

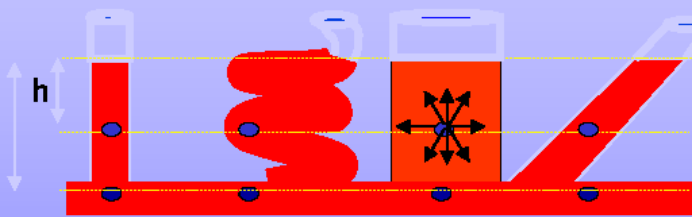
The background features a faint, light-colored diagram of a blood vessel. The vessel is shown in cross-section with a central lumen and a surrounding wall. Several labels are scattered around the vessel: 'CO₂' appears in the upper left, upper right, and lower right areas, while 'O₂' is located in the lower right area. The overall background is a dark, reddish-purple color.

Rheology of blood circulation

1. Basic physical laws of liquids

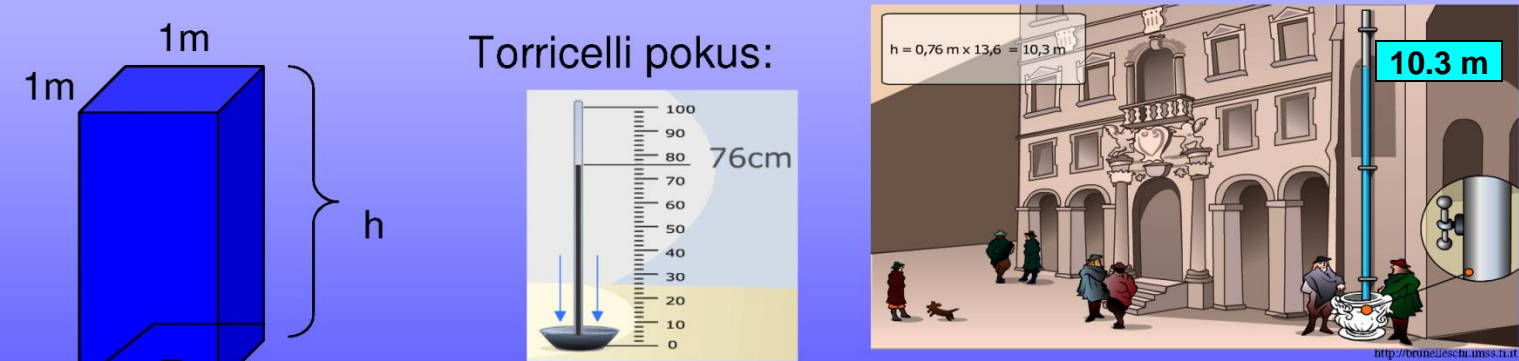
Law of Pascal

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



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

h = height
 ρ = density
 g = gravitational acceleration



1m
1m
h
Pa

Torricelli pokus:
76cm
Hg

$h = 0,76 \text{ m} \times 13,6 = 10,3 \text{ m}$
10.3 m
H₂O

Pa

mm Hg

mm H₂O

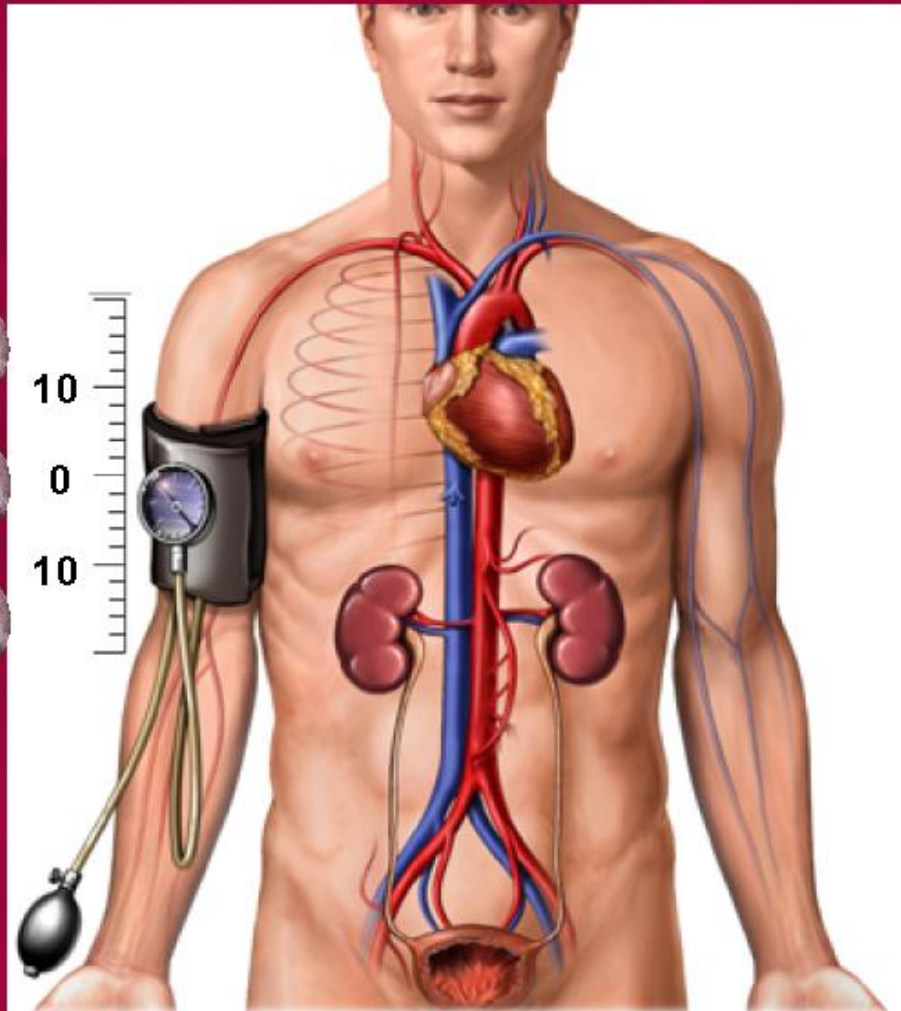
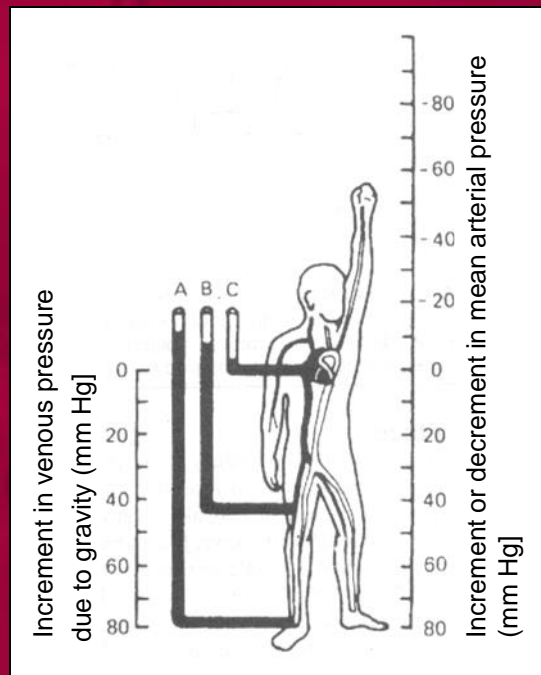
133,322 Pa = 1 mm Hg

