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# **Rheology of blood circulation**

# 1. Basic physical laws of liquids

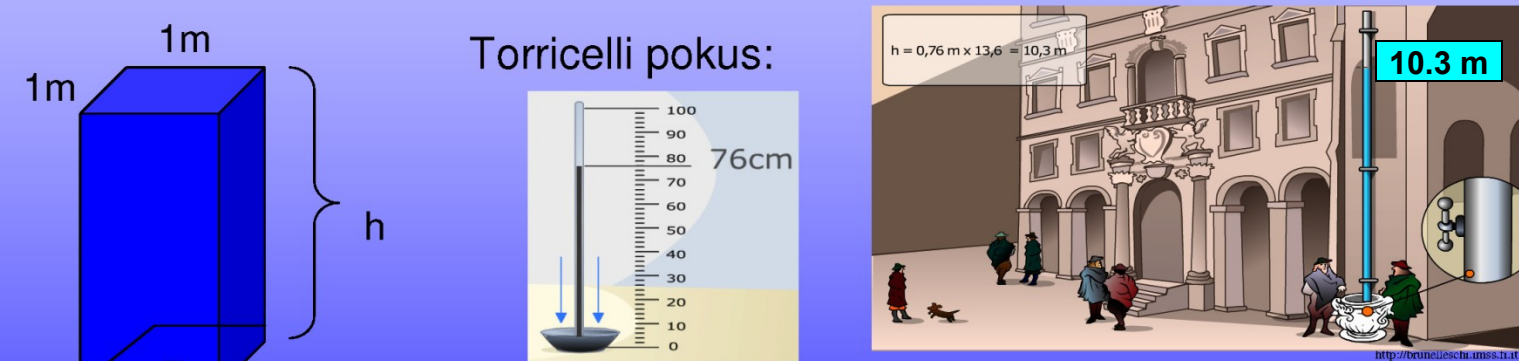
# Law of Pascal

Liquid column causes a pressure (hydrostatic pressure) that is directly proportional to the height of the liquid column ( $h$ ), density of the liquid ( $\rho$ ) and gravitational acceleration ( $g$ ).




$p = h \cdot \rho \cdot g$

- $h$  = height
- $\rho$  = density
- $g$  = gravitational acceleration



Torricelli pokus:

$Hg$



$H_2O$

$h = 0,76 \text{ m} \times 13,6 = 10,3 \text{ m}$

Pa

mm Hg

mm H<sub>2</sub>O

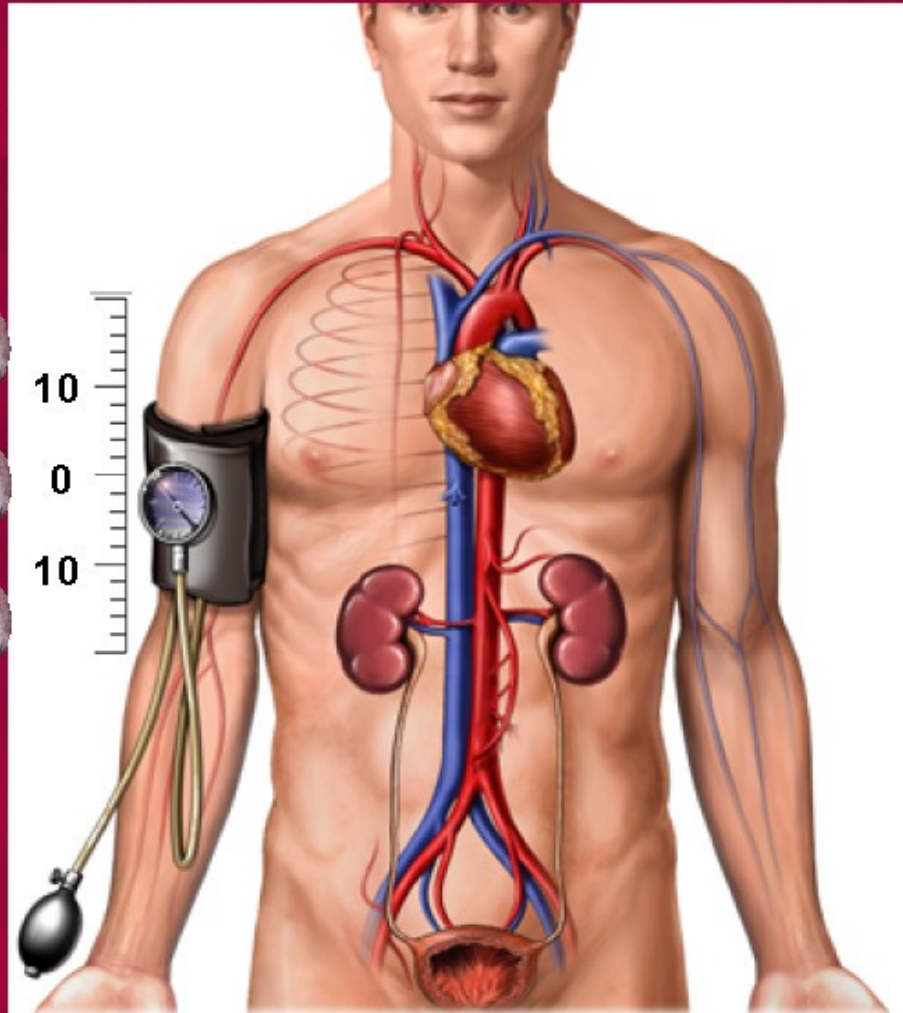
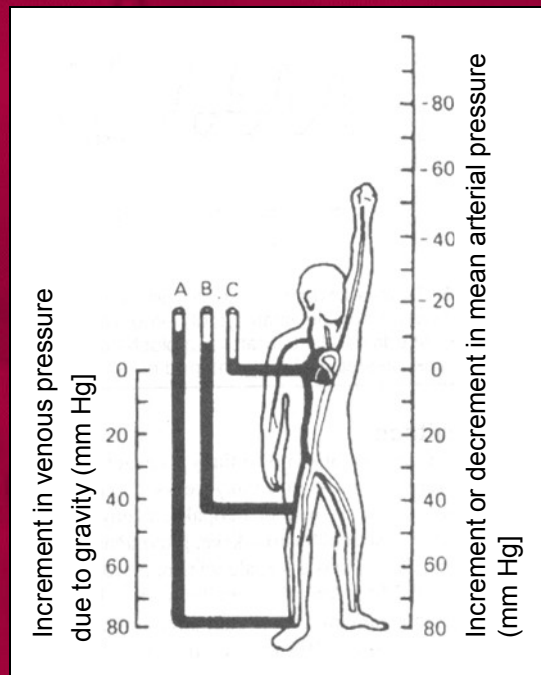
133,322 Pa = 1 mm Hg

760 mmHg = 1 atm = 10.3 m H<sub>2</sub>O

# Effect of gravity on arterial and venous pressure

Per each 10 cm

$$\Delta p = \Delta h \cdot \rho_{krve} \cdot g = 0,1 \cdot 1\,065 \cdot 9,81$$
$$= 1\,045\text{Pa} = \mathbf{7.8\text{ mm Hg}}$$





