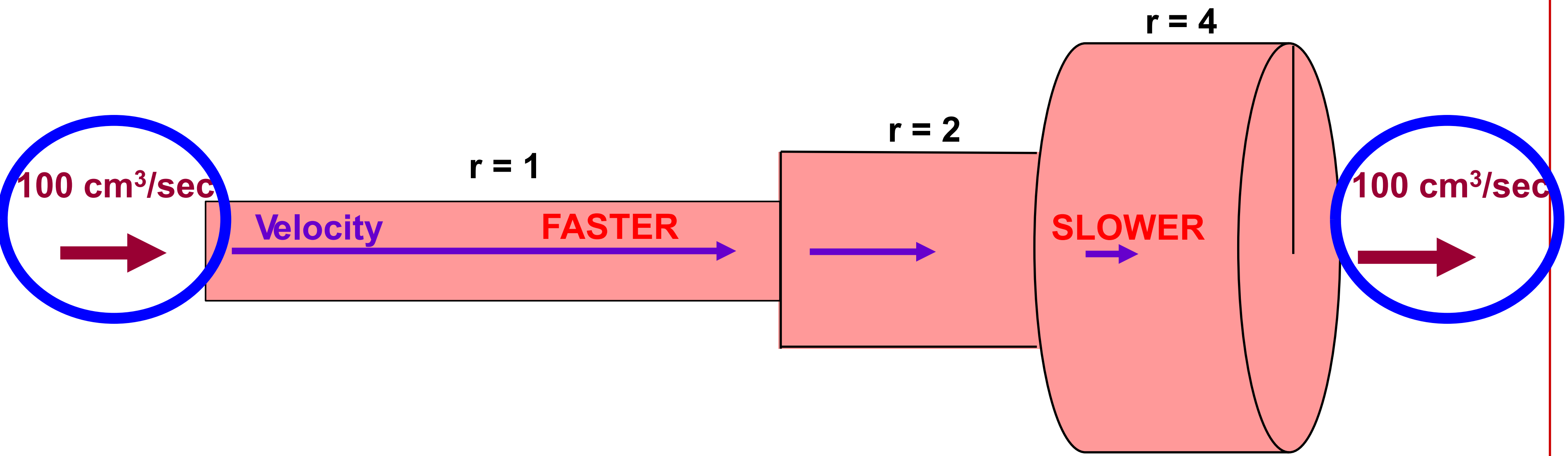
[distance per unit time in a specific direction]



