Cardiovascular system: Biophysics of circulation, Cardiac biophysics.

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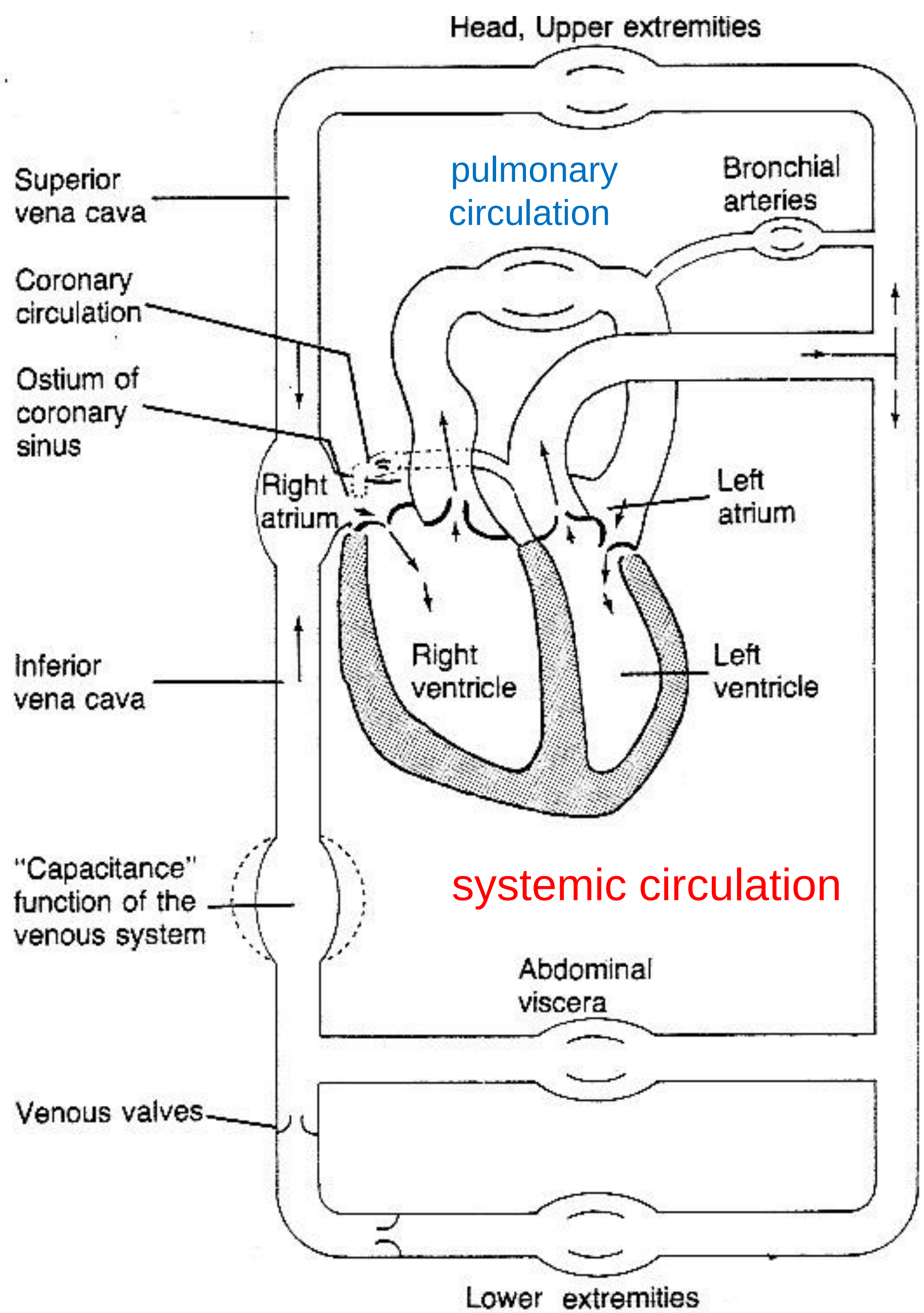
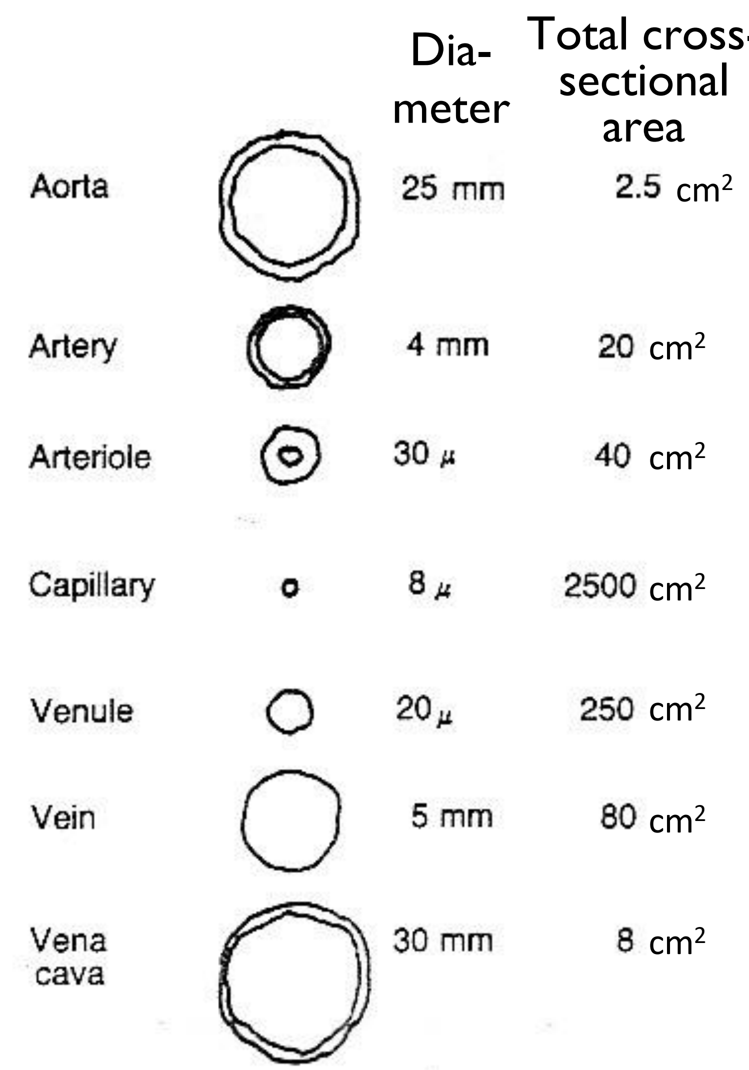
The vascular system: a closed vessel system returning into itself





- **Pressure** on blood vessel wall: ***"blood pressure"***. Pressure drop along vessel maintains blood flow.
- Reason of **pressure drop**: flow resistance — most of energy is converted to heat.
- **Arterioles** (vessels containing smooth muscle, under vegetative innervation) are pressure-regulators: ***"resistance vessels."***
- Most of blood volume in veins: ***"capacitance vessels."***

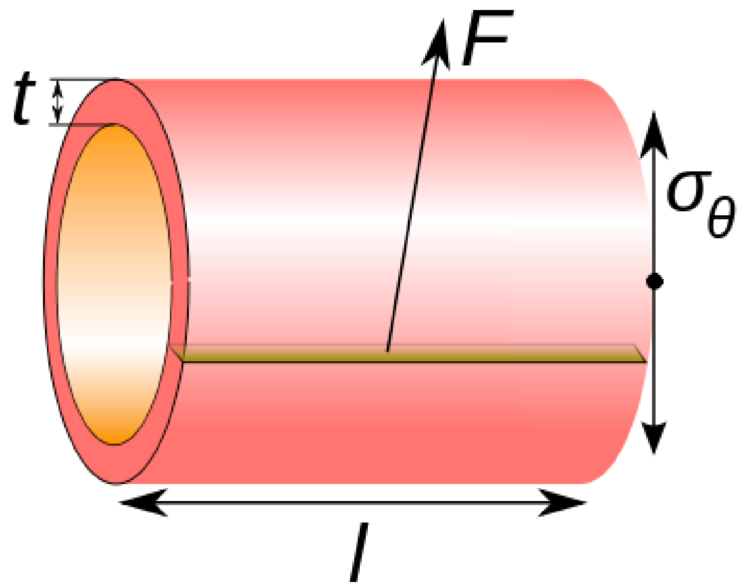
Blood vessels are flexible tubes

Young-Laplace equation

Circumferential stress (σ) depends on blood pressure:

$$\sigma = \frac{P \cdot r}{t}$$

P = blood pressure
r = radius of tube
t = wall thickness

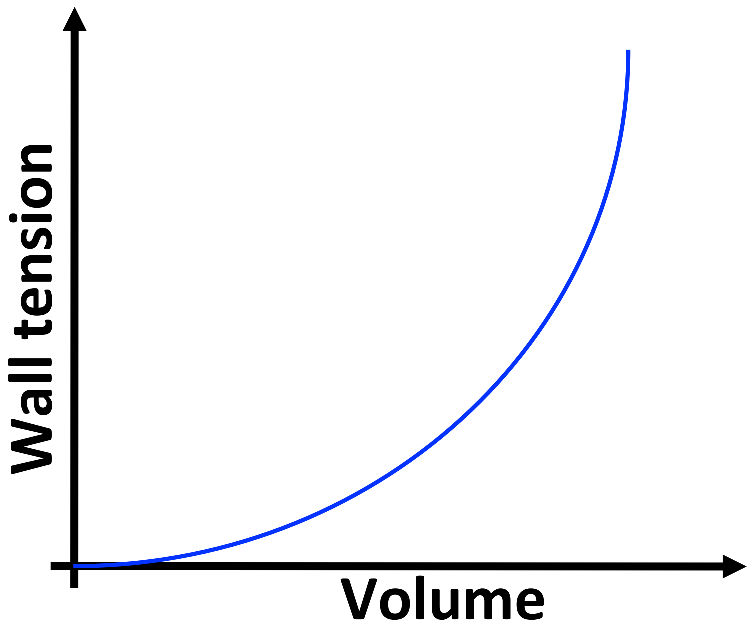


$$\sigma = \frac{F}{t \cdot l}$$

F = force
l = tube length
t = wall thickness

Wall tension or circumferential stress is the average force exerted circumferentially (perpendicular to both the axis and the radius) in the cylinder wall.

