



The background features a schematic diagram of blood circulation. A central vessel is shown with arrows indicating the direction of flow. On the left, the vessel is labeled CO_2 , and on the right, it is labeled O_2 . The vessel is surrounded by several cells, each with a nucleus and cytoplasm. The cells are also labeled with CO_2 and O_2 , indicating the exchange of these gases between the blood and the tissues.

Rheology of blood circulation

1. Basic physical laws of liquids

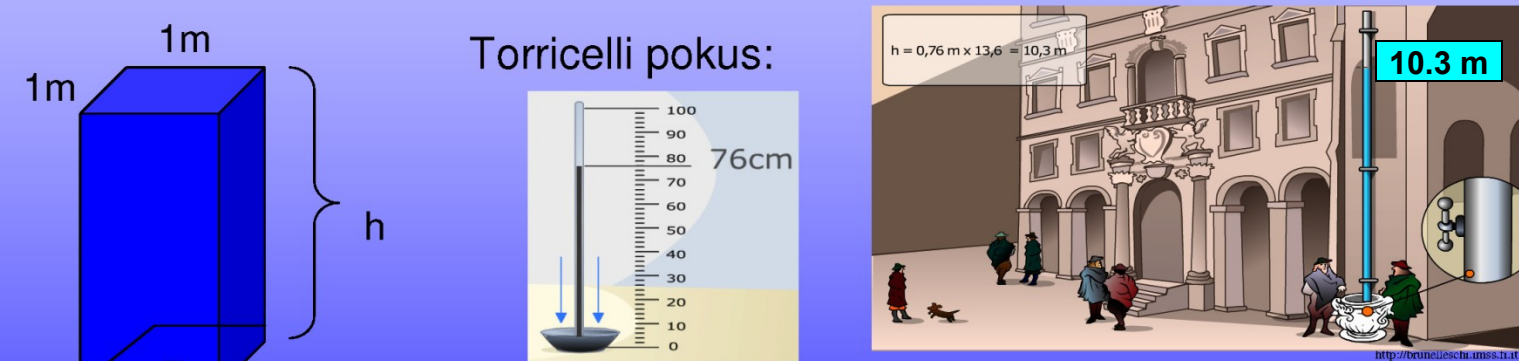
Law of Pascal

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:



100
90
80
76cm
70
60
50
40
30
20
10
0
Hg



$h = 0,76 \text{ m} \times 13,6 = 10,3 \text{ m}$
10.3 m
H₂O
<http://brunelleschi.uniss.it>

Pa

mm Hg

mm H₂O

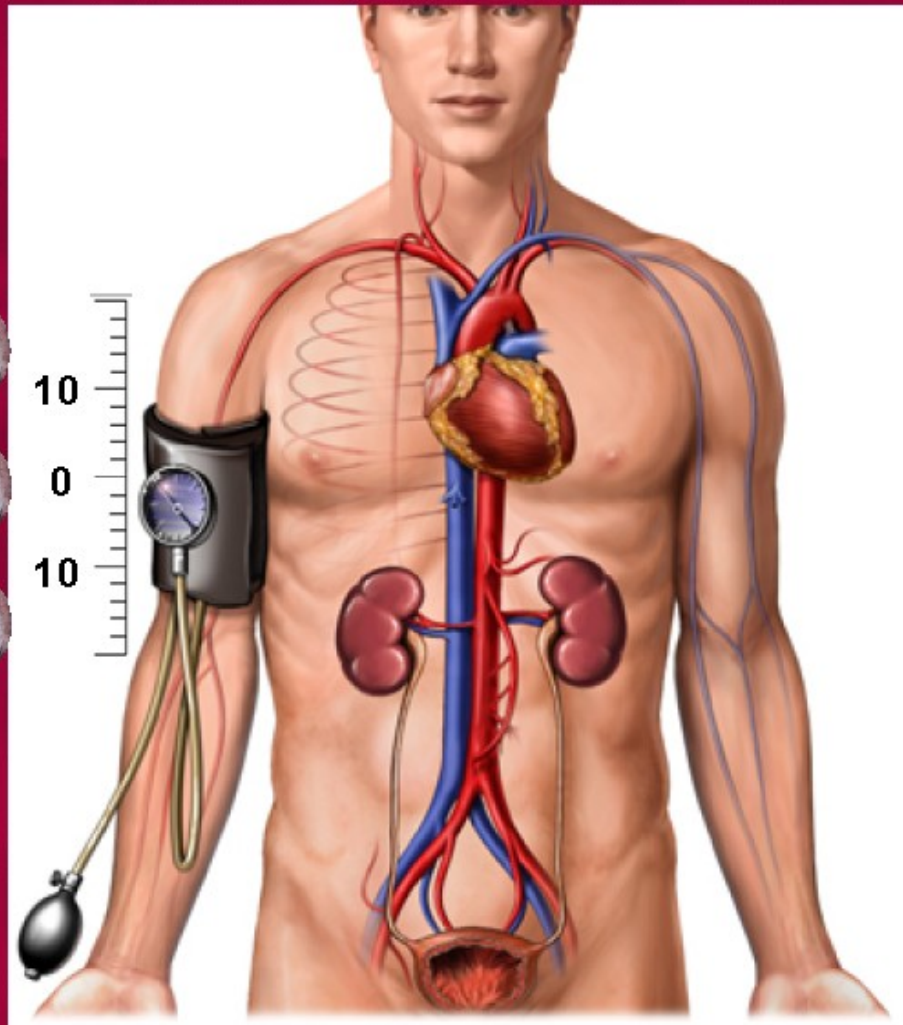
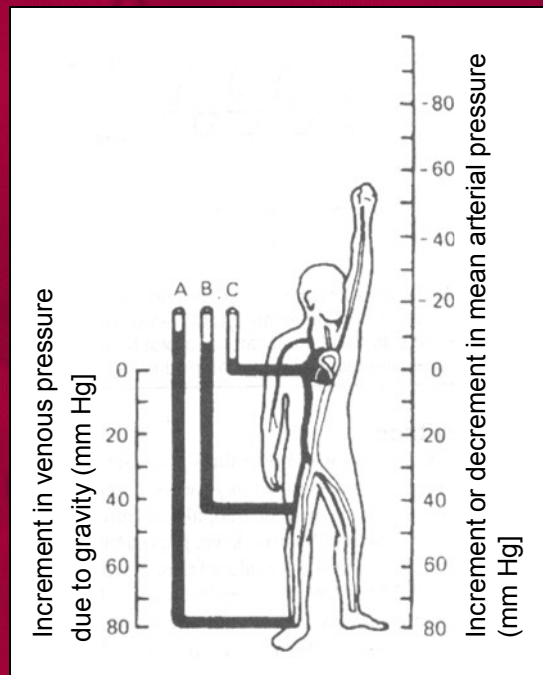
133,322 Pa = 1 mm Hg