760 mmHg = 1 atm = 10.3 m H₂O

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 [N/m²]) and tension in the wall of hollow object (T [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:

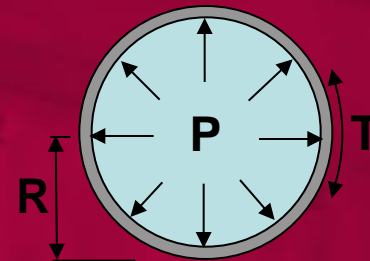
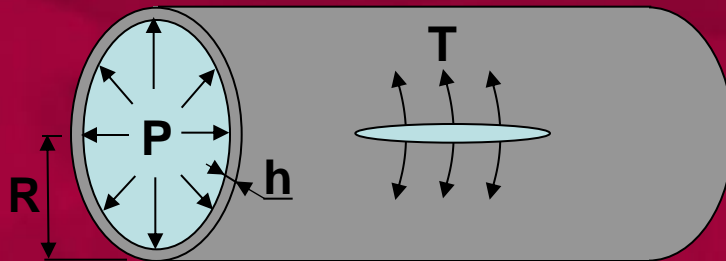
$$R_2 = \infty \Rightarrow$$

$$T = P \cdot R$$

For sphere:

$$R_1 = R_2 \Rightarrow$$

$$T = P \cdot R/2$$



Considering thickness of vessel wall (h [m]): $T = P \cdot R/h$ [N/m²]

Characteristics of vessels

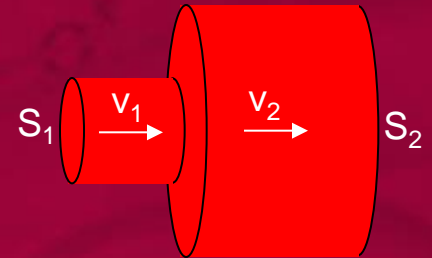
	P	R	P.R	h	P.R/h
vessel	P [kPa]	radius	tension (N/m)	wall thickness	tension (N/m ²)
aorta	13,3	13 mm nebo méně	170	2 mm	85000
arteries	12	5 mm	60	1 mm	60000
arterioles	8	150–62 μm	1,2–0,5	20 μm	40000
capillaries	4	4 μm	$1,6 \cdot 10^{-2}$	1 μm	16000
venules	2,6	10 μm	$2,6 \cdot 10^{-2}$	2 μm	13000
veins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

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



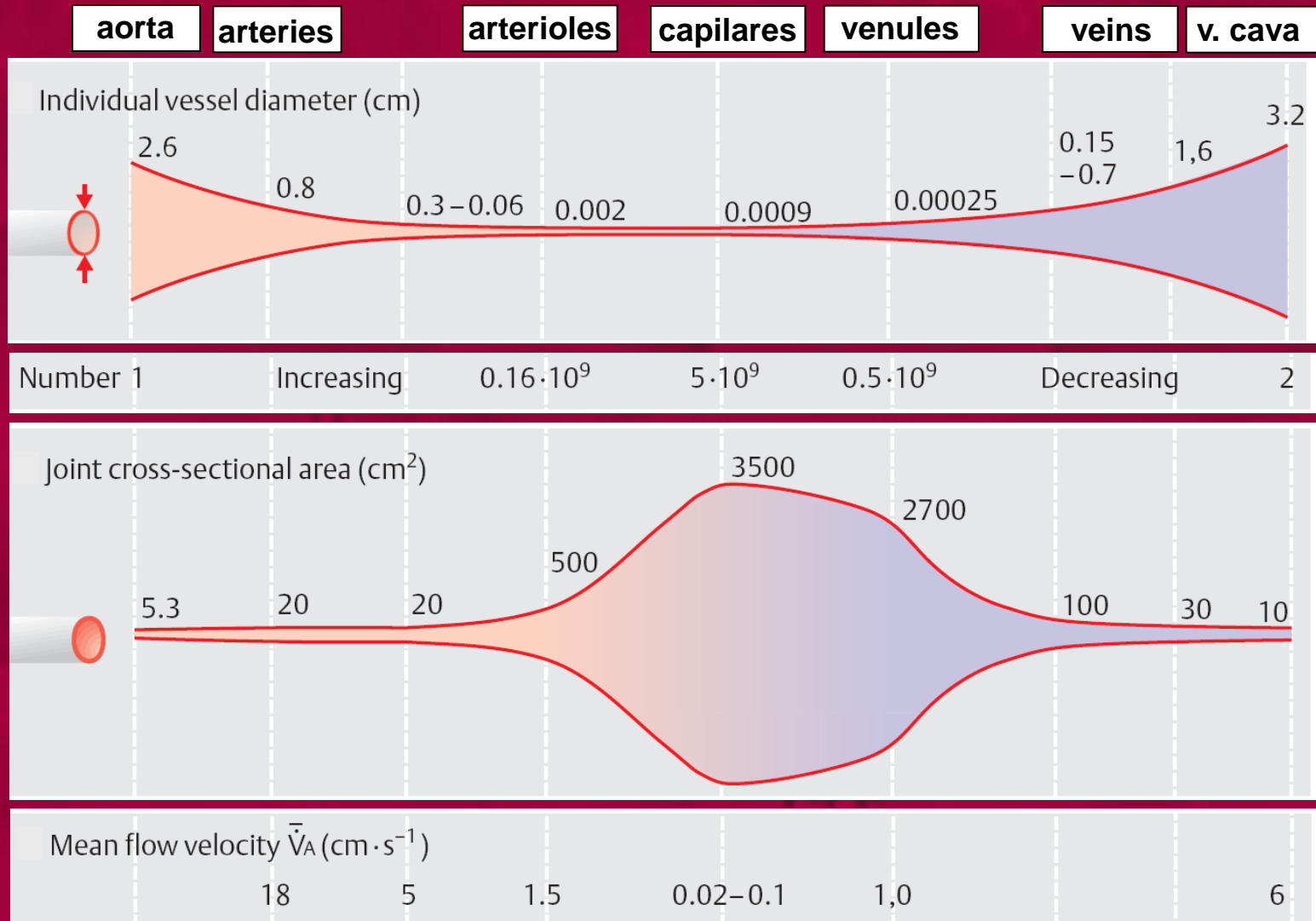
Average blood velocity in vessels

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

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

vessel	diameter	number	total area	velocity
aorta	~ 2.6 cm	1	~ 5.3 cm ²	~ 18 cm/s
arterioles	20-50 μm	~ 5×10 ⁶	~ 60 cm ²	~ 1.5 cm/s
capillaries	4-9 μm	~ 5×10 ⁹	~ 2000 cm ²	~ 0.04 cm/s
venules	~ 20 μm	~ 32×10 ⁶	~ 100 cm ²	~ 1 cm/s
vena cava	~ 3 cm	2	~ 14 cm ²	~ 7 cm/s