Vessel wall displays non-linear elastic properties



Determinants of vascular elasticity:

- Elastin
- Collagen
- Smooth muscle

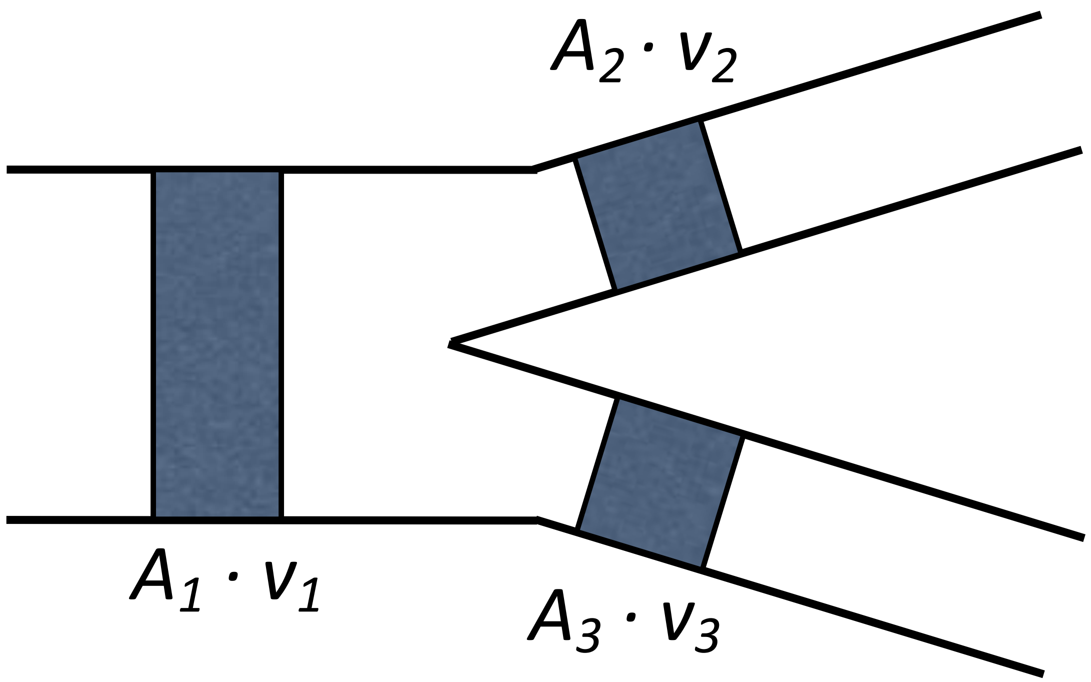
Implications of vascular elasticity:

- Storage of potential (elastic) energy
- Dampening of pressure pulses
- Constant flow rate

Laws of fluid mechanics in the vascular system

Adapted continuity equation

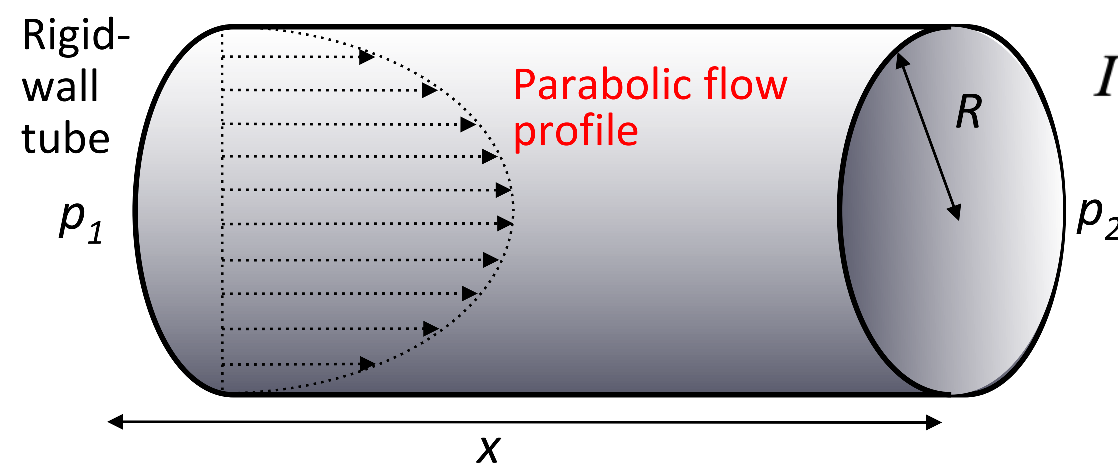
(constancy of volumetric flow rate)



$$A_1 v_1 = A_\Sigma (v)_{average} = const$$

A_Σ = total cross-sectional area

Hagen-Poiseuille's law



$$I_V = -\frac{R^4 \pi}{8 \eta \Delta x} \Delta p$$

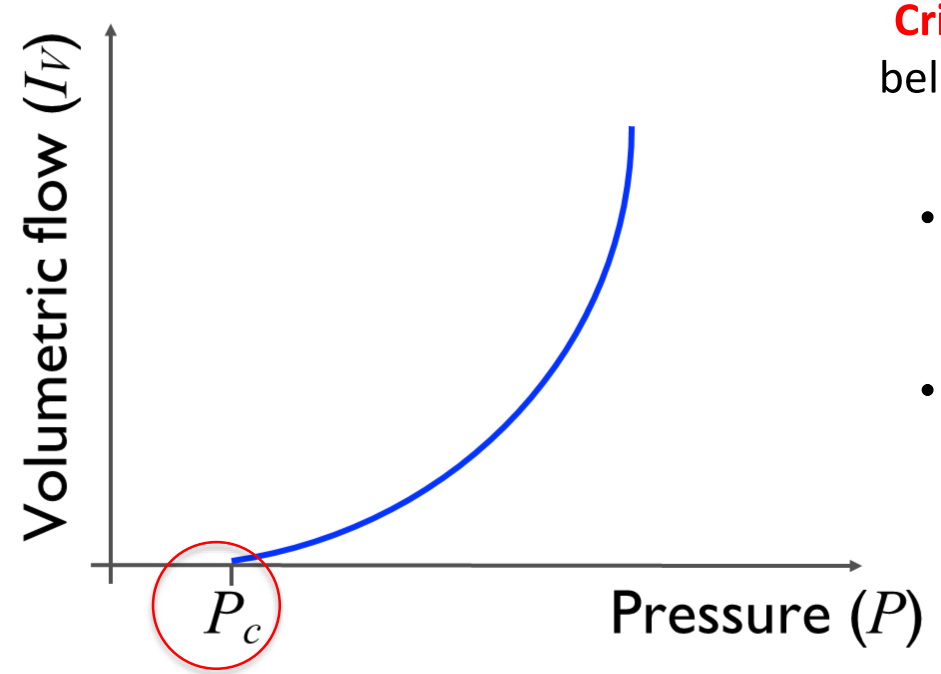
$1/R_{tube}$

$$I = \frac{1}{R} \cdot U$$

Ohm's law

V = volume
t = time
R = tube radius
η = viscosity

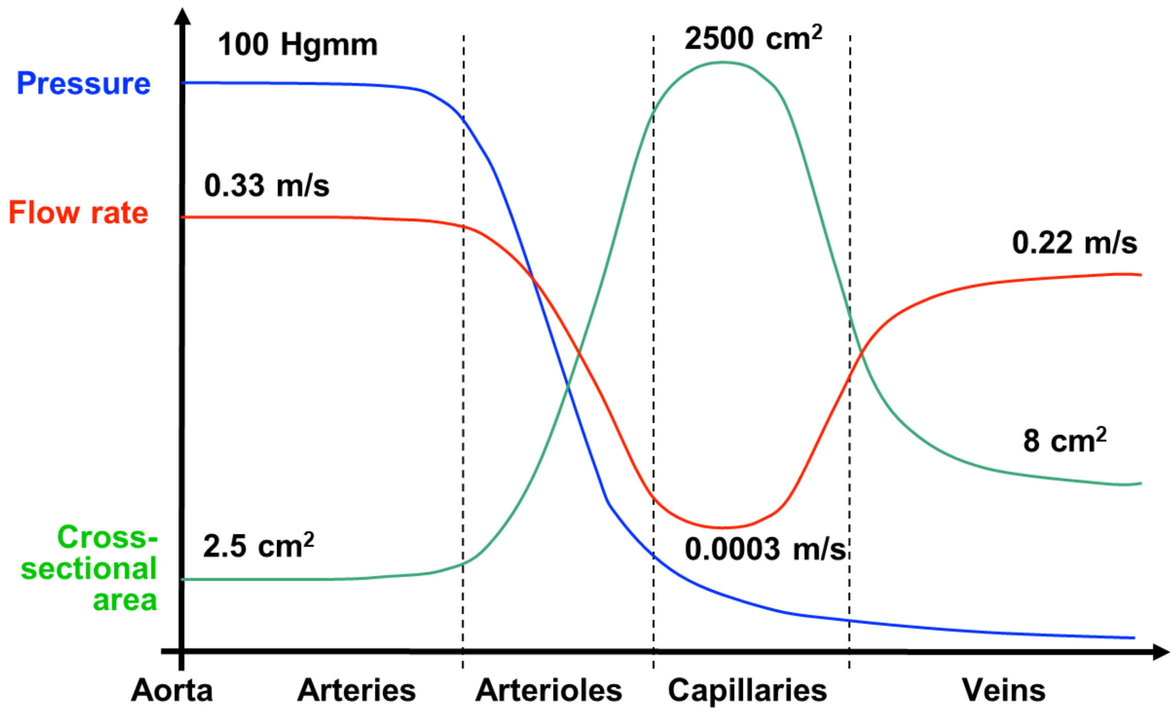
p = pressure
x = tube length
$V/t = I_V$ = volumetric flow rate
$\Delta p/\Delta x$ = pressure gradient, maintained by p_2-p_1 *(negative!)*

