

CARDIOVASCULAR SYSTEM: BIOPHYSICS OF CIRCULATION, CARDIAC BIOPHYSICS

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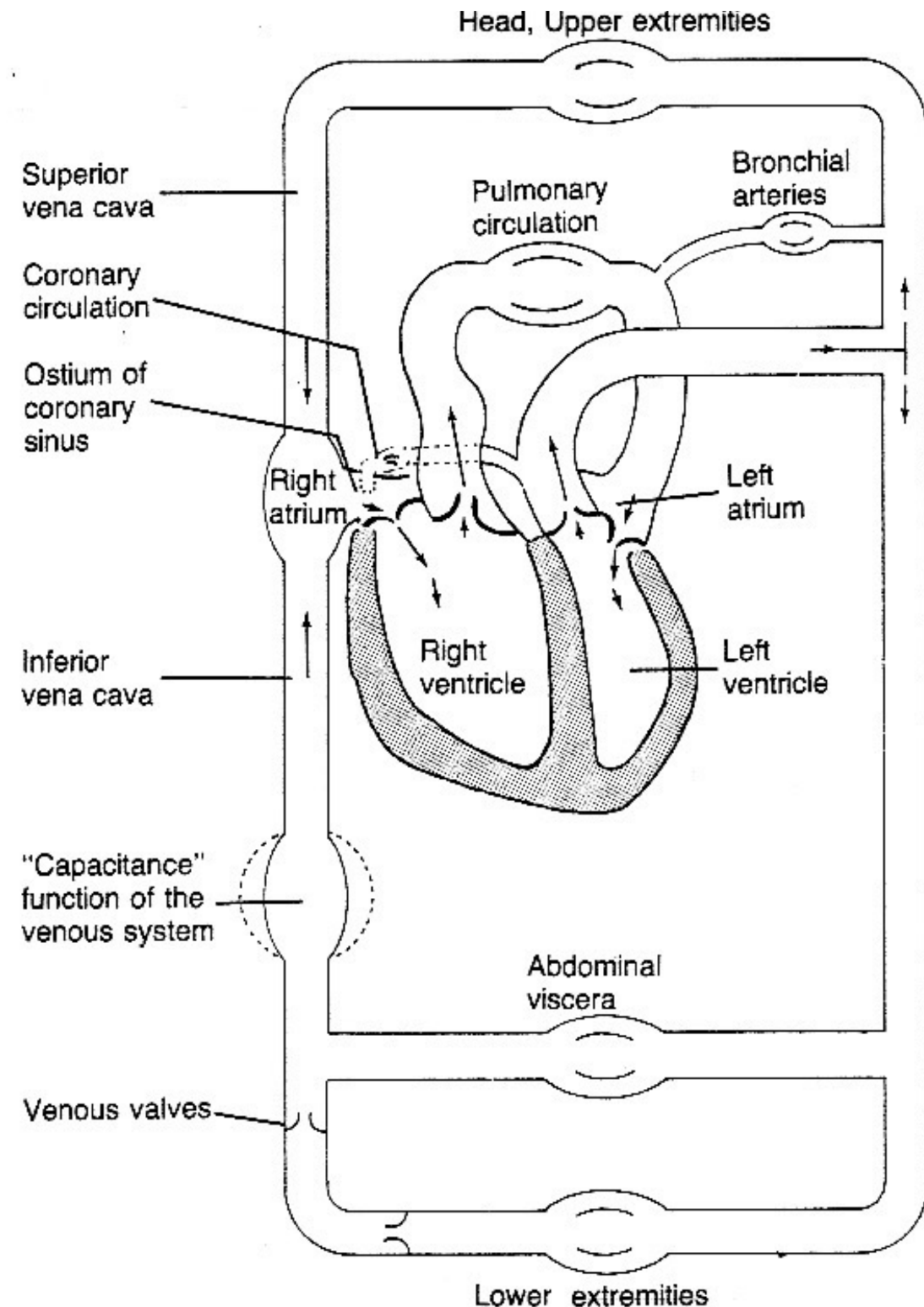
The vascular system is a closed vessel system returning into itself

A. Function:

- Maintenance of environmental parameters of cells (“steady state”)
- Transport:
 - Gases
 - Metabolites
 - Hormones, signal transmitters
 - Immunoglobulins
 - Heat

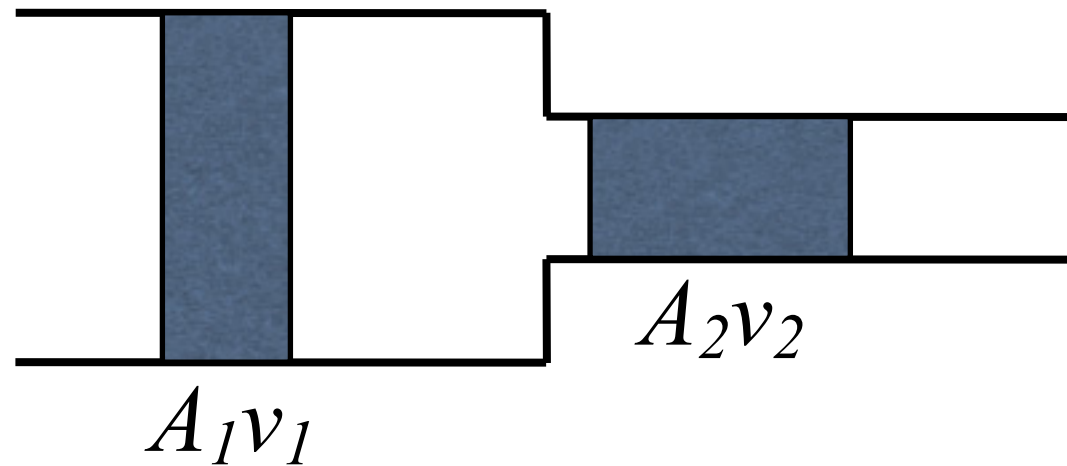
B. Hemodynamic requirements:

- Slow (matches diffusion-driven processes)
- Steady (no fluctuations)
- Unidirectional (but not open-ended!)



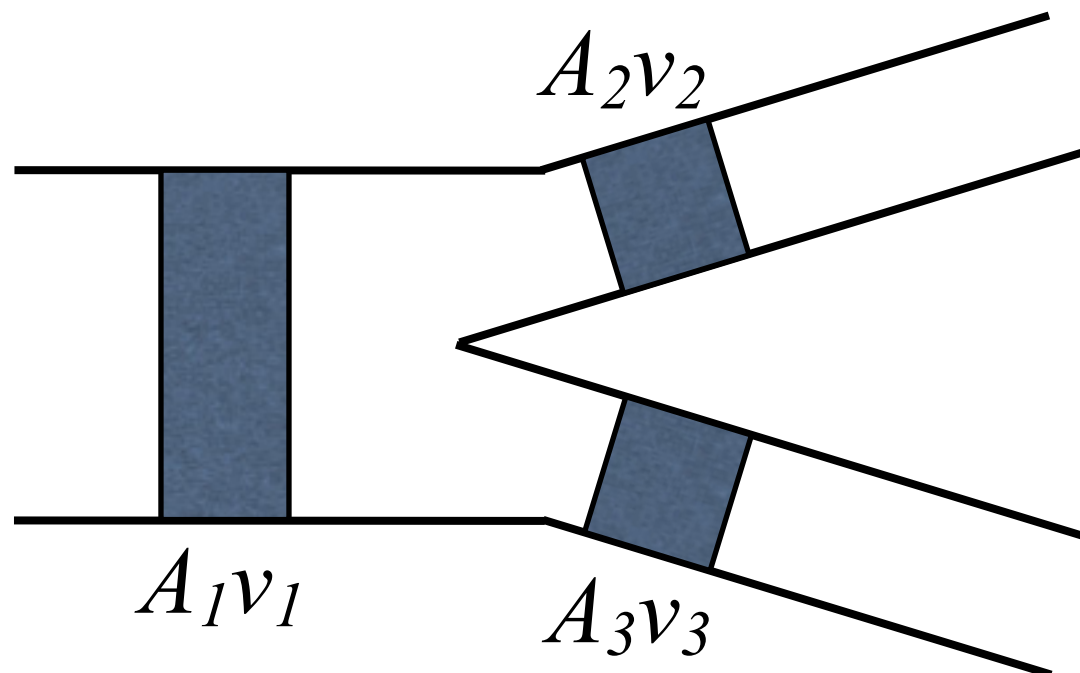
Fluid flow in a bifurcating (dividing) vessel system