# Law of Laplace

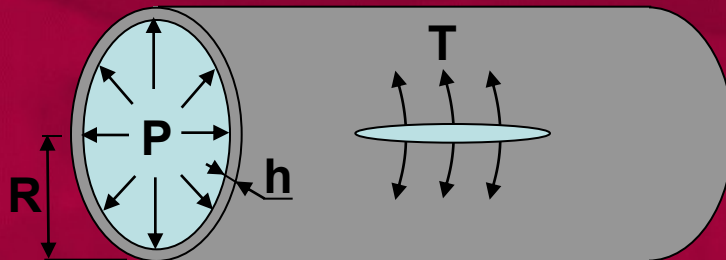
Relation between distending pressure ( $P$  [ $\text{N/m}^2$ ]) and tension in the wall of hollow object ( $T$  [ $\text{N/m}$ ]):

$$T = \frac{P}{\left(\frac{1}{R_1} + \frac{1}{R_2}\right)}$$

$R_1$  and  $R_2$  are the biggest and the smallest radii of curvature

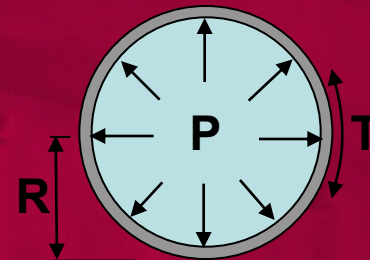
For vessel:

$$R_2 = \infty \quad T = P \cdot R$$



For sphere:

$$R_1 = R_2 \quad T = P \cdot R/2$$



Considering thickness of vessel wall ( $h$  [ $\text{m}$ ]):  $T = P \cdot R/h$  [ $\text{N/m}^2$ ]

# Characteristics of vessels

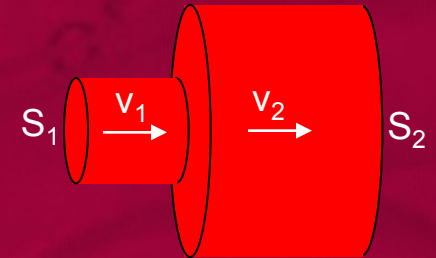
	P	R	P·R	h	P·R/h
vessel	P [kPa]	radius	tension (N/m)	wall thickness	tension (N/m <sup>2</sup> )
aorta	13,3	13 mm nebo méně	170	2 mm	<b>85000</b>
arteries	12	5 mm	60	1 mm	<b>60000</b>
arterioles	8	150–62 μm	1,2–0,5	20 μm	<b>40000</b>
capillaries	4	4 μm	$1,6 \cdot 10^{-2}$	1 μm	<b>16000</b>
venules	2,6	10 μm	$2,6 \cdot 10^{-2}$	2 μm	<b>13000</b>
veins	2	200 μm a více	0,4	0,5 mm	<b>800</b>
vena cava	1,33	16 mm	21	1,5 mm	<b>14000</b>

# Continuity equation

The volume of fluid flowing through a tube (vessel) per unit of time ( $Q$  [l/s]) is constant.

$$Q = S_1 \cdot v_1 = S_2 \cdot v_2 = \text{constant}$$

$v$  – velocity       $S$  – area



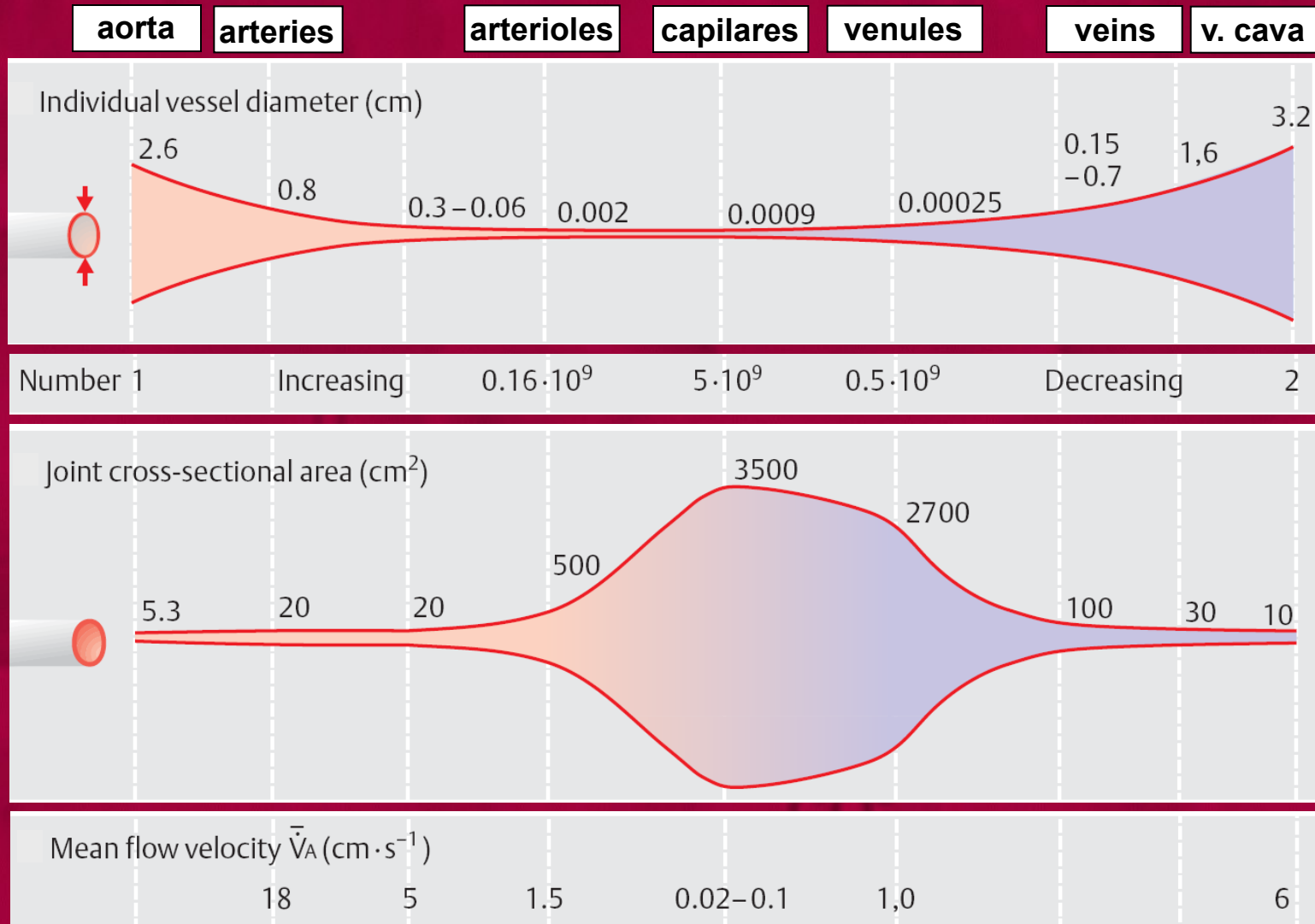
## Average blood velocity in vessels

$$v = \frac{Q}{S}$$

$$Q_{rest} \approx 5.6 \text{ l/min}$$

vessel	diameter	number	total area	velocity
aorta	2.6 cm	1	5.3 cm <sup>2</sup>	~ 18 cm/s
arterioles	20-50 μm			~ 1.5 cm/s
capillaries	4-9 μm	5×10 <sup>9</sup>	2000 cm <sup>2</sup>	~ 0.04 cm/s
venules				~ 1 cm/s
vena cava		2		~ 7 cm/s