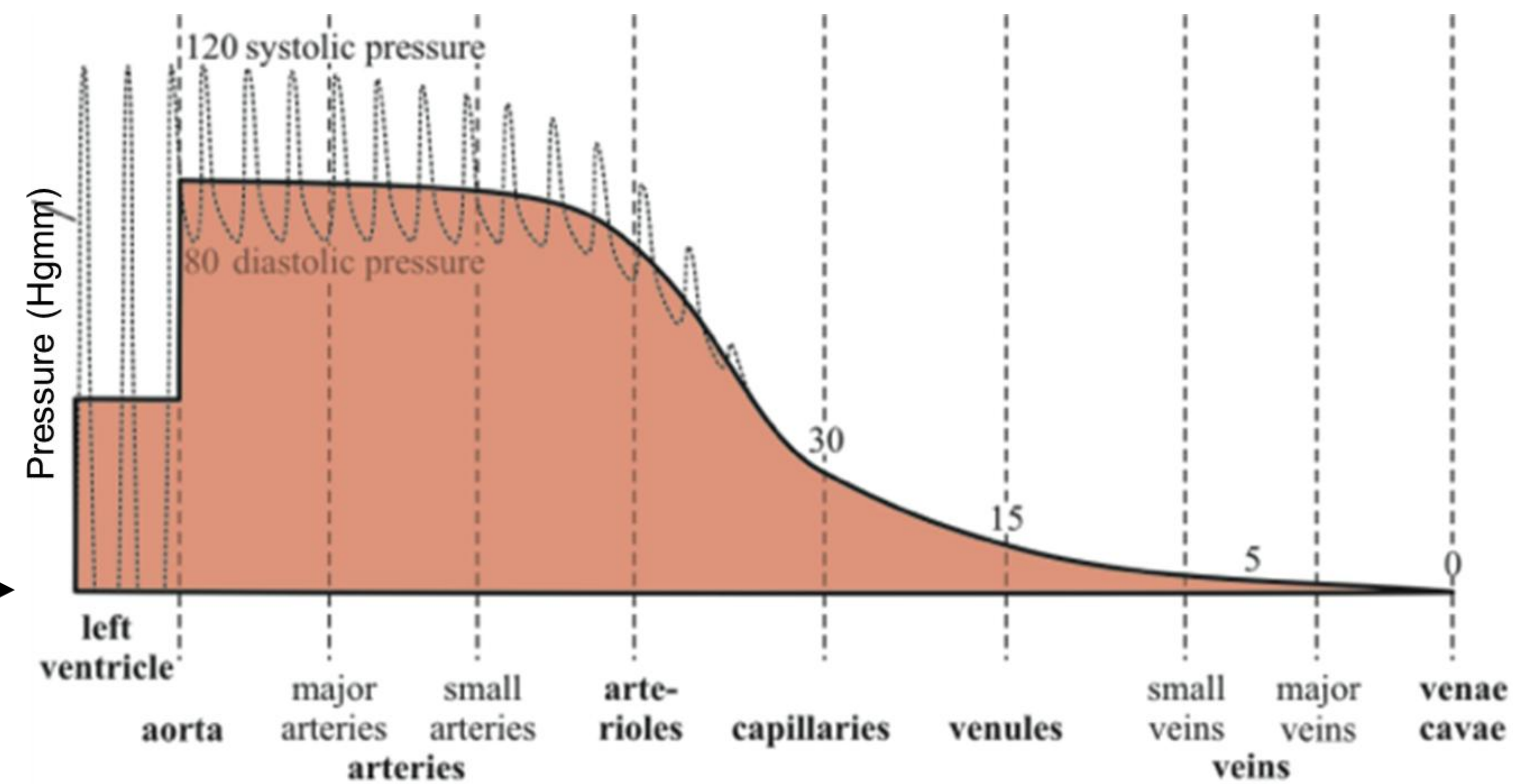


Critical Closing Pressure (P_c): below certain pressure vessels collapse

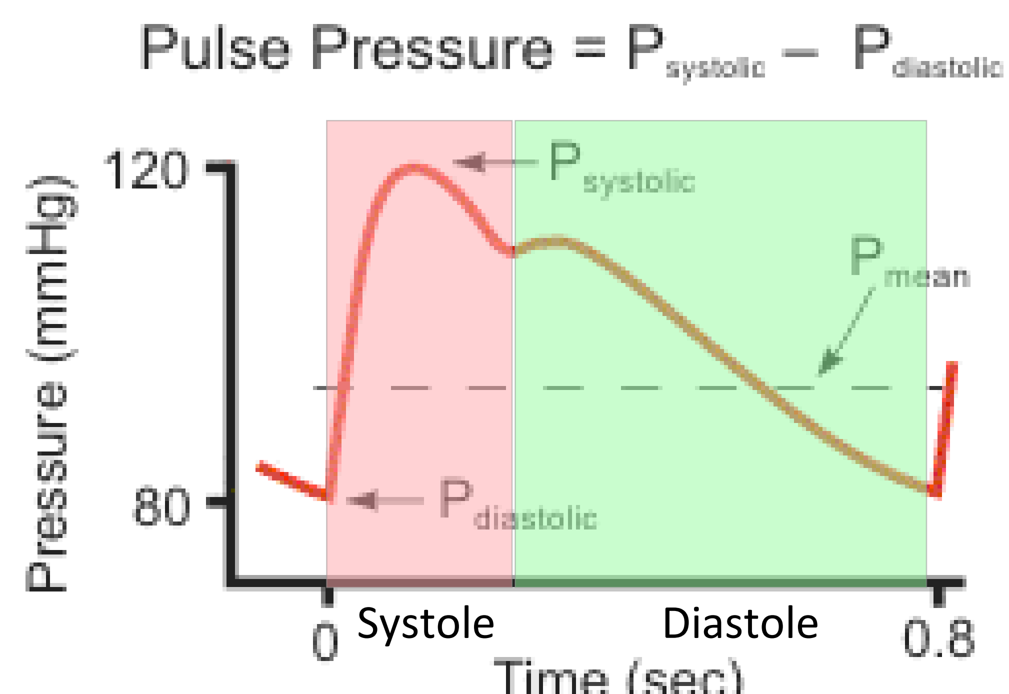
- in arteries, at resting conditions, its value is ~20 mmHg
- during blood pressure measurement we compress the limb by raising the cuff pressure above the local P_c

Dynamic pressure-changes in the arterial system





- **Flow rate** and total **cross-sectional area** change inversely (based on equation of continuity, $A \cdot v$ = constant).
- Flow rate typically does not exceed the **critical** value (see Reynolds number), and flow remains laminar. (Exceptions: behind aortic valve, constricted vessels, low-viscosity conditions, Korotkoff sound).
- **Windkessel effect:** sudden pressure fluctuations are smoothed out due to the elasticity of the blood vessel wall.
- As the pulsation smooths out, the **volumetric flow rate increases**.



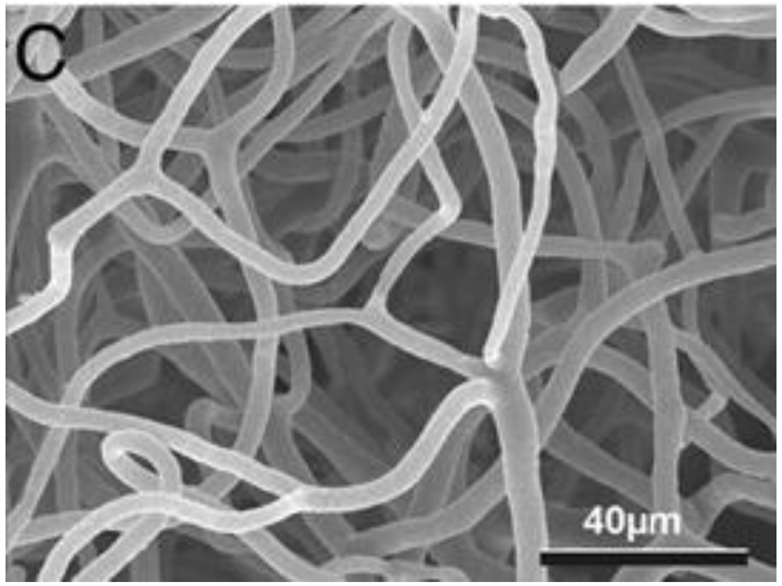
Capillary circulation, fluid exchange

Capillaries:

Length: 400-700 µm
Diameter: 5-10 µm
Mean distance: 30 µm

Open state depends on function!

Number of open capillaries in muscle:
Rest - 5/mm²
Activity - 200/mm²



„SEM image of cortical capillaries. Capillary diameters range from 4 to 6 µm and intercapillary distances are ≈30 µm."
Meyer et al, PNAS, 2008 105 (9) 3587-3592

Capillary fluid exchange:

fluid movement between blood plasma and interstitium
driven by: difference in blood pressure and colloid osmotic pressure
Colloid osmotic (oncotic) pressure:
osmotic pressure caused by the presence of colloidal proteins (2.6 kPa)

	Arterioles	Capillaries	Venules
Bood pressure	4.0 kPa	2.6 kPa	1.3 kPa
Colloid osmotic pressure	2.6 kPa	2.6 kPa	2.6 kPa

Auxiliary factors of circulation

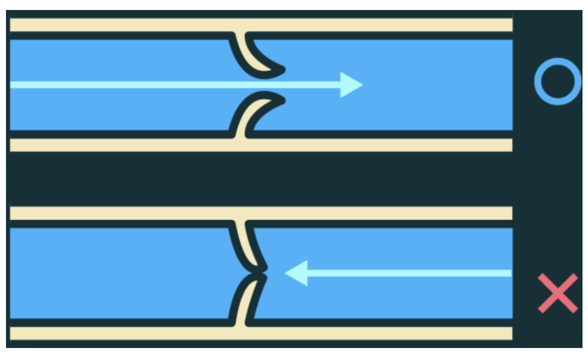
factors that maintain the continuity of the blood flow