Adapted continuity equation
(constancy of volumetric flow rate)



$$A_1 v_1 = A_2 v_2 = \textit{const}$$

A = cross-sectional area
 v = flow rate



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

A_{Σ} = total cross-sectional area

Law of viscous fluid flow in rigid-wall vessel

Hagen-Poiseuille's law

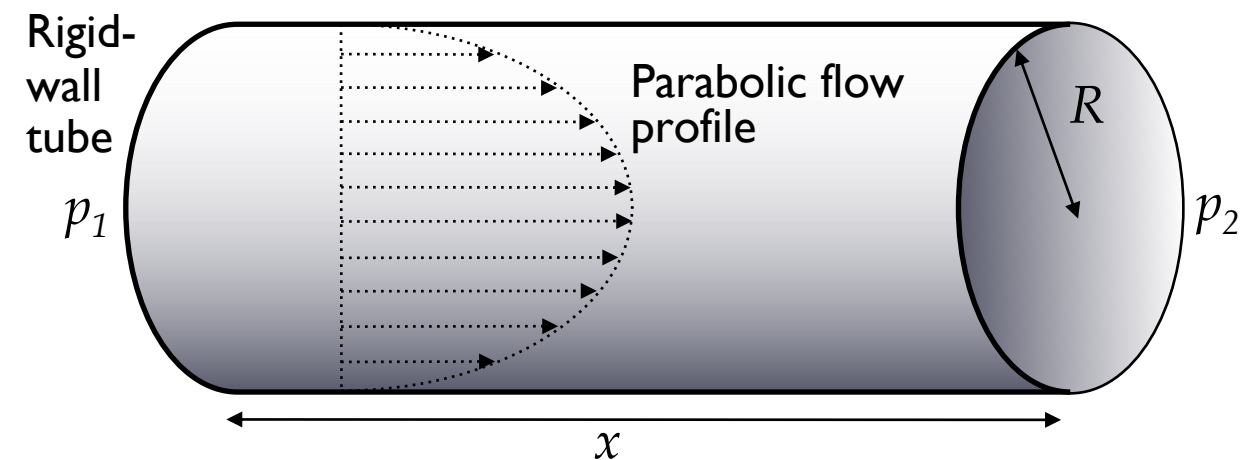


G.H.L. Hagen
(1797-1884)



J.-L.-M. Poiseuille
(1799-1869)

Thermodynamic current	Relevant intensive variable (its difference maintains current)	Current density	Physical law
Volumetric flow	Pressure (p)	$J_v = -\frac{R^2}{8\eta} \frac{\Delta p}{\Delta x}$	Hagen-Poiseuille



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!)
 A = cross-sectional area of tube
 I_v = volumetric flow rate

$$J_v = \frac{V}{tA} = \frac{R^2}{8\eta} \frac{\Delta p}{\Delta x}$$

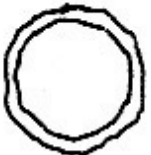






N.B. 1: $A = R^2 \pi \Rightarrow I_v = \frac{V}{t} = -\frac{R^4 \pi}{8\eta} \frac{\Delta p}{\Delta x}$

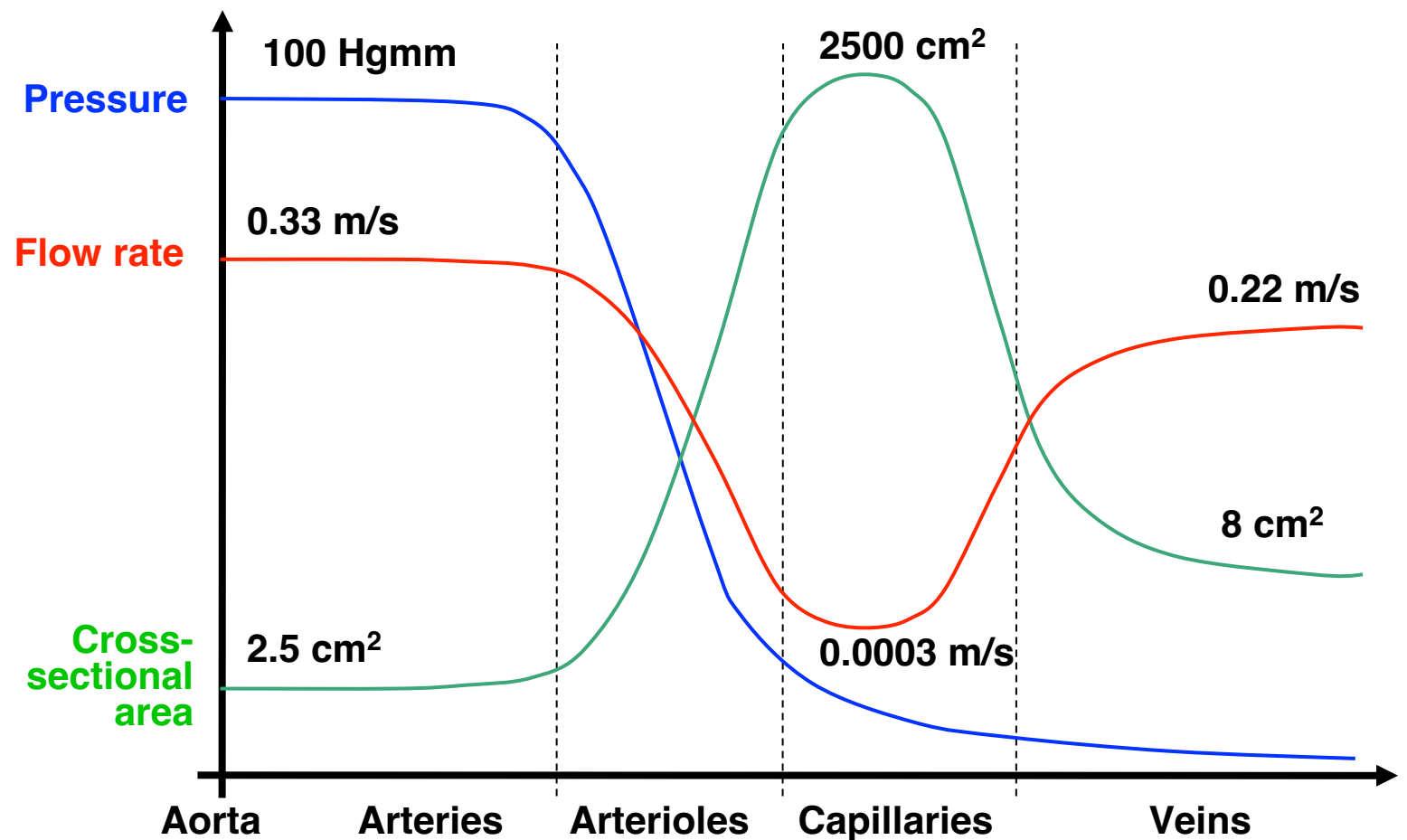
N.B. 2: $I_v = -\frac{R^4 \pi}{8\eta \Delta x} \Delta p \Rightarrow -\Delta p = R_{tube} \cdot I_v \Rightarrow U = R \cdot I$
 Ohm's law!

N.B. 3: $\frac{\Delta v}{\Delta r} \sim r \Rightarrow \left(\frac{\Delta v}{\Delta r} \right)_{\max} = R \Rightarrow \tau_{\max} = R$

Shear stress is maximal at the tube wall because of the parabolic flow profile.

Structure and physical properties of the vascular system

		Diameter	Total cross-sectional area
Aorta		25 mm	2.5
Artery		4 mm	20
Arteriole		30 μ	40
Capillary		8 μ	2500
Venule		20 μ	250
Vein		5 mm	80
Vena cava		30 mm	8



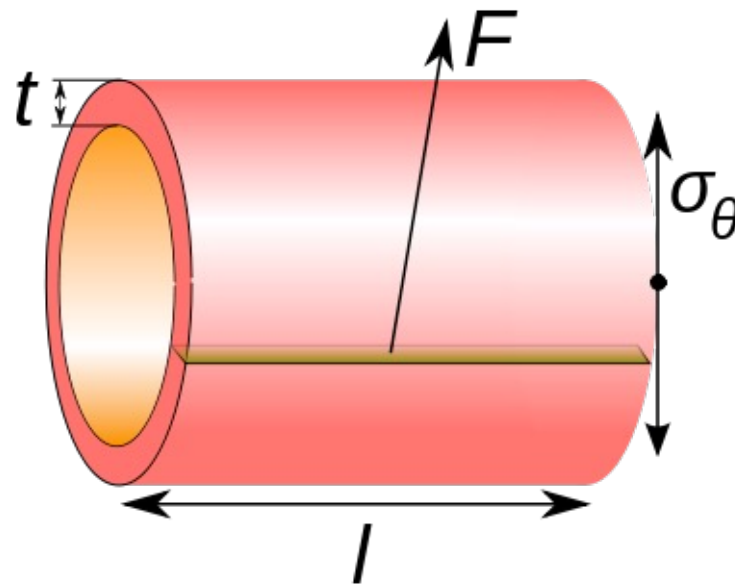
- **Pressure** on blood vessel wall: "**blood pressure**". Pressure drop along vessel maintains blood flow.
- Reason of **pressure drop**: flow resistance — most of energy is converted to heat.
- **Flow rate** and total **cross-sectional area** change inversely (based on equation of continuity, $Av = \text{constant}$).
- Flow rate typically does not exceed the **critical** (see Reynolds number), and flow remains laminar. (Exceptions: behind aortic valve, constricted vessels, low-viscosity conditions, Korotkoff sound).
- **Arterioles** (vessels containing smooth muscle, under vegetative innervation) are pressure-regulators: "**resistance vessels**."
- Most of blood volume in veins: "**capacitance vessels**."

