

The background is a dark red color with a faint, repeating pattern of a blood vessel and red blood cells. The vessel is shown in cross-section, with red blood cells (represented as biconcave discs) inside. Labels for CO_2 and O_2 are scattered around the vessel, indicating gas exchange. The text "Rheology of blood circulation" is centered within a bright orange-to-yellow gradient oval.

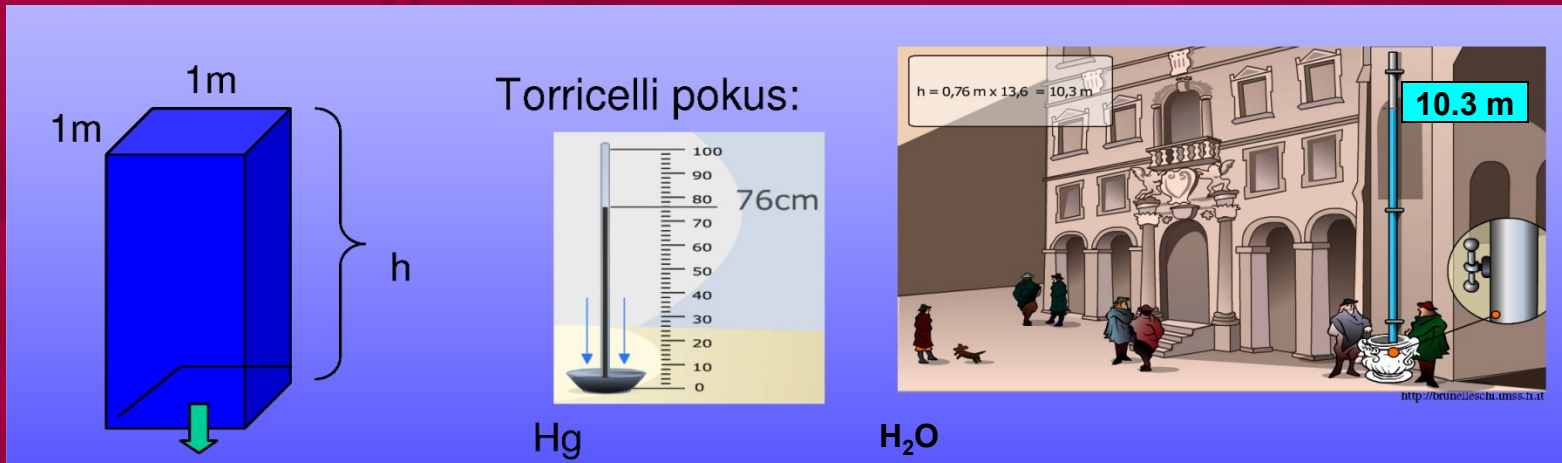
Rheology of blood circulation

The background is a solid dark red color. It features several faint, light-colored chemical formulas scattered across the surface, including CO_2 and O_2 . A prominent, light-colored wavy line, resembling a liquid surface or a molecular structure, curves horizontally across the middle of the image.

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).



Pa

mm Hg

mm H₂O

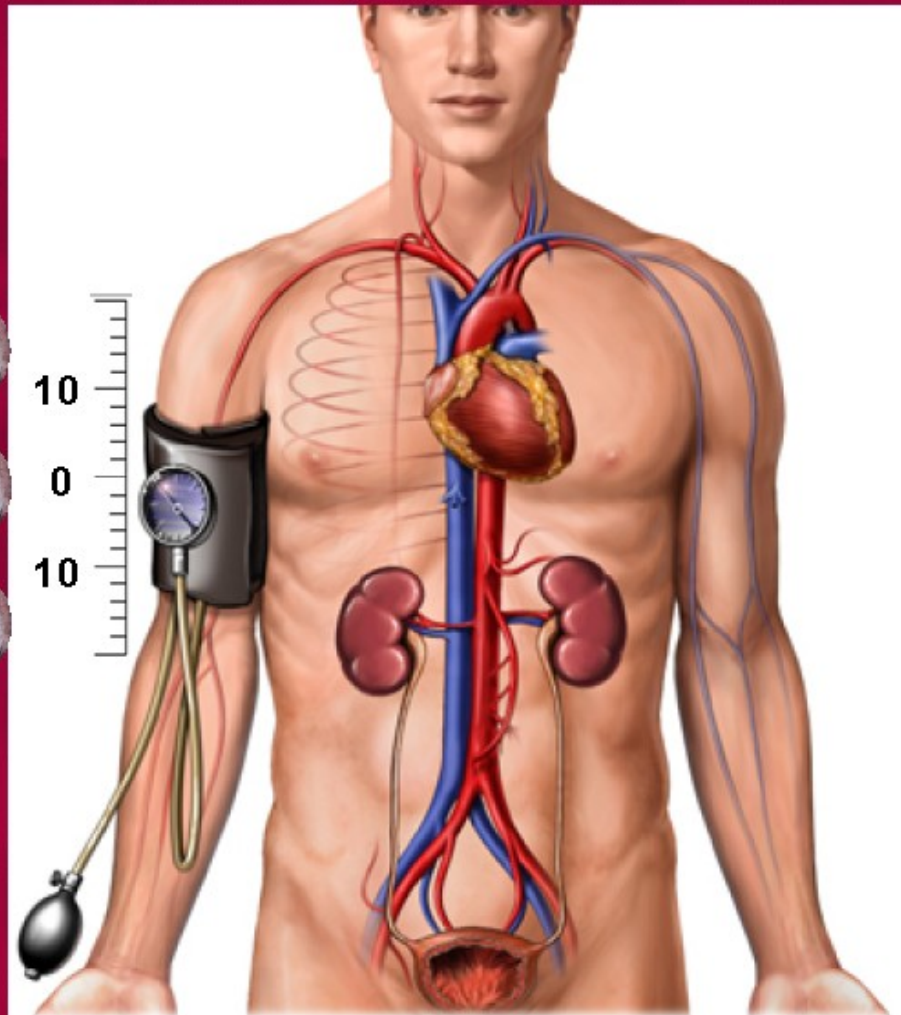
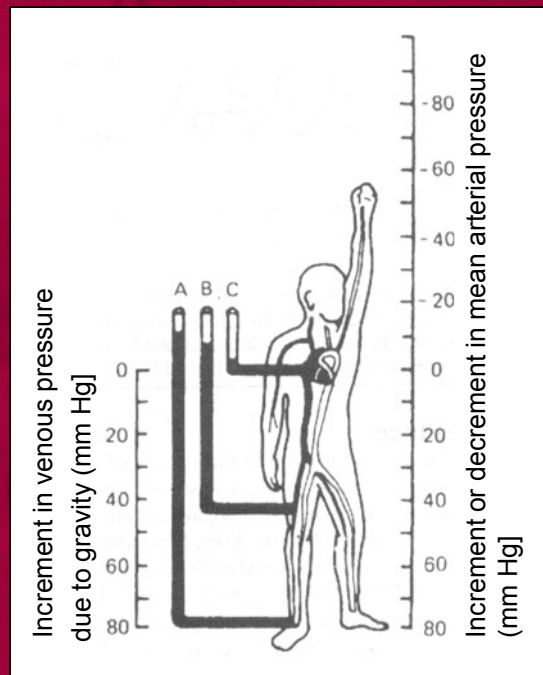
133,322 Pa = 1 mm Hg