760 mmHg = 1 atm = 10.3 m H₂O

Effect of gravity on arterial and venous pressure

Per each 10 cm

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



Law of Laplace

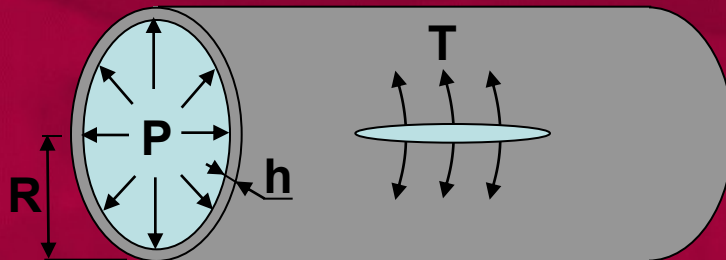
Relation between distending pressure (P [N/m^2]) and tension in the wall of hollow object (T [N/m]) :

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

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

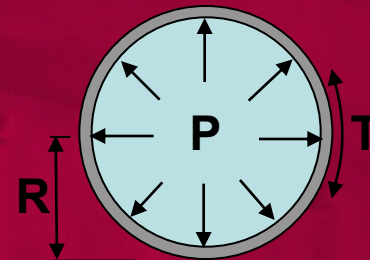
For vessel:

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



For sphere:

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



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

Characteristics of vessels

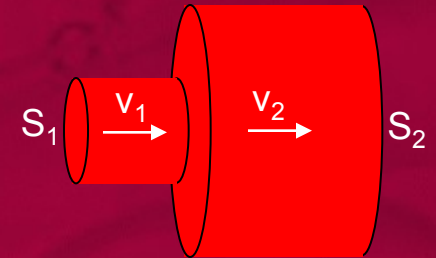
	P	R	P·R	h	P·R/h
vessel	P [kPa]	radius	tension (N/m)	wall thickness	tension (N/m ²)
aorta	13,3	13 mm nebo méně	170	2 mm	85000
arteries	12	5 mm	60	1 mm	60000
arterioles	8	150–62 μm	1,2–0,5	20 μm	40000
capillaries	4	4 μm	$1,6 \cdot 10^{-2}$	1 μm	16000
venules	2,6	10 μm	$2,6 \cdot 10^{-2}$	2 μm	13000
veins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



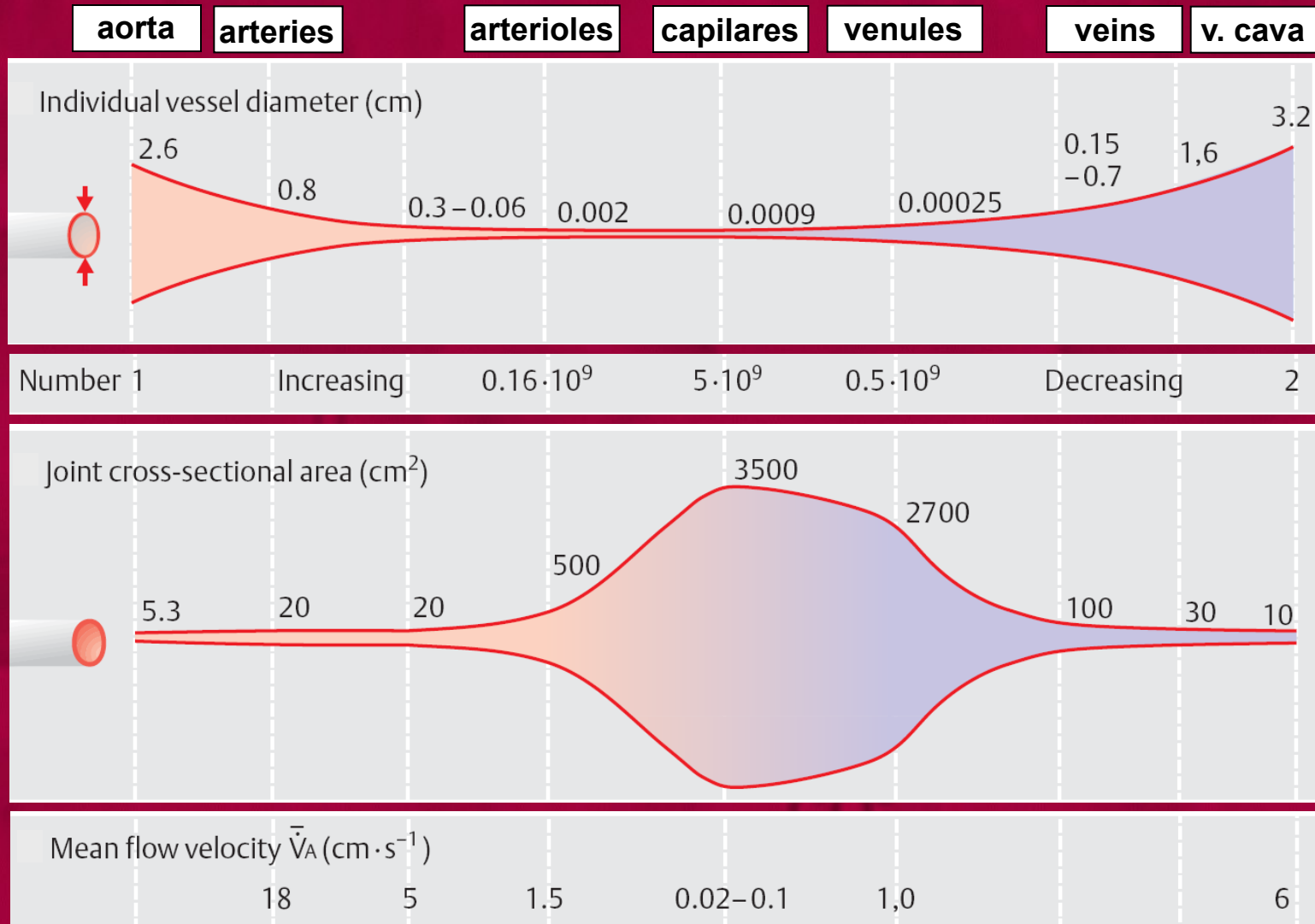
Average blood velocity in vessels

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

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

vessel	diameter	number	total area	velocity
aorta	2.6 cm	1	5.3 cm ²	~ 18 cm/s
arterioles	20-50 μm			~ 1.5 cm/s
capillaries	4-9 μm	5×10 ⁹	2000 cm ²	~ 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