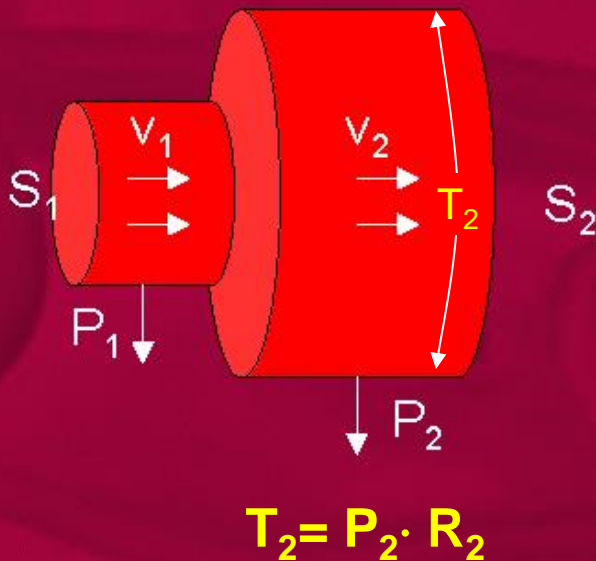
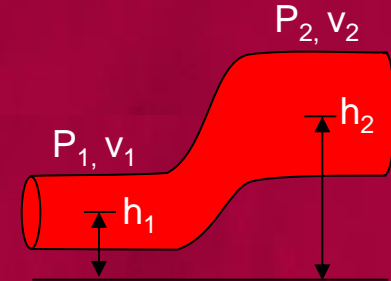
Relation between total cross-sectional area of vessels and mean flow velocity



Bernoulli's principle

Law of energy conservation for fluid :

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



Implication at aortic aneurysm

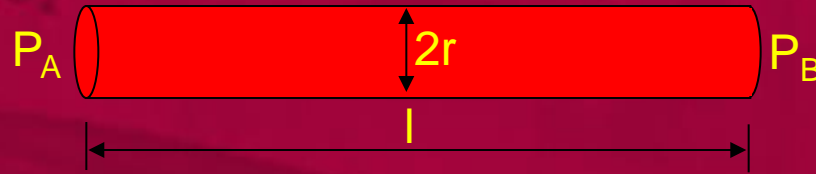
$S_1 v_1 = S_2 v_2$ a je-li $S_1 < S_2$, musí platit: $v_1 > v_2$

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

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

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 (η).

Limitation:

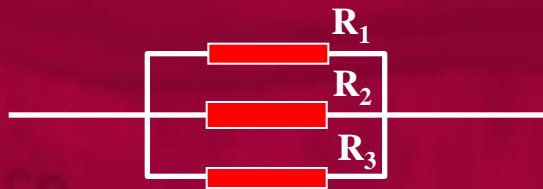
- For stationary flow in Newtonian fluids where viscosity is constant and independent on flow velocity.

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

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



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

pro $R_1=R_2=R_3=R_n$

$$R_c = R/n$$

Series arrangement of vessels

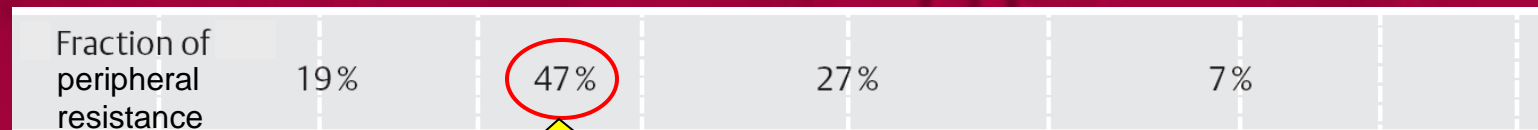
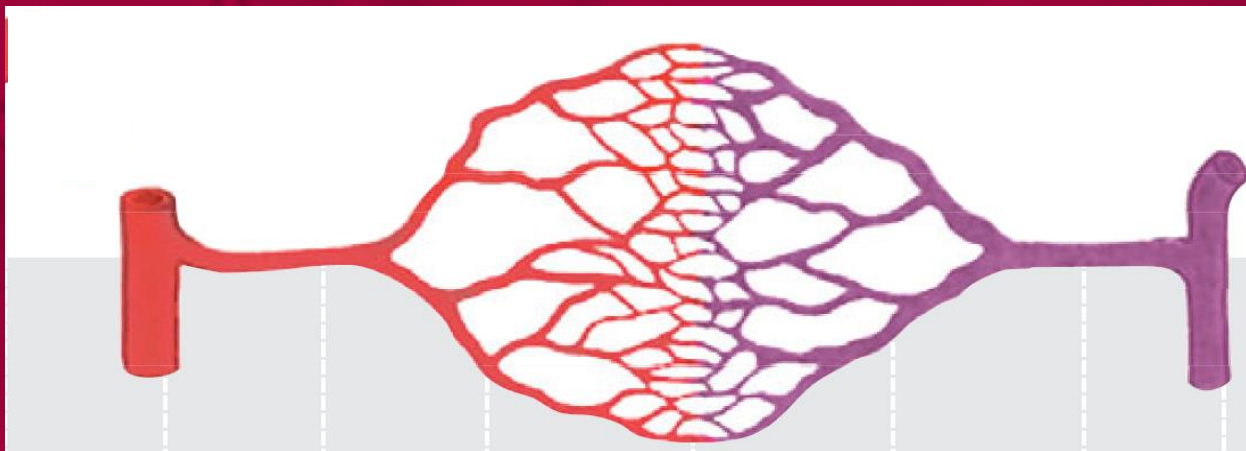
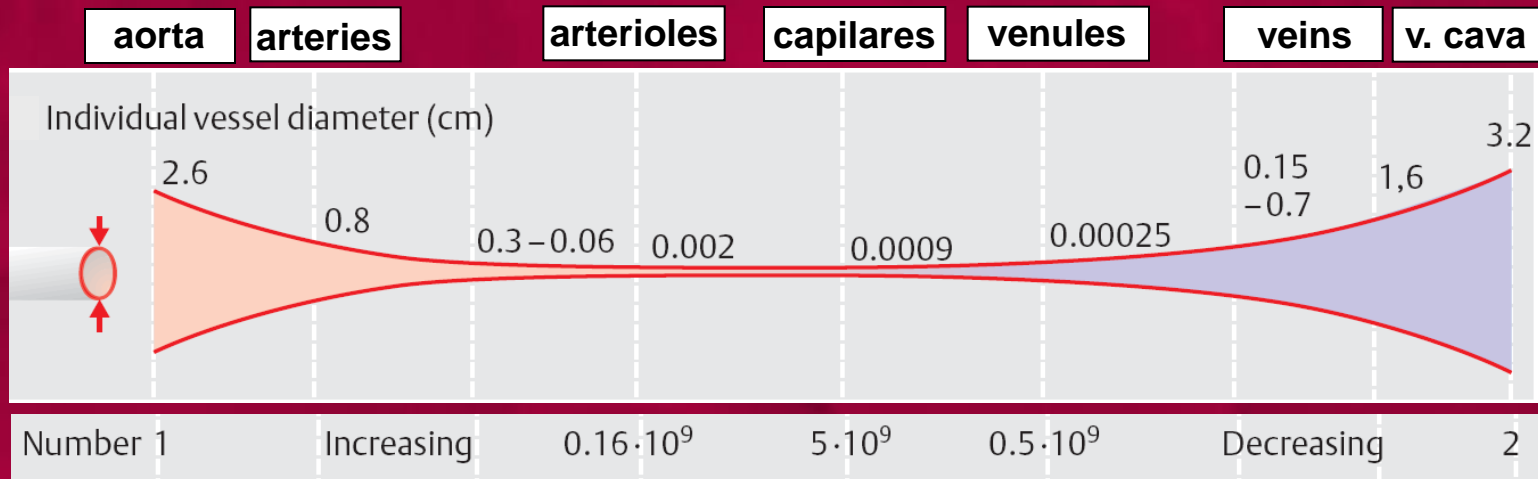


