



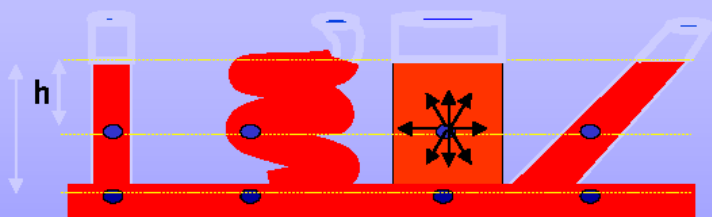
The background features a schematic diagram of blood circulation. A central horizontal vessel is shown with a red-to-yellow gradient. On the left, a red blood cell is depicted. On the right, a white blood cell is shown. The vessel is surrounded by a network of smaller vessels and cells. Labels CO_2 and O_2 are scattered throughout the diagram, indicating the exchange of these gases between the blood and the surrounding tissue.

Rheology of blood circulation

1. Basic physical laws of liquids

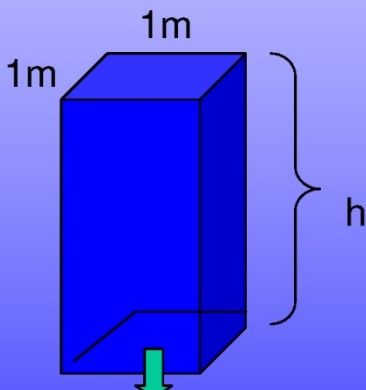
Law of Pascal

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).



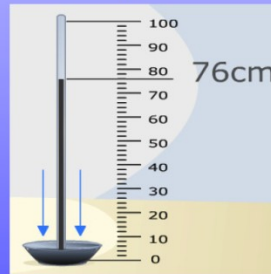
$p = h \cdot \rho \cdot g$

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

Pa

mm Hg

mm H₂O

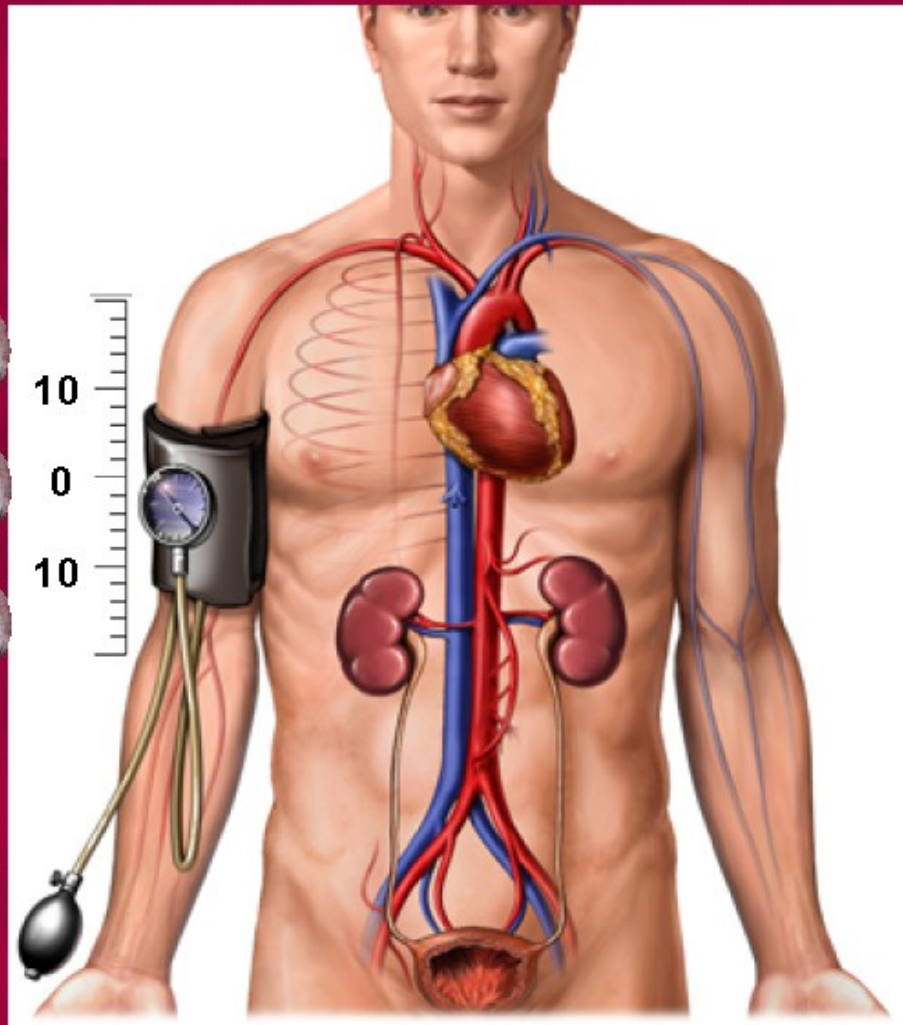
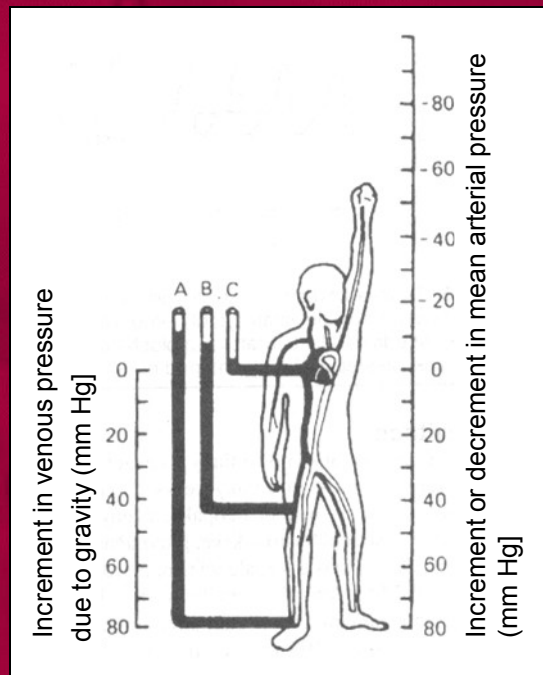
133,322 Pa = 1 mm Hg

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

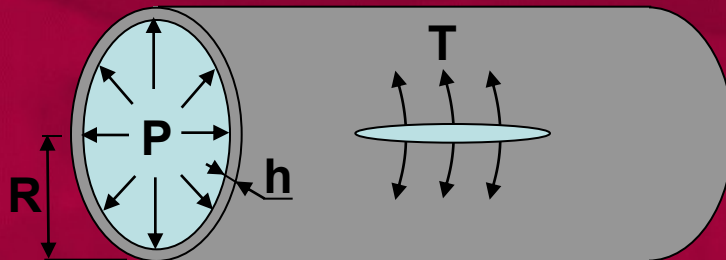
Relation between distending pressure (P [N/m²]) and tension in the wall of hollow object (T [N/m]) :