1. Arterial elasticity

elastic fibers ➛ storage of potential energy

2. Venous valves (Harvey's experiment)

"Exercitatio anatomica de motu cordis et sanguinis in animalibus" (1628)



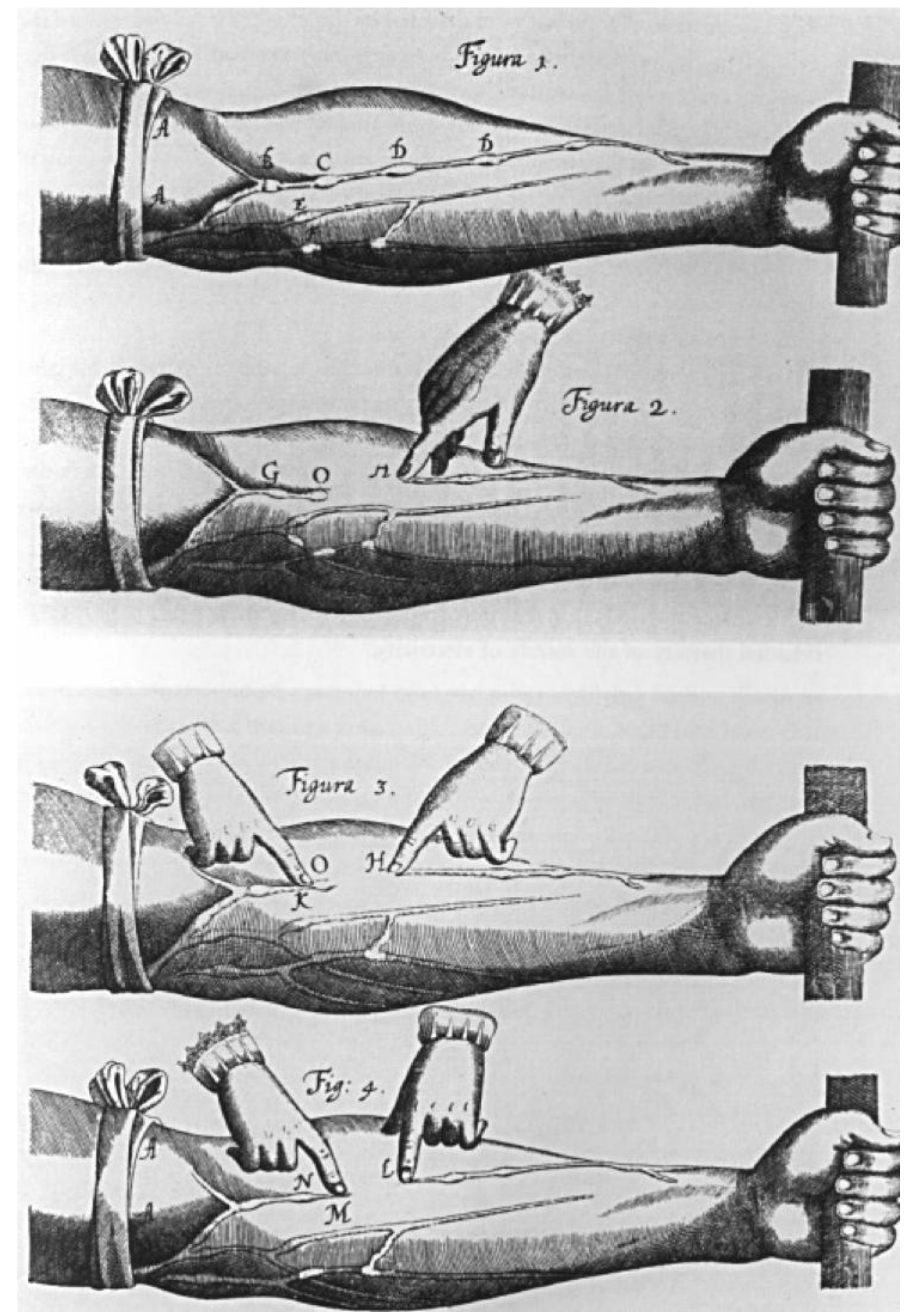
3. Muscle action

4. "Negative" intrathoracic pressure

5. "Up-and-down" movement of **atrioventricular plane**

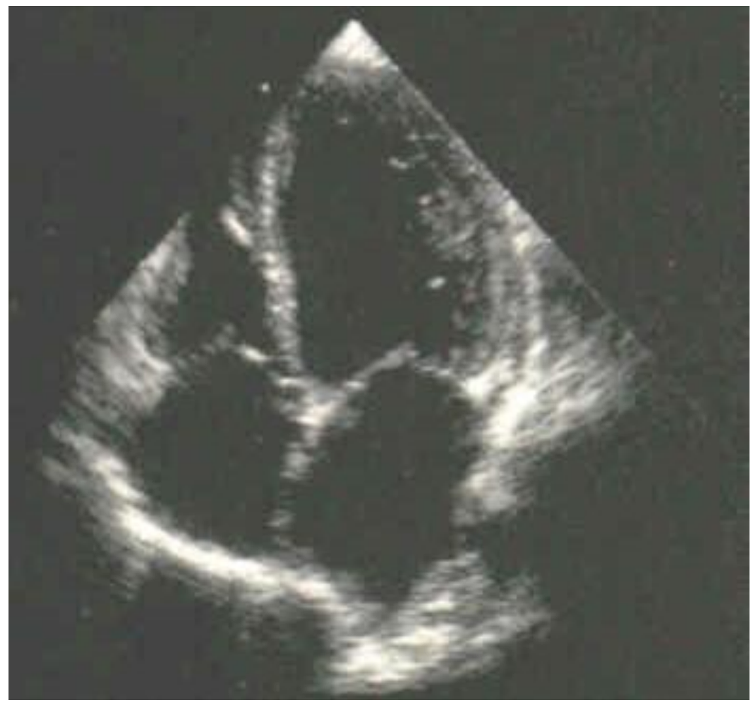
- synchronous with ventricular systole
- transient negative pressure in the right atrium

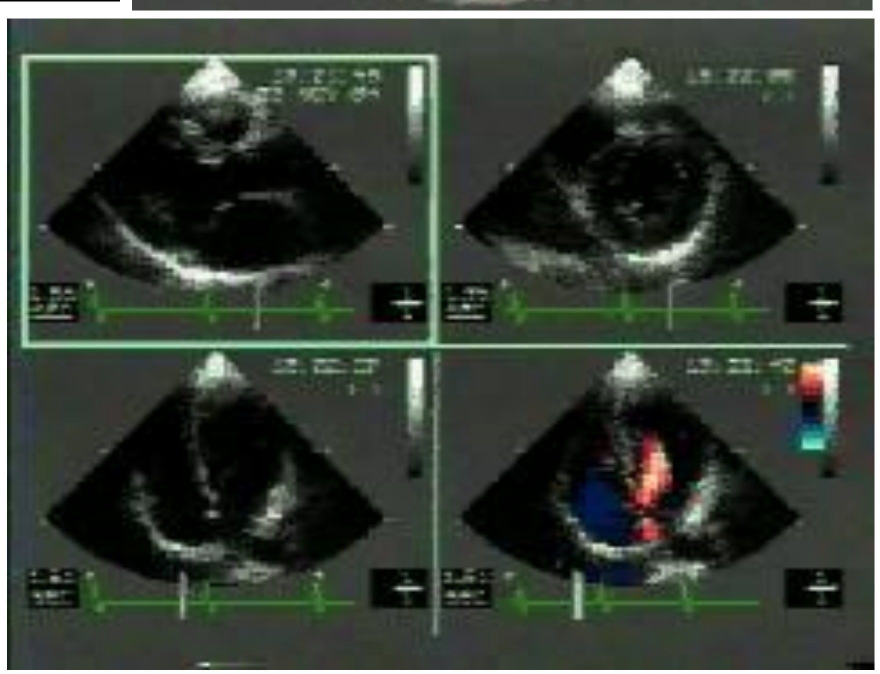
Harvey's experiment (1628)



Heart:

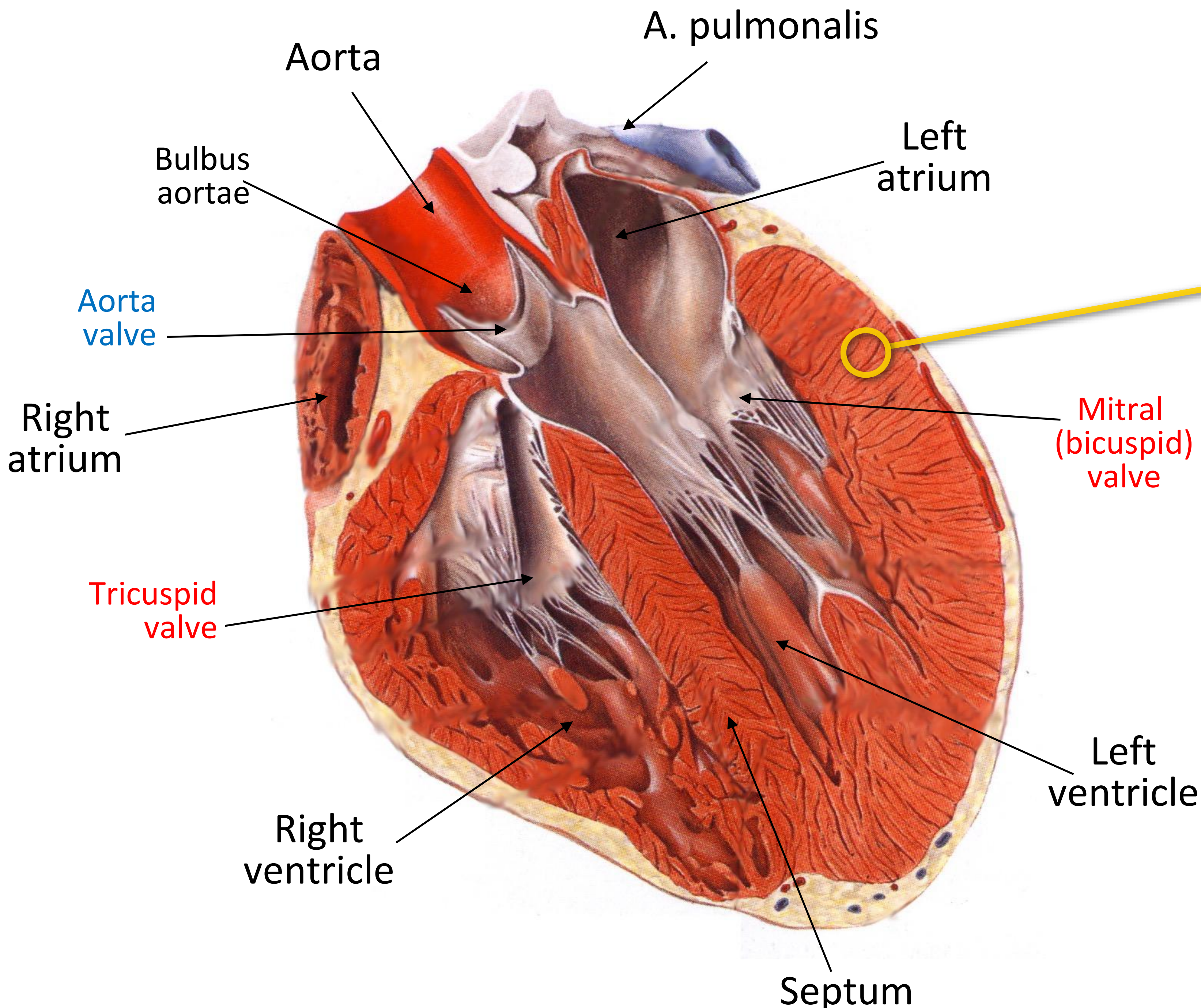
Pump of the circulatory system

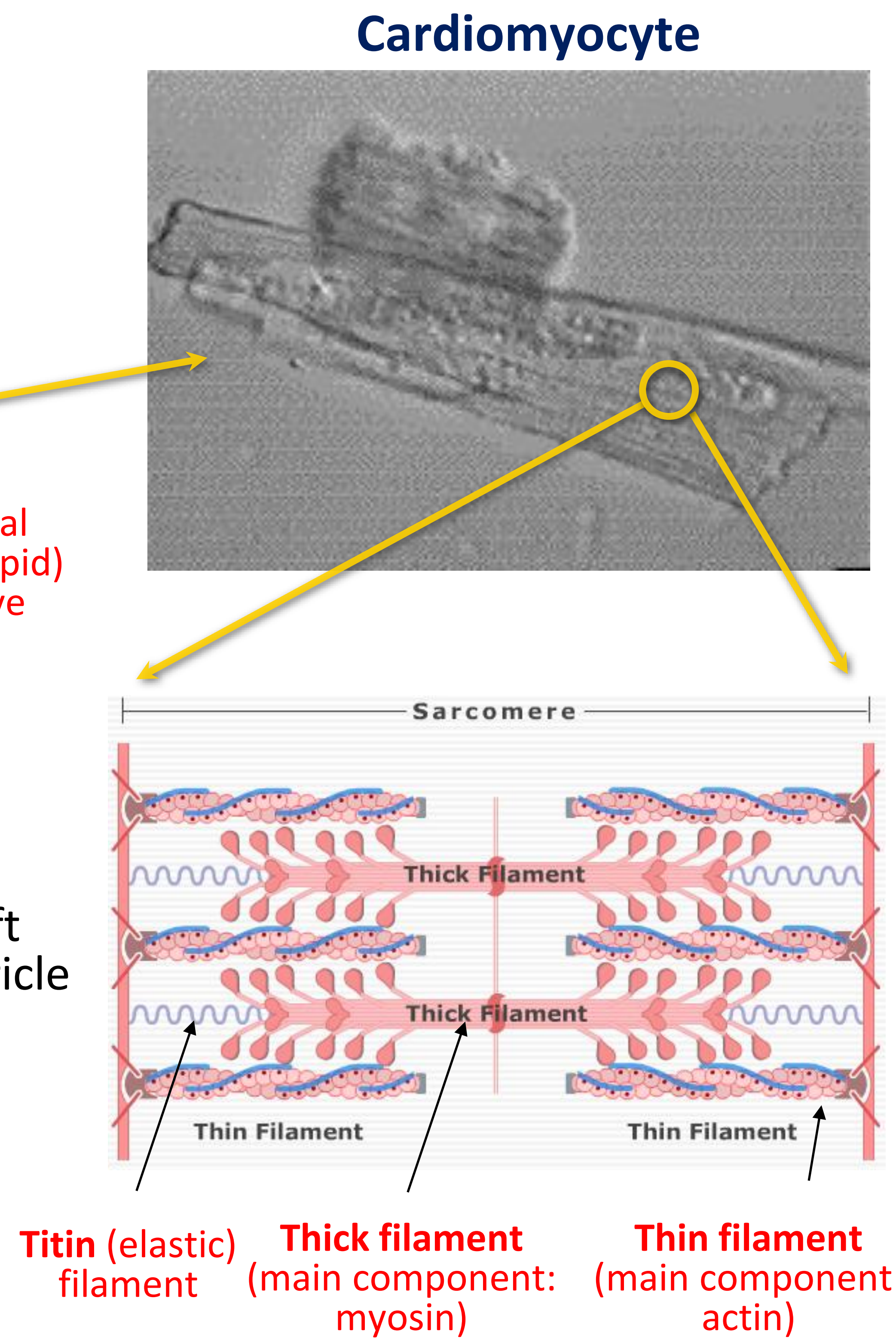




	Number of contractions	Expelled blood volume
1 min	~70	~6 l
1 day	~100 000	~8 600 l
Life (70 years)	$\sim 2.5 \times 10^9$	$\sim 220 \times 10^6$ l