760 mmHg = 1 atm = 10.3 m H₂O

Effect of gravity on arterial and venous pressure

Per each 10 cm

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



Law of Laplace

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

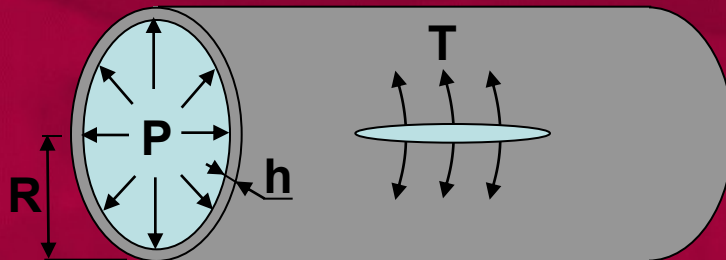
$$T = \frac{P}{\left(\frac{1}{R_1} + \frac{1}{R_2}\right)}$$

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

For vessel:

$$R_2 =$$

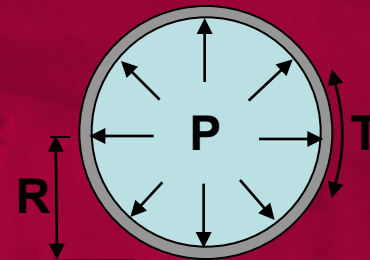
$$T = P \cdot R$$



For sphere:

$$R_1 = R_2$$

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



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

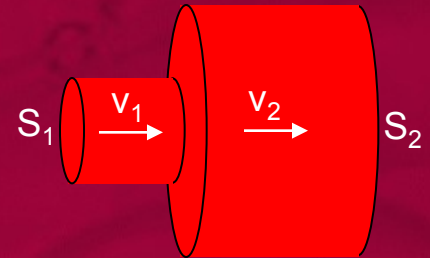
Continuity equation

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



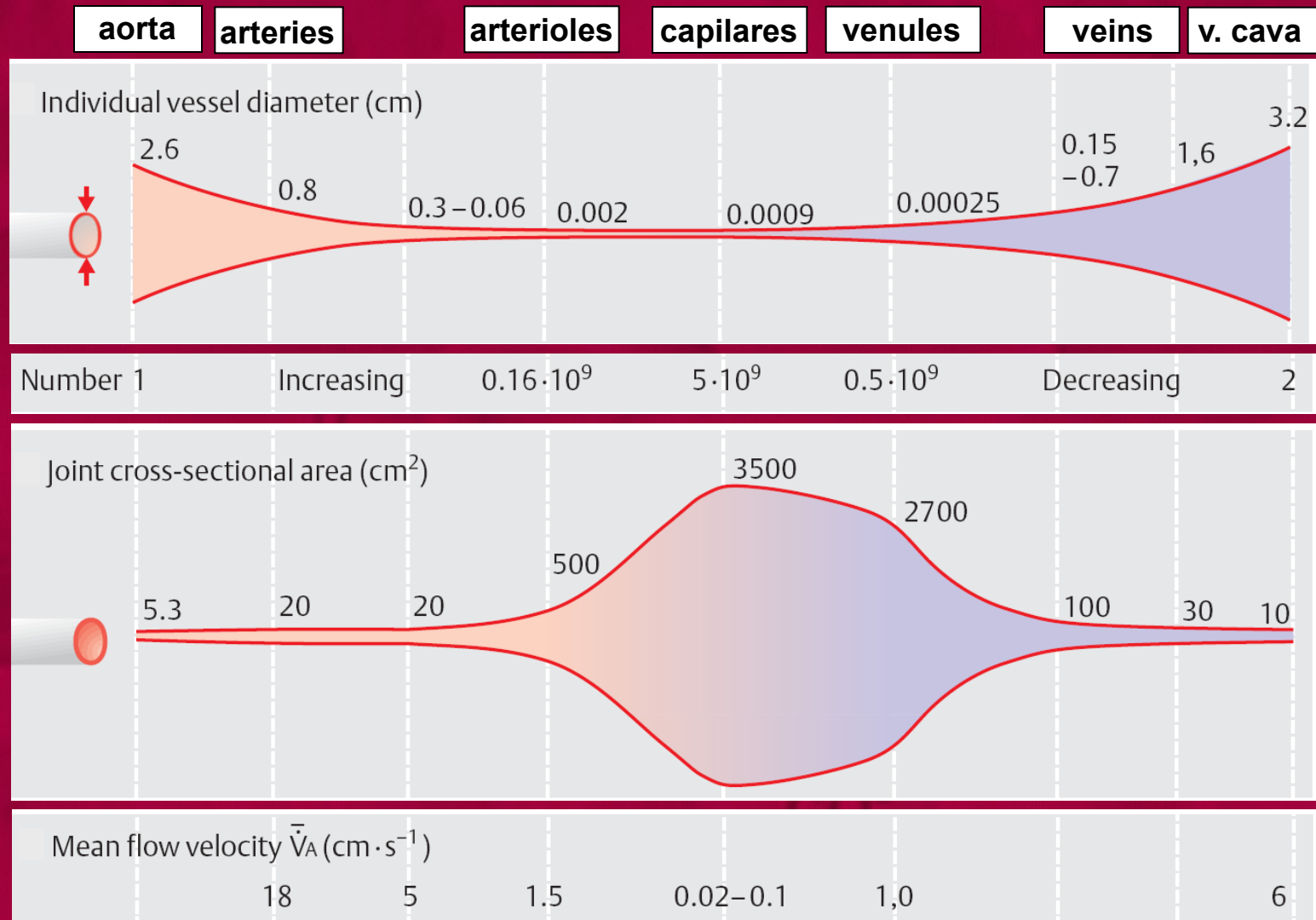
Average blood velocity in vessels

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

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

vessel	diameter	number	total area	velocity
aorta	2.6 cm	1	5.3 cm ²	~ 18 cm/s
arterioles	20-50 μ m	$\sim 5 \times 10^4$	$\sim 60 \text{ cm}^2$	~ 1.5 cm/s
capillaries	4-9 μ m	5×10^9	2000 cm ²	~ 0.04 cm/s
venules	$\sim 20 \text{ }\mu\text{m}$	$\sim 32 \times 10^9$	$\sim 150 \text{ cm}^2$	~ 1 cm/s
vena cava	$\sim 3 \text{ cm}$	2	$\sim 4 \text{ cm}^2$	~ 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 :