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

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

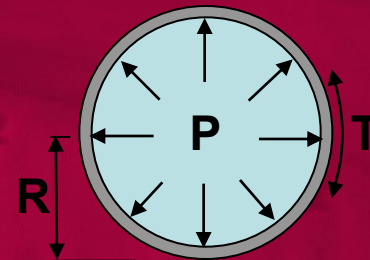
For vessel:

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



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/m²]

Characteristics of vessels

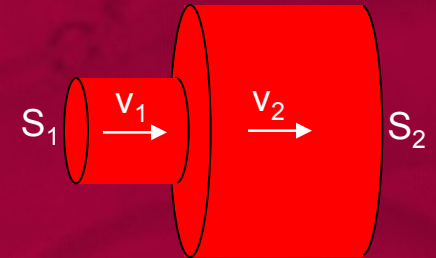
	P	R	P·R	h	P·R/h
vessel	P [kPa]	radius	tension (N/m)	wall thickness	tension (N/m ²)
aorta	13,3	13 mm nebo méně	170	2 mm	85000
arteries	12	5 mm	60	1 mm	60000
arterioles	8	150–62 μm	1,2–0,5	20 μm	40000
capillaries	4	4 μm	$1,6 \cdot 10^{-2}$	1 μm	16000
venules	2,6	10 μm	$2,6 \cdot 10^{-2}$	2 μm	13000
veins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



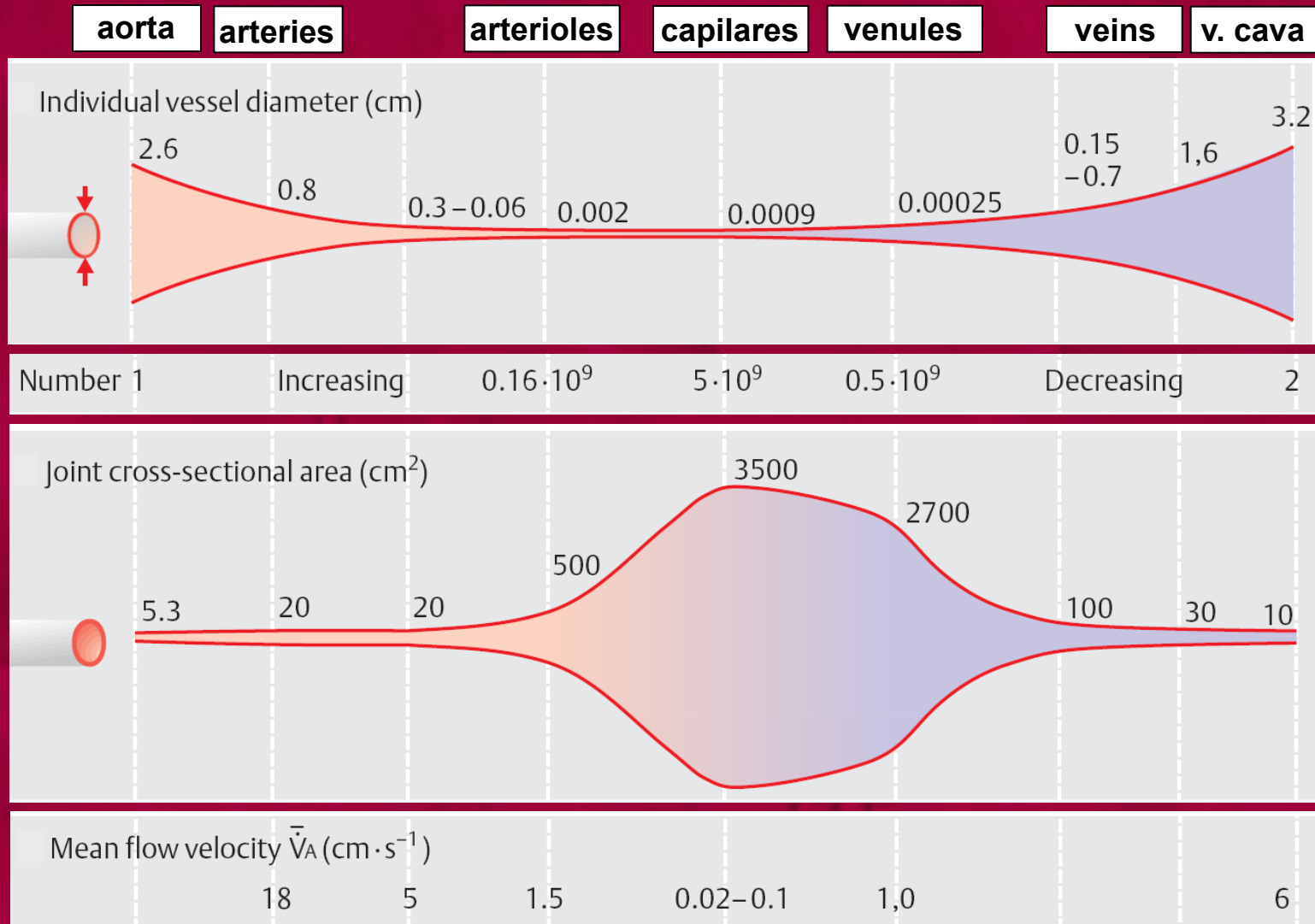
Average blood velocity in vessels

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

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

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

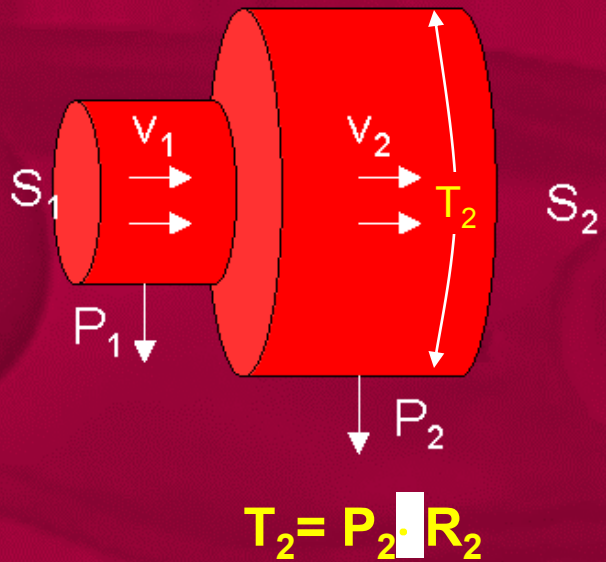
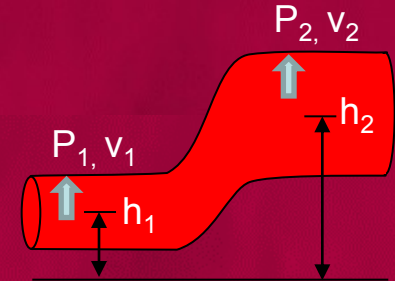