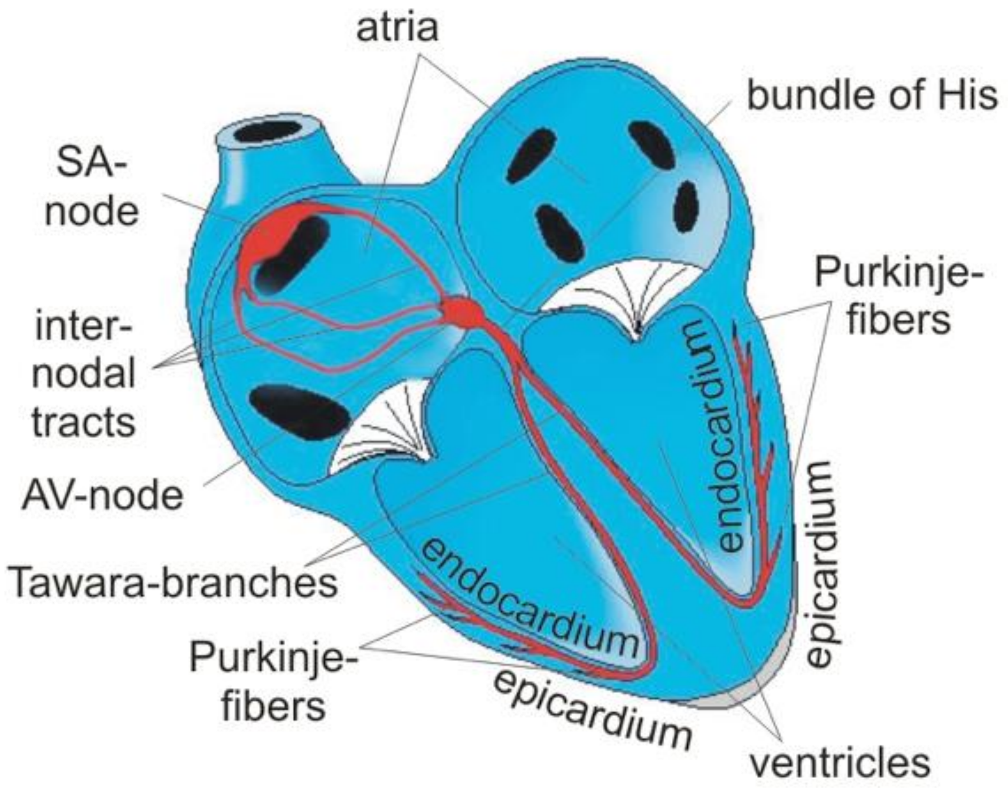
Schematic structure of the human heart



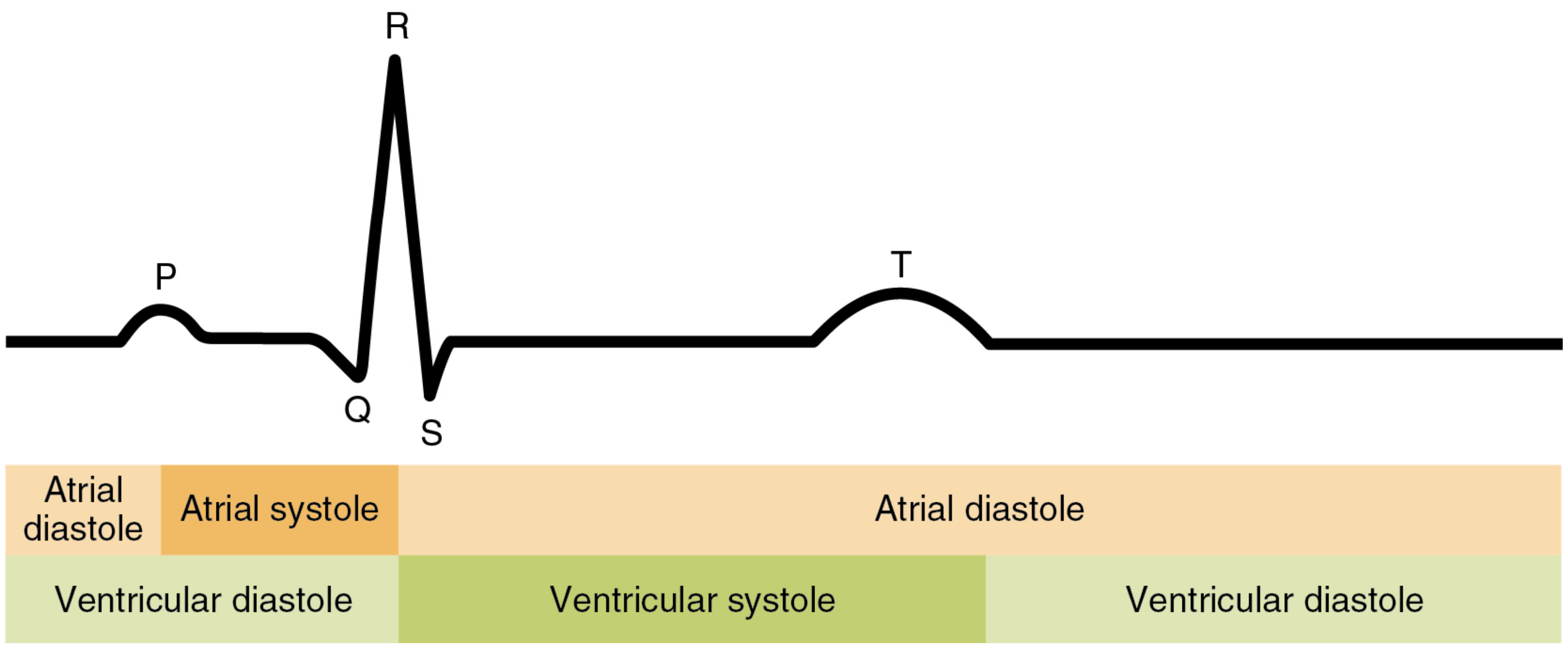


Contraction (systole) - relaxation (diastole) cycle of the heart

The cardiac cycle

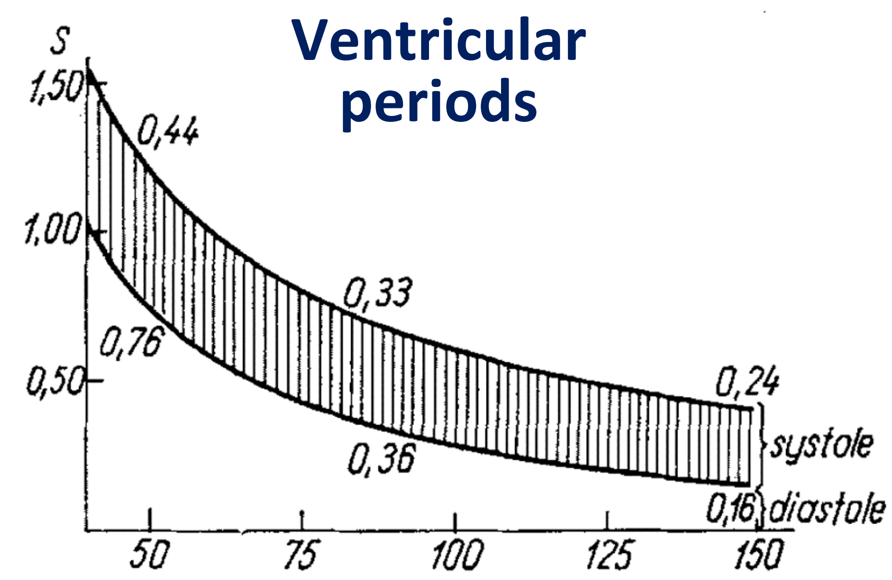


Electrocardiogram (ECG)



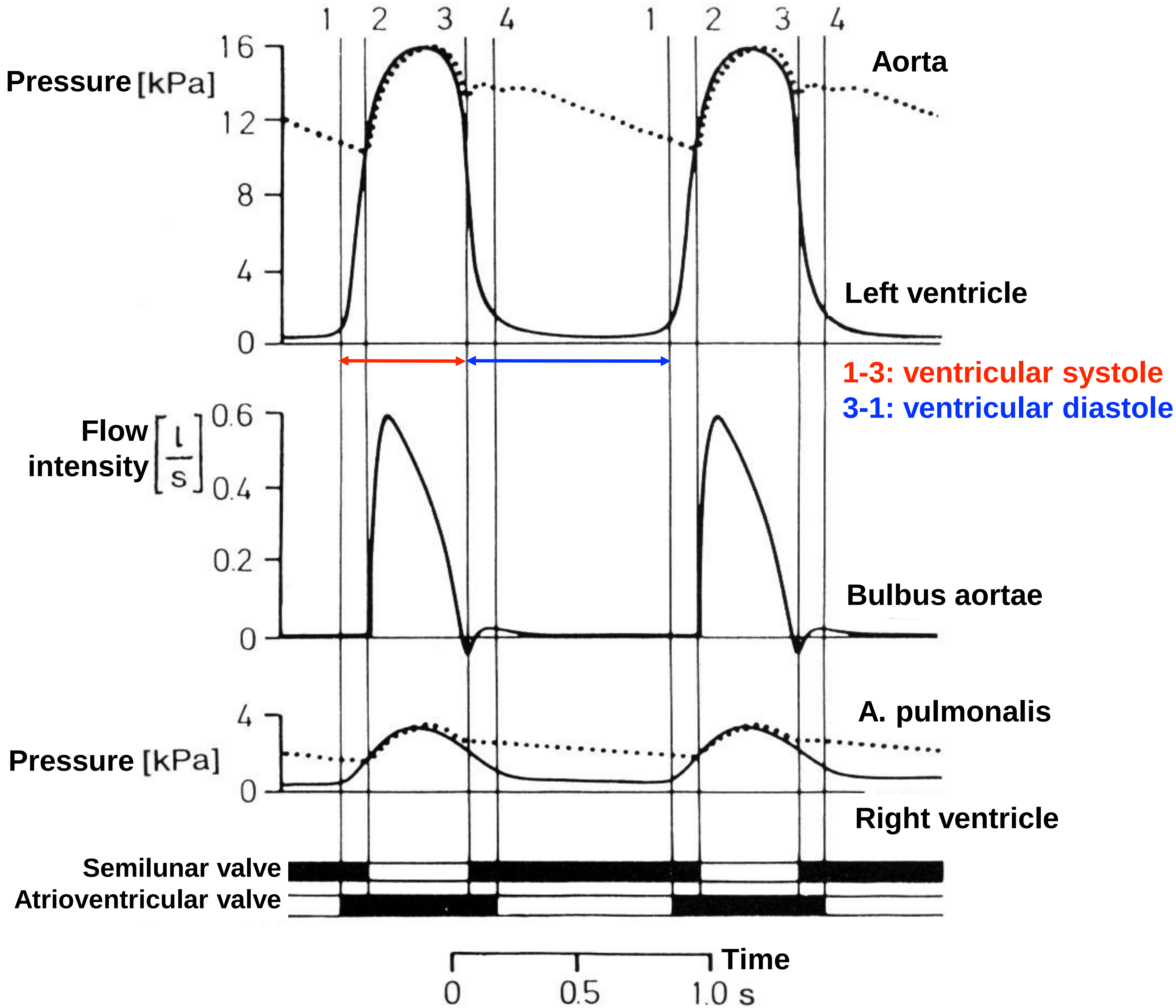
	systole	diastole
atrium	0.1 s	0.7 s
ventricle (70/min)	0.28 s	0.58 s
ventricle (150/min)	0.24 s	0.16 s