Wall tension and blood pressure

Circumferential stress (σ_θ) depends on blood pressure:
(Young-Laplace - equation)

$$\sigma_\theta = \frac{P \cdot r}{t}$$

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

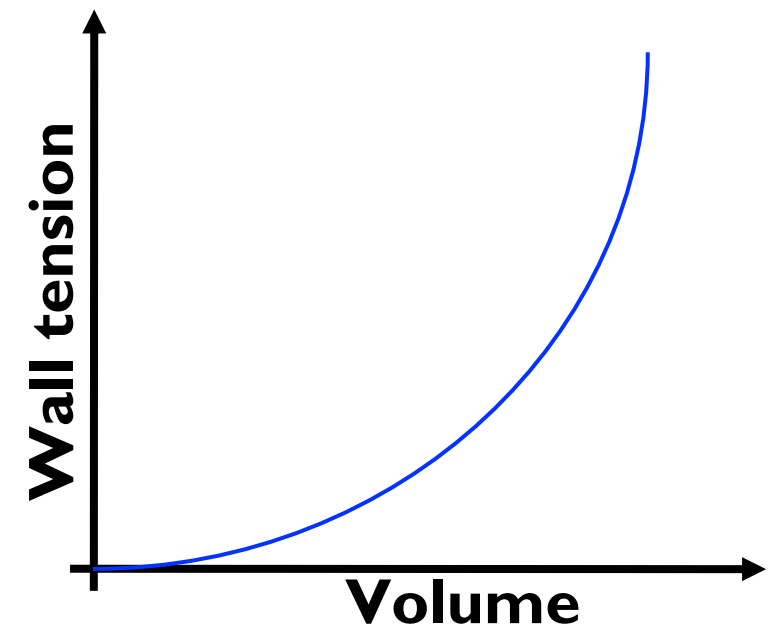


$$\sigma_\theta = \frac{F}{t \cdot l}$$

F = force
 l = tube length

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:

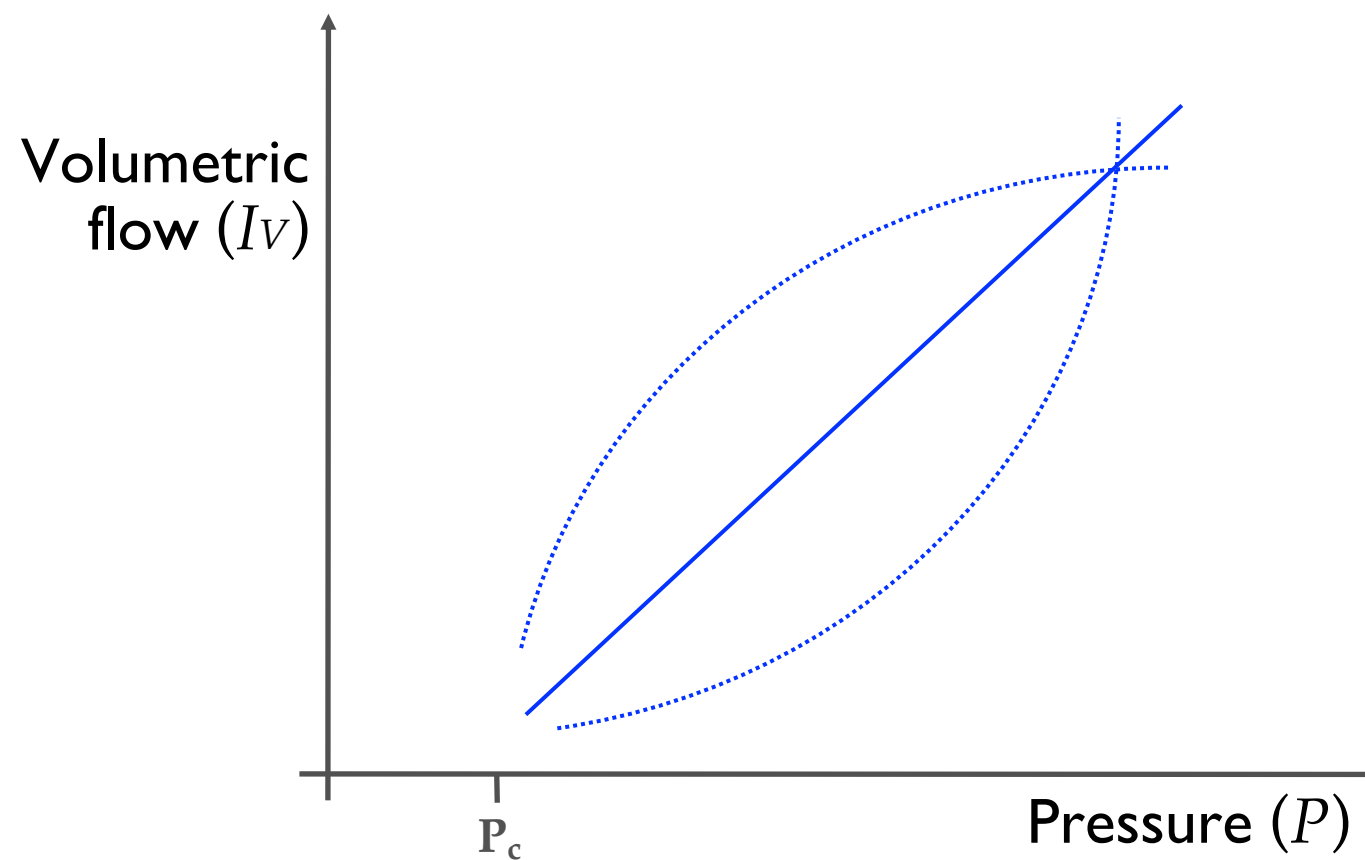
- Elastin
- Collagen
- Smooth muscle

Implications of vascular elasticity:

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

Relationship between flow intensity and pressure

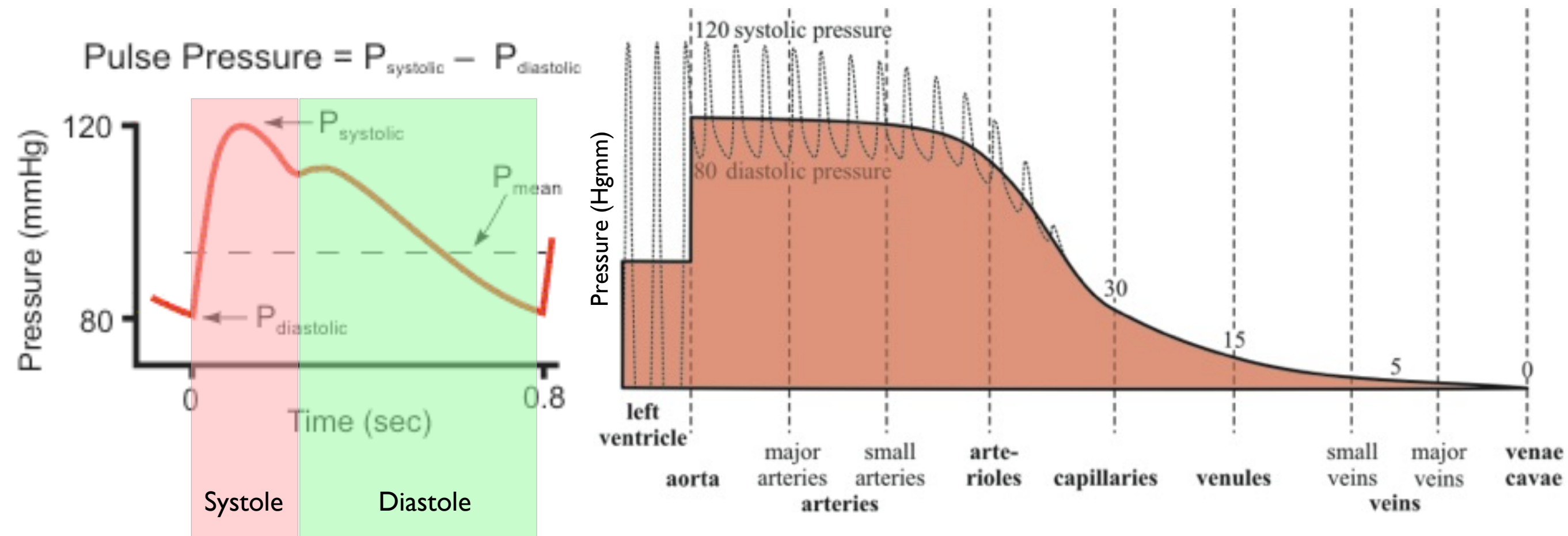
Below certain pressure vessels collapse and flow ceases



N.B.:

- The curves intersect the pressure axis at values greater than 0 (critical closing pressure, P_c).
 - P_c in arteries, at resting conditions, is ~ 20 Hgmm.
- 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



Because of vessel wall elasticity, pressure fluctuations are dampened.

Capillary circulation, fluid exchange

1. Capillaries:

Length: 400-700 μm

Diameter: 5-10 μm

2. Open state depends on function

Number of open capillaries in muscle:

Rest - 5/mm²

Activity - 200/mm²

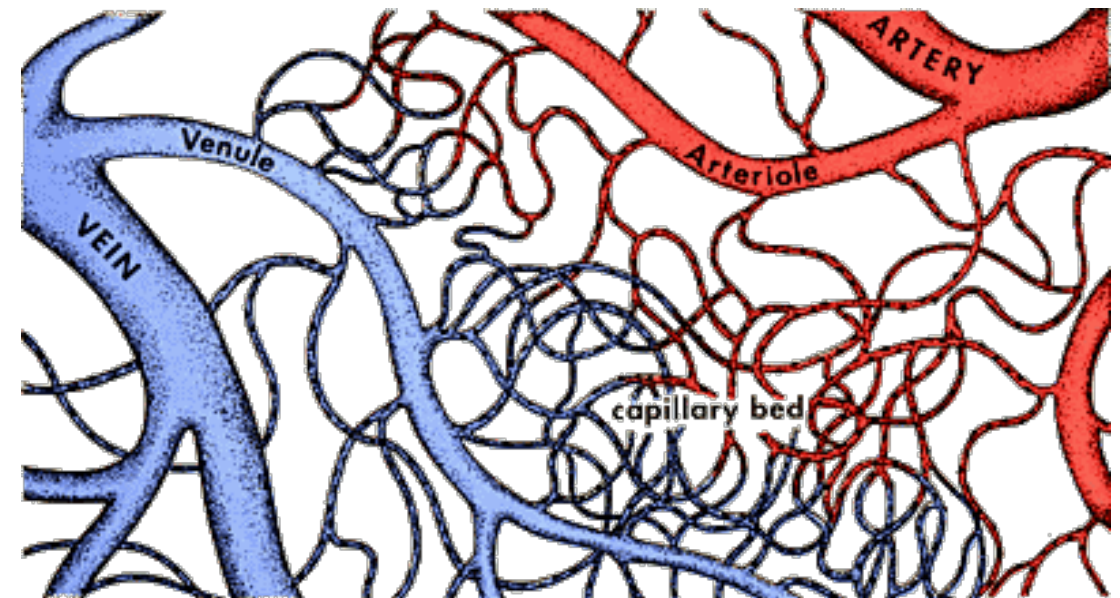
3. Capillary fluid exchange

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
Blood 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