$$R_c = R_1 + R_2 + \dots$$

pro $R_1=R_2=R_3=R_n$

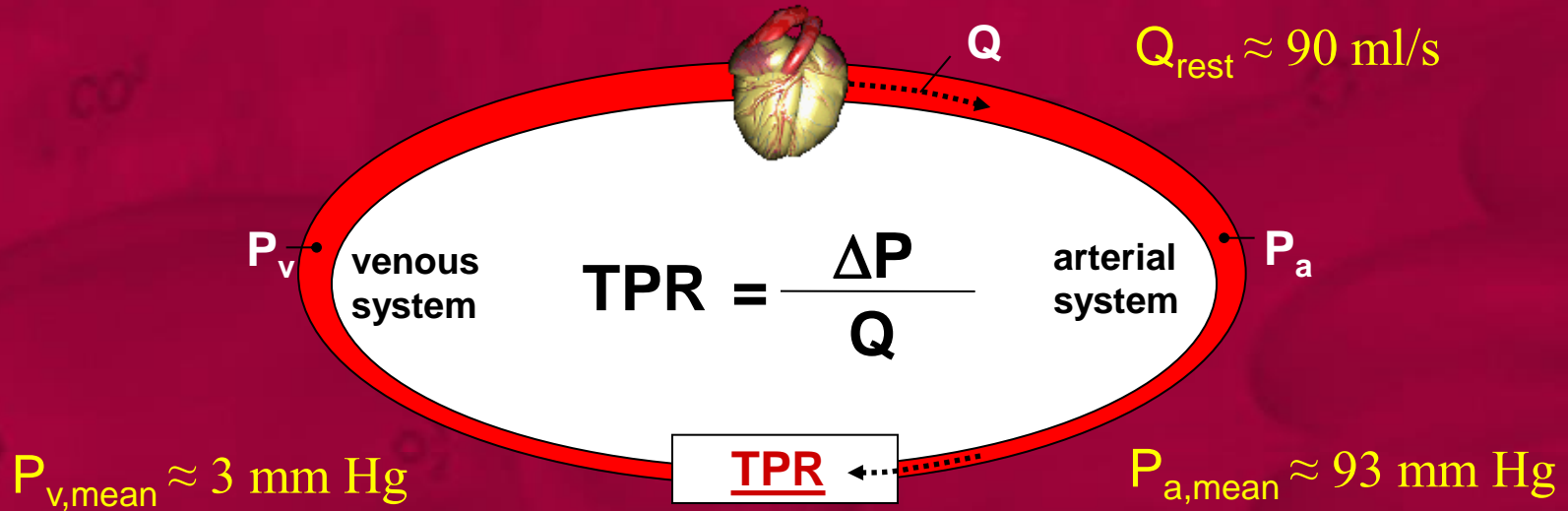
$$R_c = R \cdot n$$

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 : $\uparrow TPR \Rightarrow \uparrow P_a \Rightarrow$ hypertension,....

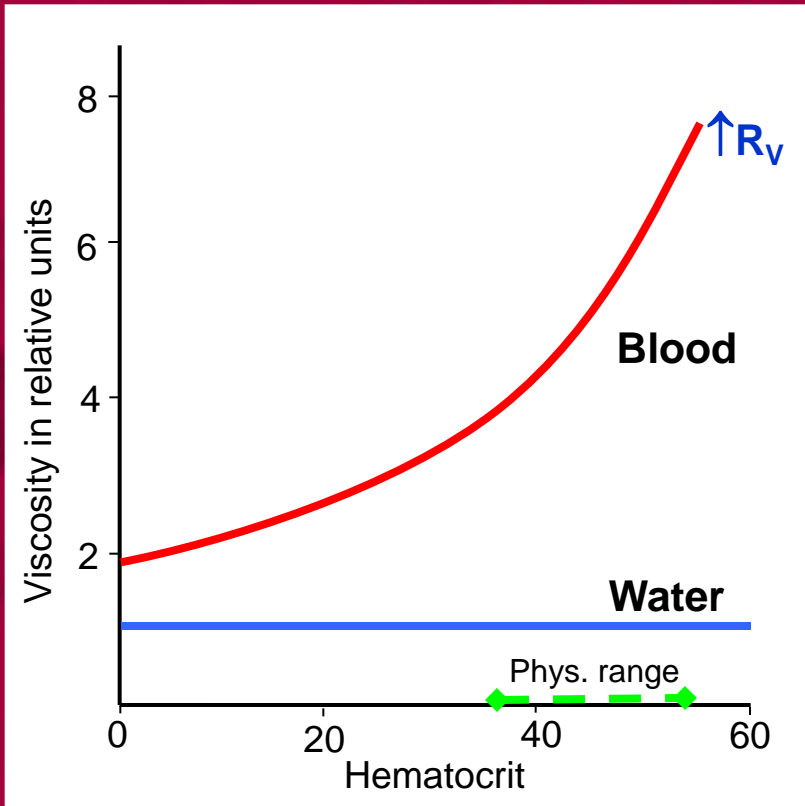
The background of the slide is a dark red color with a faint, semi-transparent diagram of a blood vessel. The diagram shows a vessel with a wavy wall, and several red blood cells are depicted as red circles. Labels for CO_2 and O_2 are scattered throughout the diagram, indicating the transport of these gases. The text "2. Rheological features of blood and vessels" is centered in a white box with a black gradient background.