$$E_k + E_p + E_{ps} = \text{const.}$$

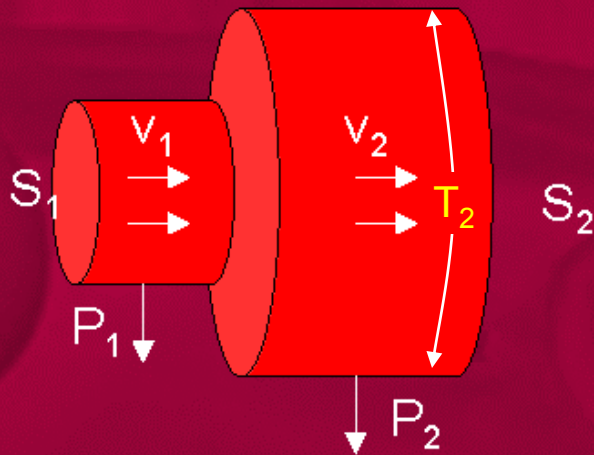
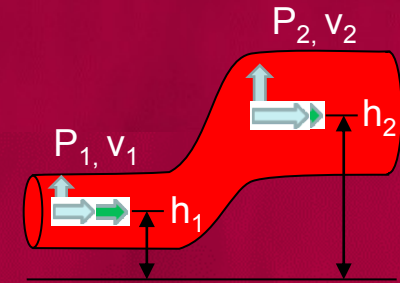
$$[\text{J/m}^3] = [\text{Pa}]$$

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

dynamic pressure

+ static pressure

= total pressure



$$T_2 = P_2 \cdot R_2$$

Implication for aortic aneurysm

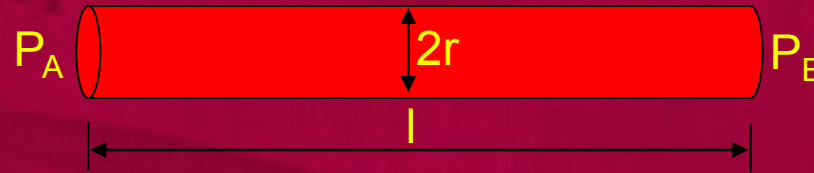
$S_1 v_1 = S_2 v_2$ a je-li $S_1 < S_2$, musí platit: $v_1 > v_2$

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

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

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.

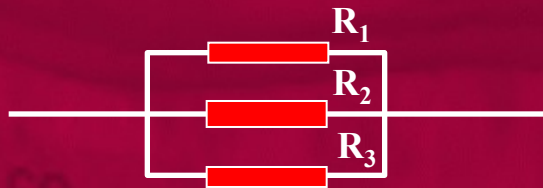
$$Q = \frac{\pi \cdot \Delta P \cdot r^4}{8 \cdot l \cdot \eta}$$