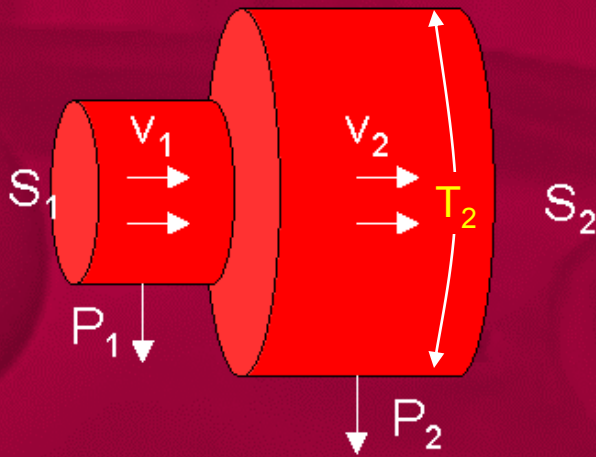
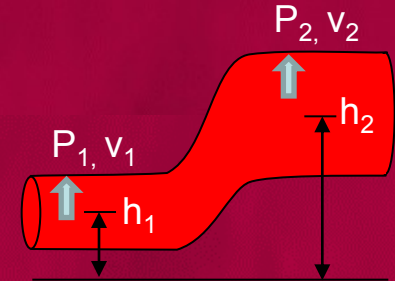
Bernoulli's principle

Law of energy conservation for fluid :

dynamic pressure

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

static pressure



$$T_2 = P_2 \cdot R_2$$

Implication for aortic aneurysm

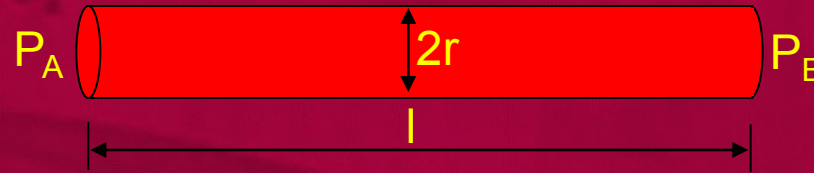
$S_1 v_1 = S_2 v_2$ a je-li $S_1 < S_2$, musí platit: $v_1 > v_2$

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

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

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 (η)

Limitation:

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

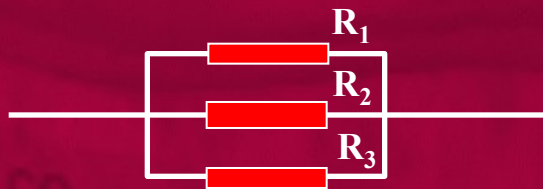
$$Q = \frac{\pi \cdot \Delta P \cdot r^4}{8 \cdot l \cdot \eta}$$

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

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

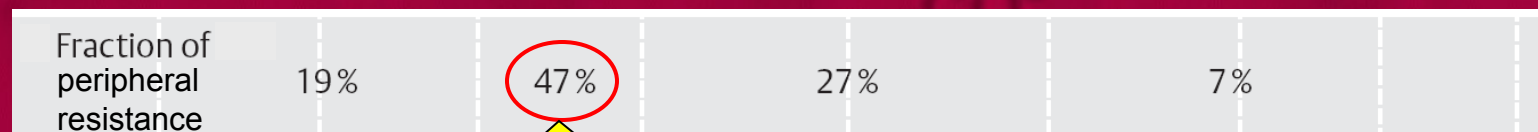
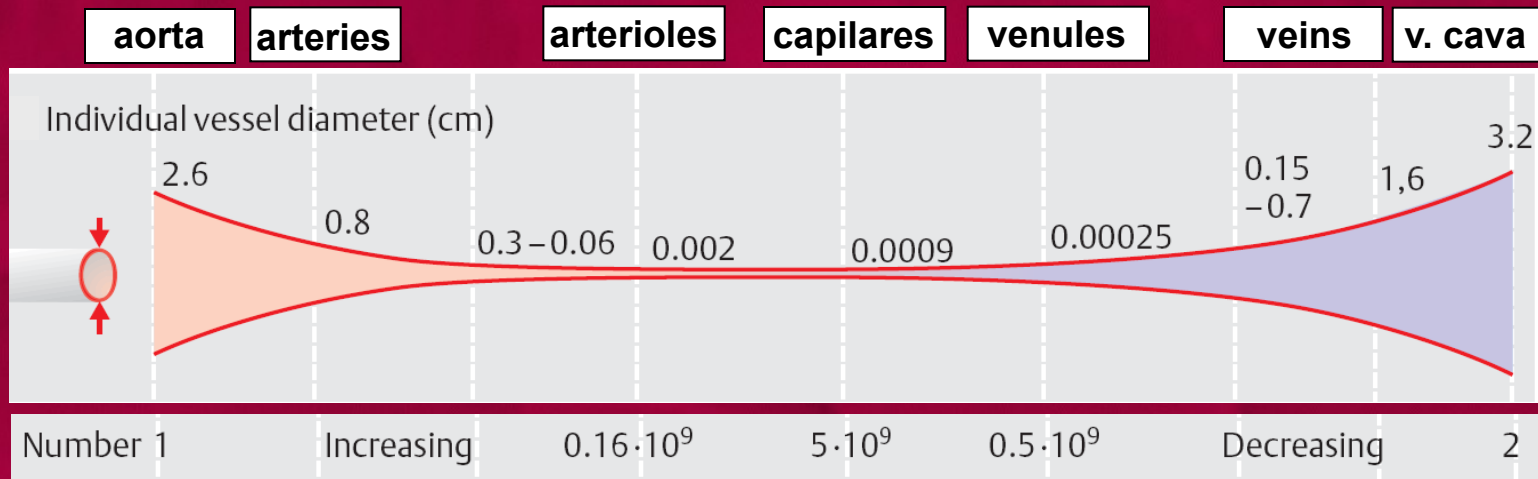