# Relation between total cross-sectional area of vessels and mean blood flow velocity

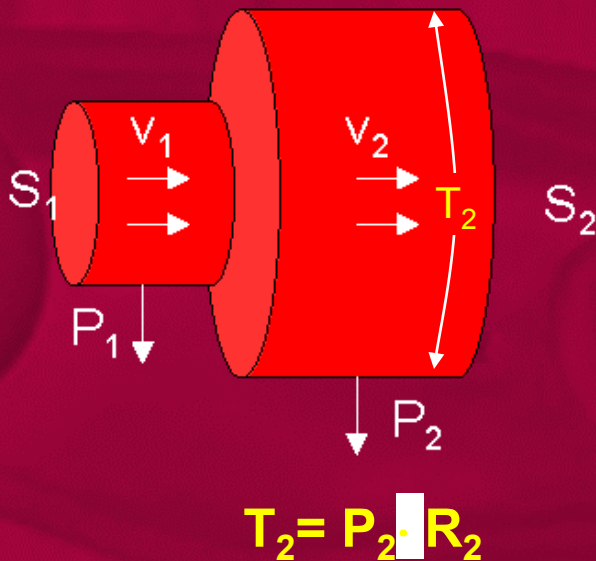
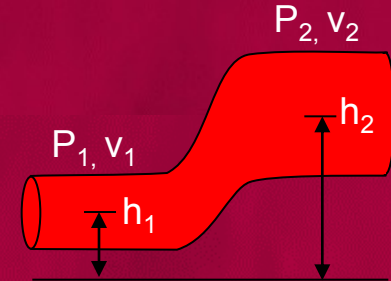




# Bernoulli's principle

Law of energy conservation for fluid :

$$\frac{1}{2} \rho v^2 + h \cdot \rho \cdot g + P = \text{constant}$$



Implication for aortic aneurysm

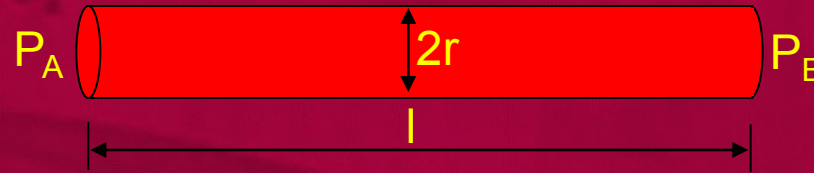
$S_1 v_1 = S_2 v_2$  a je-li  $S_1 < S_2$ , musí platit:  $v_1 > v_2$

$$\frac{1}{2} \rho v_1^2 + \cancel{h \cdot \rho \cdot g} + P_1 = \frac{1}{2} \rho v_2^2 + \cancel{h \cdot \rho \cdot g} + P_2$$

$$\frac{1}{2} \rho v_1^2 + P_1 = \frac{1}{2} \rho v_2^2 + P_2$$

For  $v_2 < v_1 \Rightarrow P_2 > P_1$

# Poiseuille – Hagen equation



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

*The flow of liquid* in the cylindrical tube ( $Q$ ) is directly proportional to the pressure difference between two ends of the tube ( $\Delta P = P_A - P_B$ ), to the fourth power of the tube radius ( $r$ ) and inversely proportional to tube length ( $l$ ) and to the viscosity of liquid ( $\eta$ )

## *Limitation:*

- For stationary flow in Newtonian fluids where viscosity is constant and independent on flow velocity.

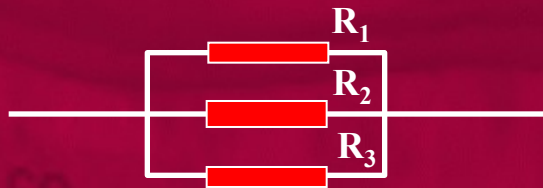
$$Q = \frac{\pi \cdot \Delta P \cdot r^4}{8 \cdot l \cdot \eta}$$

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

**Vascular resistance ( $R_v$ ):** a consequence of the friction between fluid and vessel wall.

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

Parallel arrangement of vessels



$$\frac{1}{R_c} = \frac{1}{R_1} + \frac{1}{R_2} + \dots$$

$$\text{pro } R_1=R_2=R_3=R_n$$

$$R_c = R/n$$

Series arrangement of vessels

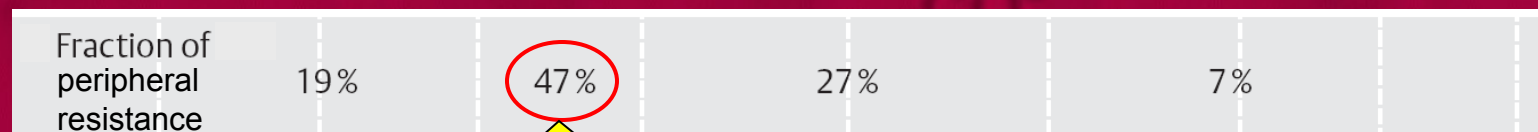
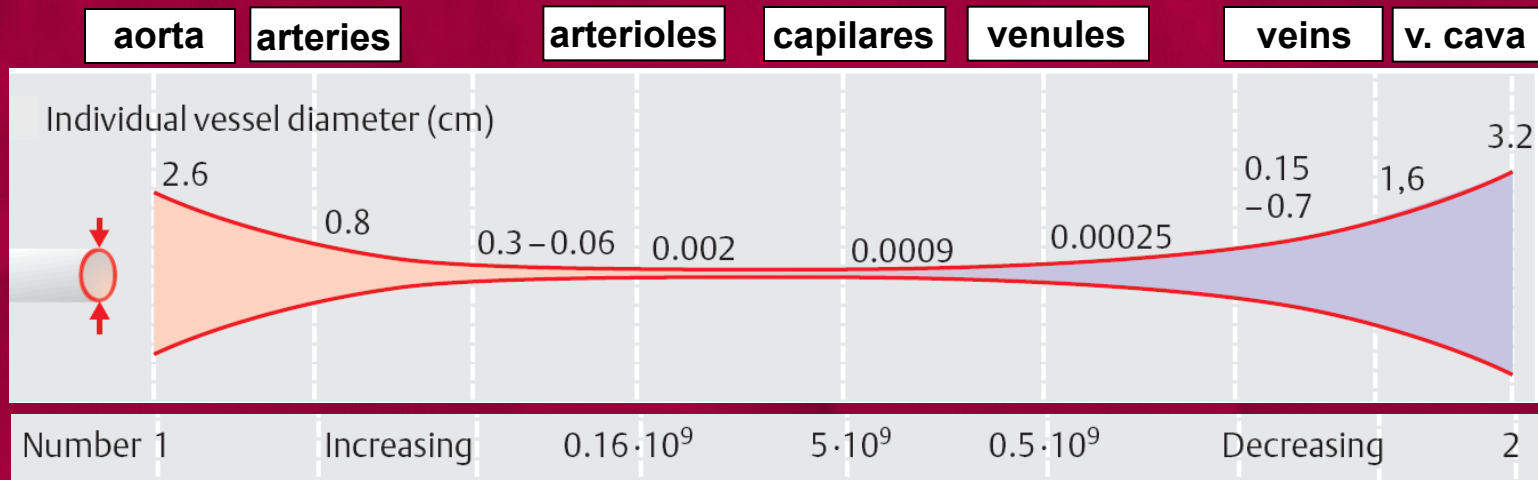