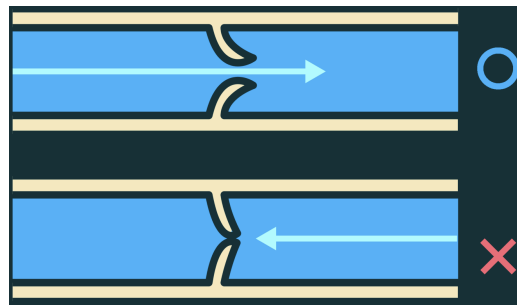
Harvey's experiment (1628)

1. Arterial elasticity

elastic fibers → storage of potential energy

2. Venous valves (Harvey's experiment)

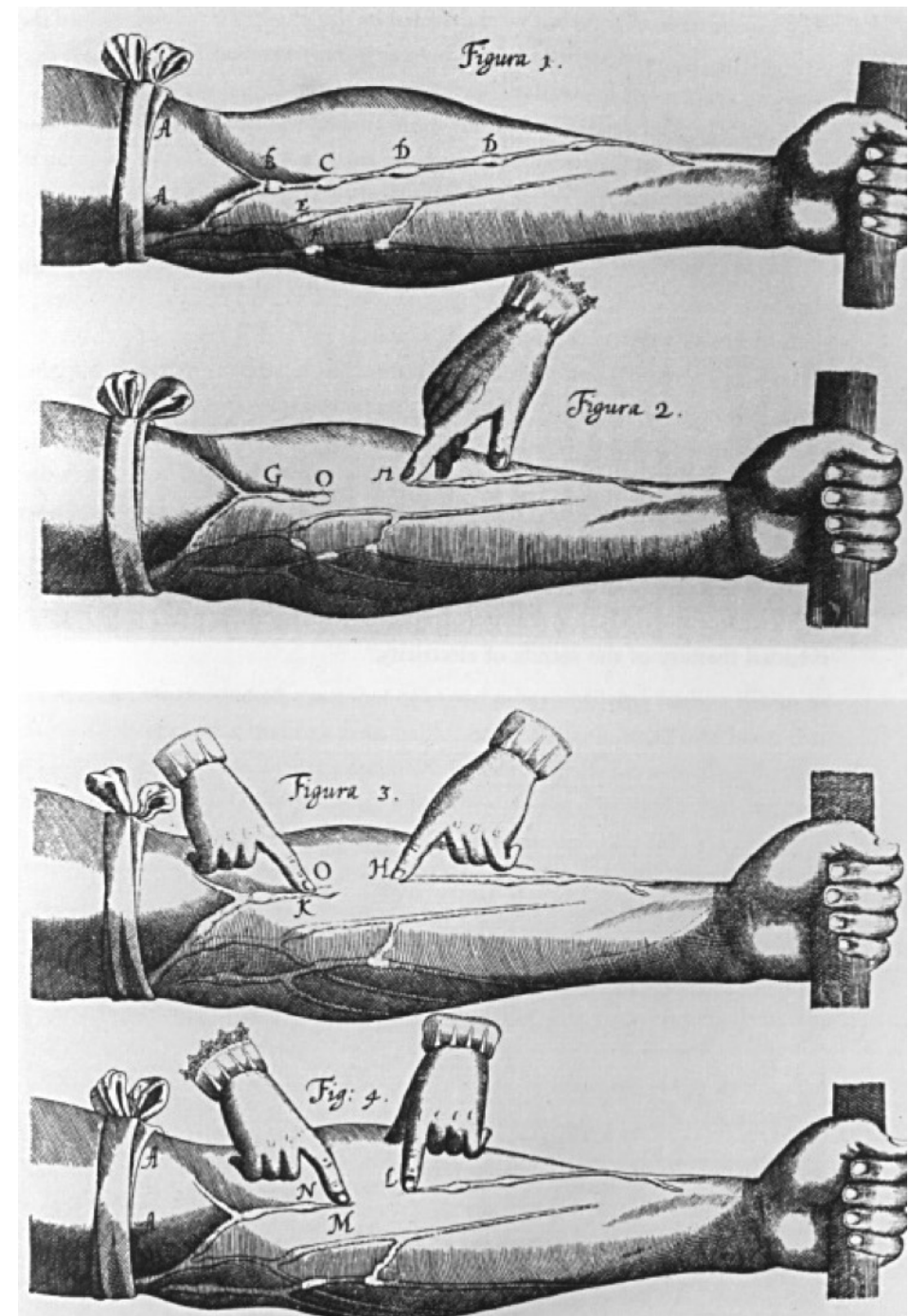
"Exercitatio anatomica de motu cordis et sanguinis in animalibus" (1628)



3. Muscle action

4. "Negative" intrathoracic pressure

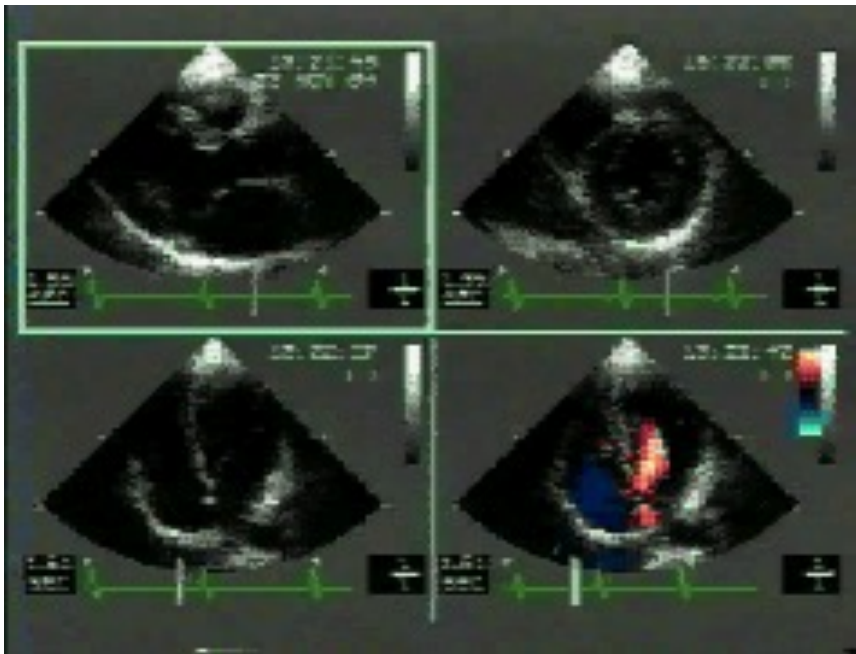
5. "Up-and-down" movement of atrioventricular plane



CARDIAC BIOPHYSICS

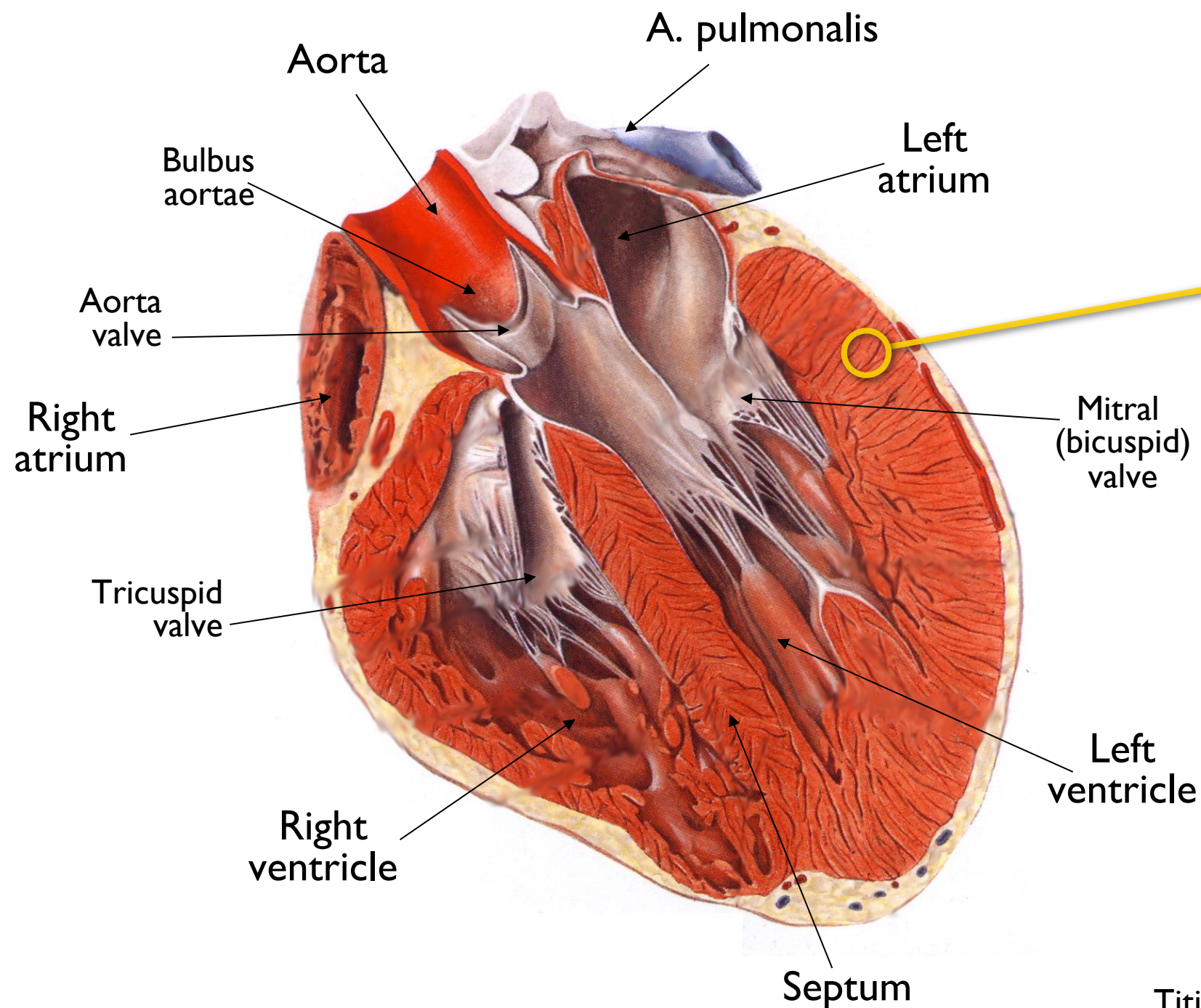
Heart:

Pump of the circulatory system

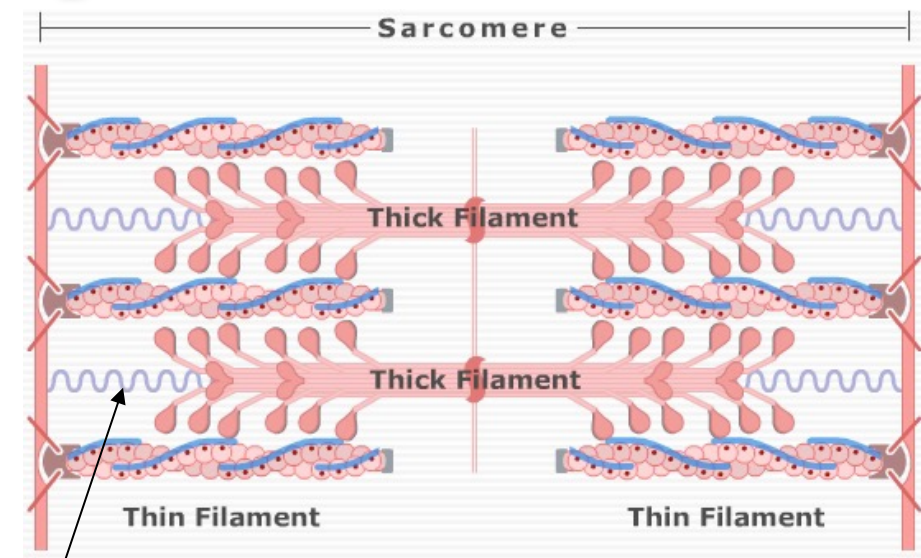
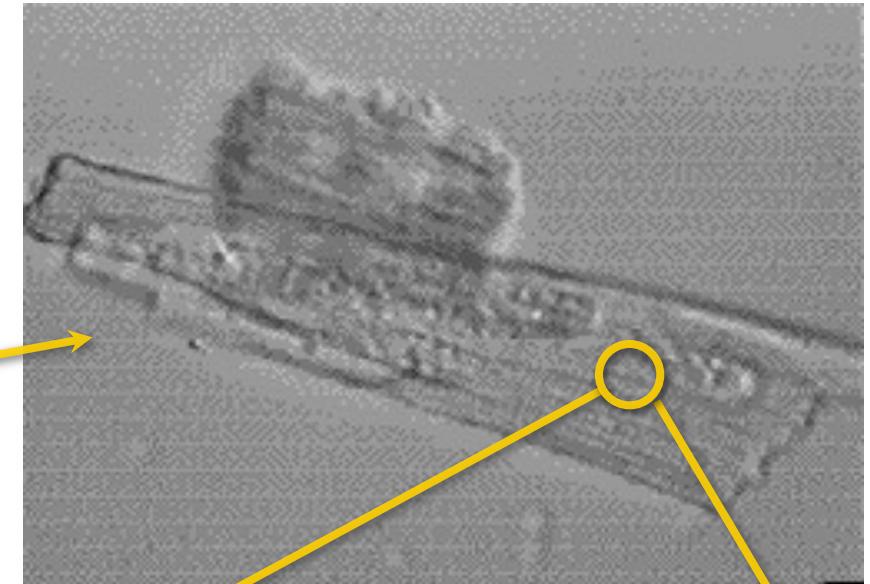


	Number of contractions	Expelled blood volume
1 min	~70	~6 l
1 day	~100.000	~8600 l
Life (70 yrs)	$\sim 2.5 \times 10^9$	$\sim 220 \times 10^6 \text{ l}$