$$R_c = R_1 + R_2 + \dots$$

pro $R_1=R_2=R_3=R_n$

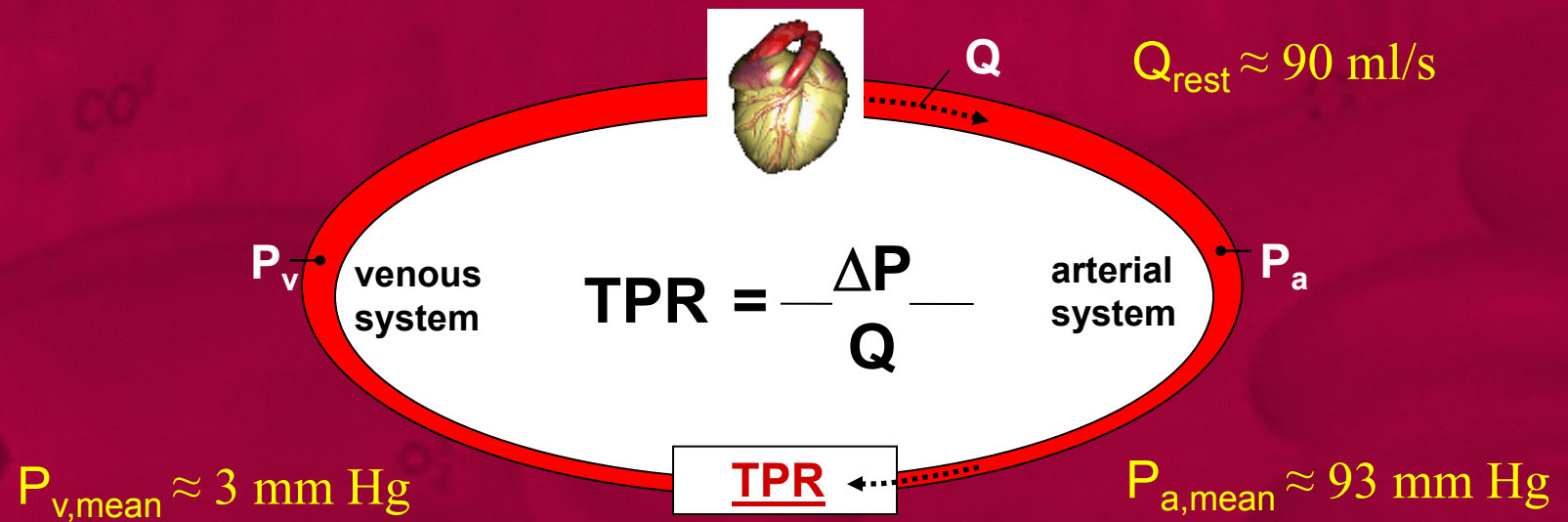
$$R_c = R \cdot n$$

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: \square PR \square P_a \square hypertension, ... cardiac disease.

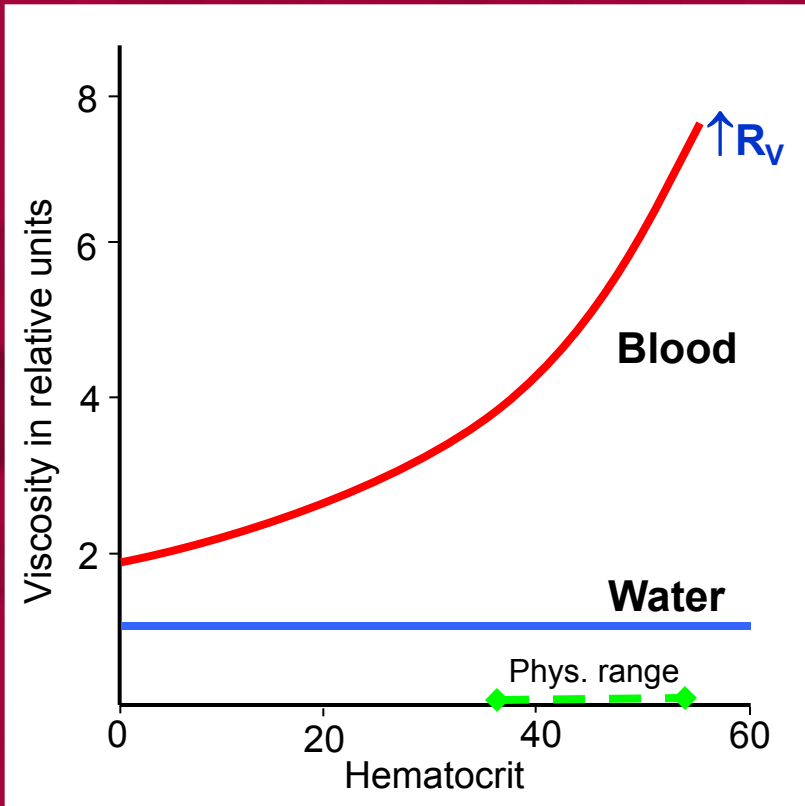
The background features a faint, light-colored diagram of a blood vessel. The vessel is shown in cross-section, with a central lumen and a surrounding wall. Several labels are scattered around the vessel: 'CO₂' appears in the upper left, upper right, and lower left areas, while 'O₂' is located in the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

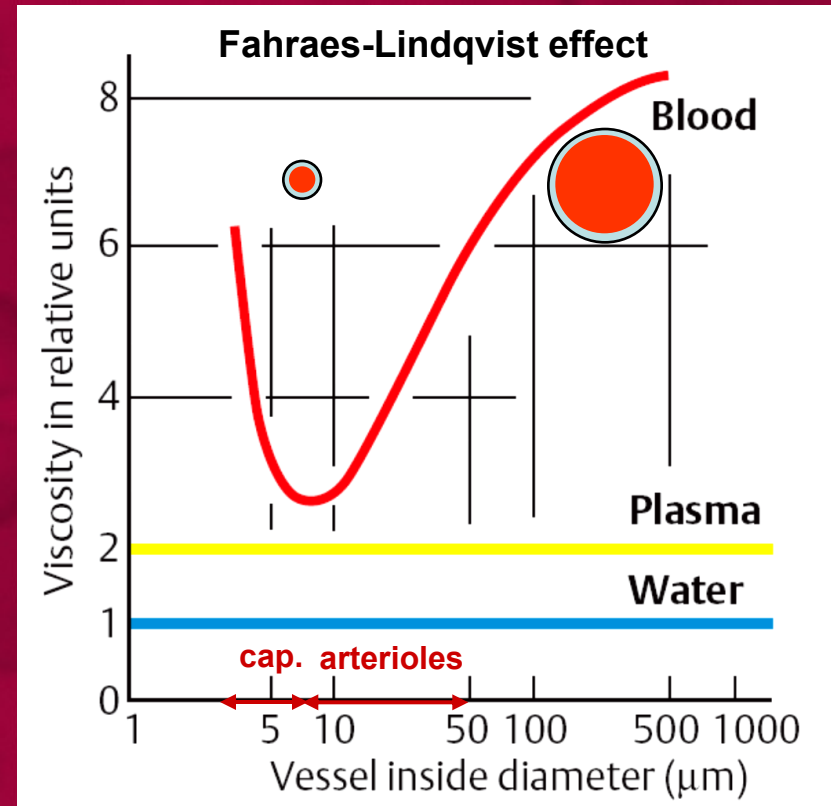
Blood viscosity

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

Effect of hematocrit



Effect of diameter in small vessels



Other factors causing increase of viscosity:

- decrease of blood flow velocity
- elevation of plasma proteins

Laminar and turbulent flow

Velocity profile in laminar and turbulent flow



The character of the flow is determined by Reynolds number

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

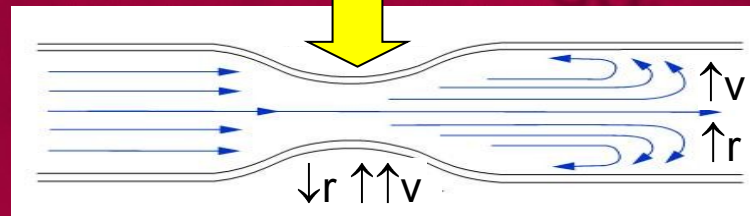
laminar flow

$Re < 2000$

turbulent flow

$Re > 3000$

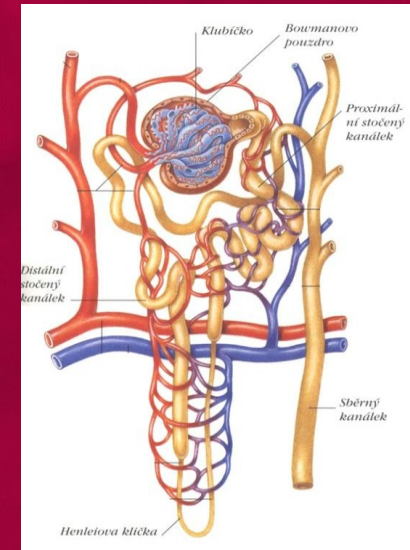
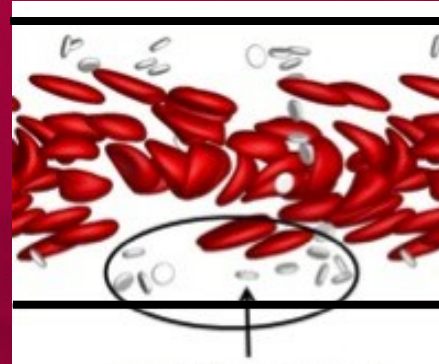
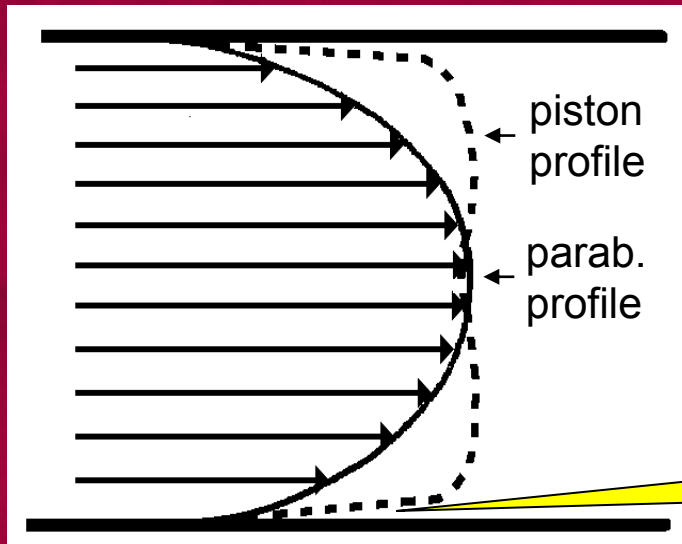
Sudden change of vessel diameter



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

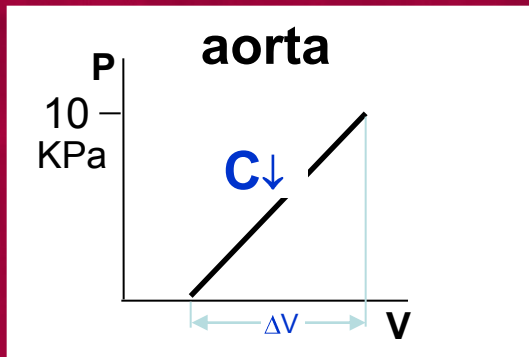
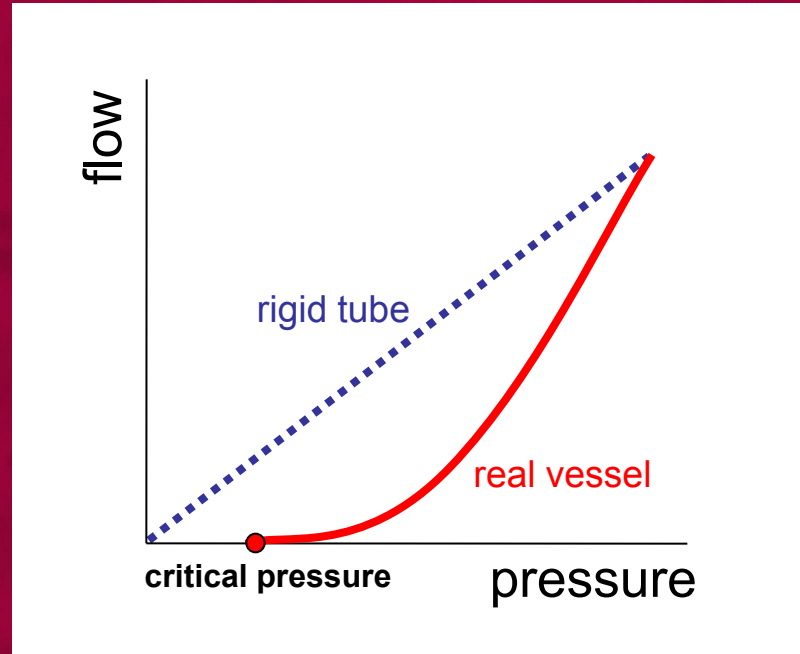
Pathological states causing turbulent flow: aneurisma, stenosis, arteriosclerosis, decreased blood viscosity, .

Velocity profile of the blood flow in vessels



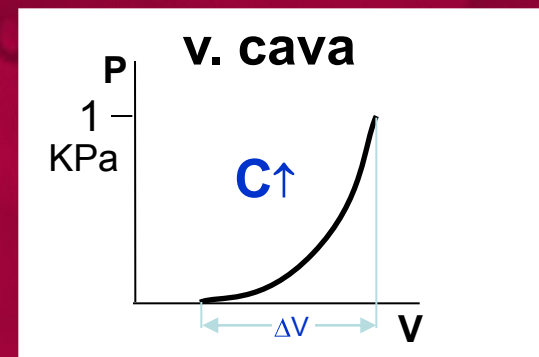
- In small arteries (at $r < 100 \mu\text{m}$), the central movement of erythrocytes causes a piston-like profile of the blood flow.
- In bigger arteries (at $r > 500 \mu\text{m}$), the laminar flow prevails and the velocity profile of the blood flow has a parabolic shape.
- In big arteries (especially in aorta), a higher cardiac output causes a turbulent flow ($R_e > 3000$) and the parabolic profile of the blood flow changes to the piston one.