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

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



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

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

$$R_c = R/n$$

Series arrangement of vessels

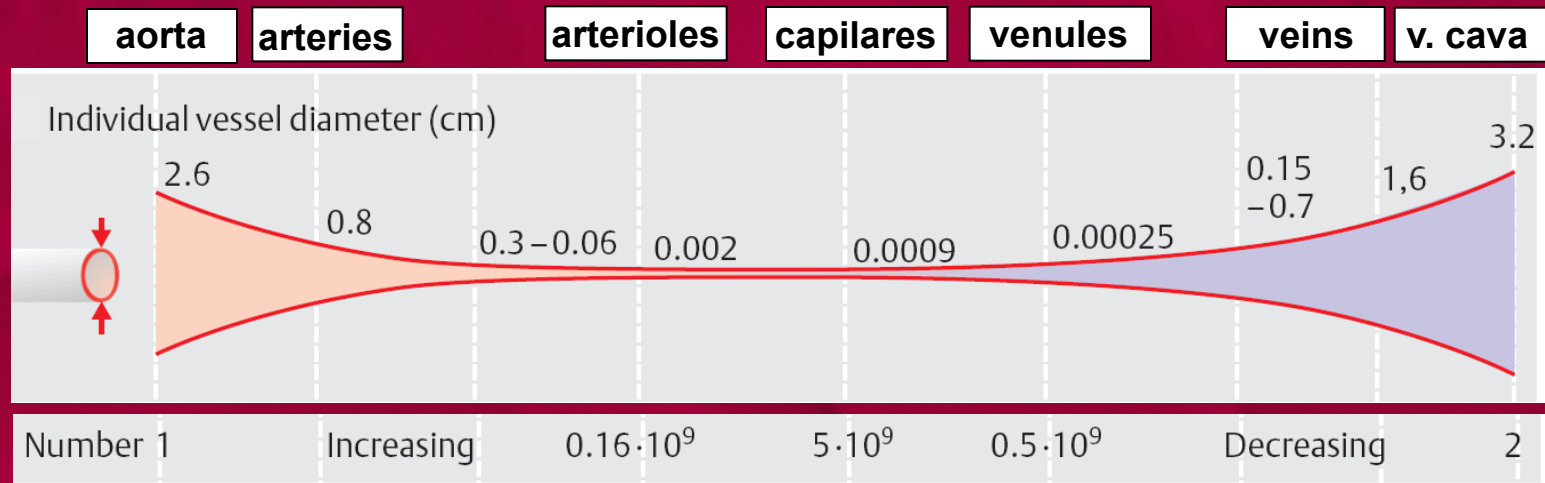


$$R_c = R_1 + R_2 + \dots$$

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

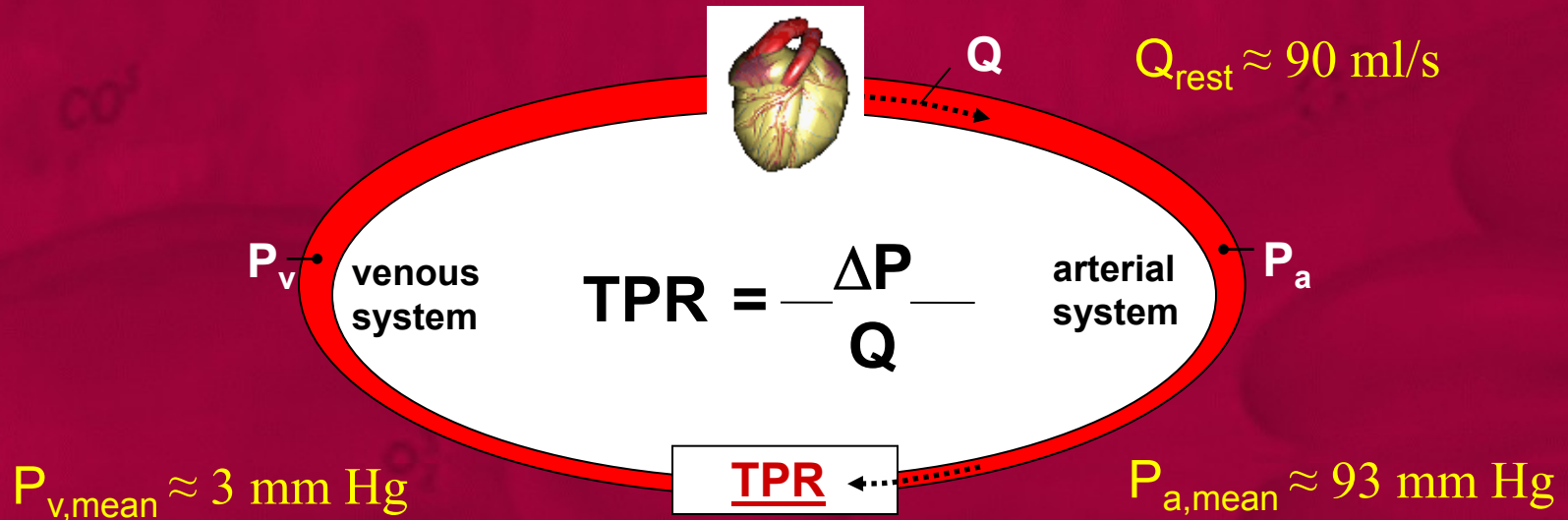
$$R_c = R \cdot n$$

Relation between vessel radius and peripheral resistance



highly variable

Total peripheral resistance (TPR) of vascular system



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

$$P_a \approx \text{TPR} \times Q$$

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

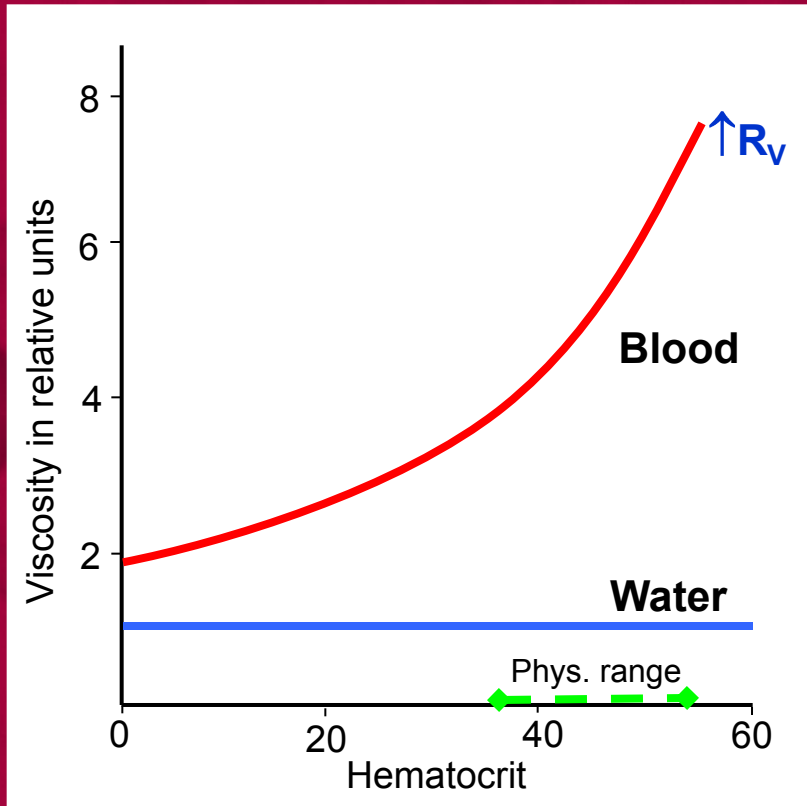
The background is a deep red color with a faint, stylized illustration of blood vessels. A large, winding vessel runs horizontally across the middle. Several smaller, circular vessels are scattered around it. Faint chemical formulas are visible: CO_2 appears in the upper left, upper right, and lower left areas, while O_2 appears in the upper right and lower right areas. The overall theme is related to blood and gas exchange.