2. Rheological features of blood and vessels

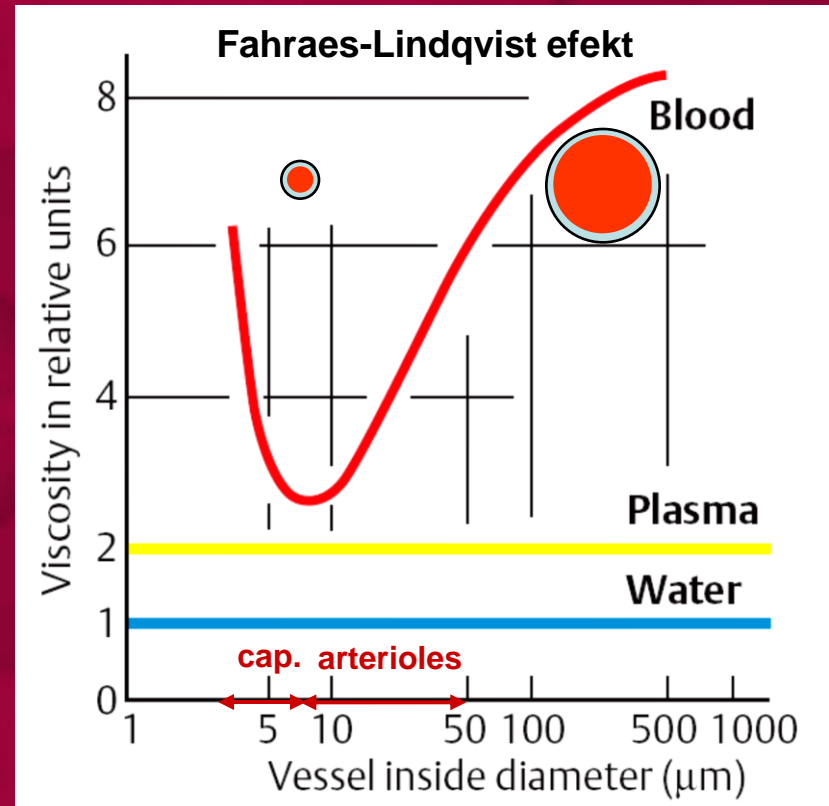
Blood viscosity

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

Effect of hematocrit



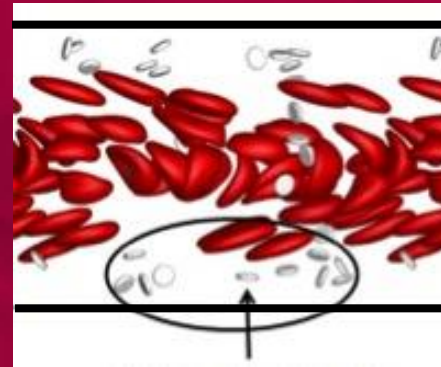
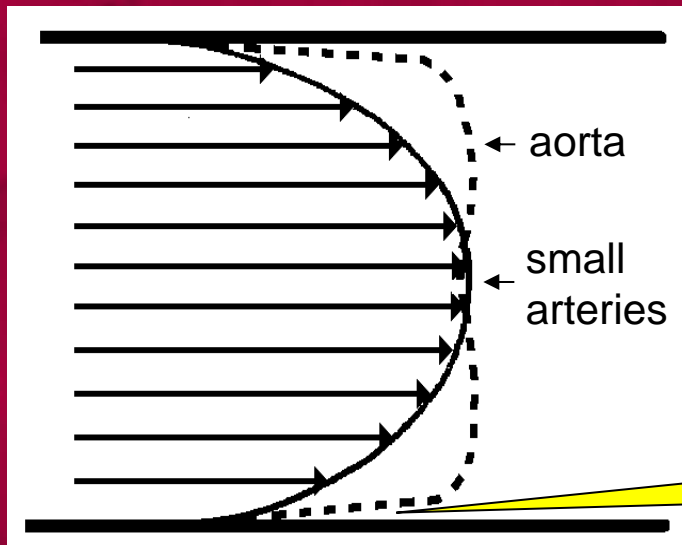
Effect of diameter in small vessels



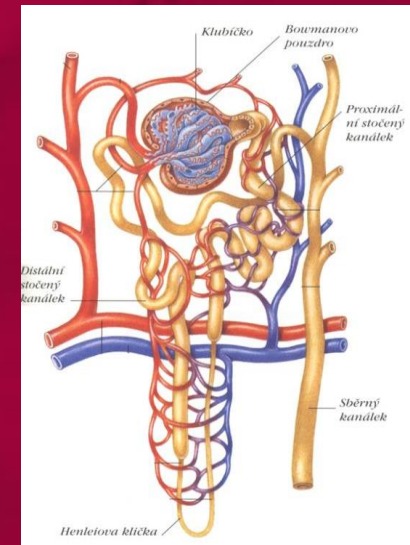
Other factors causing increase of viscosity:

- decrease of blood flow velocity
- elevation of plasma proteins

Velocity profile of the blood flow in vessels



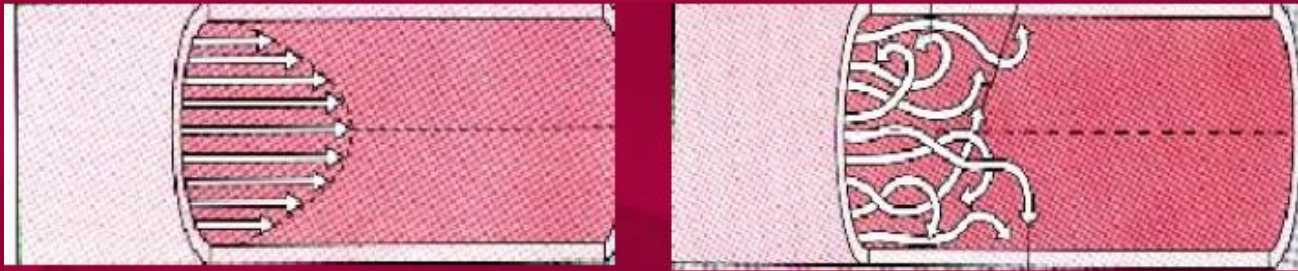
plasma-skimming



- 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

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

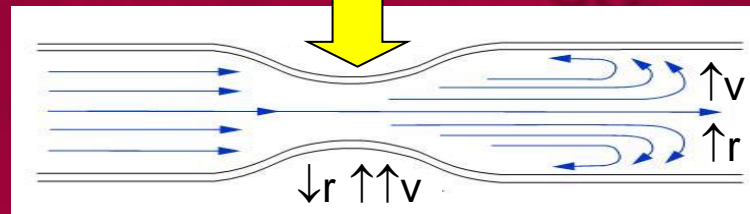
laminar flow

$Re < 2000$

turbulent flow

$Re > 3000$

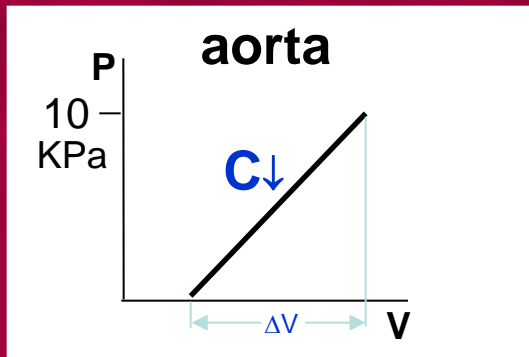
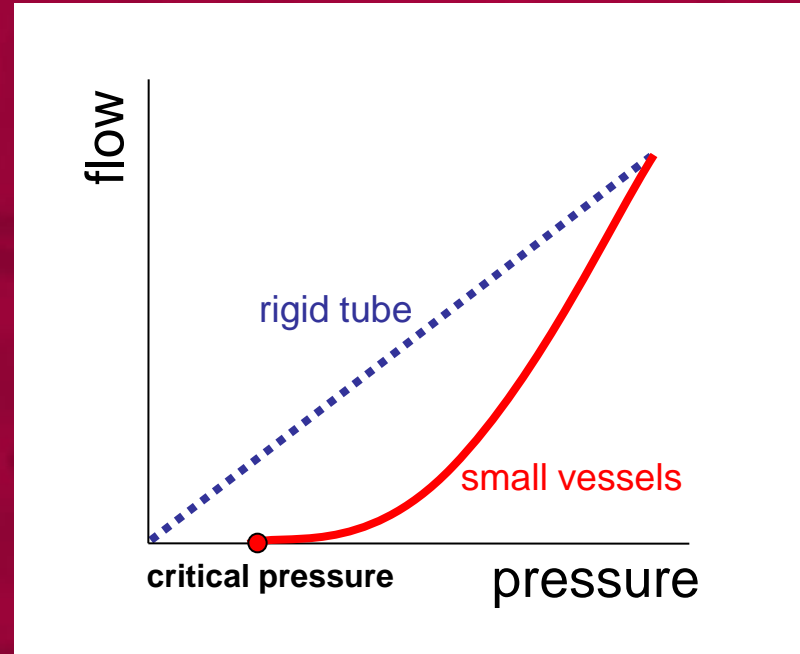
Sudden change of vessel diameter



$$\uparrow R_e \Rightarrow \uparrow R_v$$

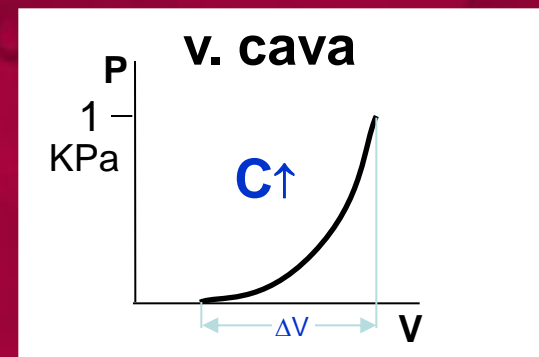
Pathological states causing turbulent flow: aneurisma, stenosis, arteriosclerosis, decreased blood viscosity, .

Elasticity of vessels

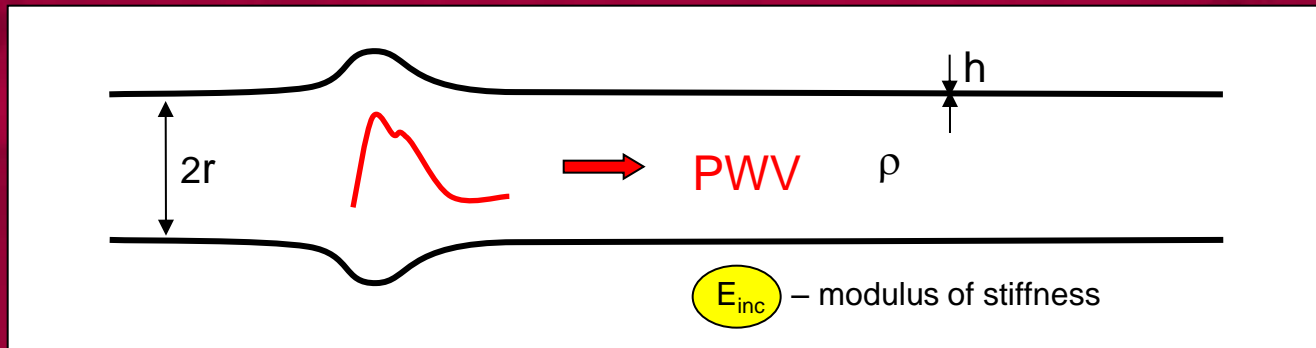


compliance

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



Pulse wave velocity (PWV)