Elasticity of vessels

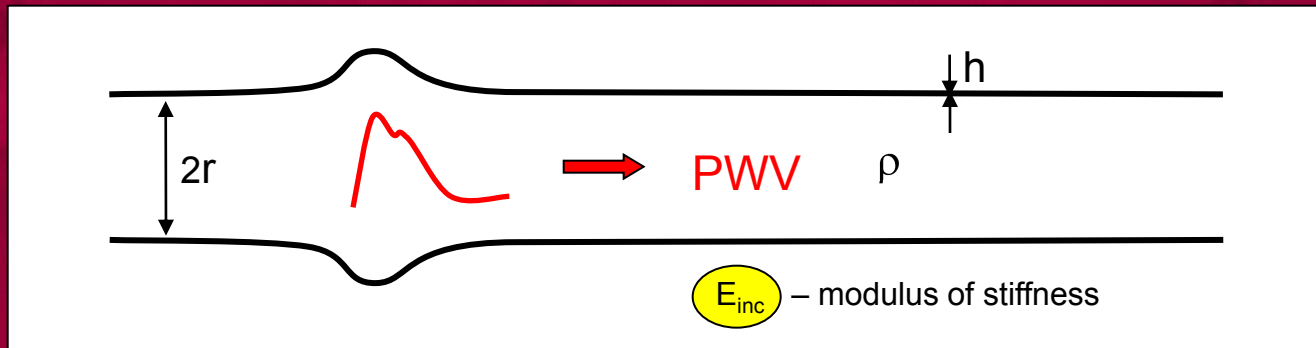


compliance

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



Pulse wave velocity (PWV)

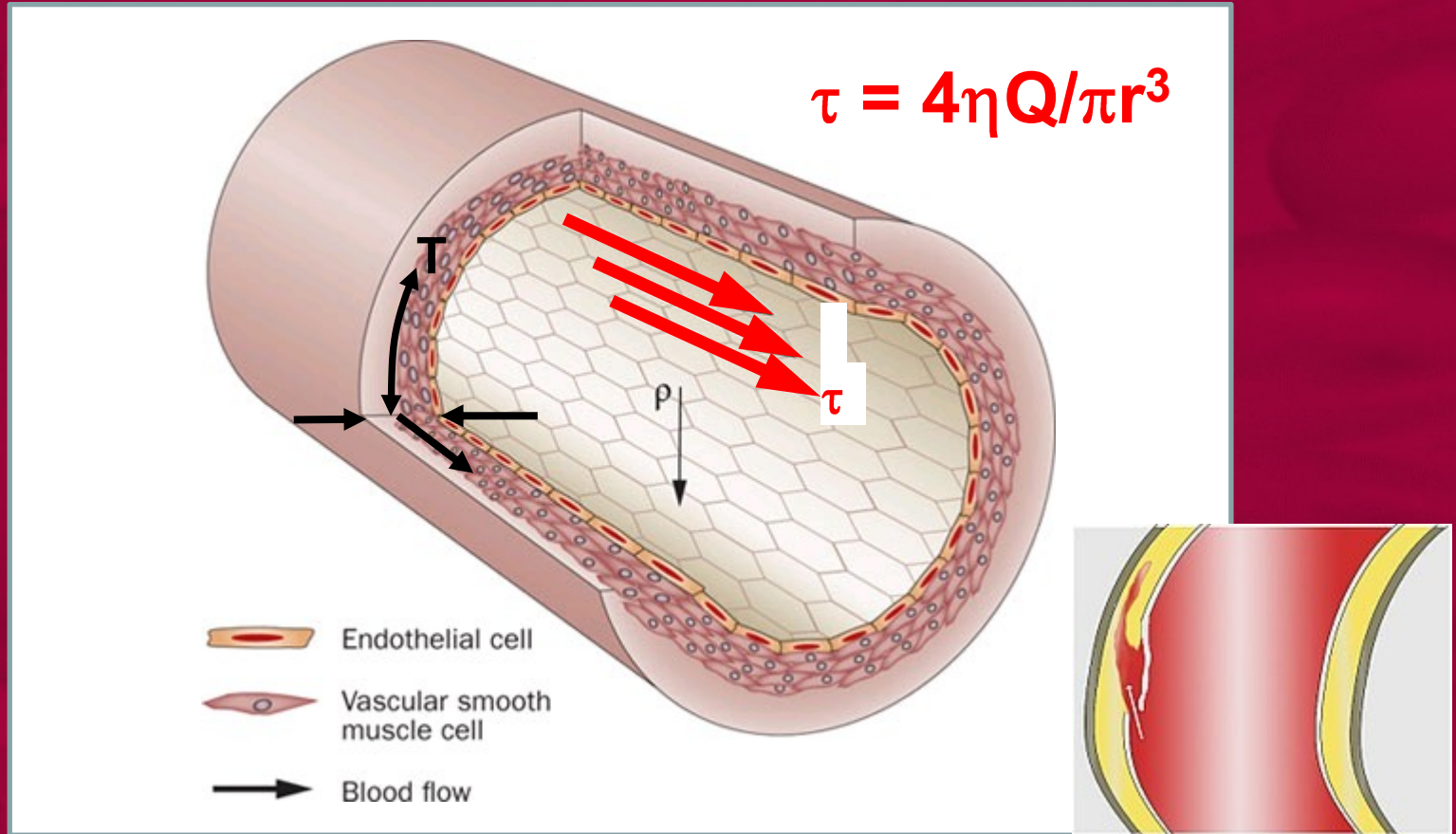


Moens-Korteweg (1878)