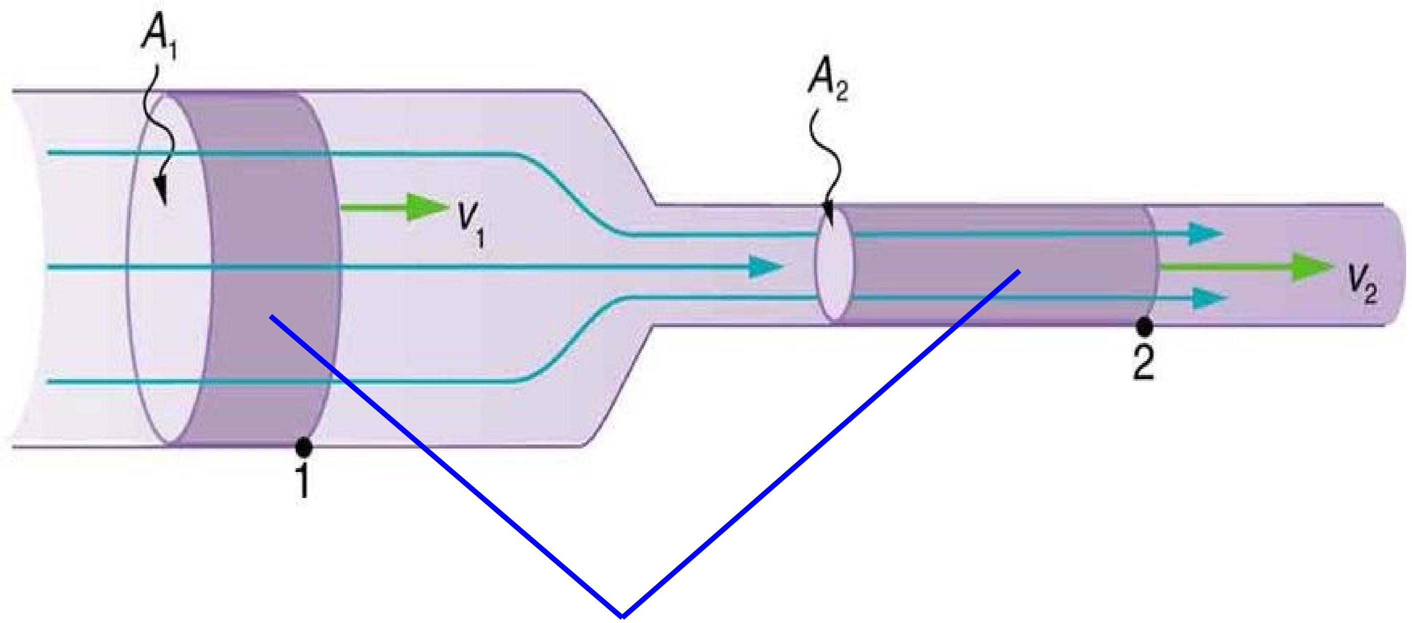
Velocity = Flow / Cross sectional area

Radius	(cm)	1	2	4
Area (πr^2)	(cm^2)	3.14	12.56	50.24
Flow	(cm^3/sec)	100	100	100
Fluid Velocity	(cm/sec)	32	8	2

Assumption: **constant flow** (no resistance)

Velocity of Blood Flow

For incompressible fluids, flow rate at various points is constant



When a tube narrows, the **same volume** occupies a greater length.

For the **same volume** to pass points 1 and 2 in a given time, the speed must be greater at point 2.

Velocity of Blood Flow

Calculation:

Blood is pumped from the heart at a **rate of 5.0 L / min** into the aorta (of **radius 1.0 cm**).

Determine the **velocity** of blood through the aorta.

Solution:

Flow = 5 L / min

= 5,000 cm^3 / 60 s

= 83.3 cm^3 / s

Velocity (cm/s) = Flow (cm^3/s) / Cross sectional area (cm^2)

= 83.3 (cm^3/s) / (3.14 x 1 cm x 1 cm)

= 83.3 (cm^3/s) / 3.14 cm^2

= **26.5 cm/s**

Resistance

$$Q = \Delta P / R$$

$$\uparrow \text{Flow} = \frac{\text{Pressure Difference}}{\text{Resistance}\downarrow}$$

Resistance

Opposition to flow

- Measure of the amount of friction blood encounters as it passes through vessels
- Generally encountered in the systemic circulation: referred to as peripheral resistance (PR)

Factors that affect resistance:

1. Blood viscosity *[more ‘sticky” → higher resistance]*
2. Total blood vessel length *[long vessel → higher resistance]*
3. Blood vessel radius

Regulated

Poiseuille's Law

Regulation of blood vessel radius
→ Change in blood flow

Jean Léonard Marie Poiseuille
(1797 - 1869)

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

viscosity length

r^4 can be regulated (especially in arterioles)