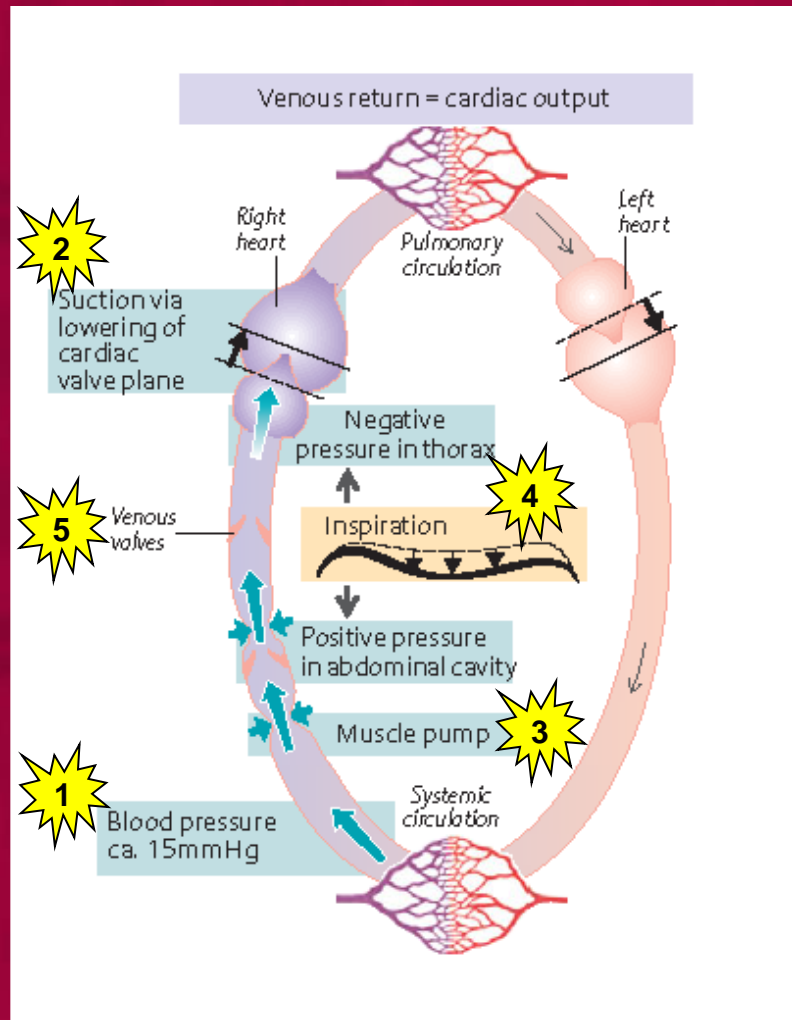


Moens-Korteweg (1878)

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

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

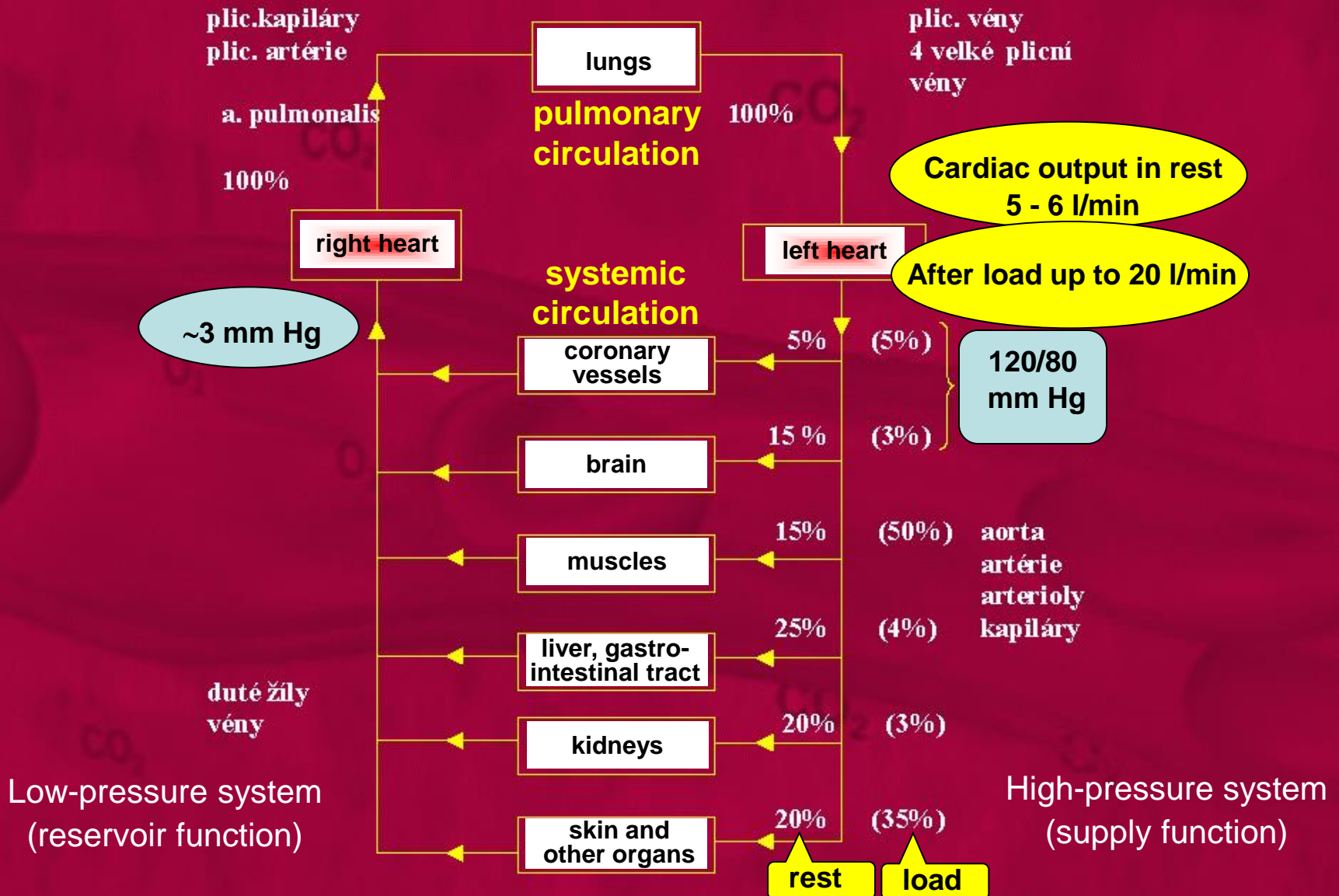
Mechanisms of venous return



The background features a faint, light-colored diagram of a blood vessel with a wavy wall. The vessel is shown in cross-section, with arrows indicating the direction of flow. Several chemical formulas are scattered around the vessel: 'CO2' appears in the upper and lower regions, while 'O2' is located in the middle-right section. The overall background is a solid, dark red color.