Bernoulli's principle

Law of energy conservation for fluid :

$$E_k + E_p + E_{ps} = \text{kost.} \Rightarrow \frac{1}{2} \rho v^2 + h \cdot \rho \cdot g + P = \text{constant}$$

dynamic pressure static pressure



Implication for aortic aneurysm

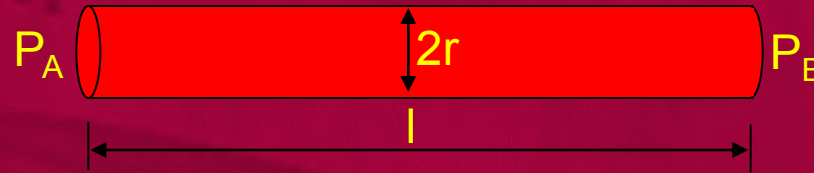
$S_1 v_1 = S_2 v_2$ a je-li $S_1 < S_2$, musí platit: $v_1 > v_2$

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

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

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.

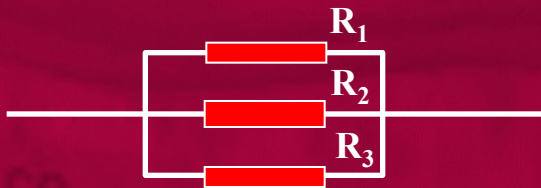
$$Q = \frac{\pi \cdot \Delta P \cdot r^4}{8 \cdot l \cdot \eta}$$

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

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

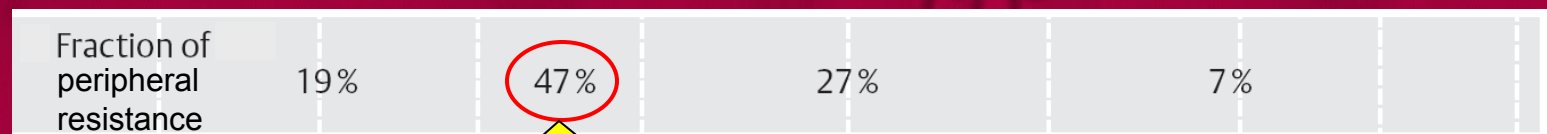
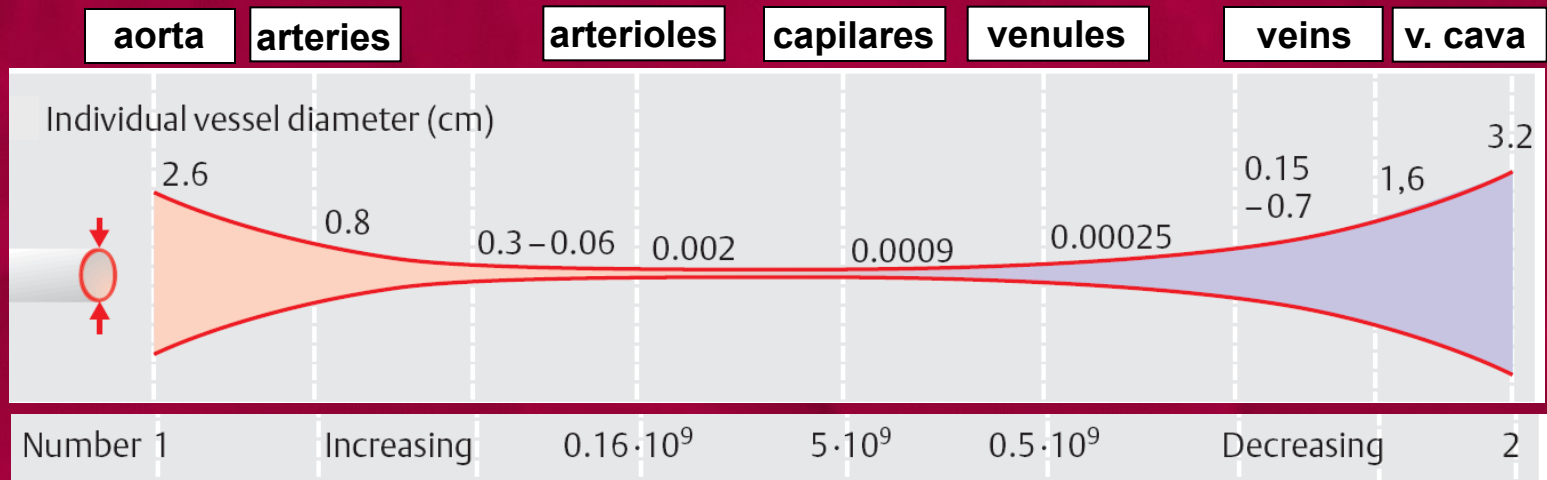


$$R_c = R_1 + R_2 + \dots$$

pro $R_1=R_2=R_3=R_n$

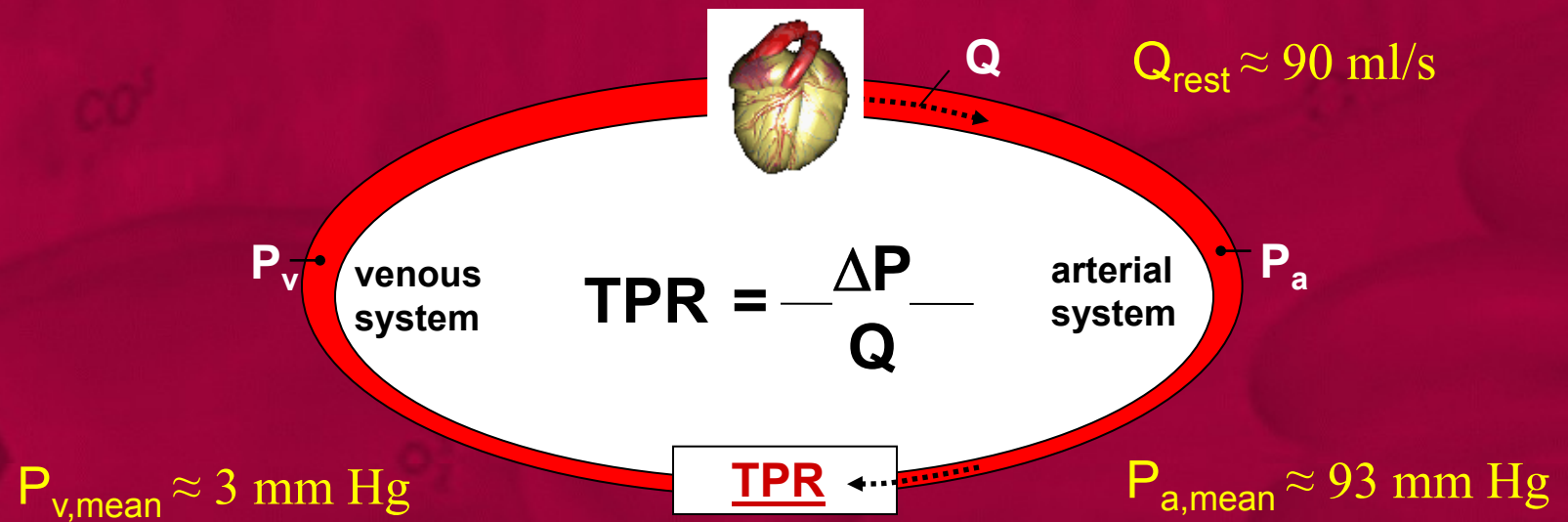
$$R_c = R \cdot n$$

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: \uparrow TPR $\rightarrow \uparrow P_a$ \rightarrow hypertension, ... cardiac disease.