ΔP is not subject to significant short-term regulation

η, l are not subject to significant regulation by body

8, π are constant

Poiseuille's Law

Regulation of blood vessel radius
→ Change in blood flow

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

↑ r

↑ Q

↓ Resistance

$$Q = \frac{\Delta P}{R}$$

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

Poiseuille's Law

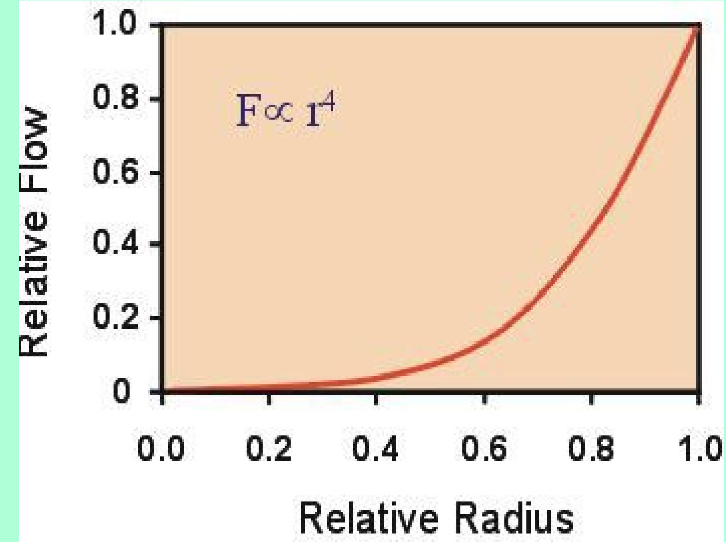
Regulation of blood vessel radius
→ Change in blood flow

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

↑ r

↑ Q

↓ Resistance



Resistance varies inversely with the 4th power of vessel radius
(e.g. if radius is doubled, resistance becomes 1/16 as much)

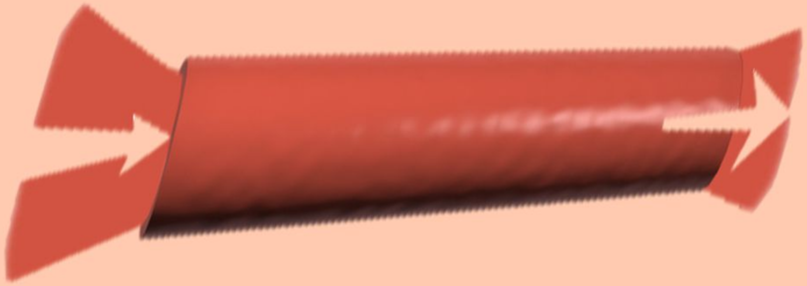
Small changes in radius result in large changes in resistance