$$R_c = R_1 + R_2 + \dots$$

$$\text{pro } R_1=R_2=R_3=R_n$$

$$R_c = R \cdot n$$

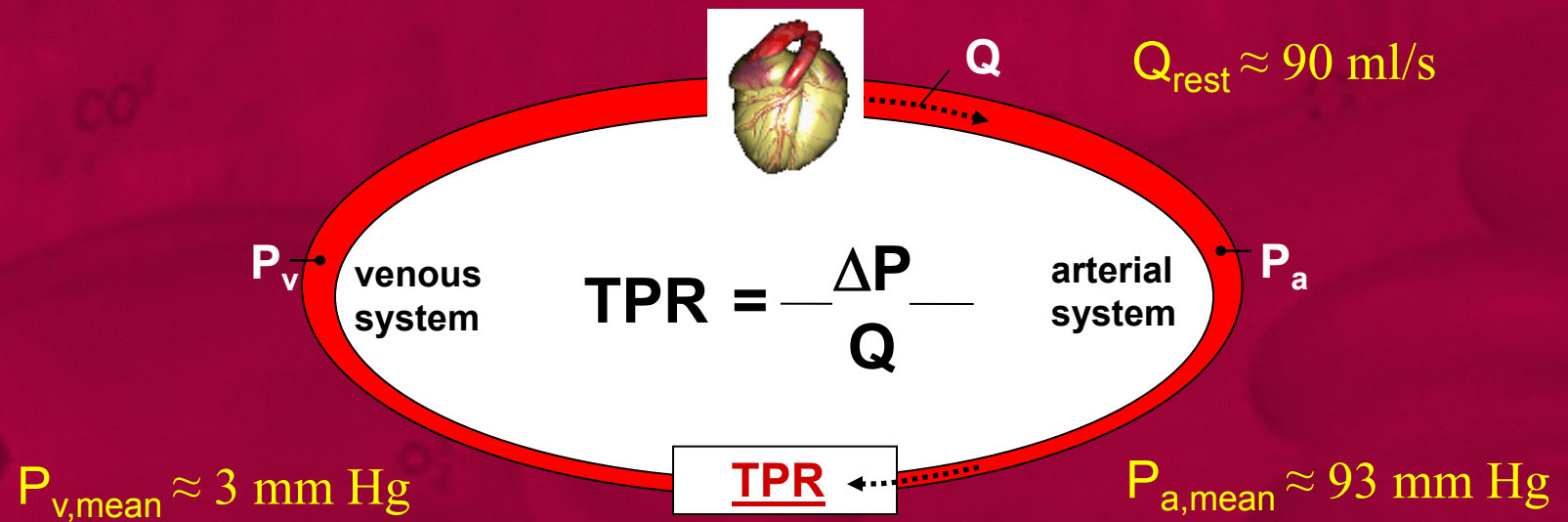
# Relation between vessel radius and peripheral resistance



highly variable



# Total peripheral resistance (TPR) of vascular system



$$TPR = \frac{\Delta P}{Q} = \frac{P_a - P_v}{Q} \approx \frac{P_a}{Q} = \frac{93}{90} \approx 1 \frac{\text{mmHg s}}{\text{ml}}$$

For constant Q:  $\square$  PR  $\square$   $P_a$   $\square$  hypertension, ... cardiac disease.

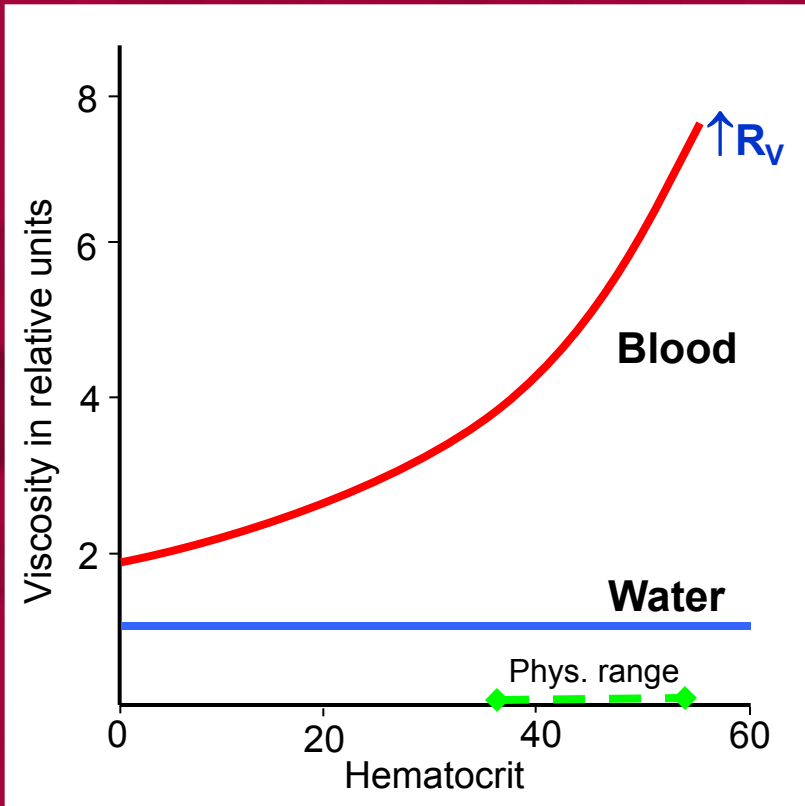
The background features a faint, light-colored diagram of a blood vessel. The vessel is shown in cross-section, with a central lumen and a surrounding wall. Several labels are scattered around the vessel: 'CO<sub>2</sub>' appears in the upper left, upper right, and lower left areas, while 'O<sub>2</sub>' is located in the upper right area. The diagram is rendered in a light, semi-transparent style against a dark red background.