2. Rheological features of blood and vessels

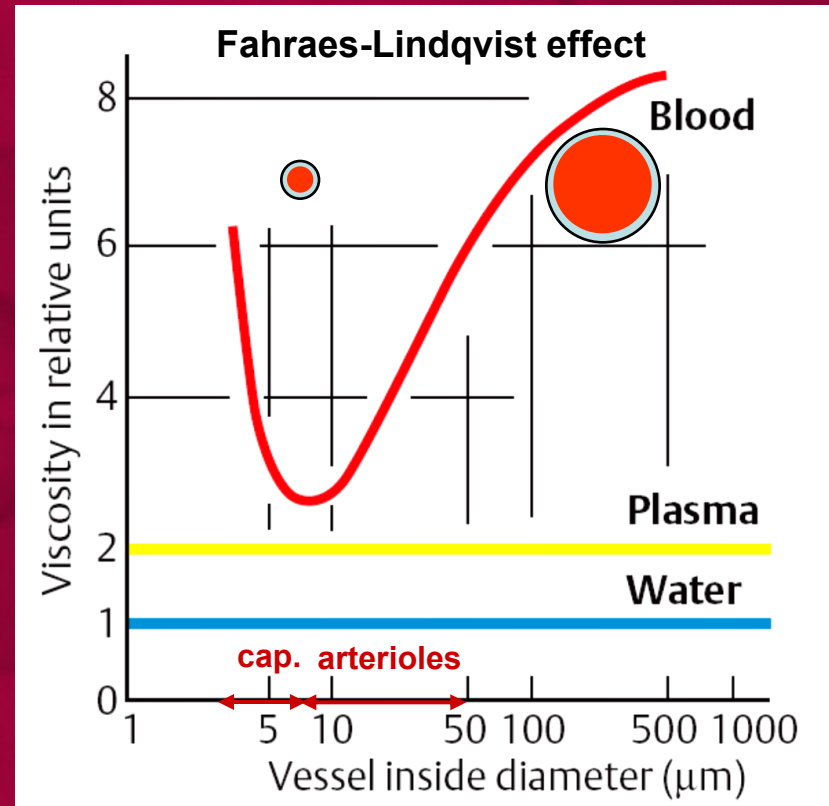
Blood viscosity

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

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

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

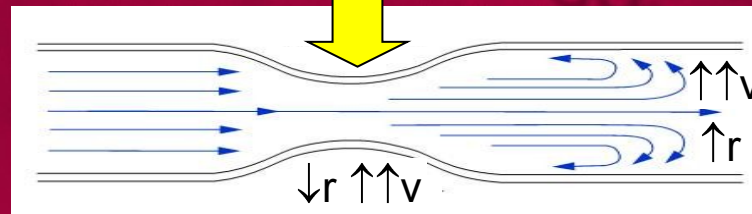
laminar flow

$Re < 2000$

turbulent flow

$Re > 3000$

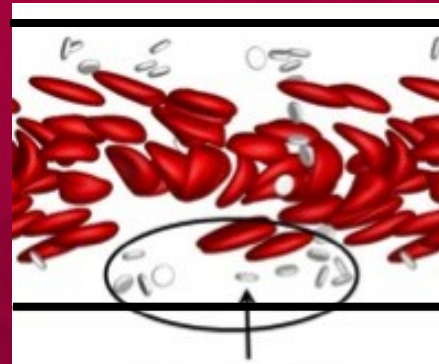
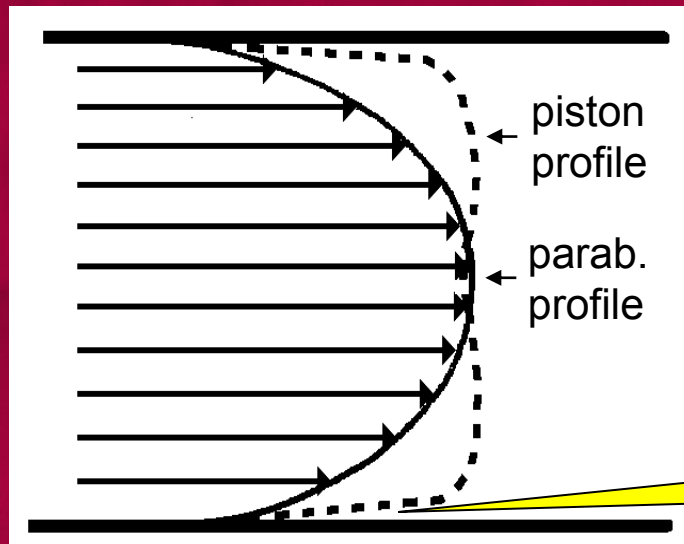
Sudden change of vessel diameter



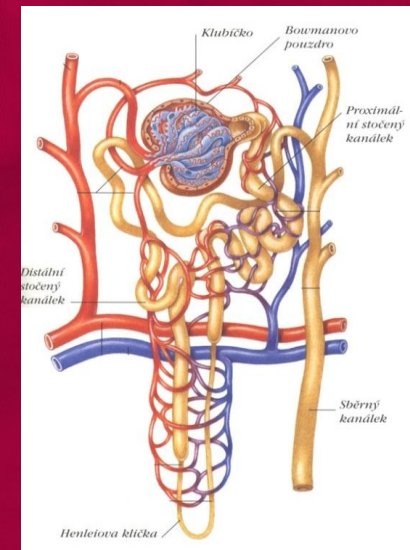
$$\uparrow R_e \Rightarrow R_v$$

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

Velocity profile of the blood flow in vessels

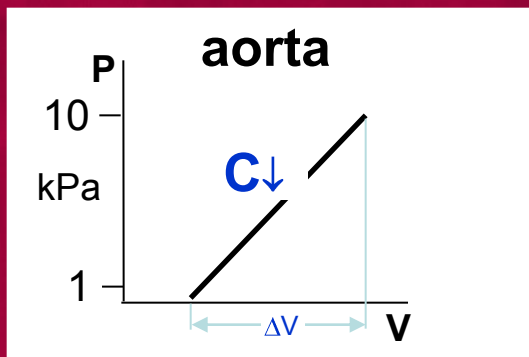
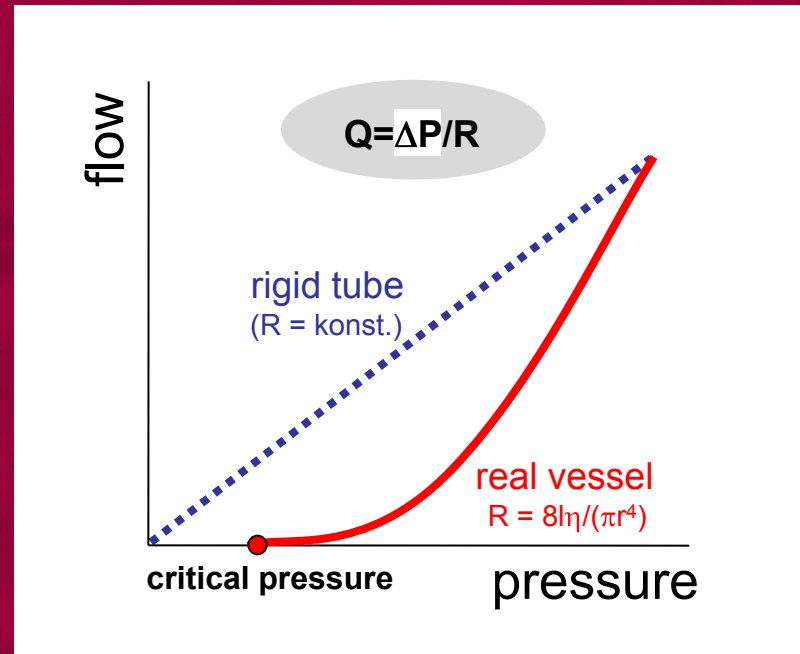


plasma-skimming



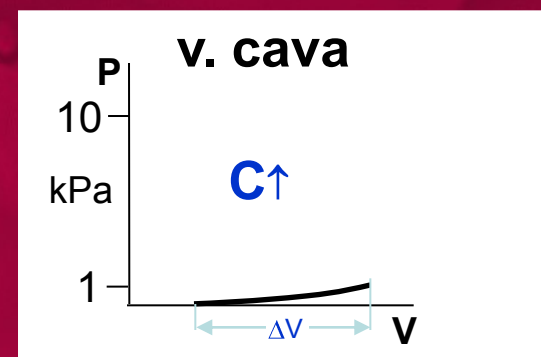
- In small arteries (at $r < 100 \mu\text{m}$), the central movement of erythrocytes causes a piston-like profile of the blood flow.
- In bigger arteries (at $r > 500 \mu\text{m}$), the laminar flow prevails and the velocity profile of the blood flow has a parabolic shape.
- In big arteries (especially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