Schematic structure of the human heart

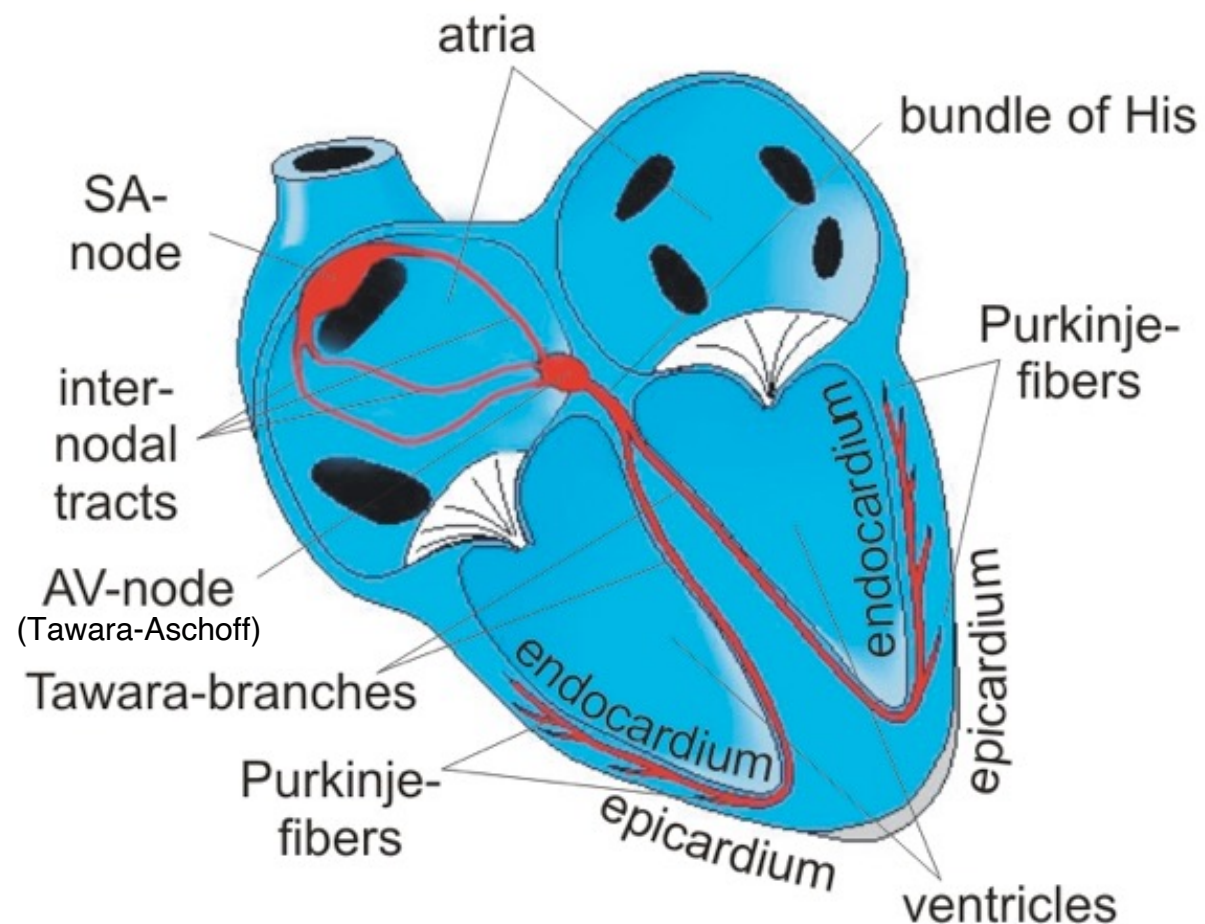


Cardiomyocyte

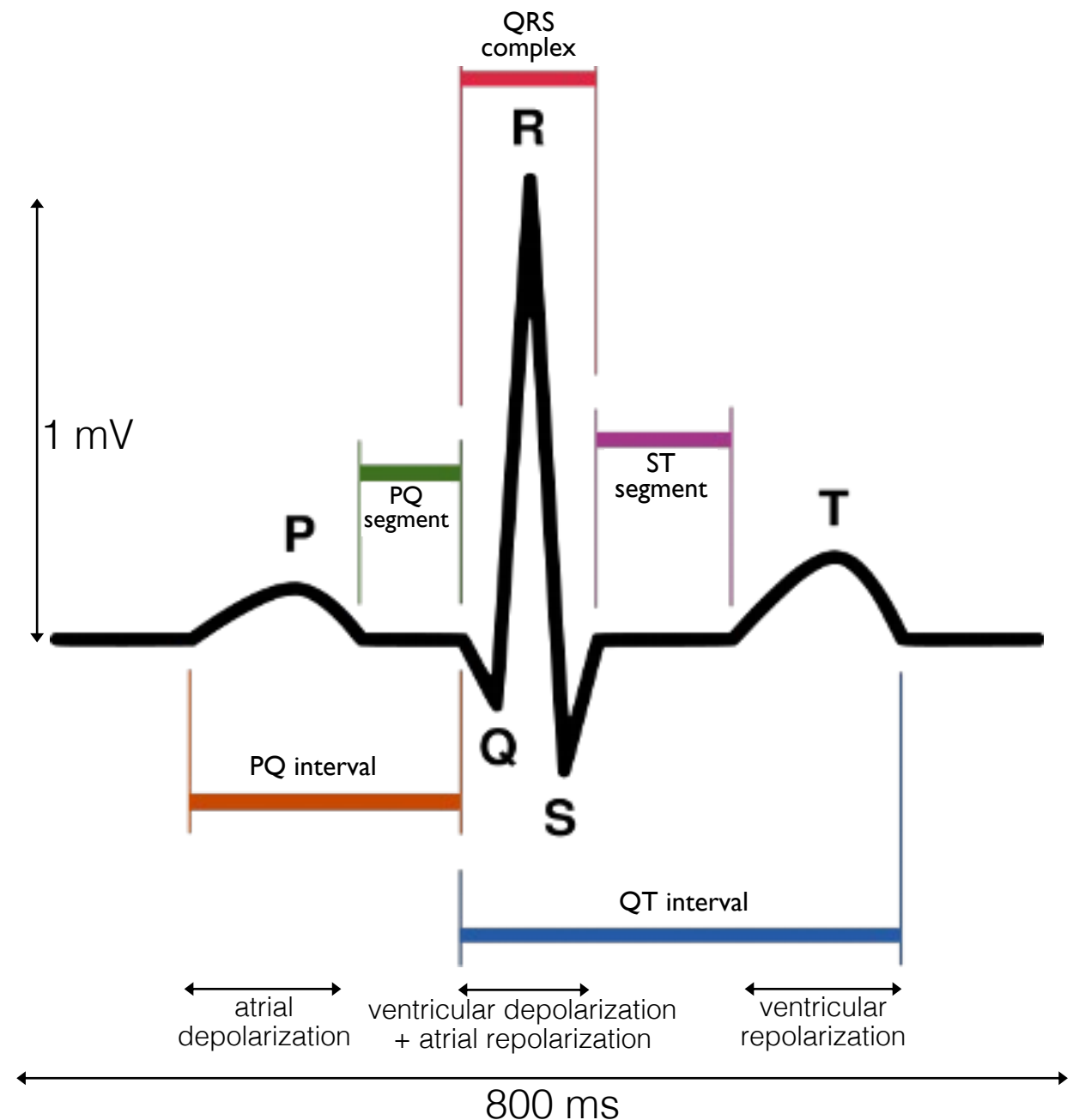


Titin (elastic) filament

Activation of coordinated cardiac contractions

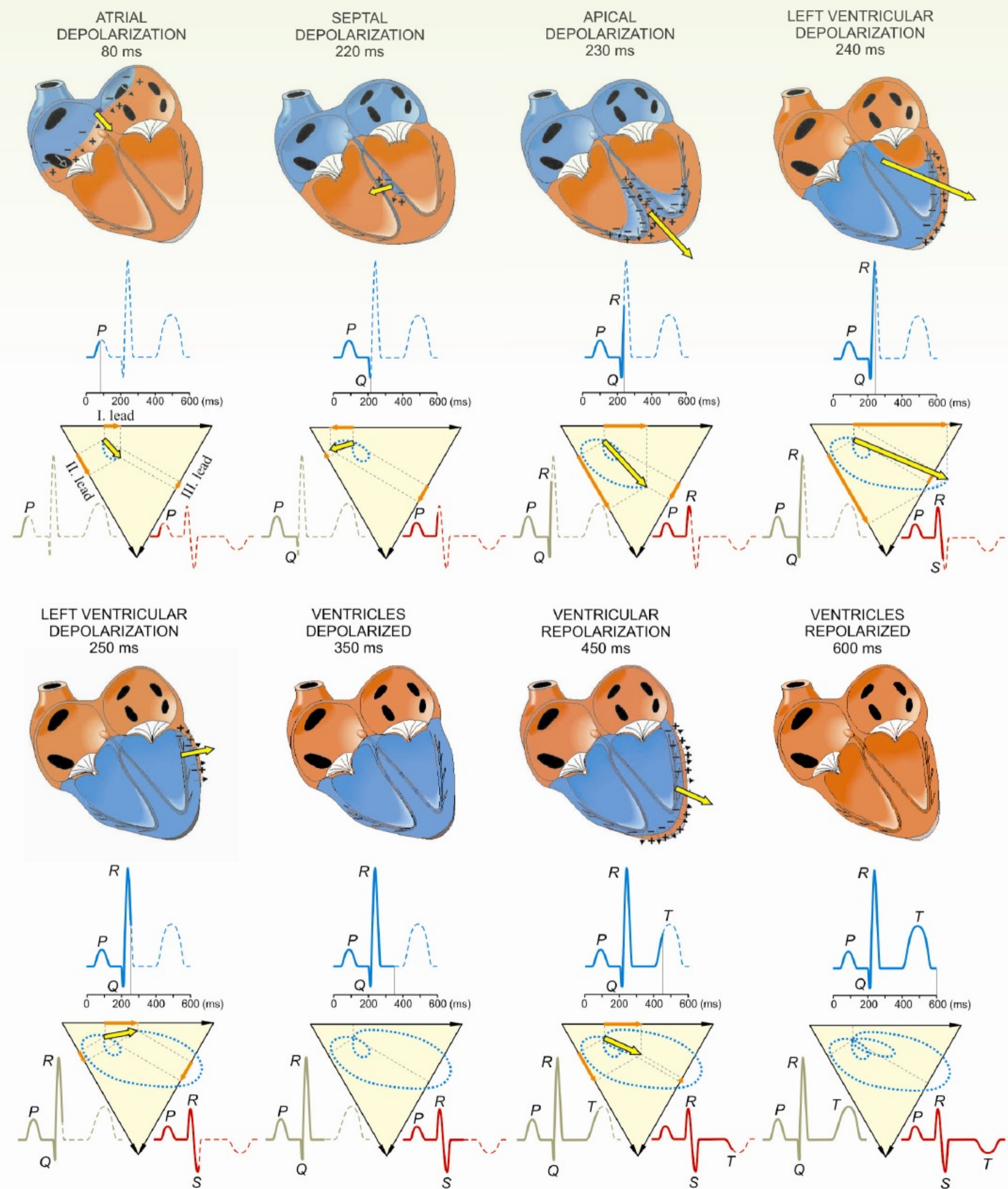


Electrocardiogram (ECG)



EKG:

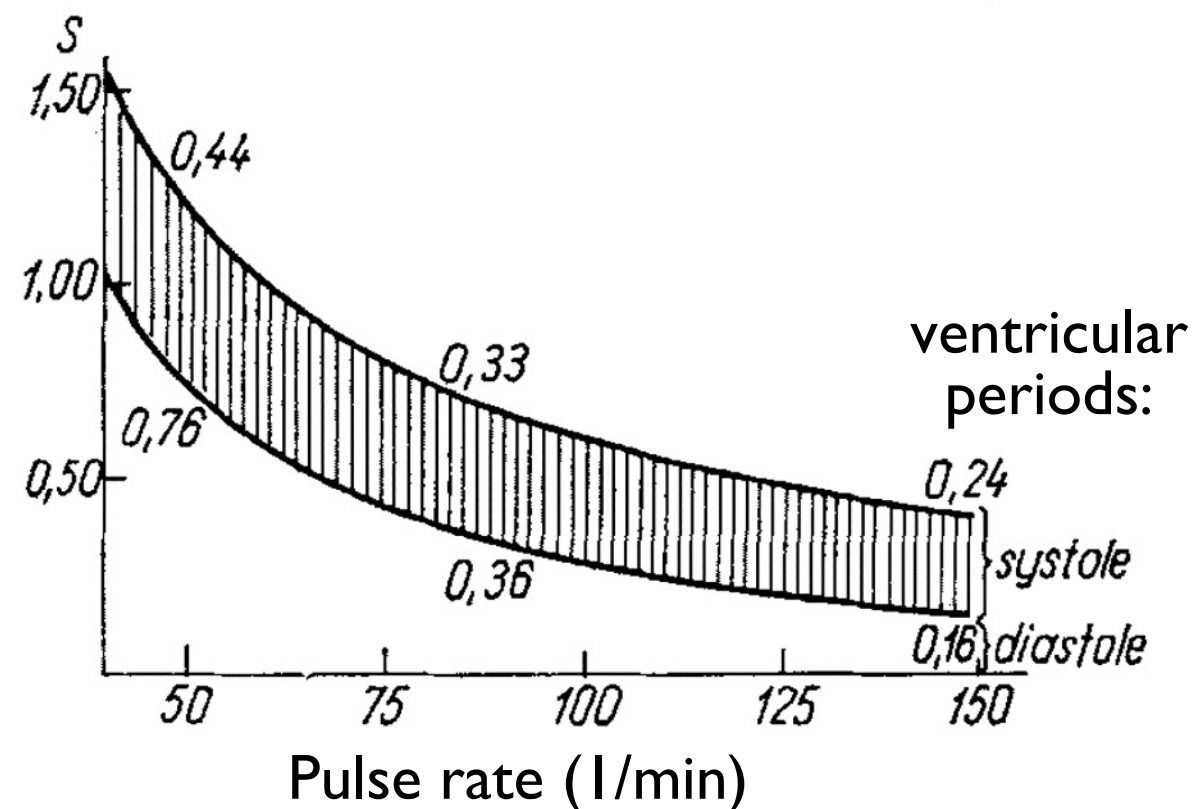
Vectorial projections (according to leads) of the resultant dipole (integral vector) that changes in time and space during myocardial depolarization and repolarization.