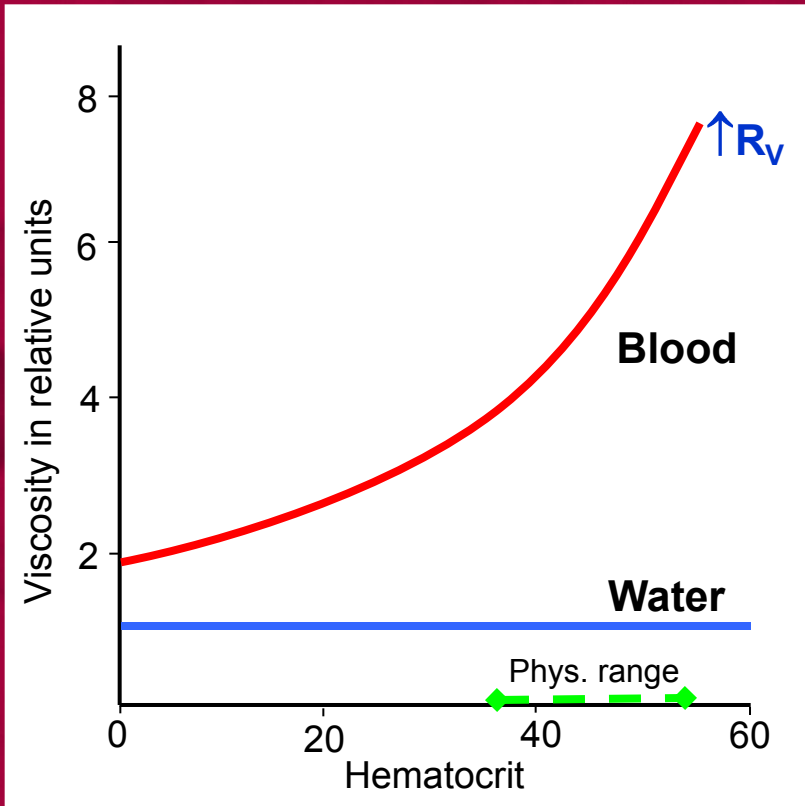
The background features a faint, light-colored diagram of a blood vessel. The vessel is shown in cross-section, with a central lumen and a surrounding wall. Several labels are scattered around the vessel: 'CO₂' appears in the upper left, upper right, and lower left areas, while 'O₂' is located in the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

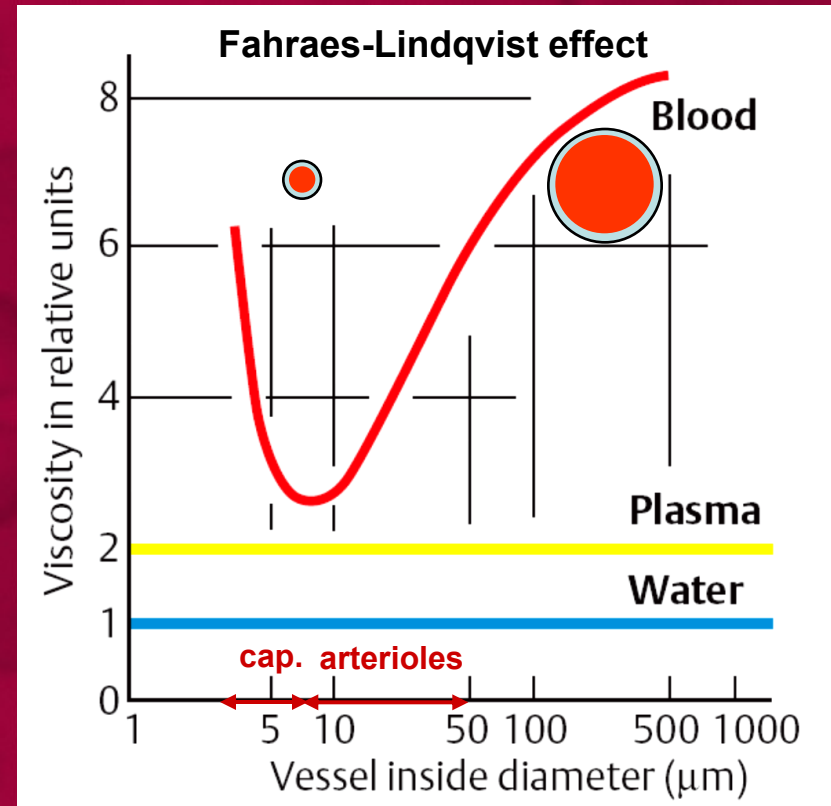
Blood viscosity

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

Effect of hematocrit



Effect of diameter in small vessels

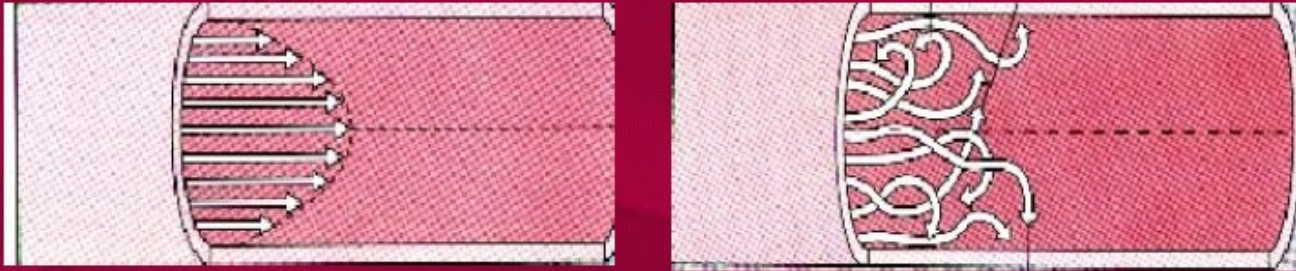


Other factors causing increase of viscosity:

- 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

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

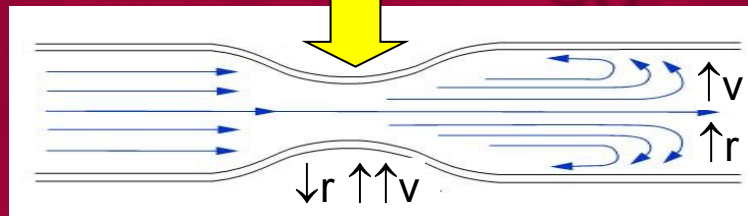
laminar flow

$Re < 2000$

turbulent flow

$Re > 3000$

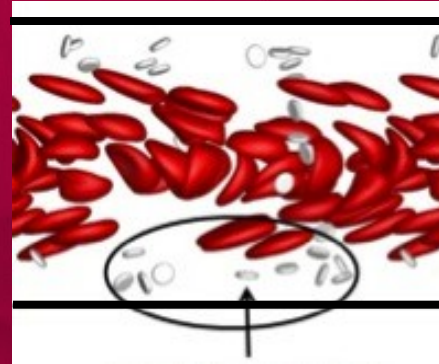
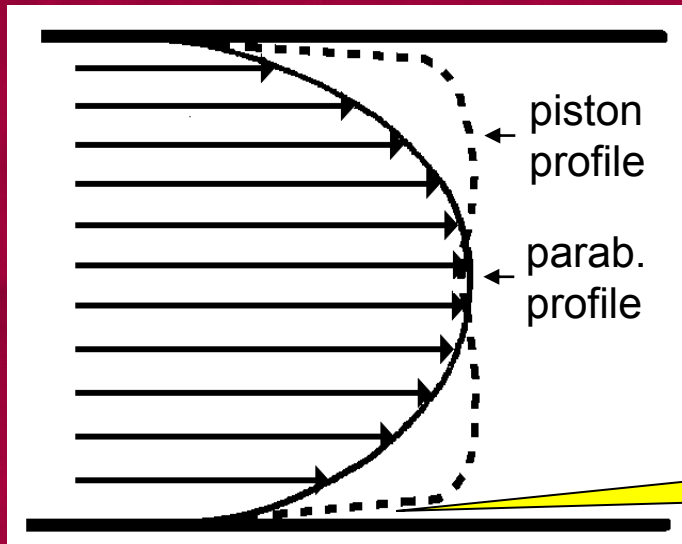
Sudden change of vessel diameter



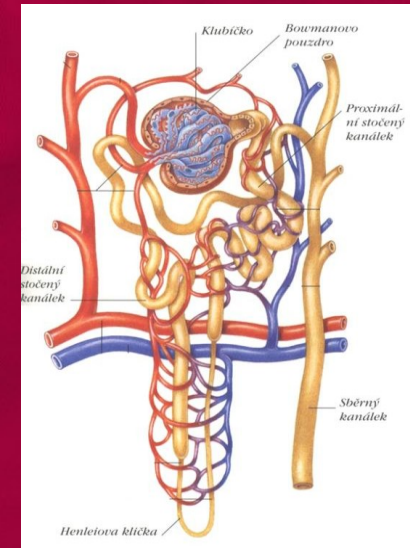
$$\uparrow R_e \Rightarrow R_v$$

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

Velocity profile of the blood flow in vessels

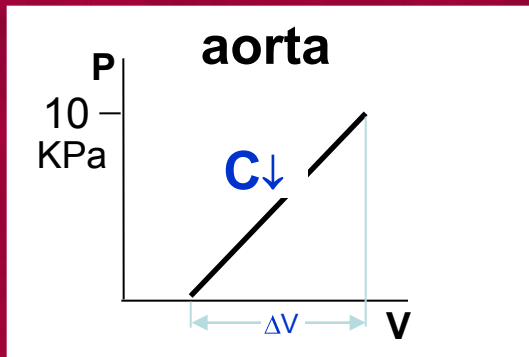
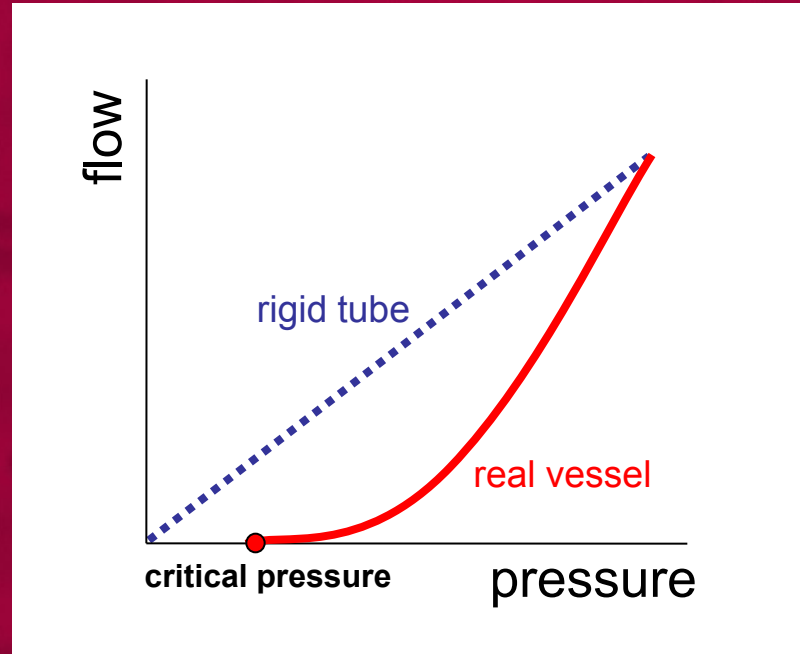


plasma-skimming



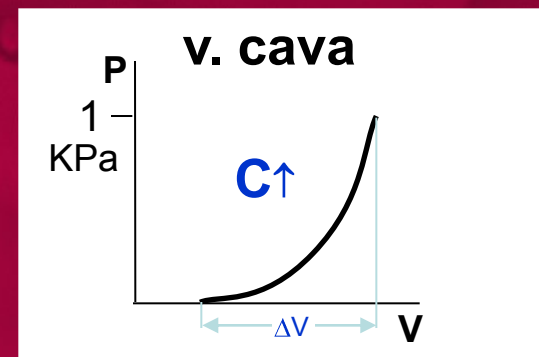
- In small arteries (at $r < 100 \mu\text{m}$), the central movement of erythrocytes causes a piston-like profile of the blood flow.
- In bigger arteries (at $r > 500 \mu\text{m}$), the laminar flow prevails and the velocity profile of the blood flow has a parabolic shape.
- In big arteries (especially 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