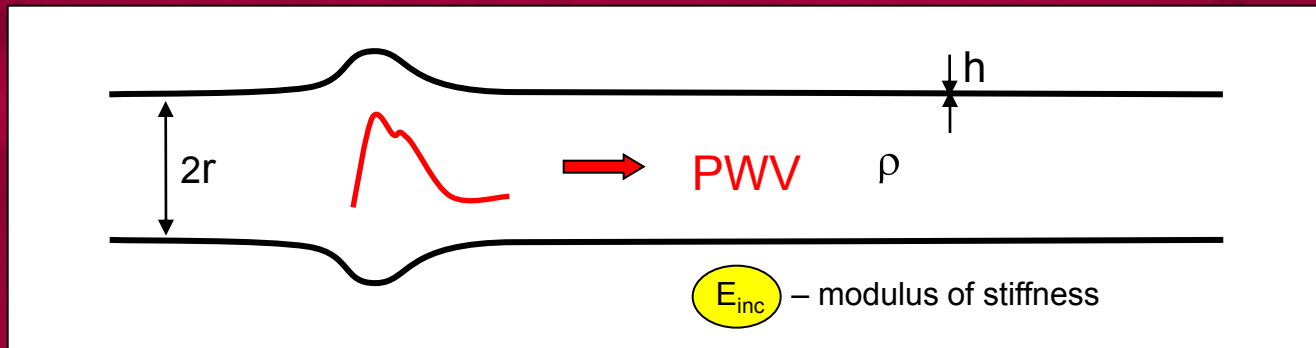


compliance

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



Pulse wave velocity (PWV)

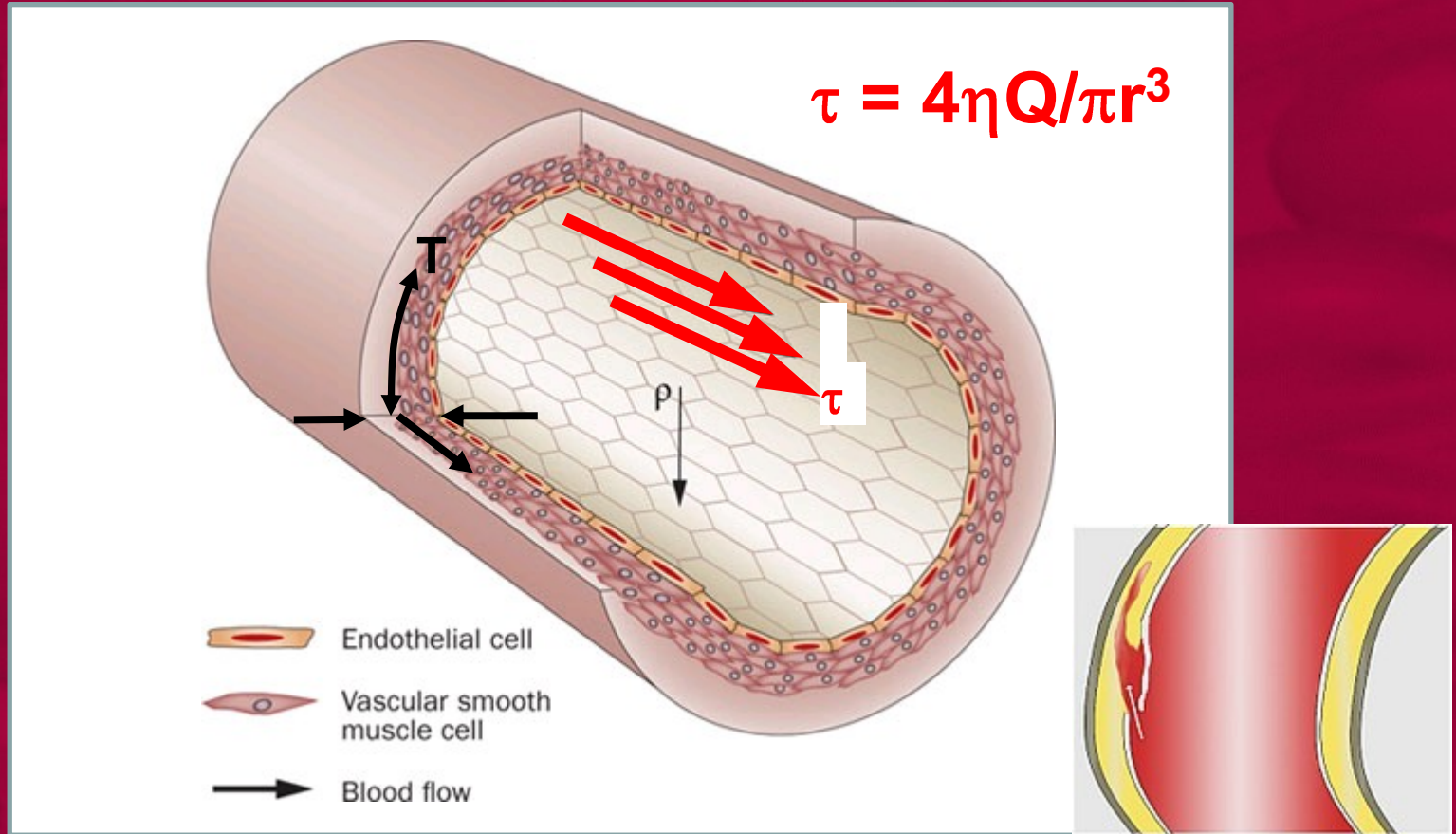


Moens-Korteweg (1878)