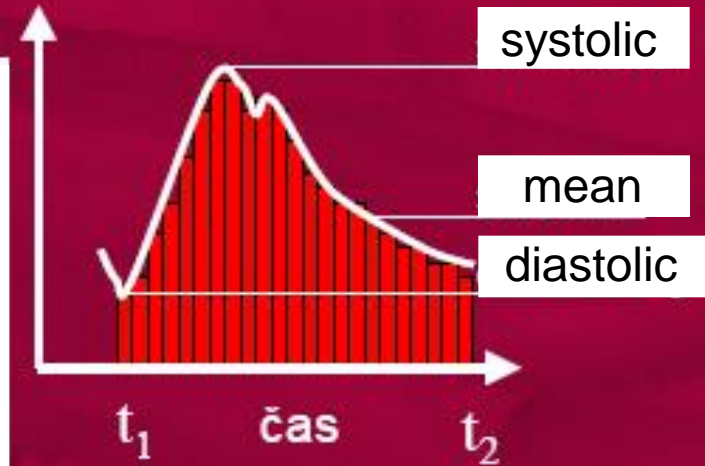
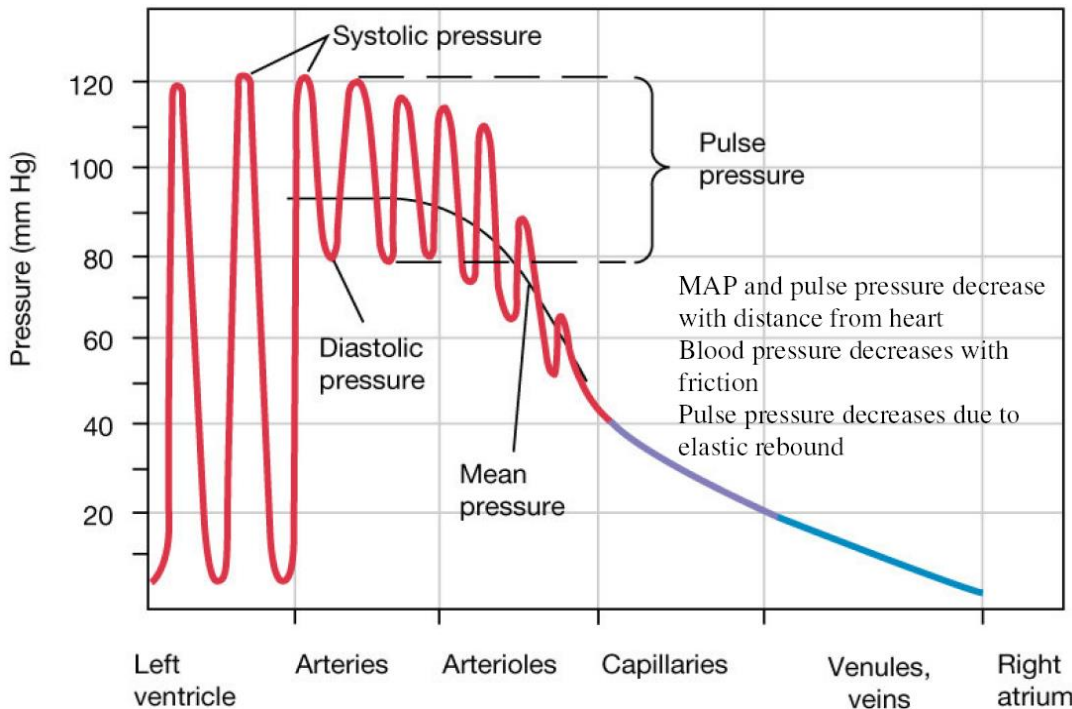
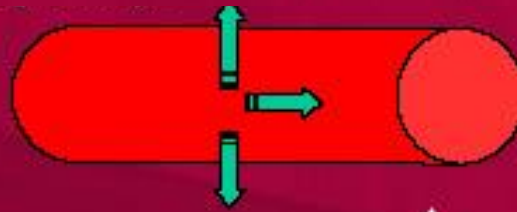
3. Blood circulation and pressure

Blood circulation



Blood pressure

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

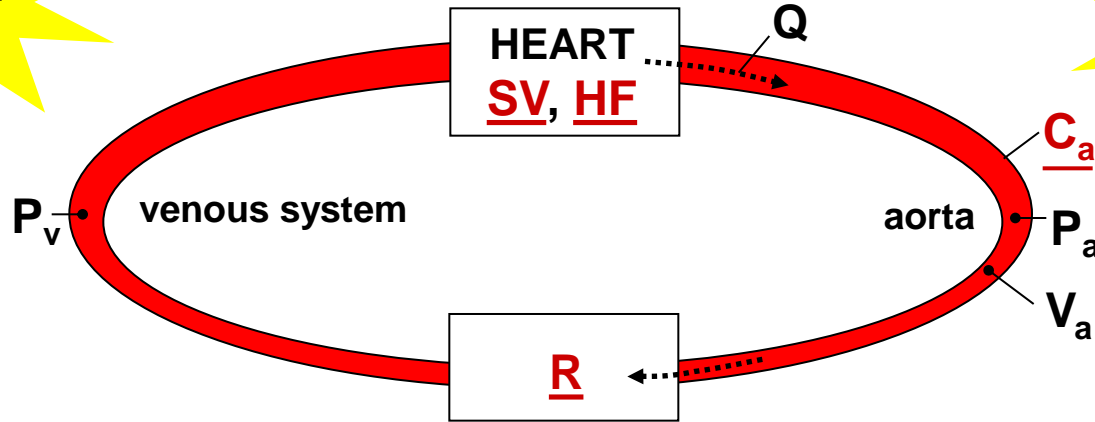


$$P_{mean} = \int_{t_1}^{t_2} \frac{P dt}{t_2 - t_1}$$

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

Dependence of blood pressure on cardiac output and vascular parameters

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



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

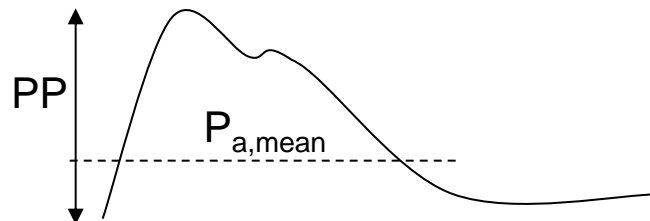
$$P_{a,mean} - P_{v,mean} = Q \cdot R$$

$$\Delta V \cong SV$$

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

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

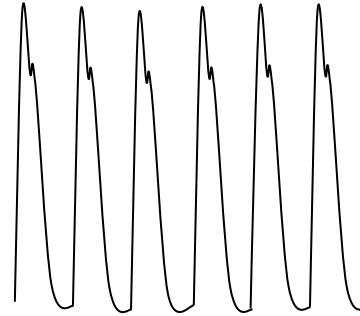
$$P_{a,mean} \cong SV \cdot HF \cdot R$$



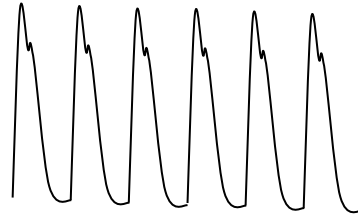
resting state

activity

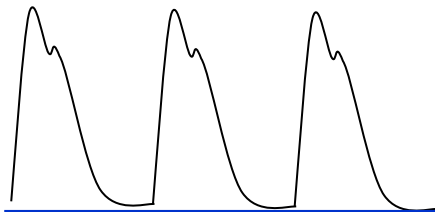
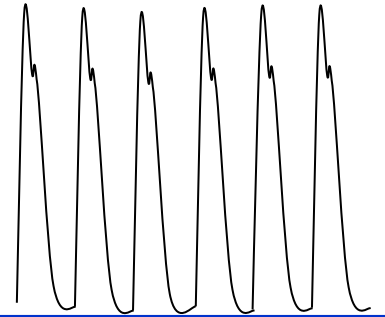
+SV↑



TF↑



+R↓



$$P_{a, \text{str}} \cong SV \cdot HF \cdot R$$

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

Model of blood pressure changes in aorta