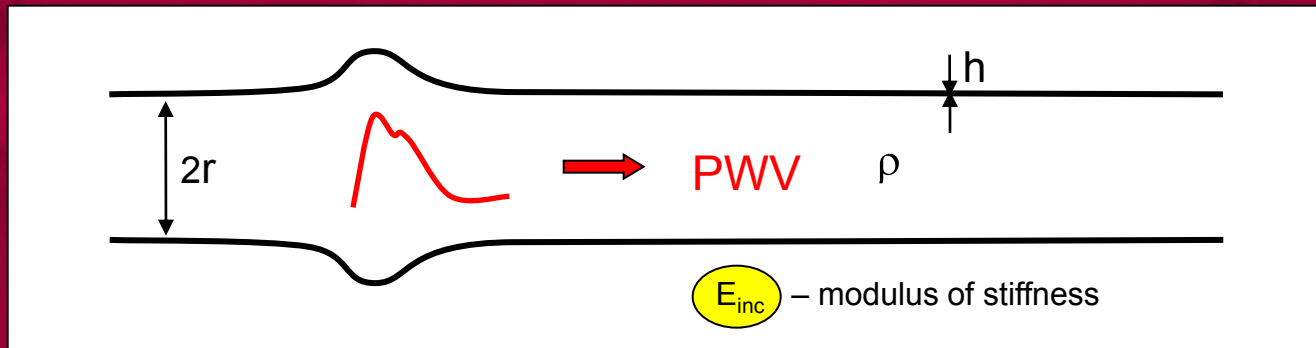


compliance

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



Pulse wave velocity (PWV)

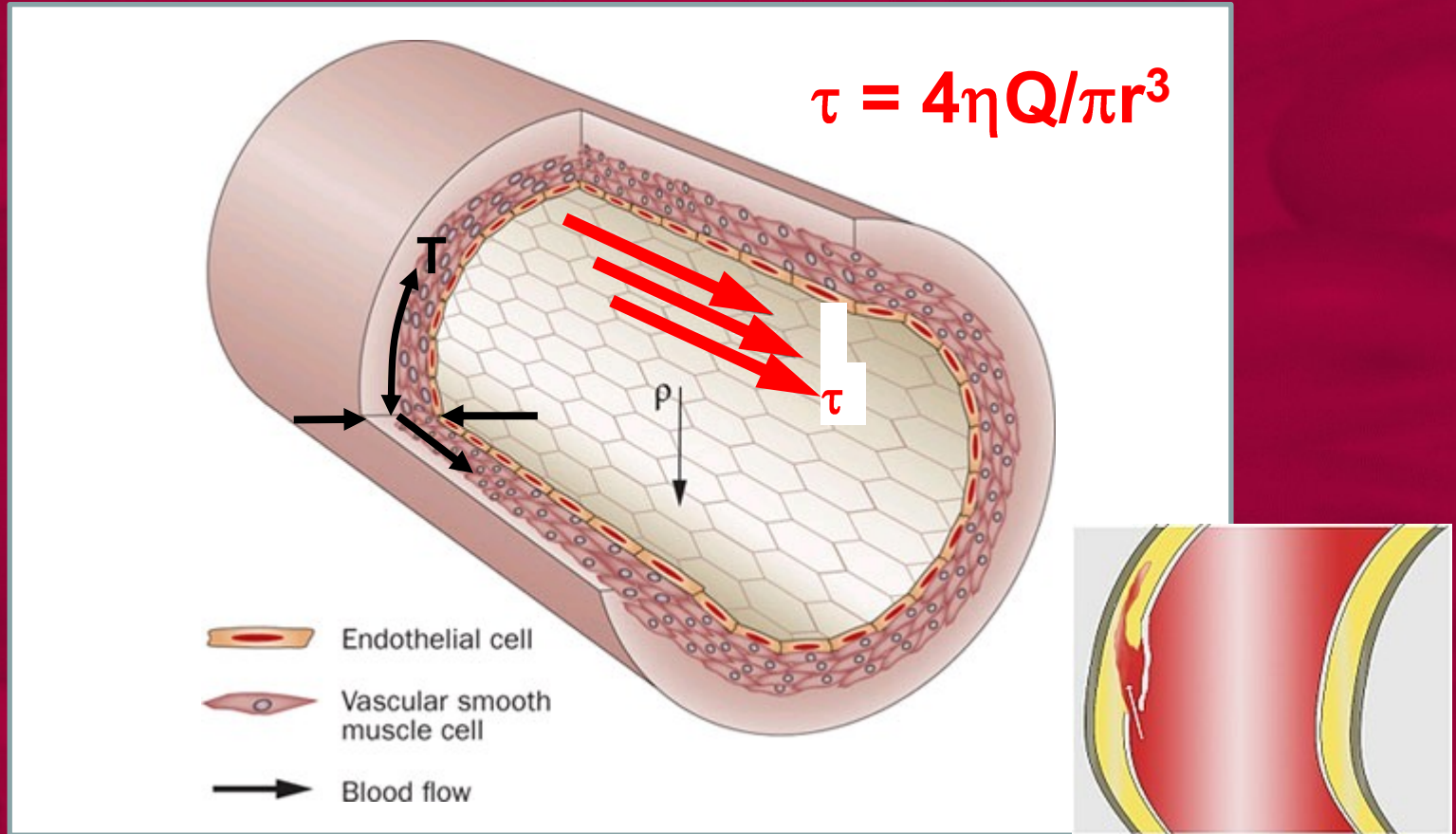


Moens-Korteweg (1878)