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

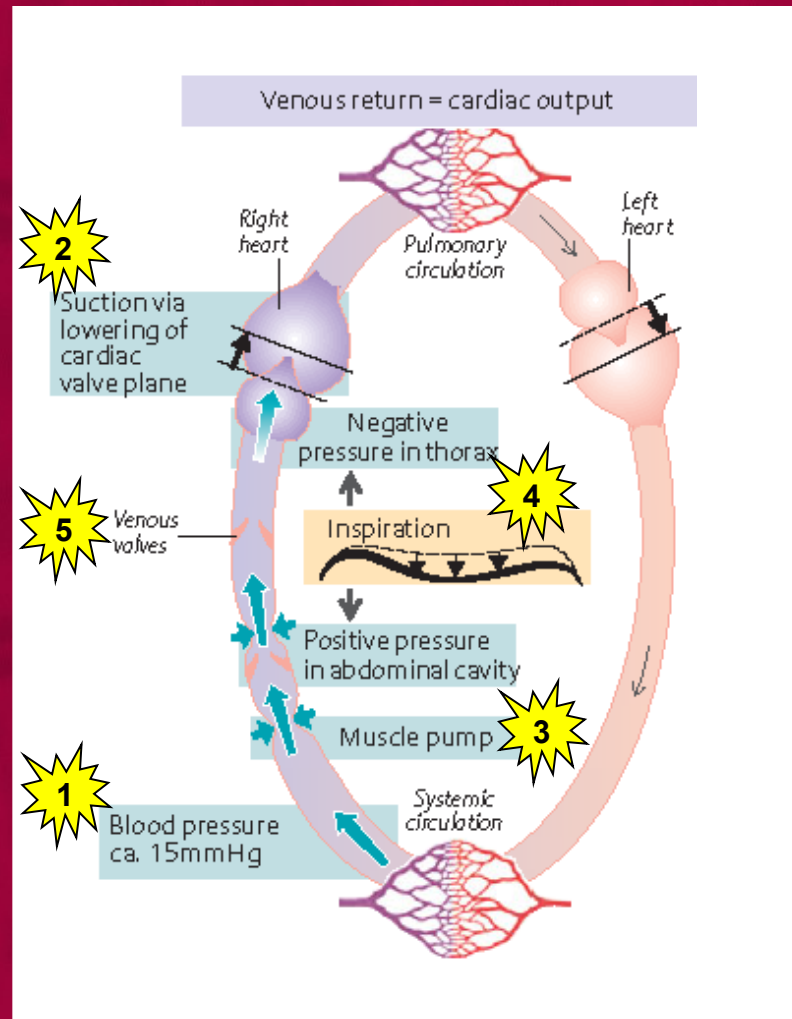
In aorta $PWV = 4 - 6 \text{ m/s}$

Share stress in vessel wall



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

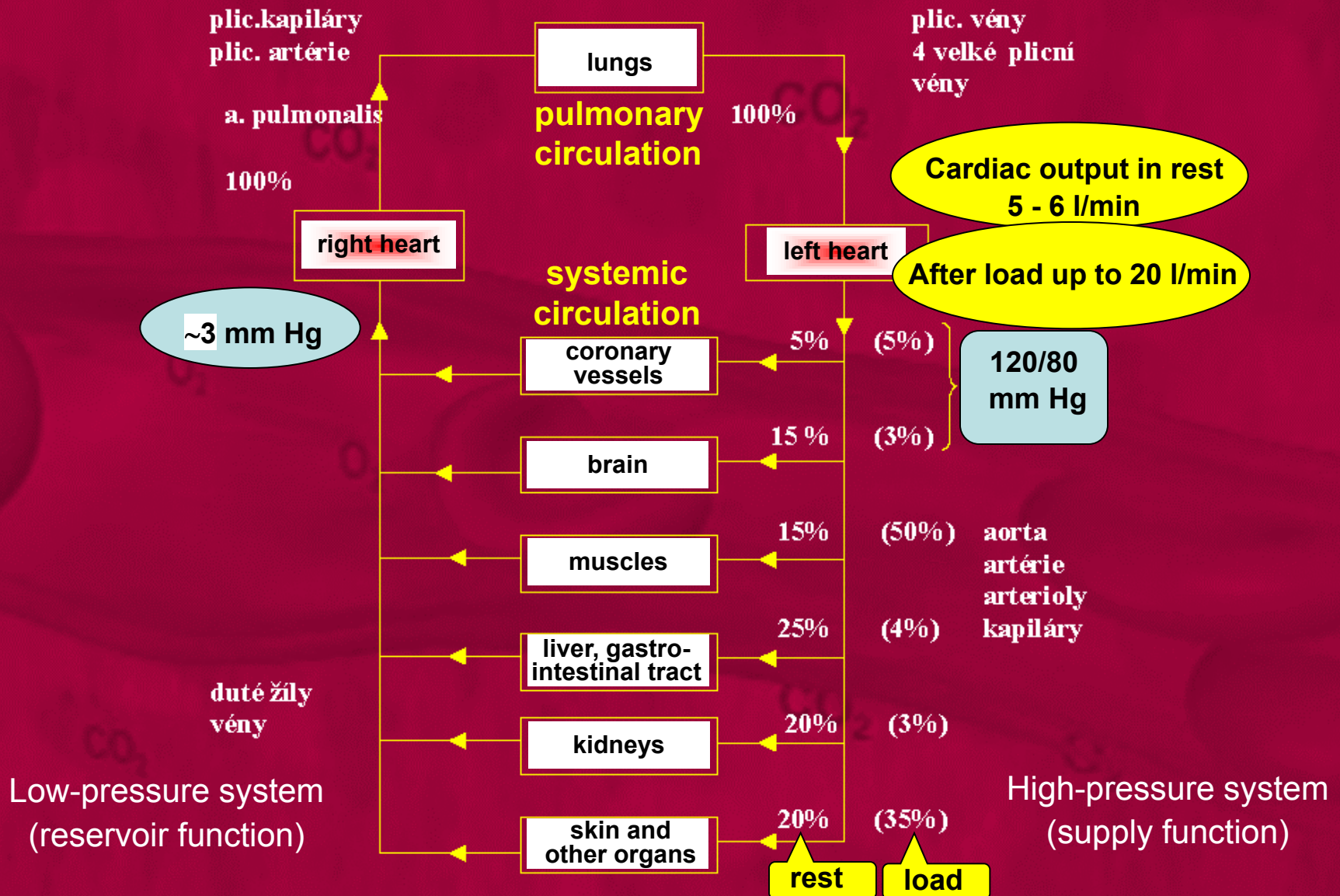
Mechanisms of venous return



The background of the slide is a dark red color. It features a faint, light-colored diagram of a blood vessel, possibly a capillary bed, with several red blood cells depicted as biconcave discs. Scattered around the vessel are several labels: 'CO₂' appears in three locations (top left, top right, and bottom left), and 'O₂' appears in two locations (top right and bottom right).