## **2. Rheological features of blood and vessels**

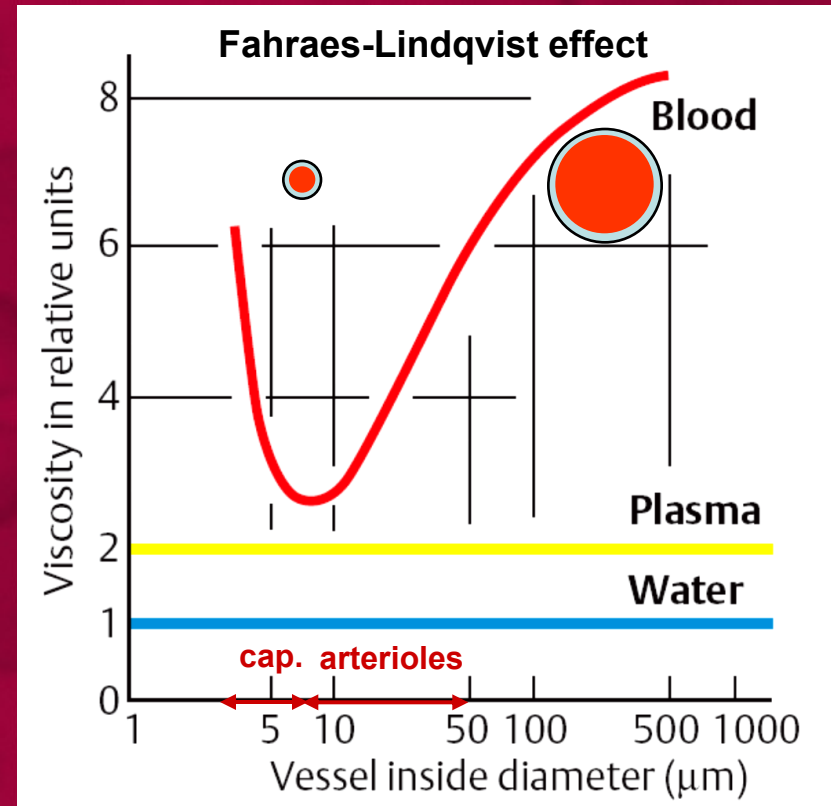
# Blood viscosity

$$R_v = 8 \cdot l \cdot \eta / (\pi \cdot r^4)$$

## Effect of hematocrit



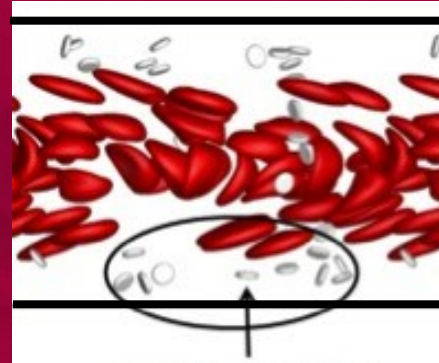
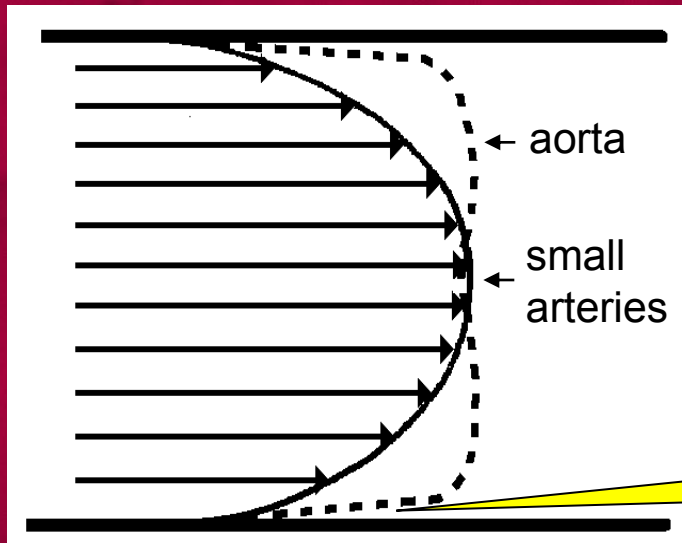
## Effect of diameter in small vessels



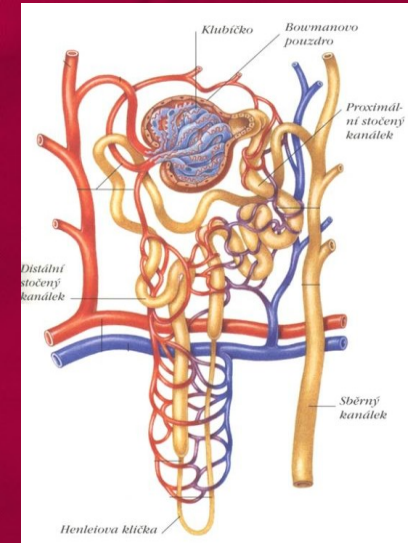
Other factors causing increase of viscosity:

- decrease of blood flow velocity
- elevation of plasma proteins

# Velocity profile of the blood flow in vessels



plasma-skimming

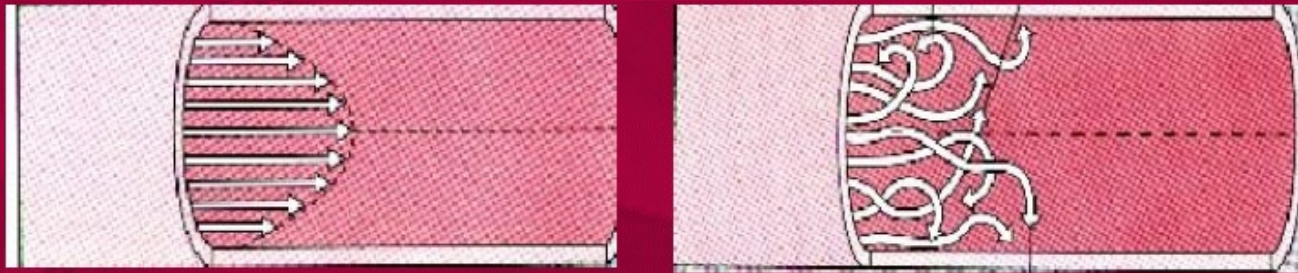


- In small arteries the velocity profile of the flowing blood has a parabolic shape. In the bigger arteries it has a piston shape.
- The layer close to vessel wall is poor of erythrocytes.



# Laminar and turbulent flow

Velocity profile in laminar and turbulent flow



The character of the flow is determined by Reynolds number

$$Re = \frac{v \cdot \rho \cdot r}{\eta}$$

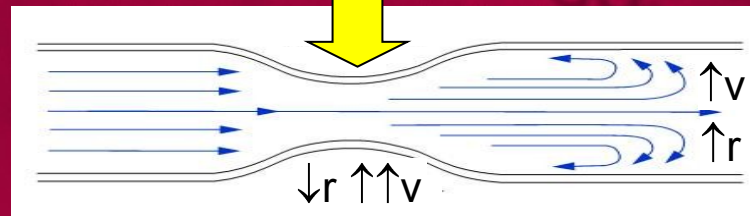
laminar flow

$Re < 2000$

turbulent flow

$Re > 3000$

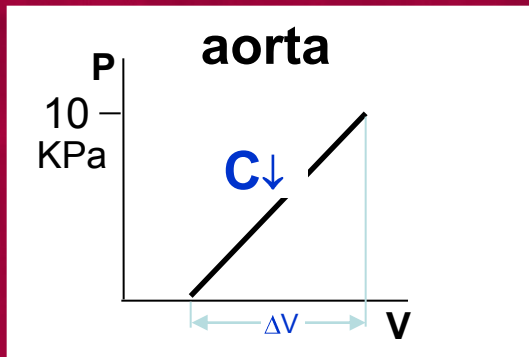
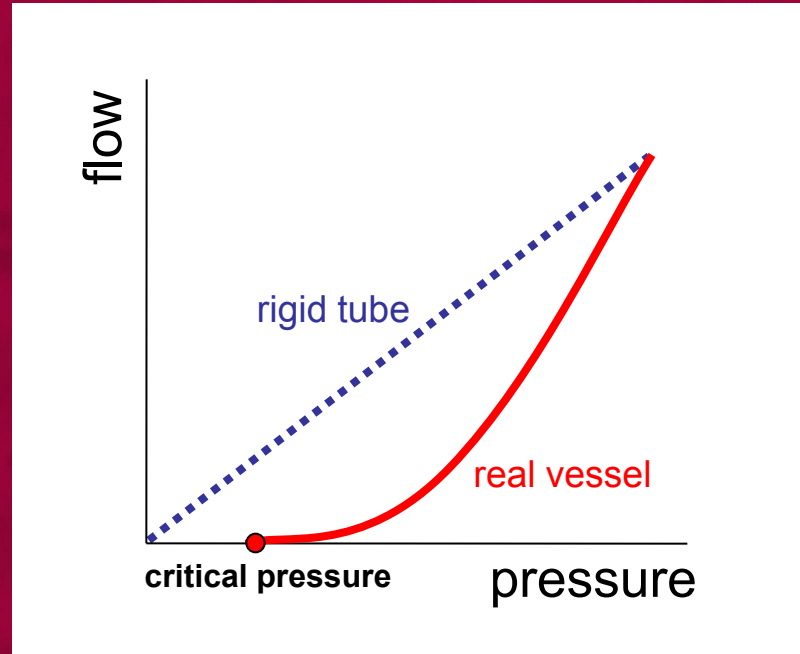
Sudden change of vessel diameter