Poiseuille's Law

Regulation of blood vessel radius
→ Change in blood flow

r = 1 mm
Resistance = R
Flow = F

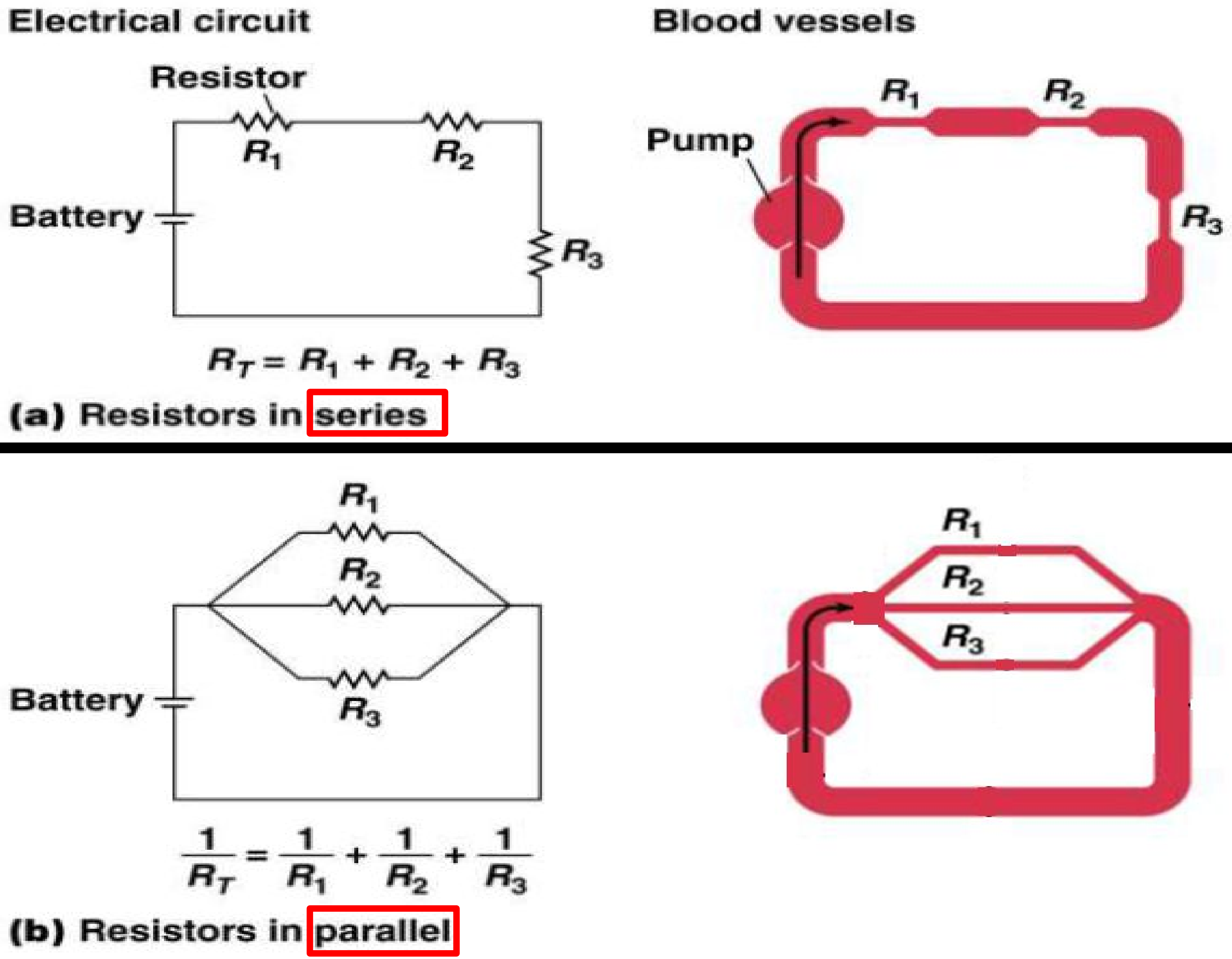
r = 2 mm
Resistance = 1/16 R
Flow = 16 F



r = 1/2 mm
Resistance = 16 R
Flow = 1/16 F

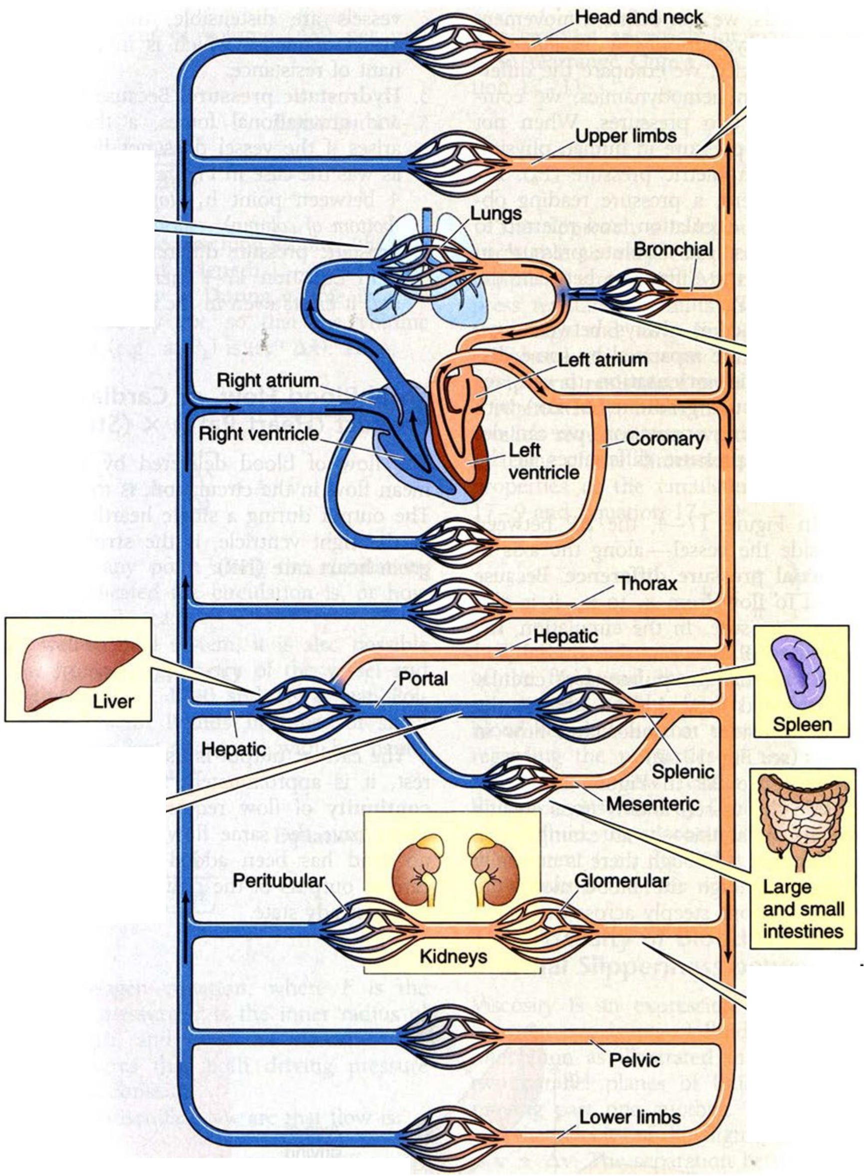
Small changes in radius result in large changes in resistance