Ventricular periods

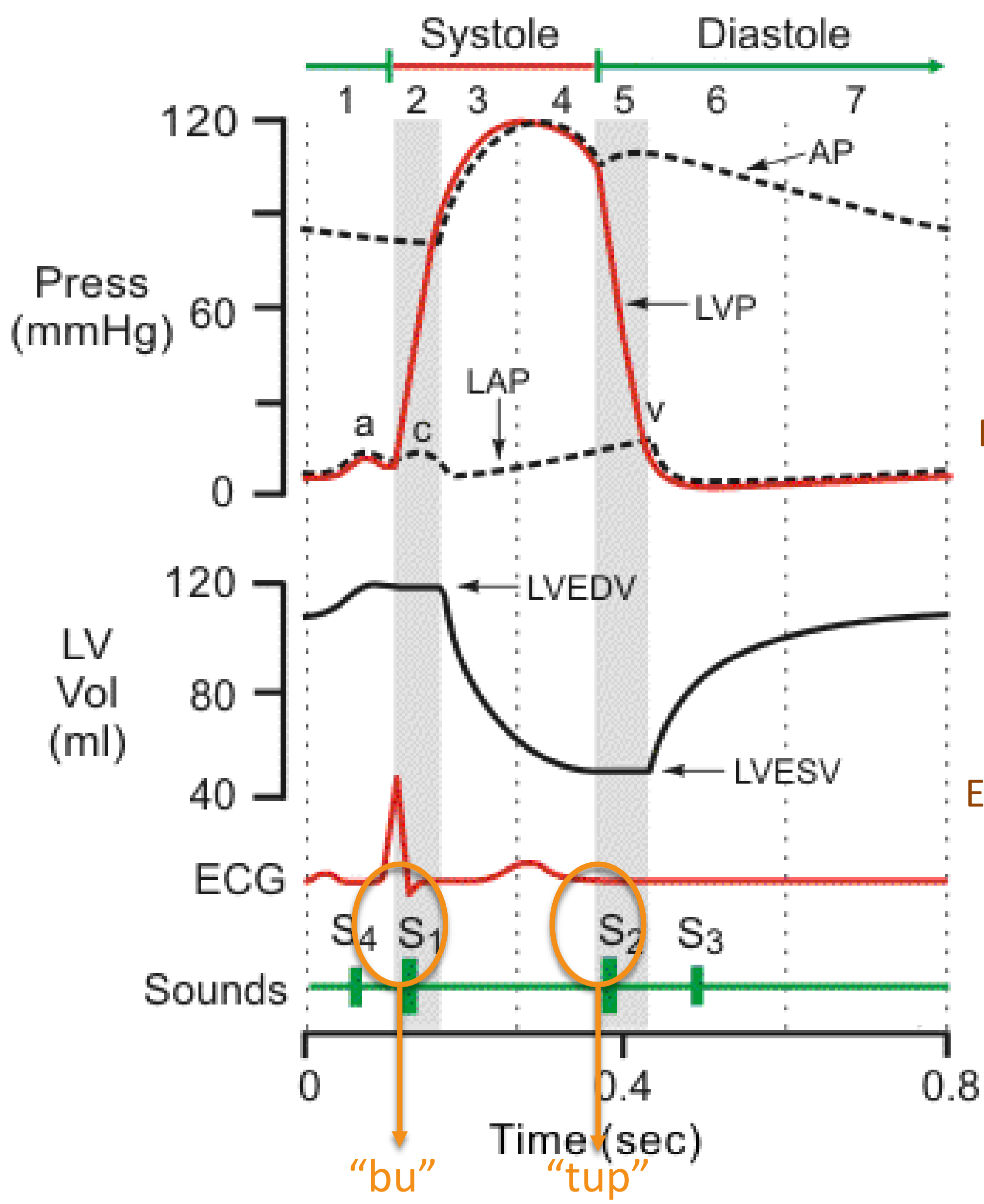


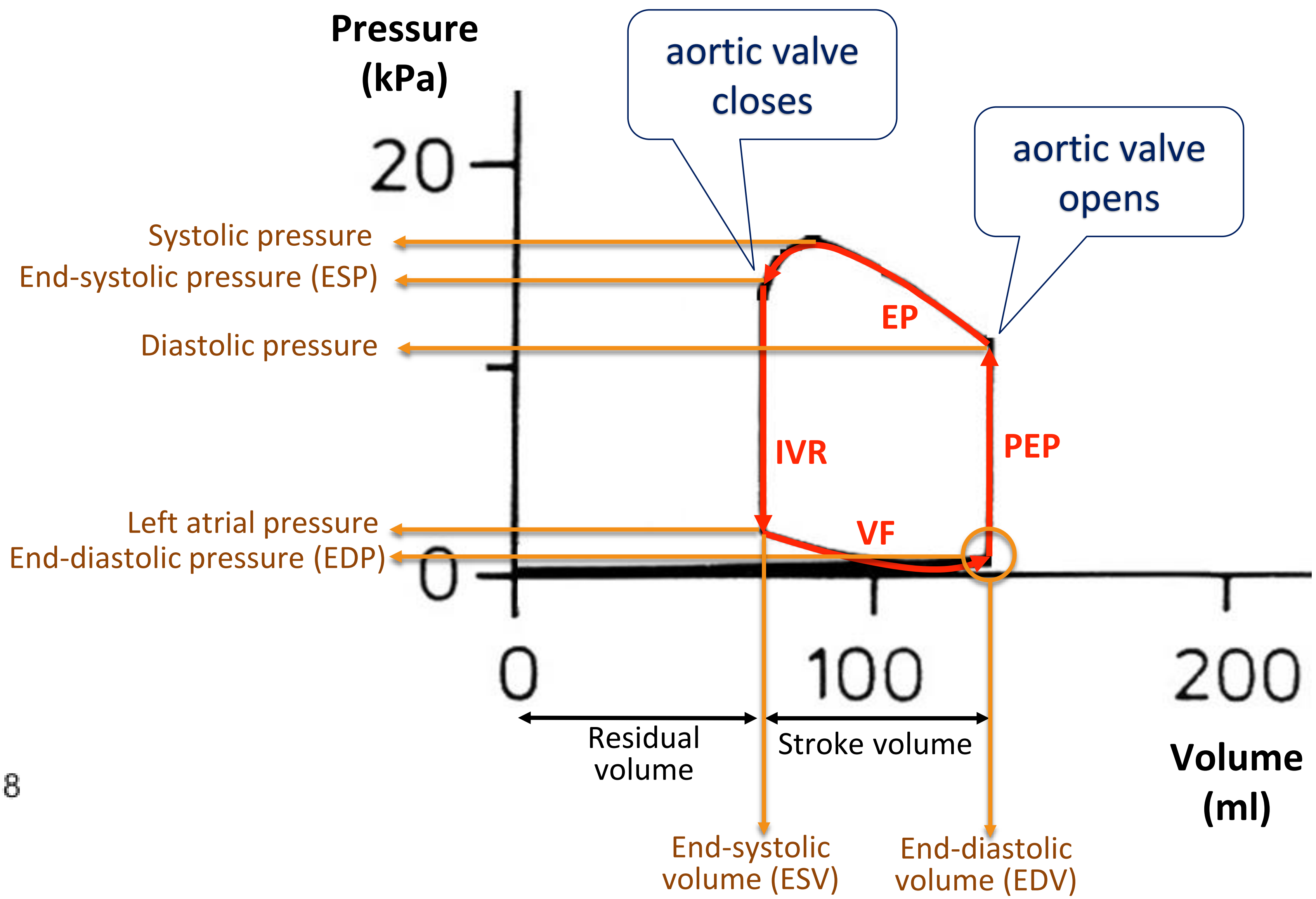
Events of the cardiac cycle

1-2: pre-ejection period (PEP) **2-3:** ejection period (EP) **3-4:** isovolumetric relaxation (IVR) **4-1:** ventricular filling (VF)



Pressure-volume diagram of the left ventricle





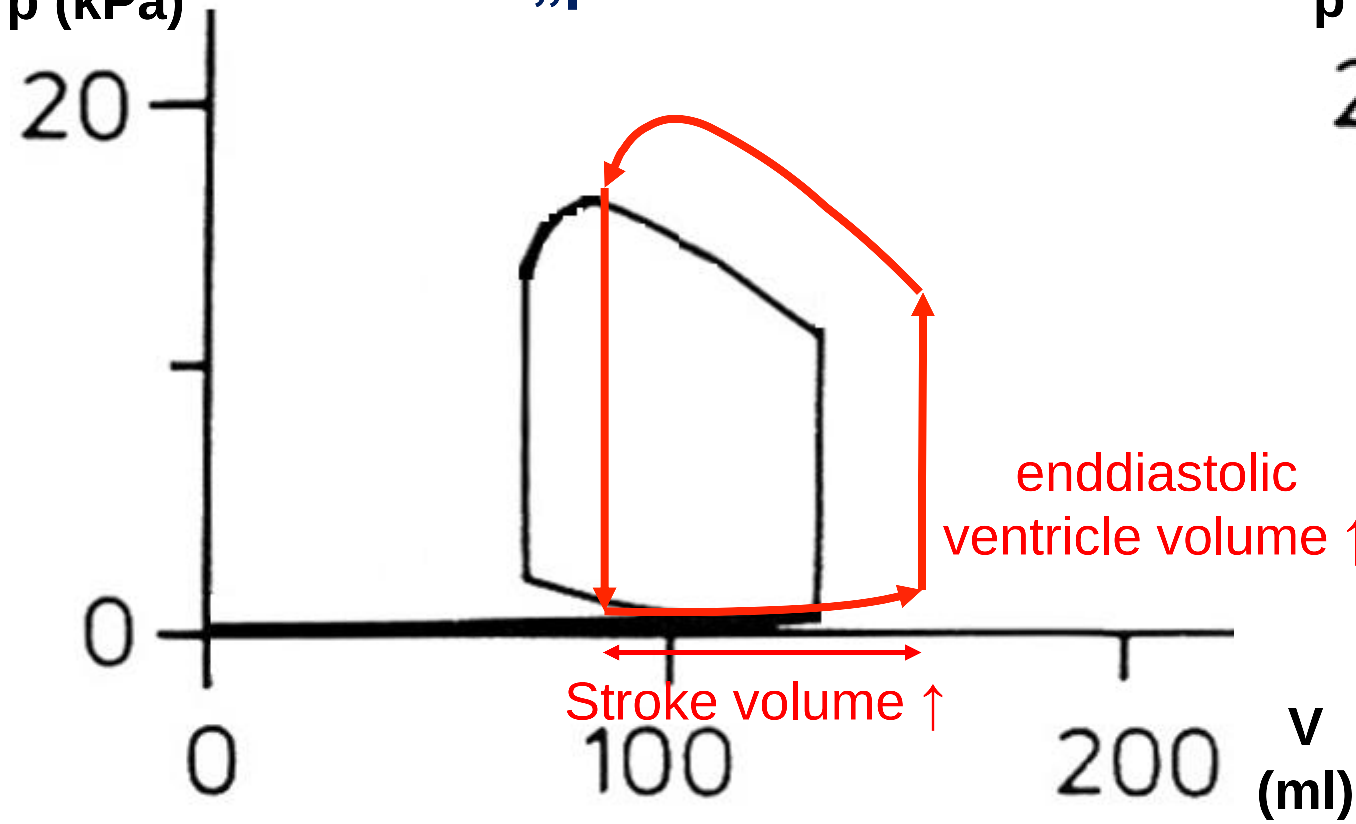
LVEDV: left ventricle enddiastolic volume
LVESV: left ventricle endsystolic volume
LAP: left atrial pressure
LVP: left ventricular pressure

VF: ventricular filling
PEP: pre-ejection period (isovolumetric contraction)
EP: ejection period
IVR: isovolumetric relaxation