The cardiac cycle

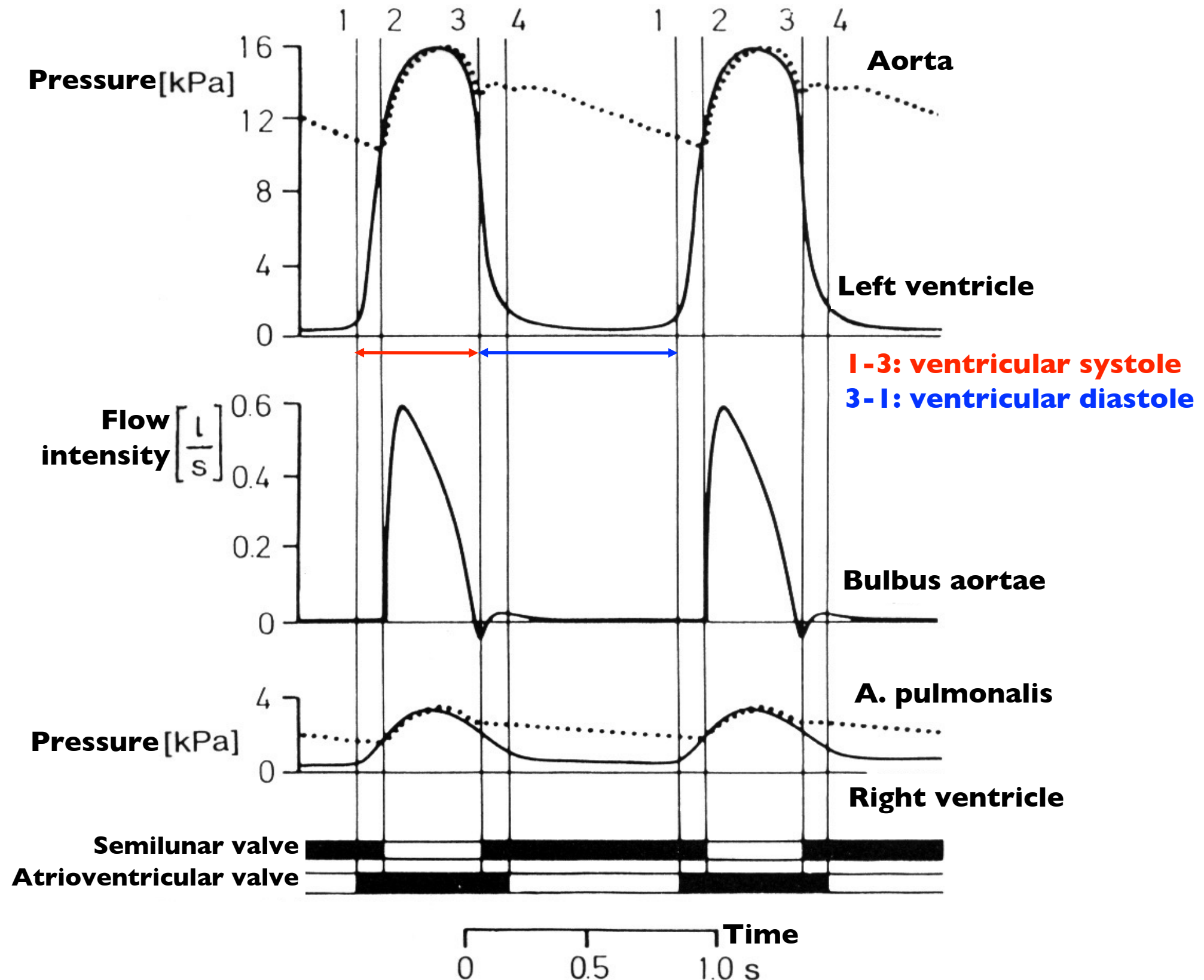
Contraction (systole) - relaxation (diastole) cycle of the heart

	systole	diastole
atrium	0,1 s	0,7 s
ventricle	0,3 s	0,5 s

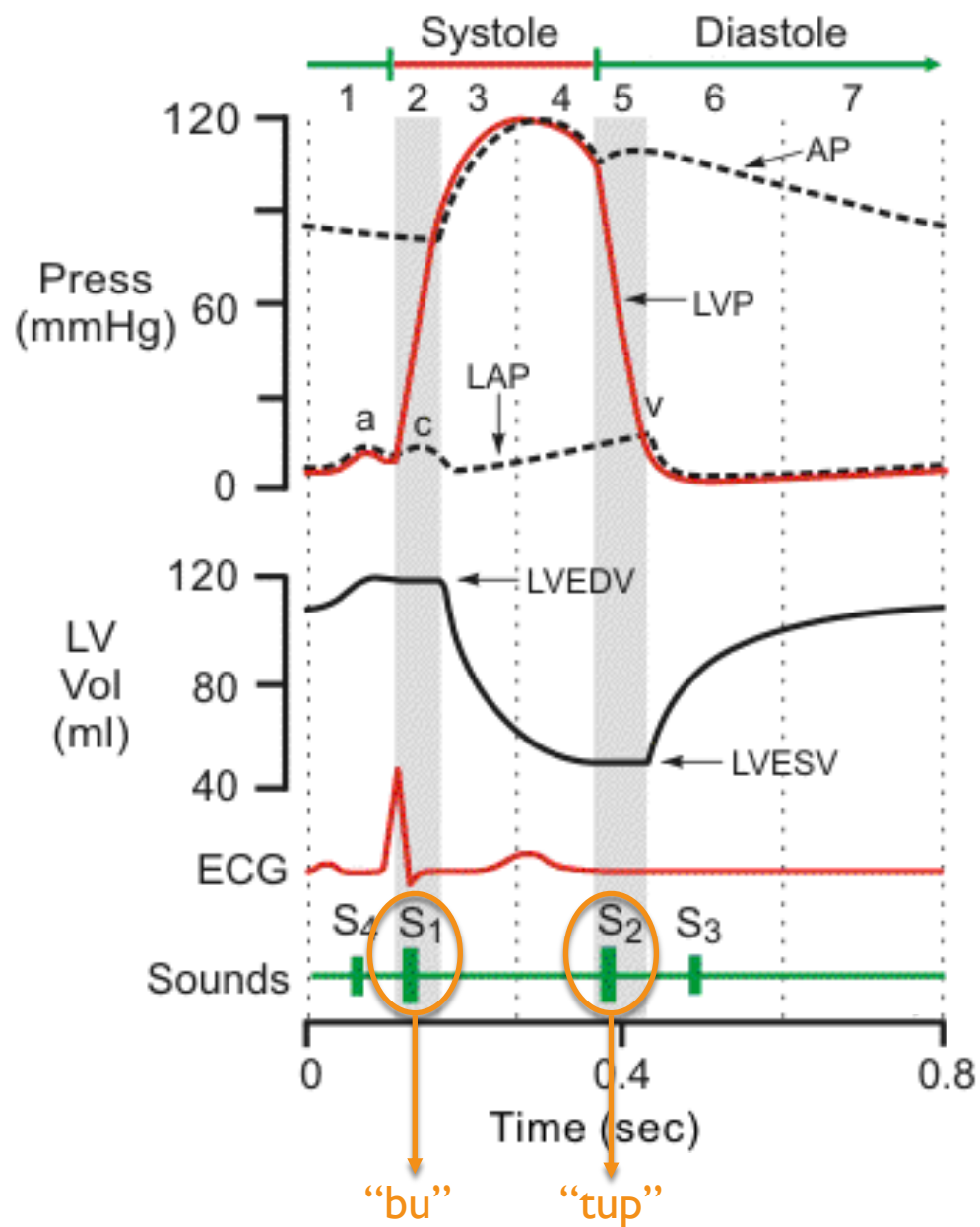


Events of the cardiac cycle I.