Series & Parallel Circuits



Series & Parallel Circuits

Systemic Circulation

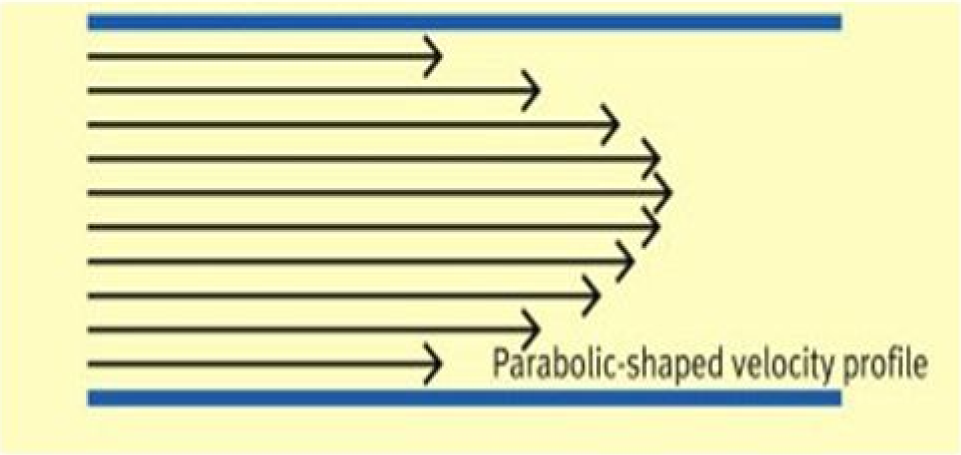


Circulatory system has both series & parallel arrangements of blood vessels.

Laminar vs. Turbulent Flow

Laminar Flow

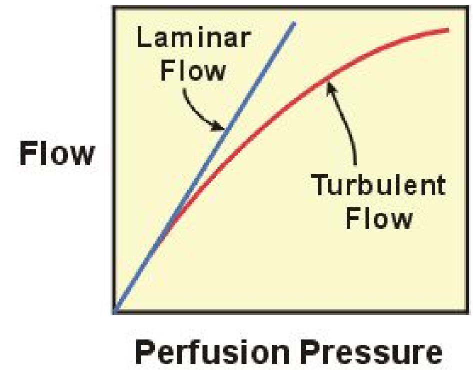
- Fluid flows in layers **parallel** to vessel wall (without disruption between layers)
- The layer of fluid in contact with the wall has lower velocity
- The layer of fluid that moves along the axis of the tube has maximal velocity