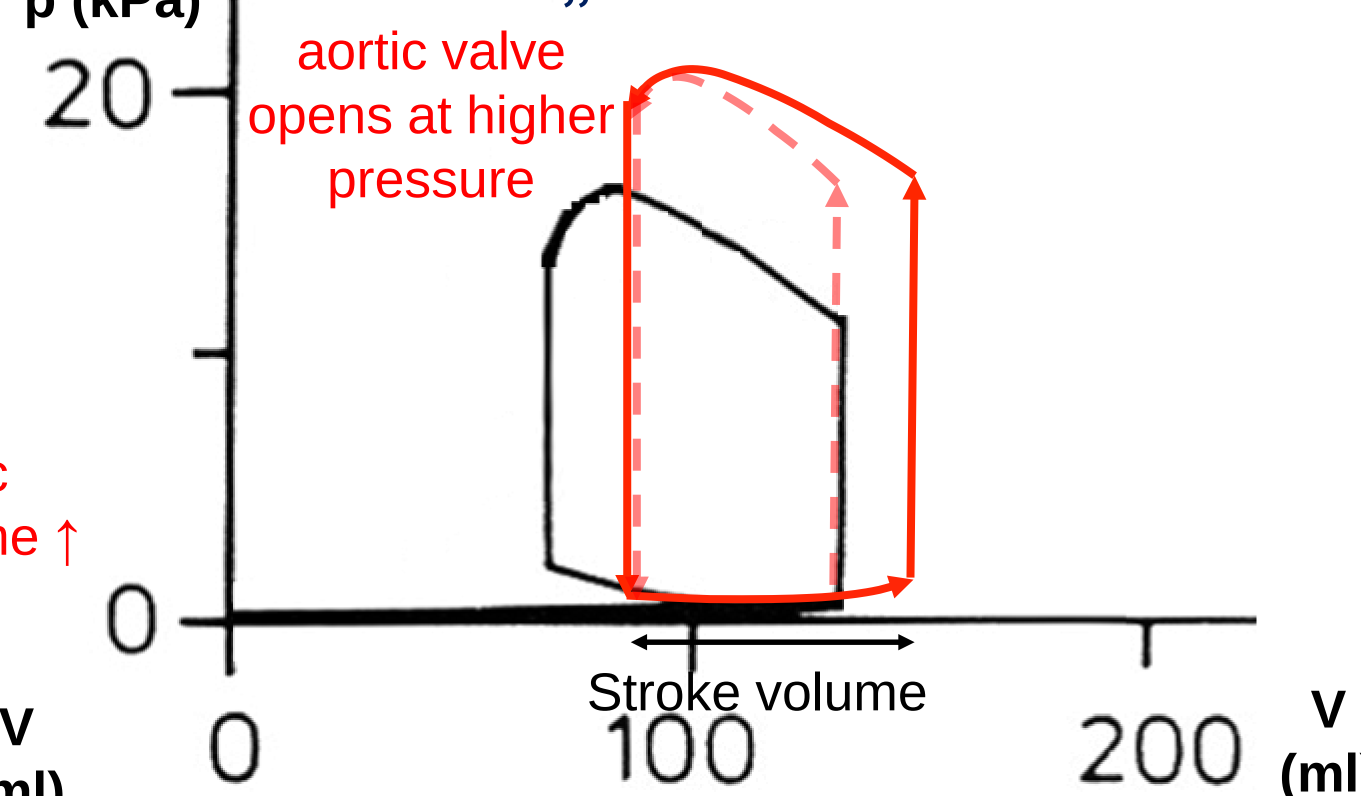
Autoregulation of the heart

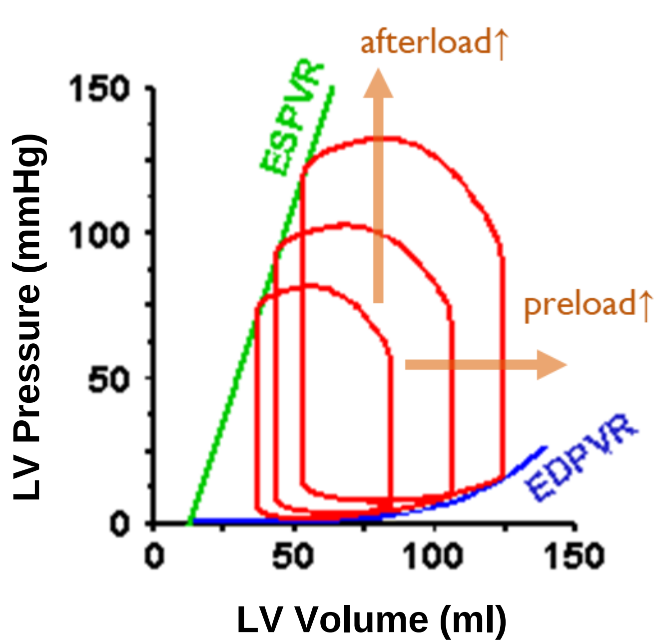
(the Frank-Starling mechanism)

increased venous return „preload”



increased peripheral vascular resistance „afterload”



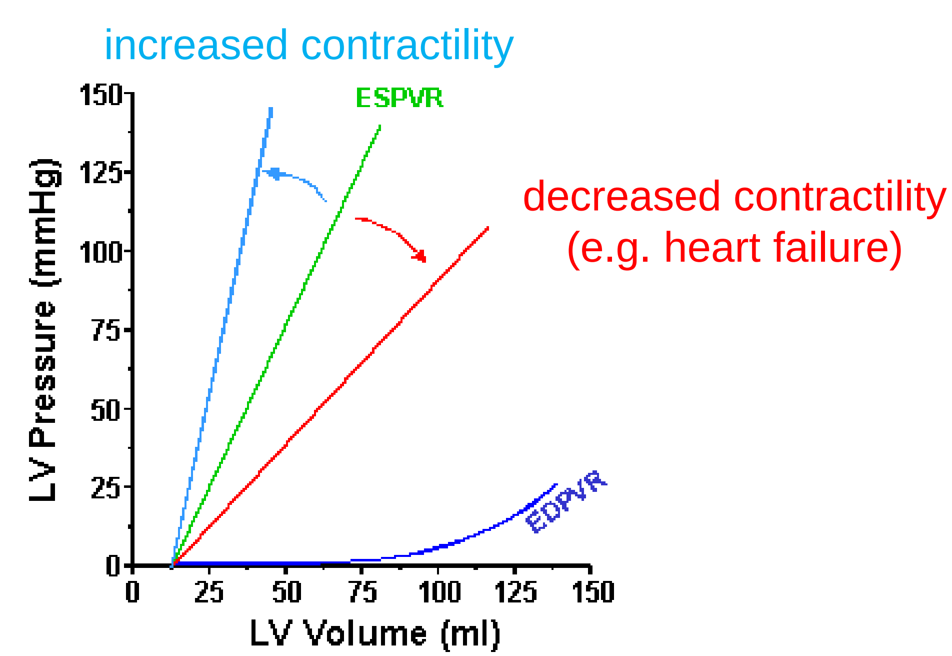


ESPVR: “end-systolic pressure-volume relationship”, determinants:

- contractility
- aortic pressure

EDPVR: “end-diastolic pressure-volume relationship”, determinants:

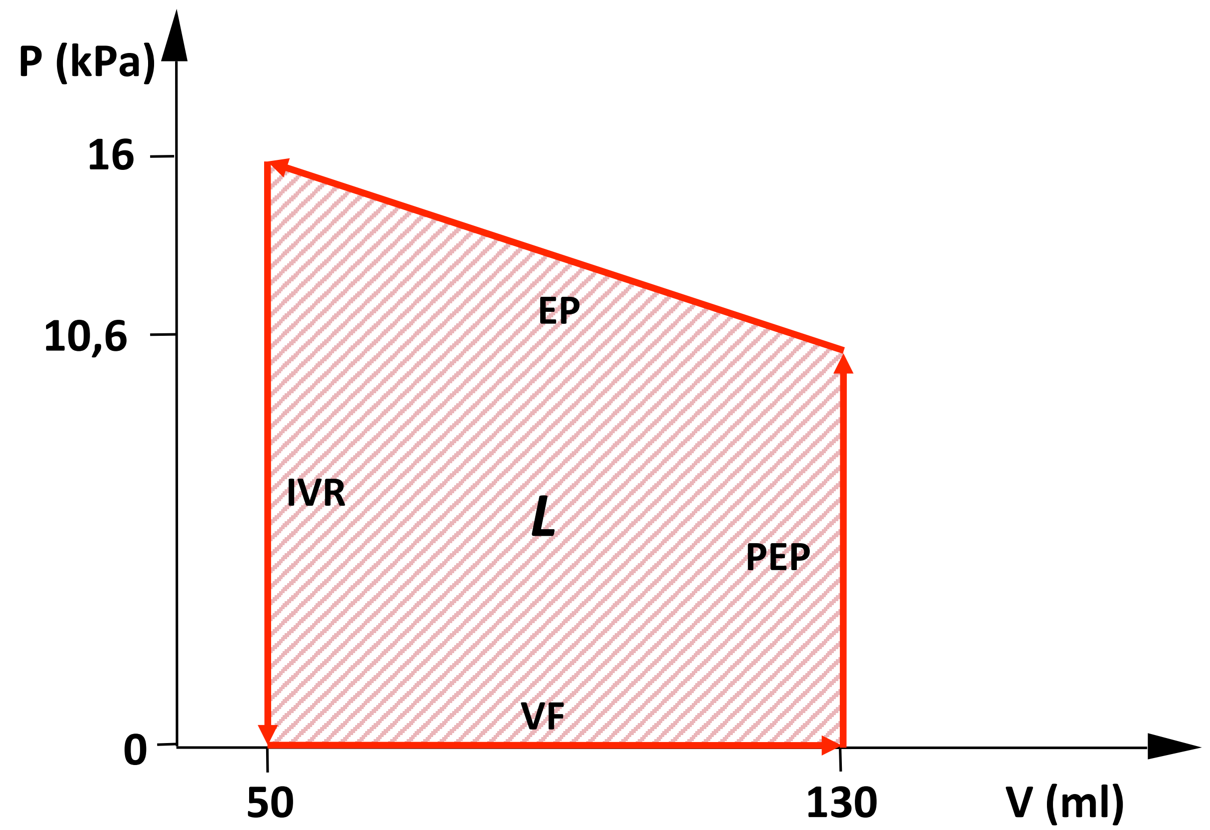
- “passive” elasticity (titin)
- volume overload



Work of the heart

(work of the left ventricle)

Indicator diagram: simplified pressure-volume relationship



$$L = p\Delta V + \frac{1}{2}mv^2$$

$p\Delta V$ = **static (volumetric) component**

½ mv^2 = **dynamic component**

p = pressure

ΔV = **stroke volume**

$$13{,}3 \cdot 10^3 N/m^2 \times 0{,}08 \cdot 10^{-3} m^3 + \frac{1}{2} 0{,}08 kg \times (1 m/s)^2 = 1{,}06 Nm + 0{,}04 Nm = 1{,}1 J$$

FEEDBACK

THANK YOU FOR YOUR ATTENTION!