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

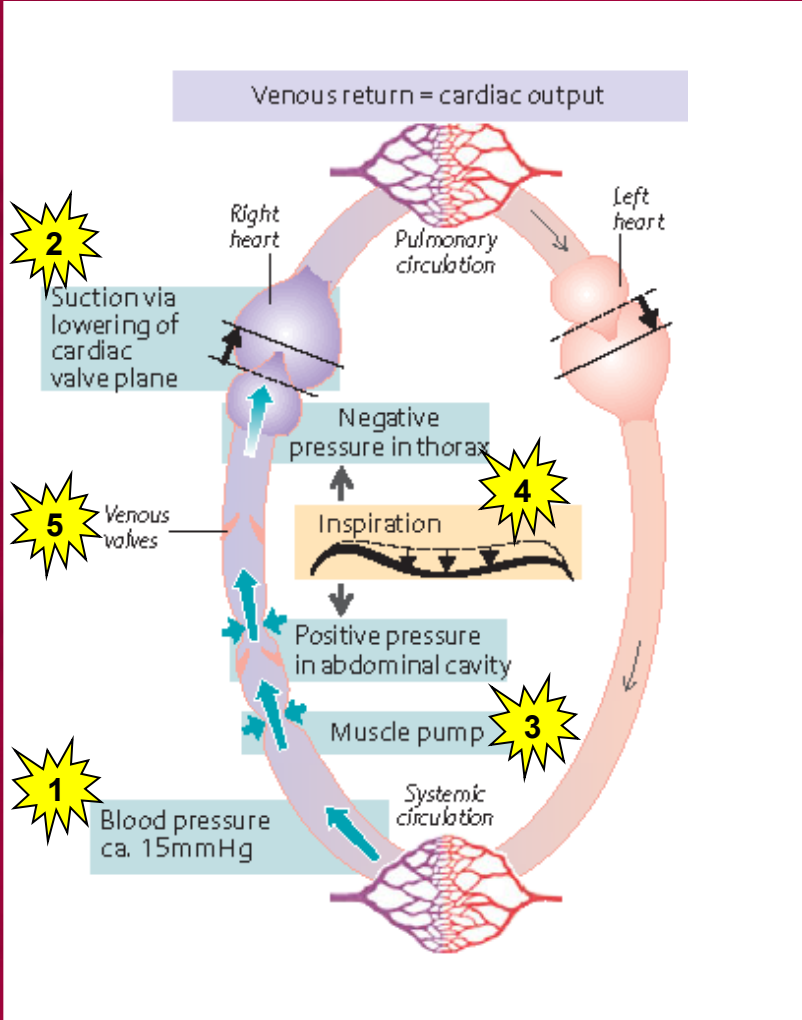
In aorta $PWV = 4 - 6 \text{ m/s}$

Share stress in vessel wall



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

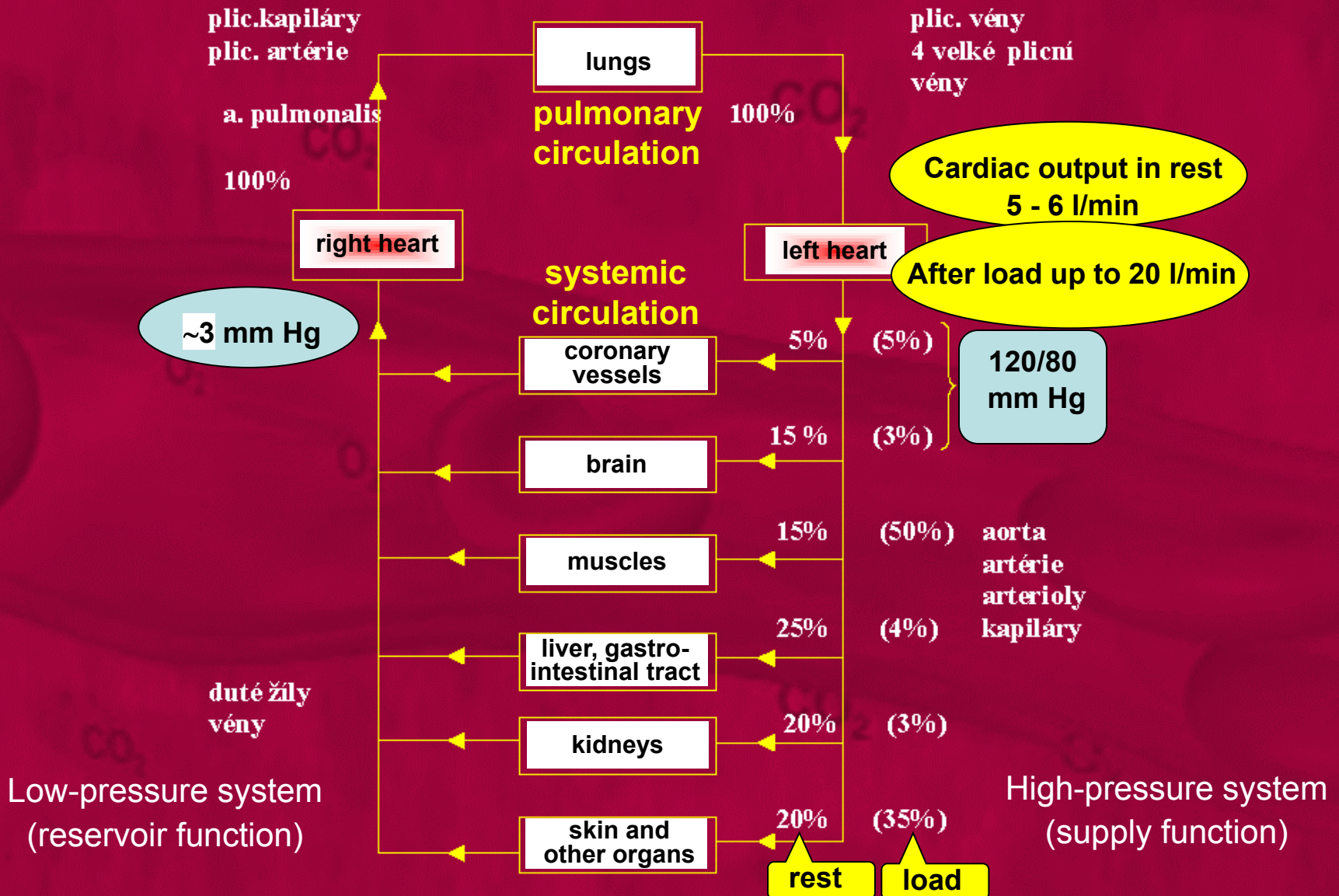
Mechanisms of venous return



The background features a faint, light-colored diagram on a dark red background. It depicts a cross-section of a blood vessel with red blood cells inside. Arrows indicate the exchange of gases: CO₂ is shown moving from the vessel into the surrounding tissue, and O₂ is shown moving from the vessel into the tissue. The text '3. Blood circulation and pressure' is overlaid on a white banner in the center of the image.