$$\uparrow Re \Rightarrow \uparrow R_v$$

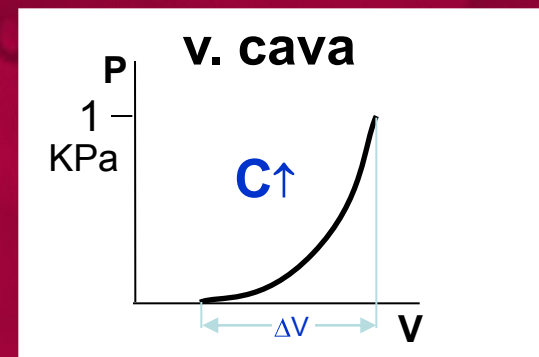
Pathological states causing turbulent flow: aneurisma, stenosis, arteriosclerosis, decreased blood viscosity, .

# Elasticity of vessels

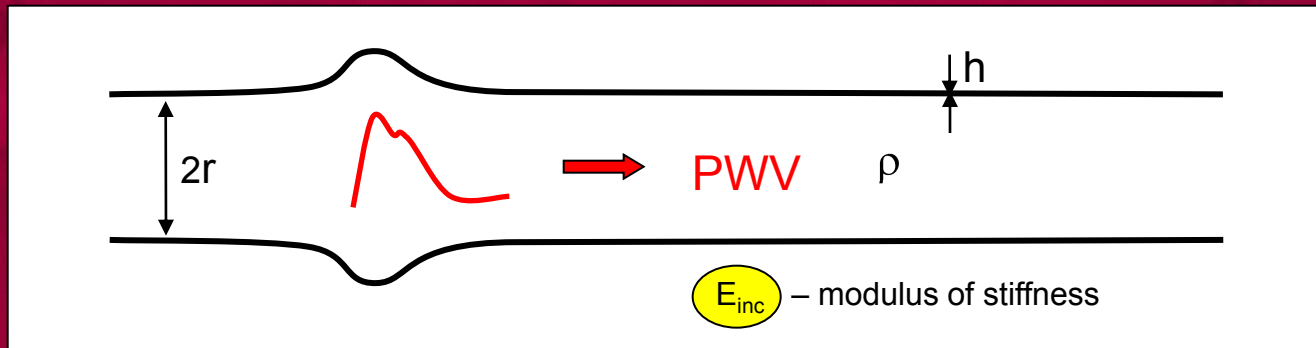


**compliance**

$$C = -\frac{\Delta V}{\Delta P}$$



# Pulse wave velocity (PWV)

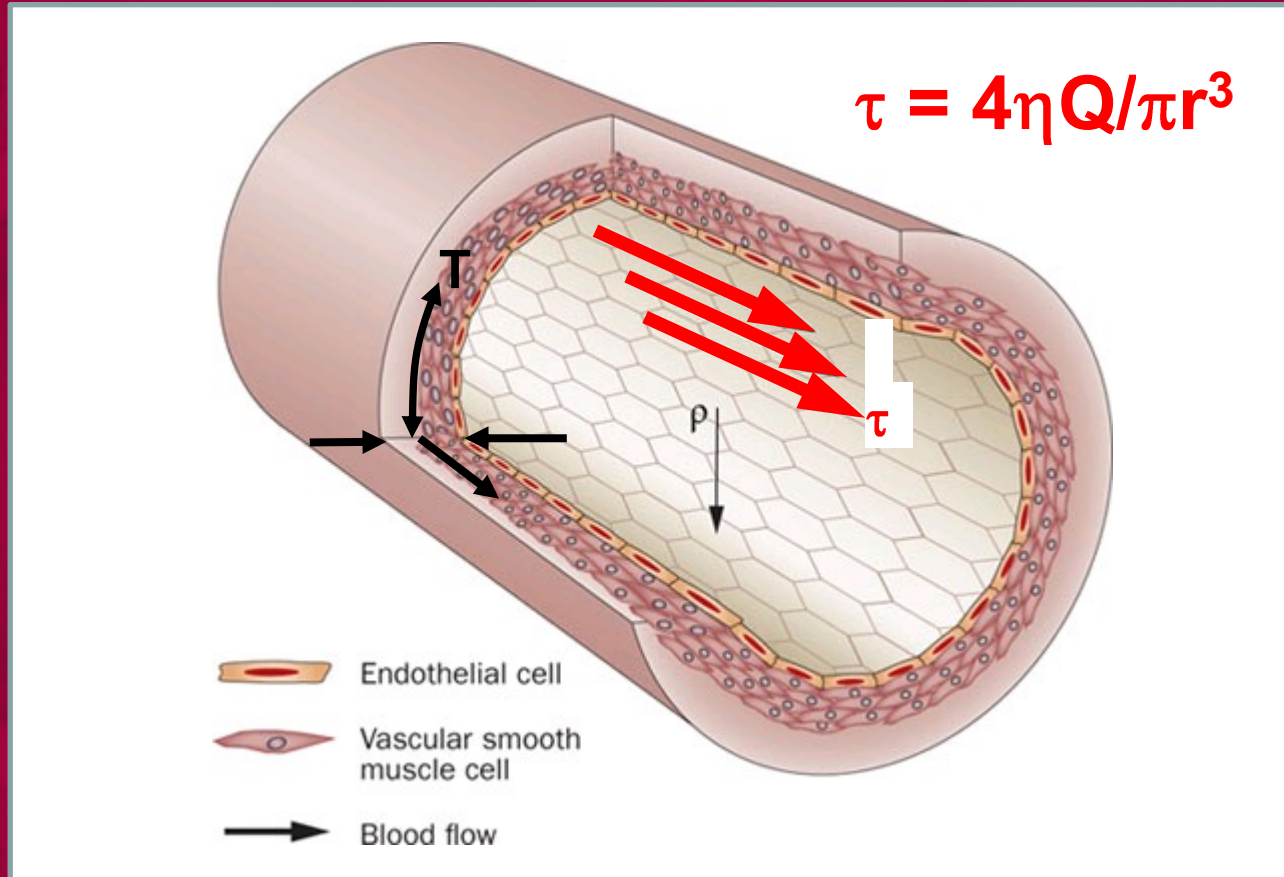


Moens-Korteweg (1878)