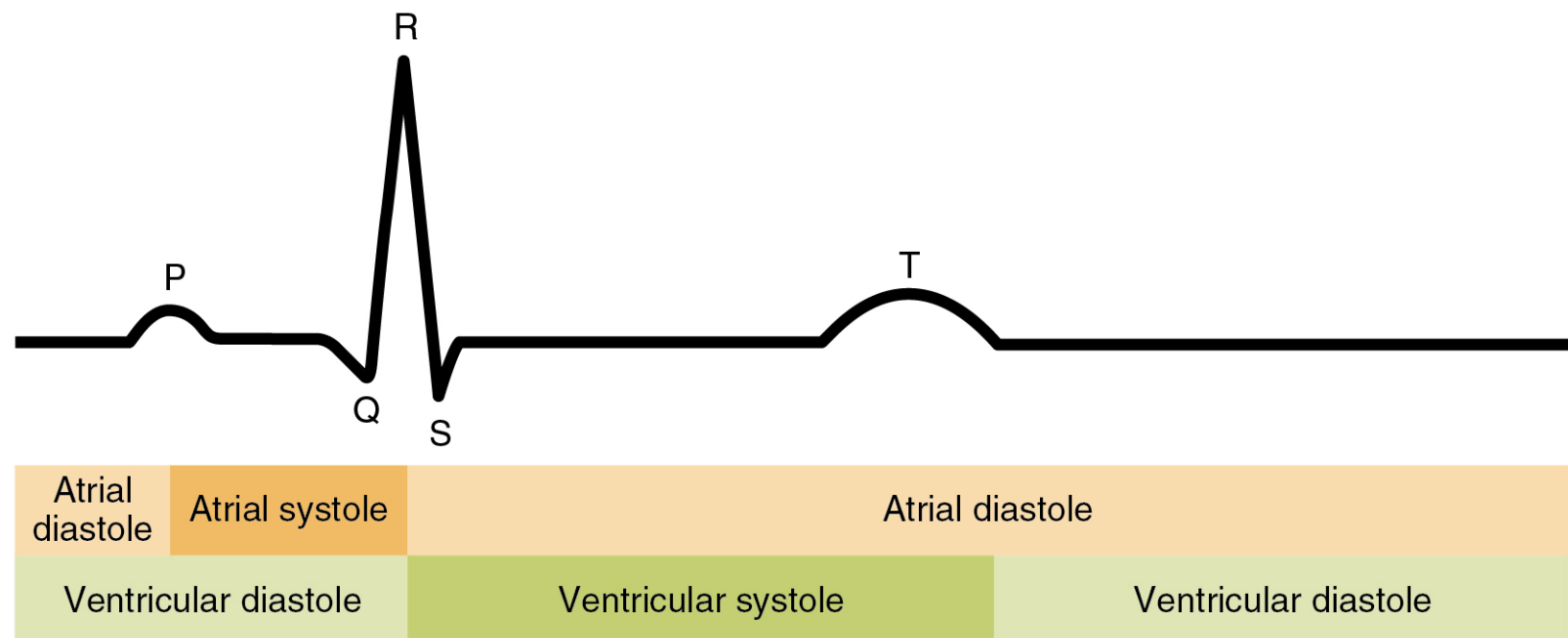
1-2: pre-ejection period (PEP) **2-3:** ejection period (EP) **3-4:** isovolumetric relaxation (IVR) **4-1:** ventricular filling (VF)



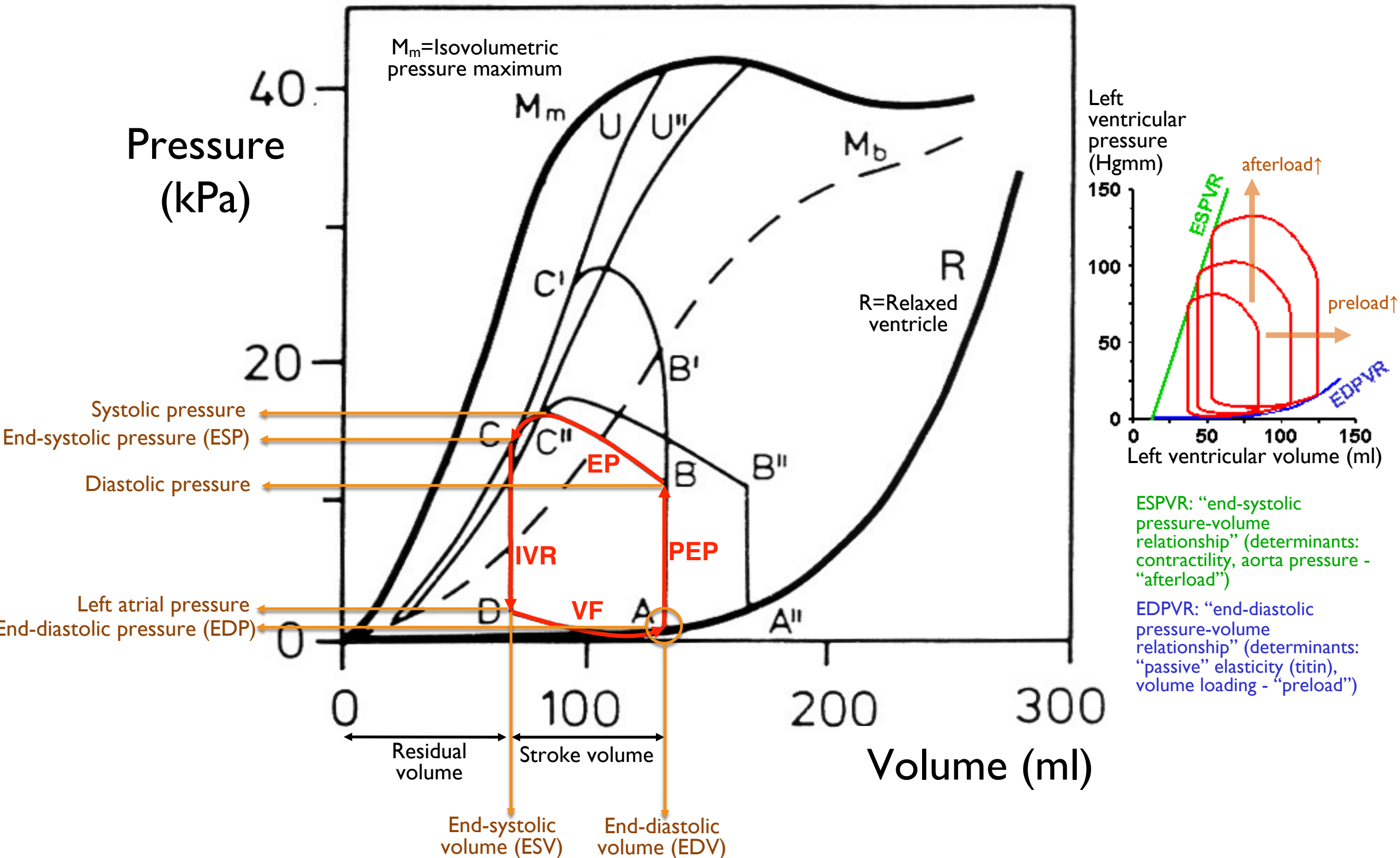
Events of the cardiac cycle 2.



Electrocardiogram (ECG)



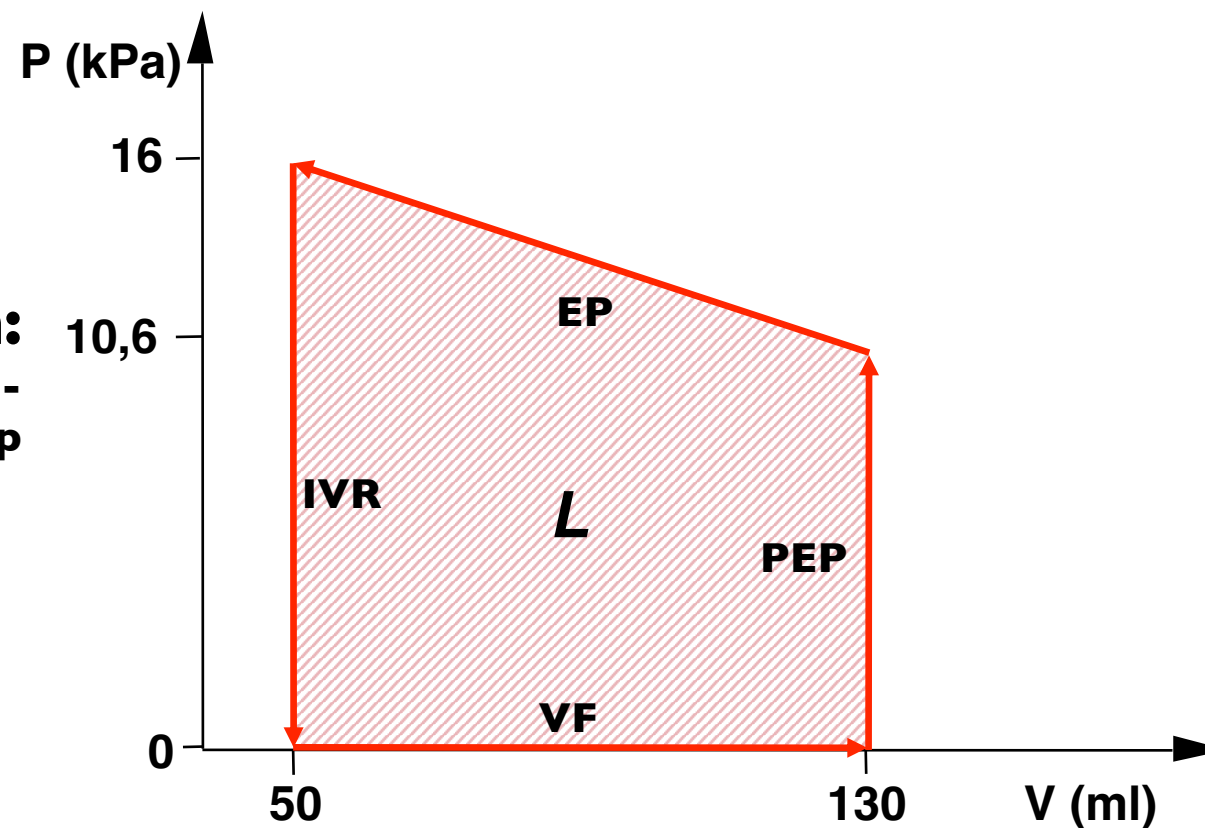
Pressure-volume diagram of left ventricle



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

$\frac{1}{2}mv^2$ =dynamic component

p =pressure

ΔV =**stroke volume**

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

Feedback



<https://feedback.semmelweis.hu/feedback/index.php?feedback-qr=Y7ZUD7HHNF89D5CF>