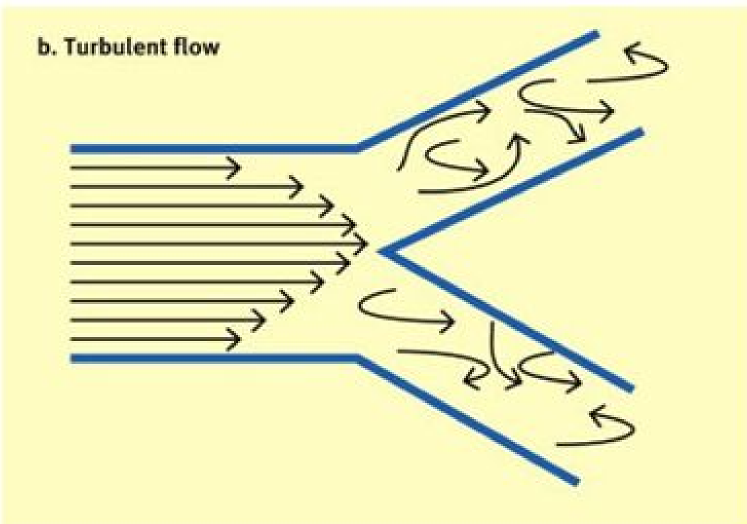
Laminar vs. Turbulent Flow

Turbulent Flow

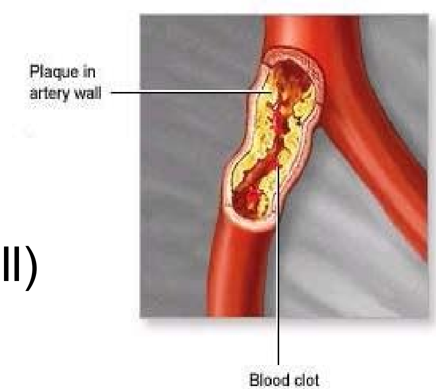
•**Irregular** movement
•Pressure & flow velocity changes rapidly
•Flow is lower than laminar flow at a given perfusion pressure



•e.g. at bifurcations of blood vessels

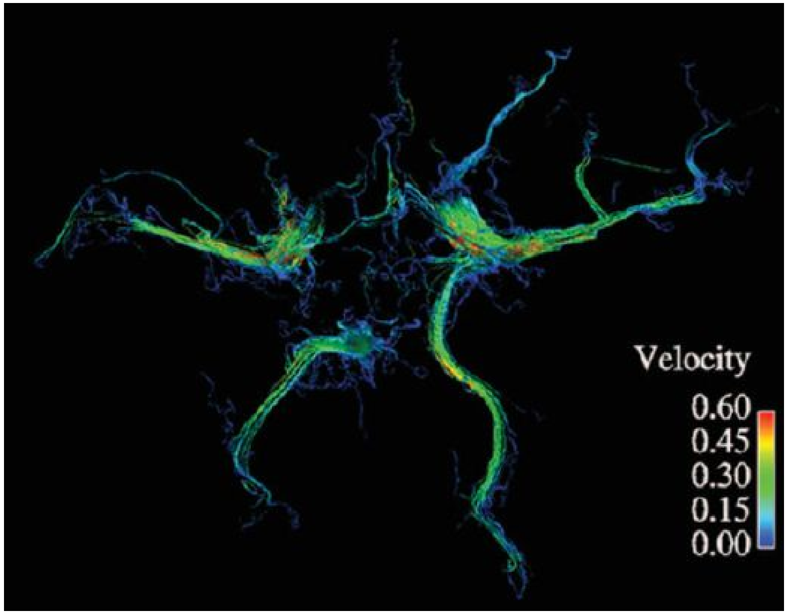


Some are pathological:
e.g. in **atherosclerosis** (fatty plaques accumulation at vessel wall)
→ resistance ↑ → workload of heart ↑