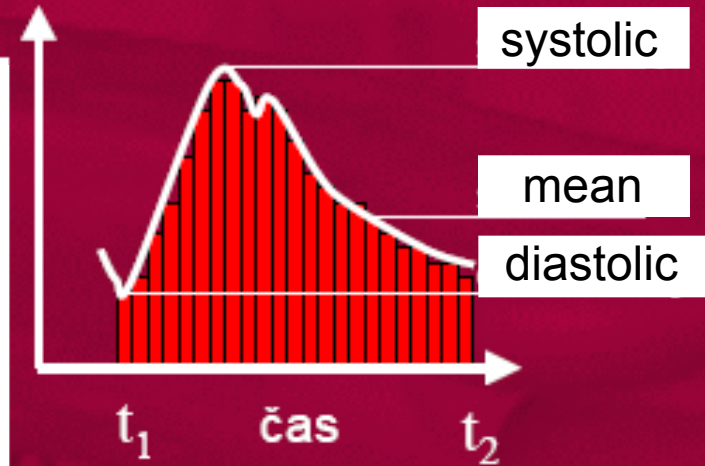
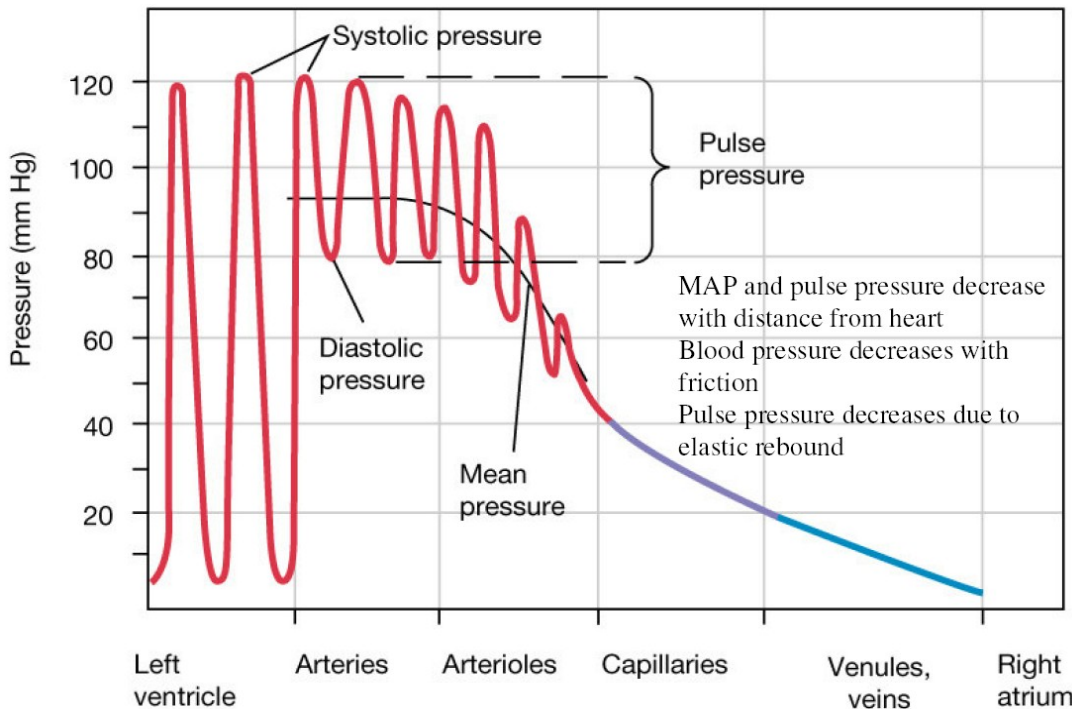
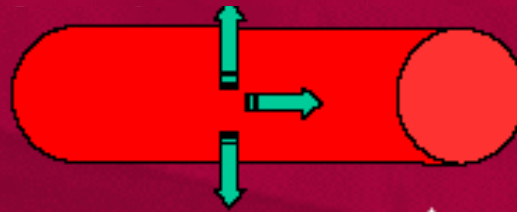
3. Blood circulation and pressure

Blood circulation



Blood pressure

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

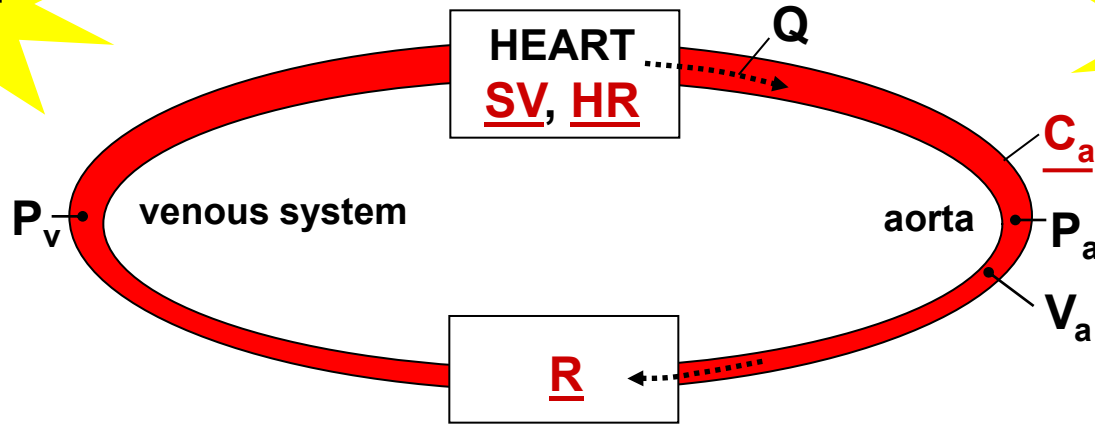


$$P_{mean} = \int_{t_1}^{t_2} \frac{P dt}{t_2 - t_1}$$

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

Dependence of blood pressure on cardiac output and vascular parameters

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



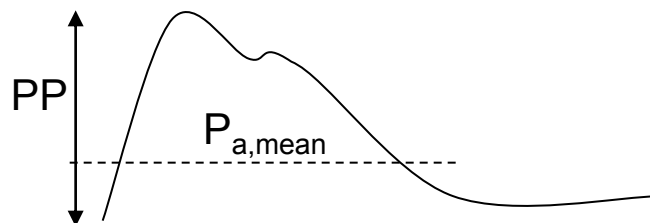
$$C = \frac{\Delta V}{\Delta P}$$

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

$$\Delta V \cong SV$$

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

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



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

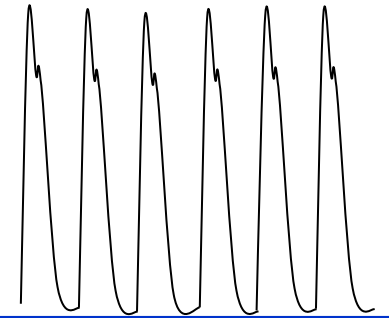
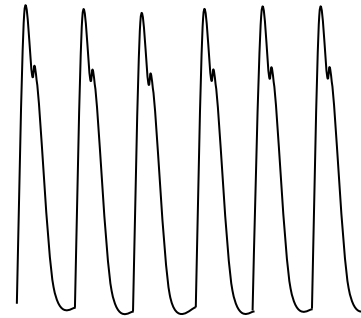
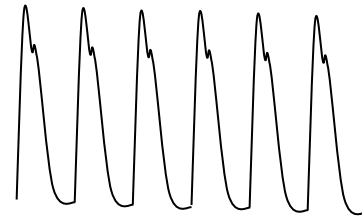
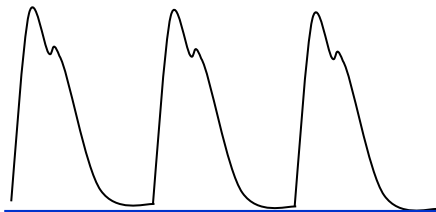
resting state

activity

+SV↑

HR↑

+R↓



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

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

Model of blood pressure changes in aorta