$$PWV = \sqrt{\frac{E_{inc} \cdot h}{2 \cdot r \cdot \rho}}$$

In aorta  $PWV = 4 - 6 \text{ m/s}$

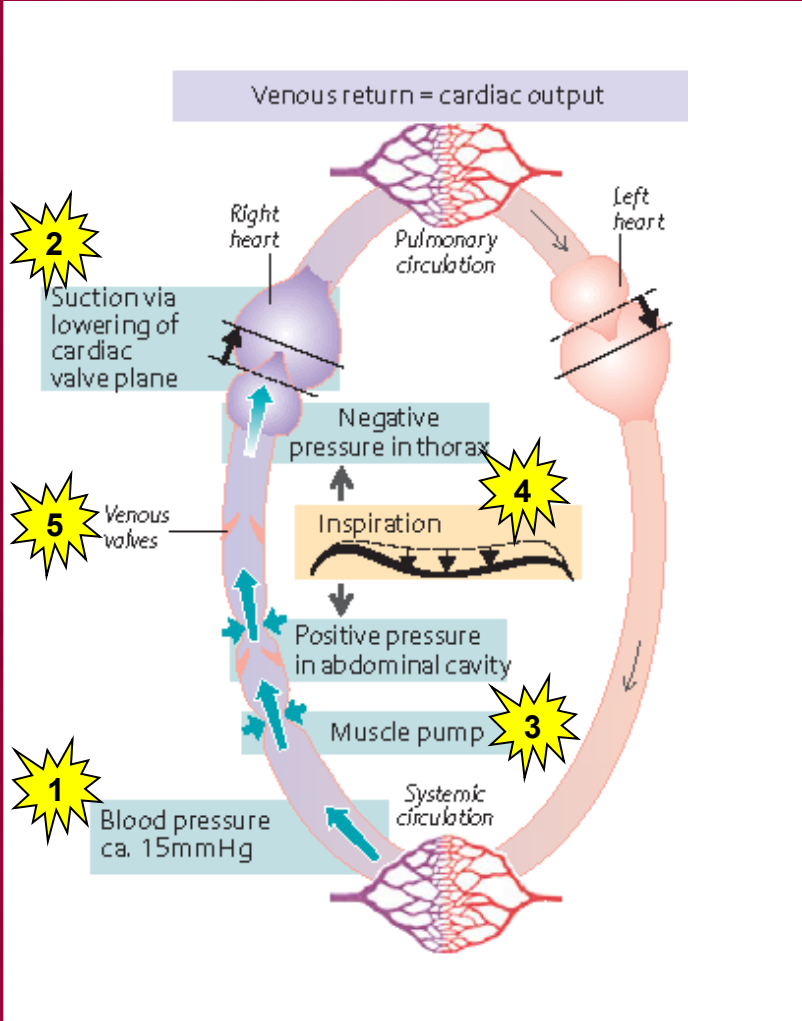
# Share stress in vessel wall



- Share stress in vessel wall may lead to a tear in endothelial layer and to arterial dissection.