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

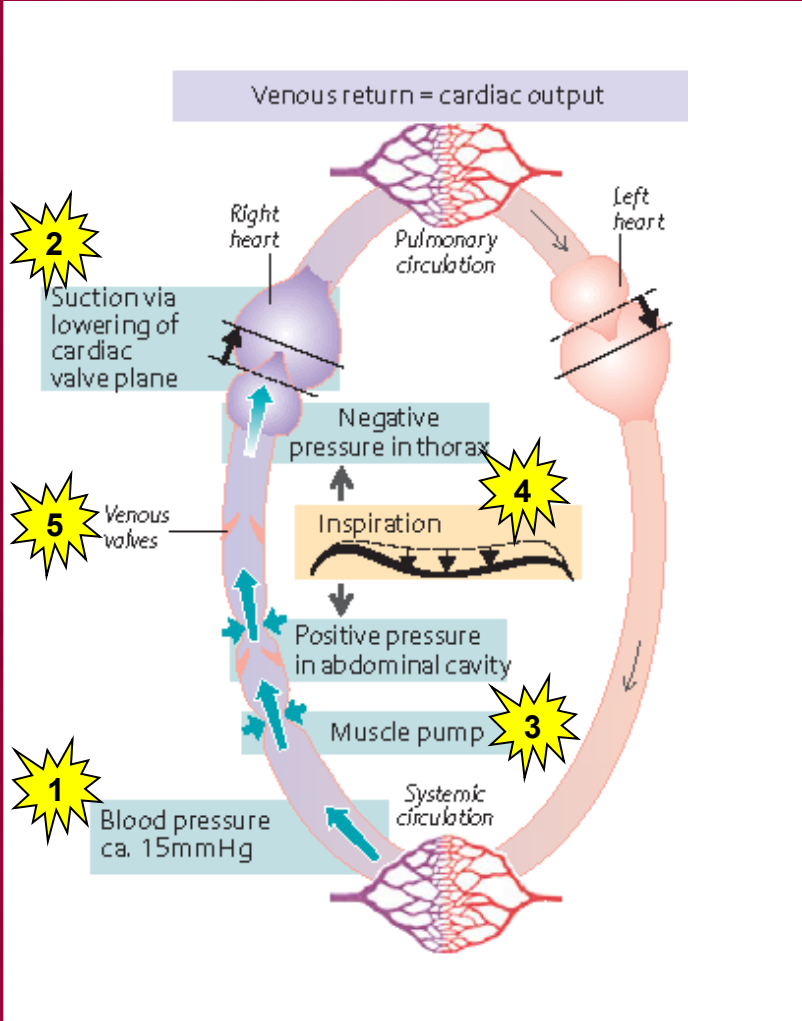
In aorta $PWV = 4 - 6 \text{ m/s}$

Share stress in vessel wall



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

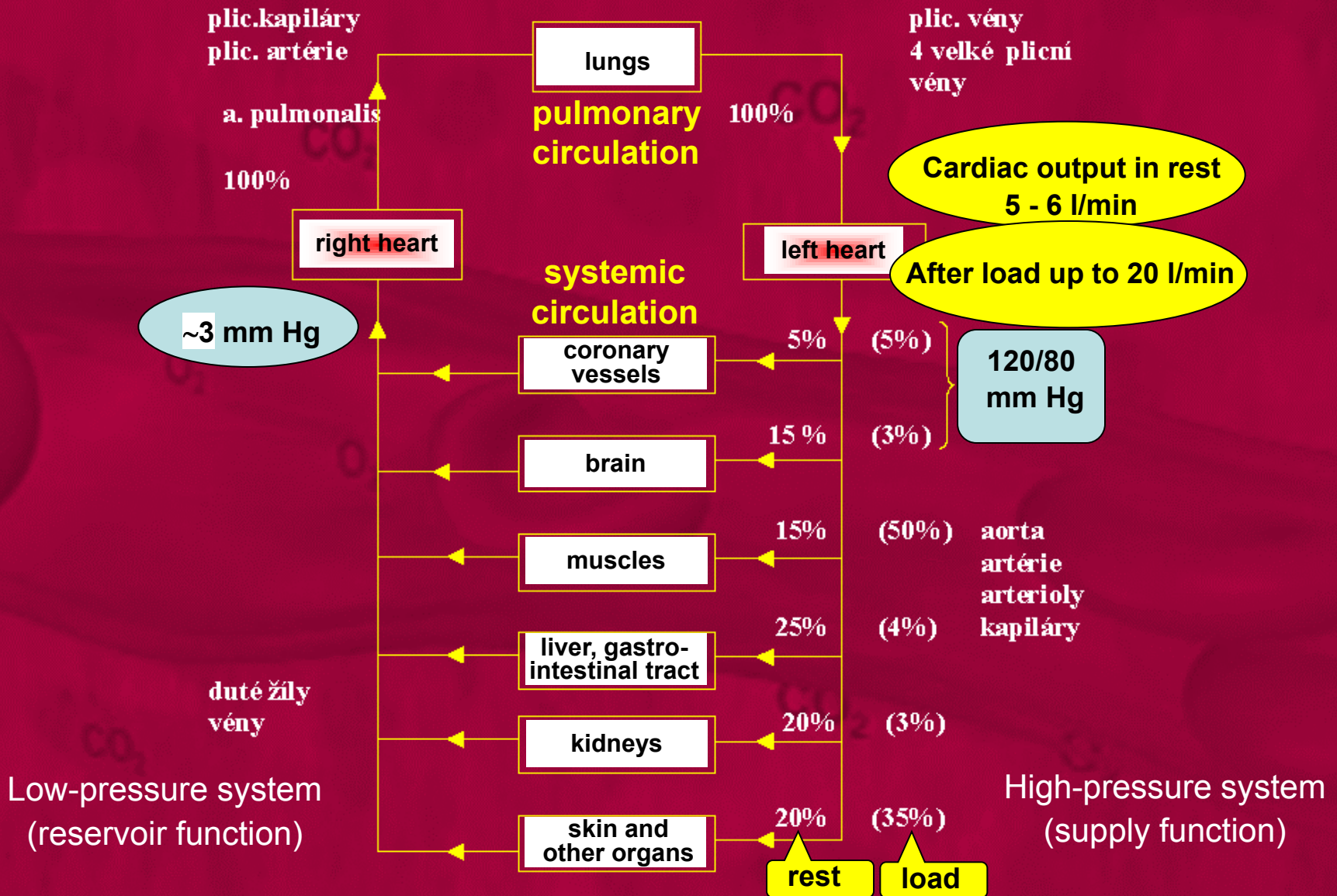
Mechanisms of venous return



The background features a faint, light-colored diagram on a dark red background. It depicts a network of blood vessels (arteries and veins) and several cells. Arrows indicate the flow of blood and the exchange of gases: CO₂ is shown moving from the cells into the blood, and O₂ is shown moving from the blood into the cells. The diagram is semi-transparent and serves as a thematic backdrop for the text.