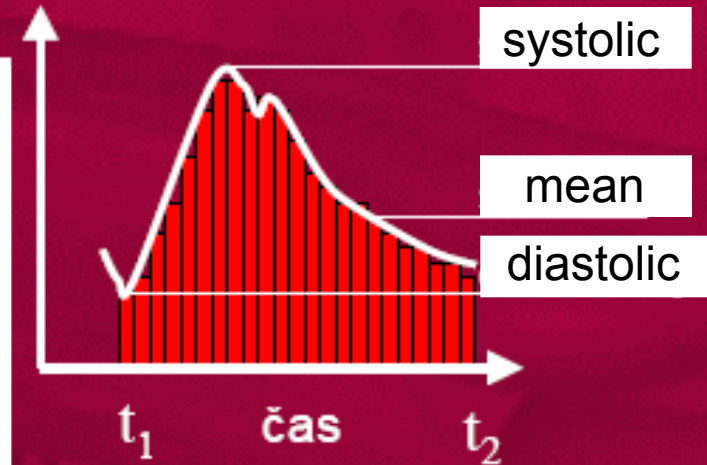
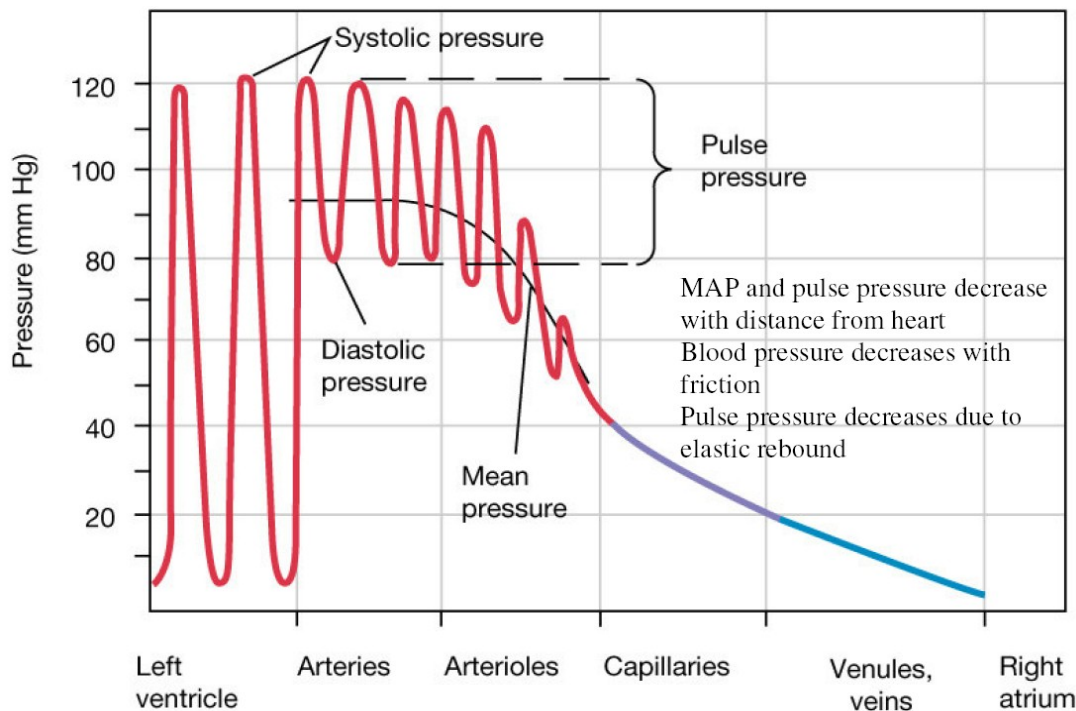
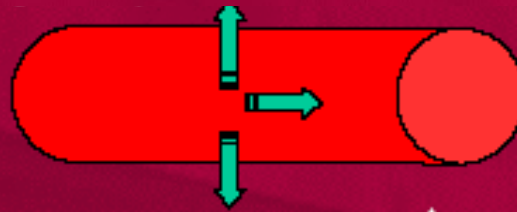
3. Blood circulation and pressure

Blood circulation



Blood pressure

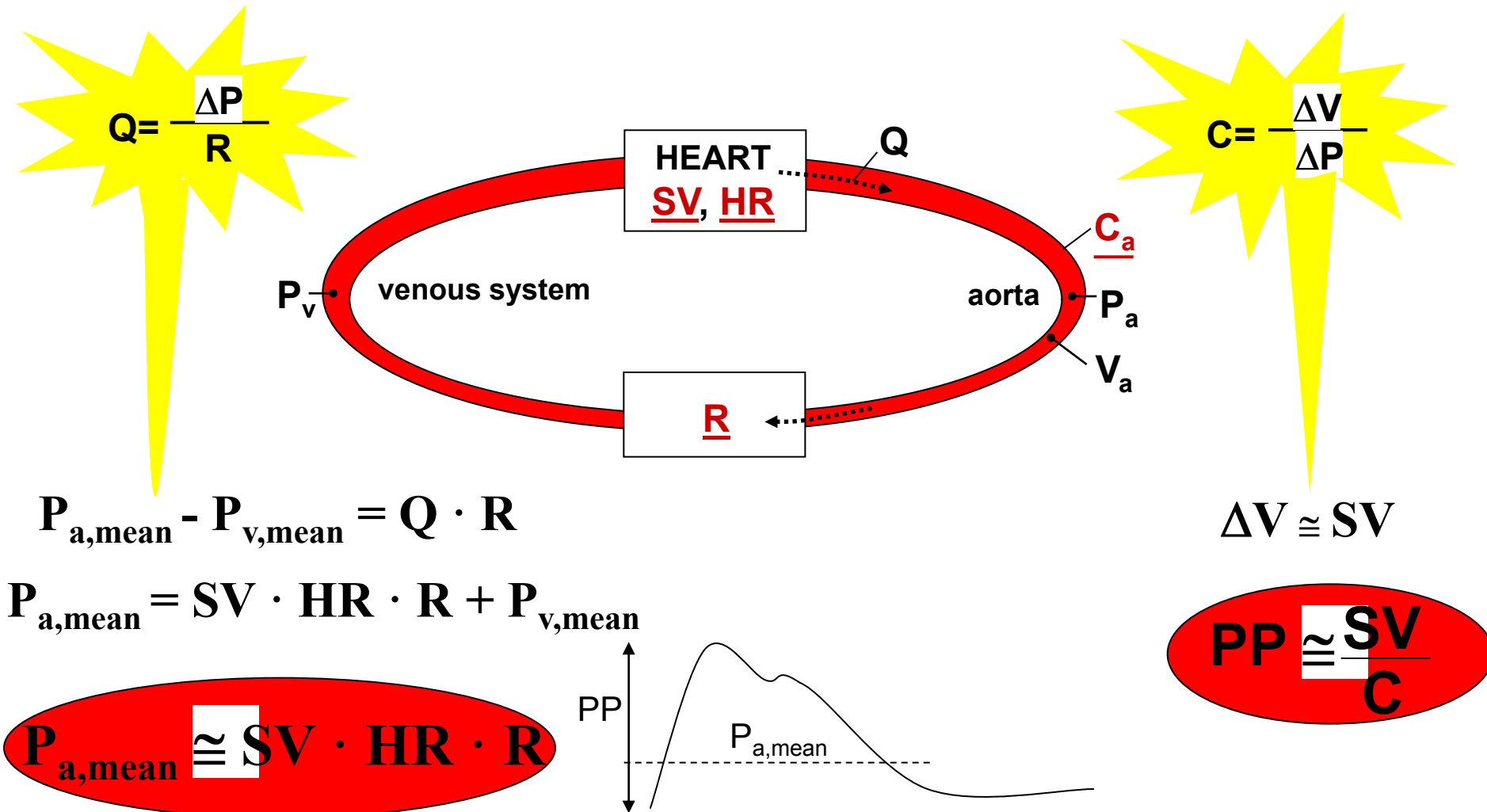
Blood pressure (BP) is the pressure exerted by circulating blood upon the walls of blood vessels.



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

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

Dependence of blood pressure on cardiac output and vascular parameters



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