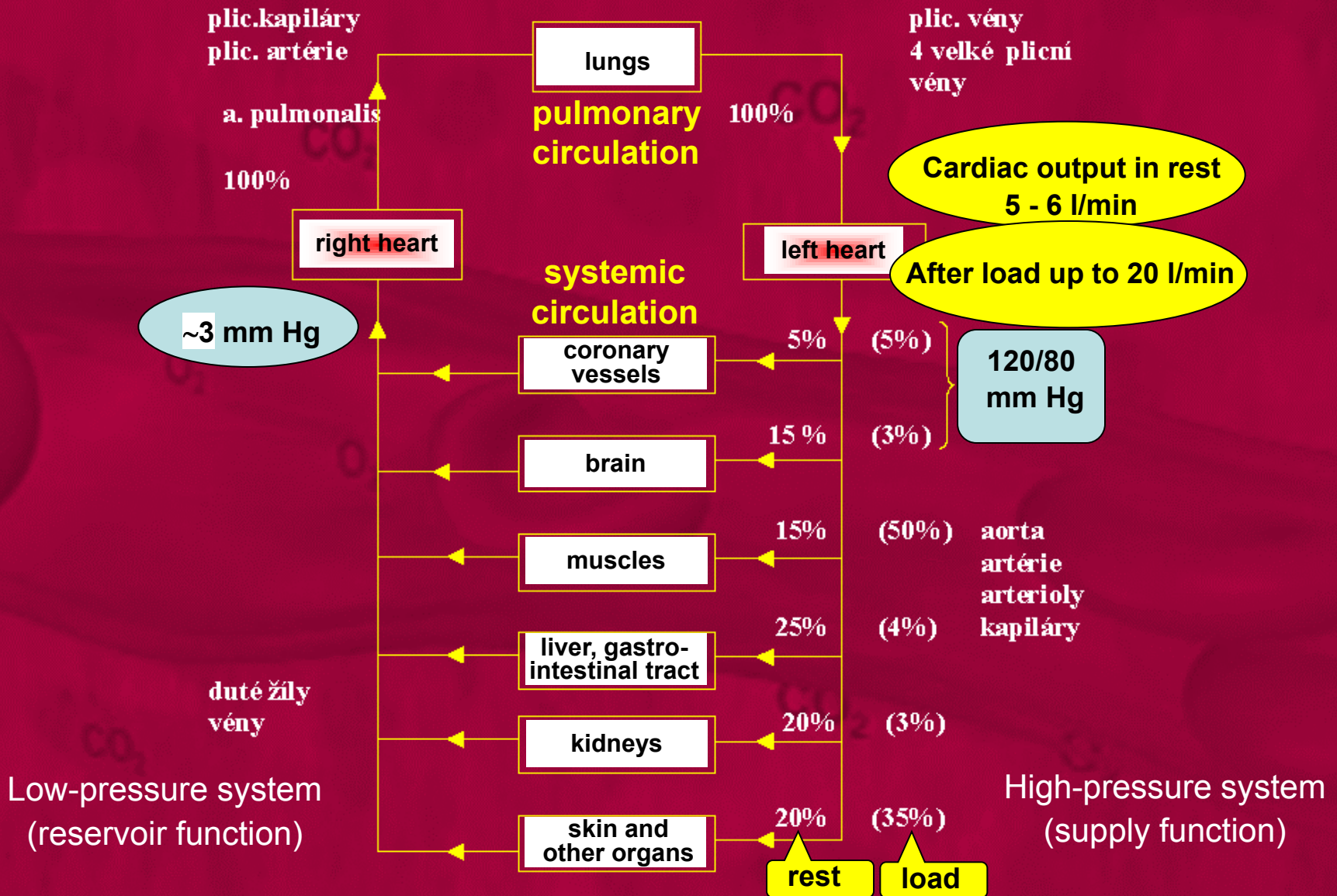
# Mechanisms of venous return





**3. Blood circulation and pressure**

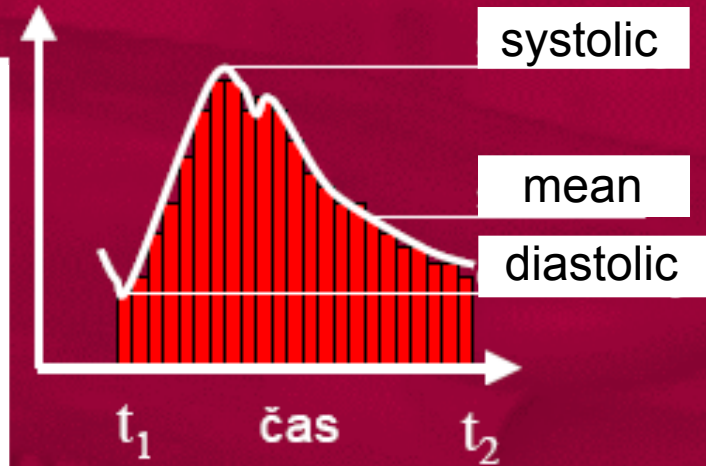
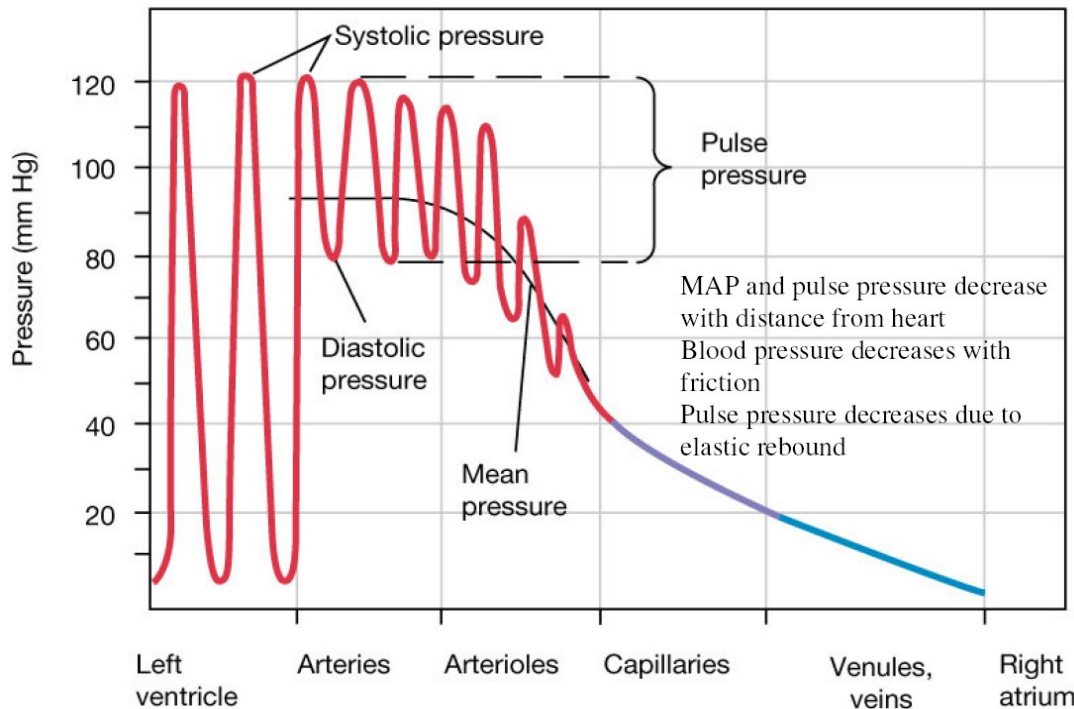
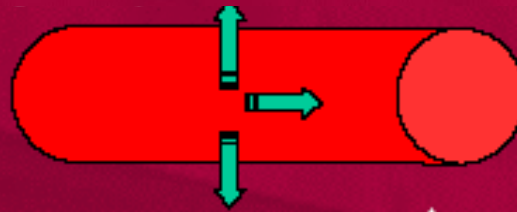
# Blood circulation





# Blood pressure

**Blood pressure (BP)** is the pressure exerted by circulating blood upon the walls of blood vessels.



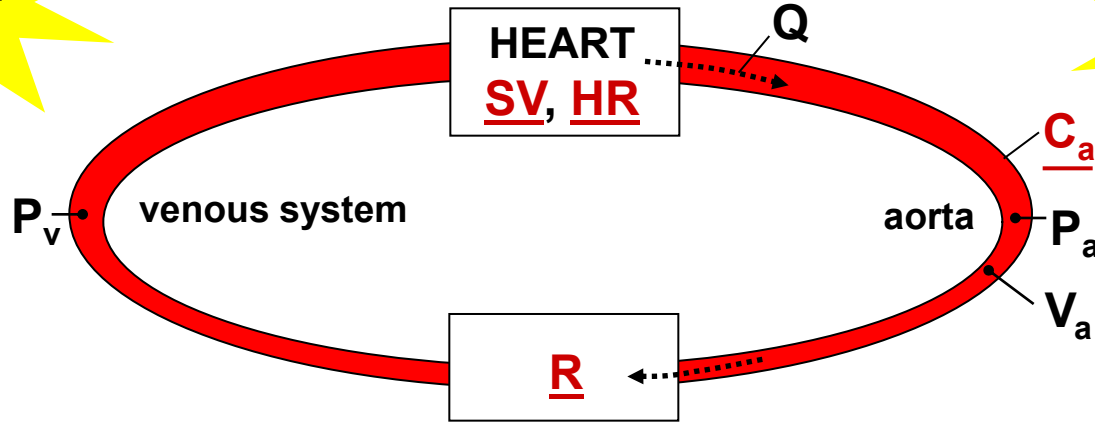
$$P_{mean} = \int_{t_1}^{t_2} \frac{P dt}{t_2 - t_1}$$

$$P_{mean} \cong Pd + \frac{1}{3}(Ps - Pd)$$



# Dependence of blood pressure on cardiac output and vascular parameters

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



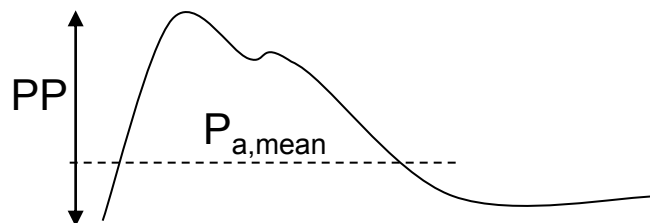
$$C = \frac{\Delta V}{\Delta P}$$

$$P_{a,mean} - P_{v,mean} = Q \cdot R$$

$$\Delta V \cong SV$$

$$P_{a,mean} = SV \cdot HR \cdot R + P_{v,mean}$$

$$P_{a,mean} \cong SV \cdot HR \cdot R$$



$$PP \cong \frac{SV}{C}$$

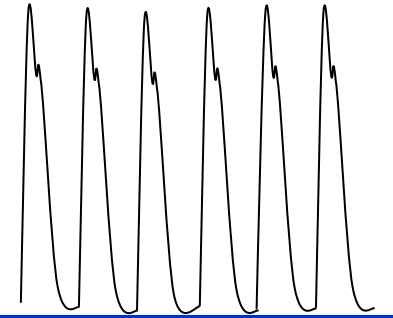
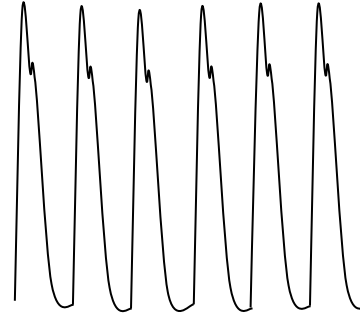
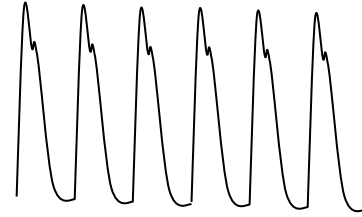
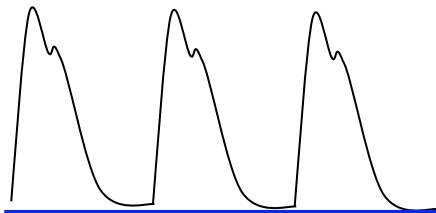
resting state

activity

+SV↑

HR↑

+R↓



$$P_{a, \text{mean}} \approx SV \cdot HR \cdot R$$

$$PP \approx \frac{SV}{C}$$

# Model of blood pressure changes in aorta