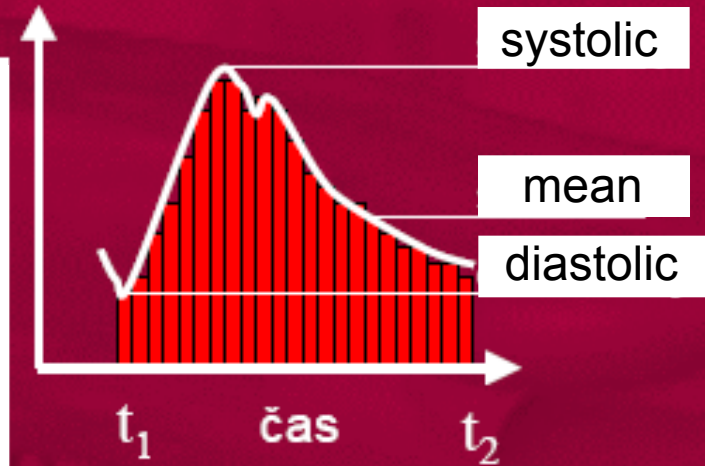
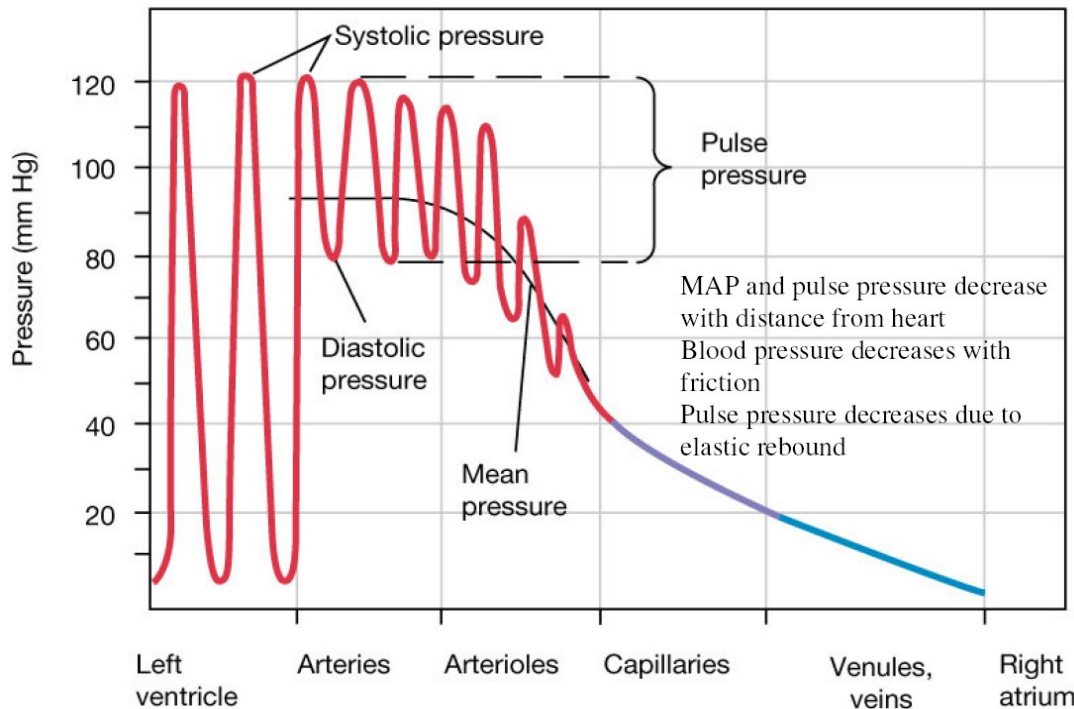
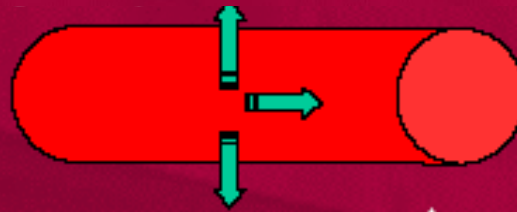
3. Blood circulation and pressure

Blood circulation



Blood pressure

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

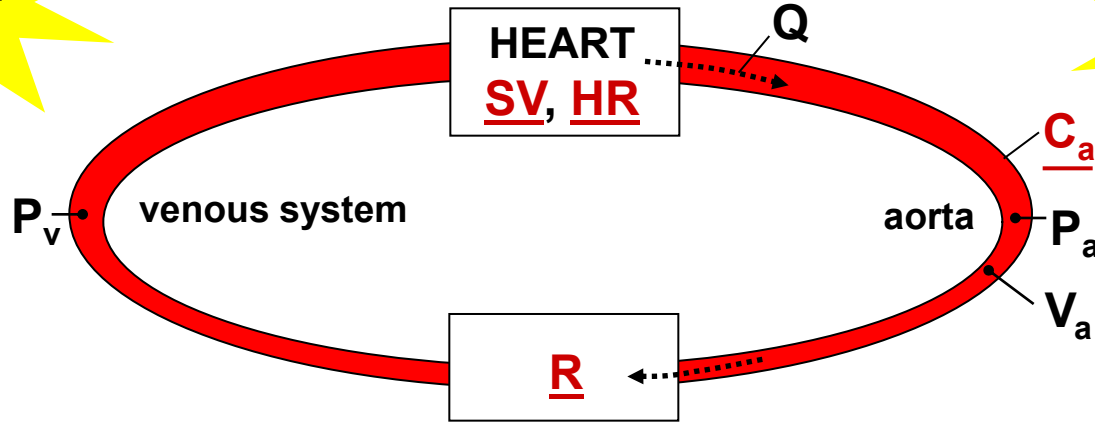


$$P_{mean} = \int_{t_1}^{t_2} \frac{P dt}{t_2 - t_1}$$

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

Dependence of blood pressure on cardiac output and vascular parameters

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



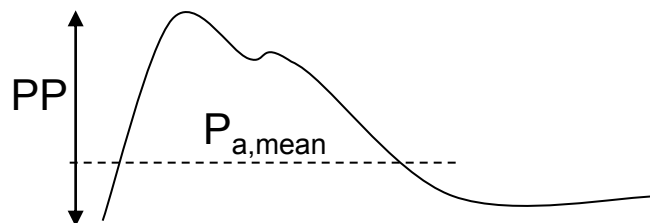
$$C = \frac{\Delta V}{\Delta P}$$

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

$$\Delta V \cong SV$$

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

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



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

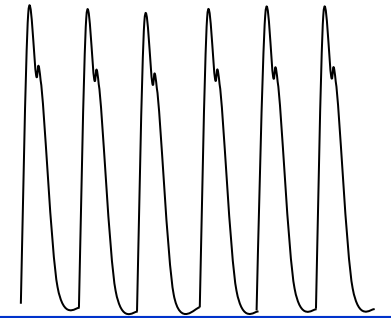
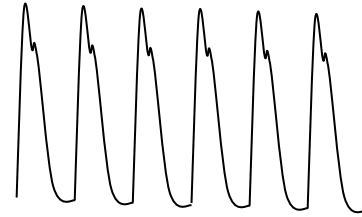
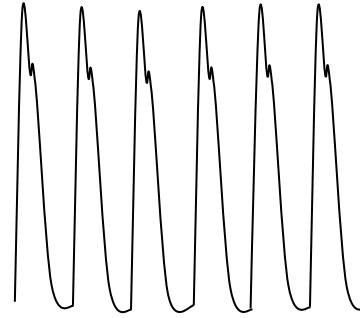
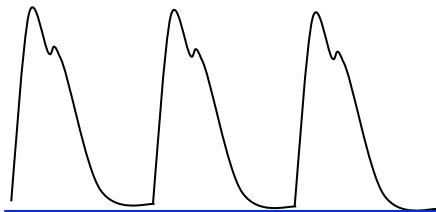
resting state

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