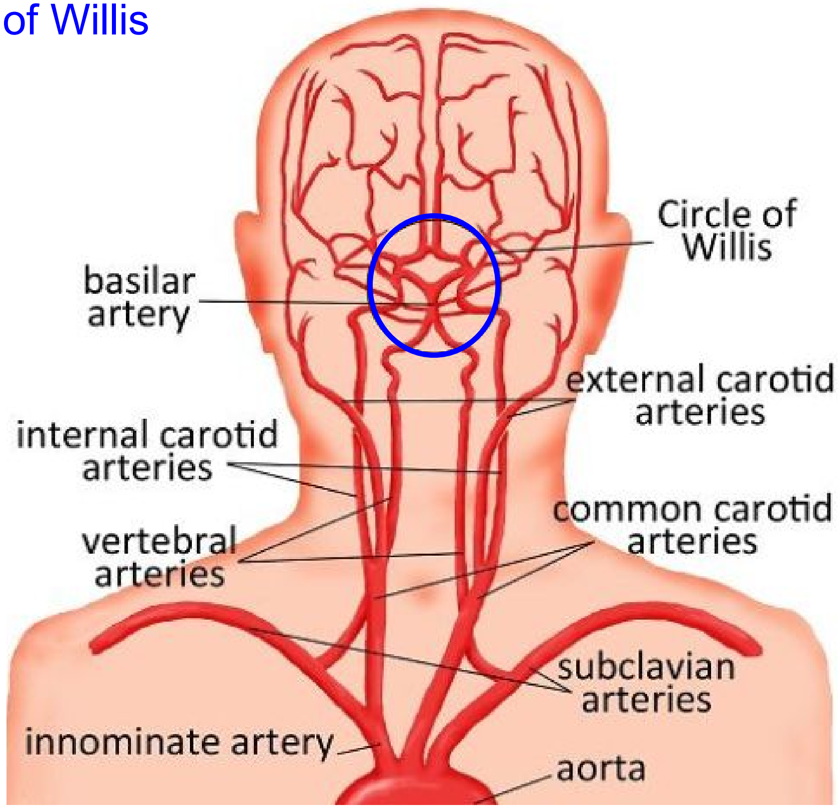


Cardiovascular Dynamics

Non-invasive visualization of intracranial arterial hemodynamics
(time-resolved 3D MRI)



Circle of Willis



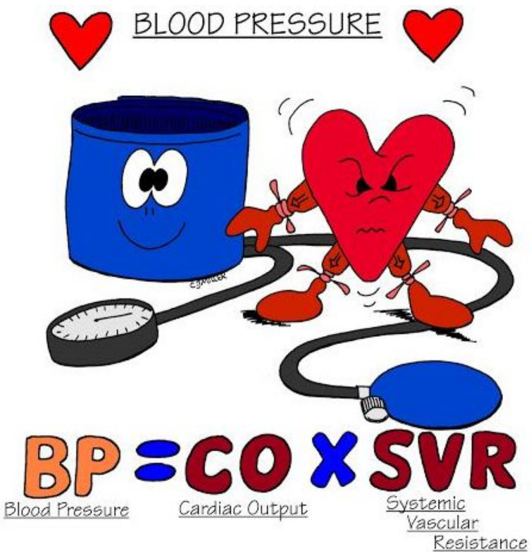
Abnormal hemodynamics in the arteries in the brain are associated with hypertension, stroke & aneurysms

Key Points

Cardiovascular System: Heart + Blood vessel

Hemodynamics: Study of blood flow

- **Cardiac Output (CO = HR x SV)**
- **Blood Flow (Q) [= CO for entire circulation]**
- **Blood Pressure (BP = CO x TPR) [→ Q = ΔP / R]**
- **Velocity (v = Q / Area)**
- **Resistance (R) [Opposition to Q]**
  - **Blood viscosity**
  - **Total vessel length**
  - **Vessel radius - regulated**
  - **Poiseuille's Law**
    - **Small change in radius → Large change in R**



Series & Parallel Circuits in Circulatory System

Laminar & Turbulent Flow

Visualization of Hemodynamics