

**CARDIOVASCULAR SYSTEM:**  
**BIOPHYSICS OF CIRCULATION**  
**CARDIAC BIOPHYSICS**

**MIKLÓS KELLERMAYER**

# 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

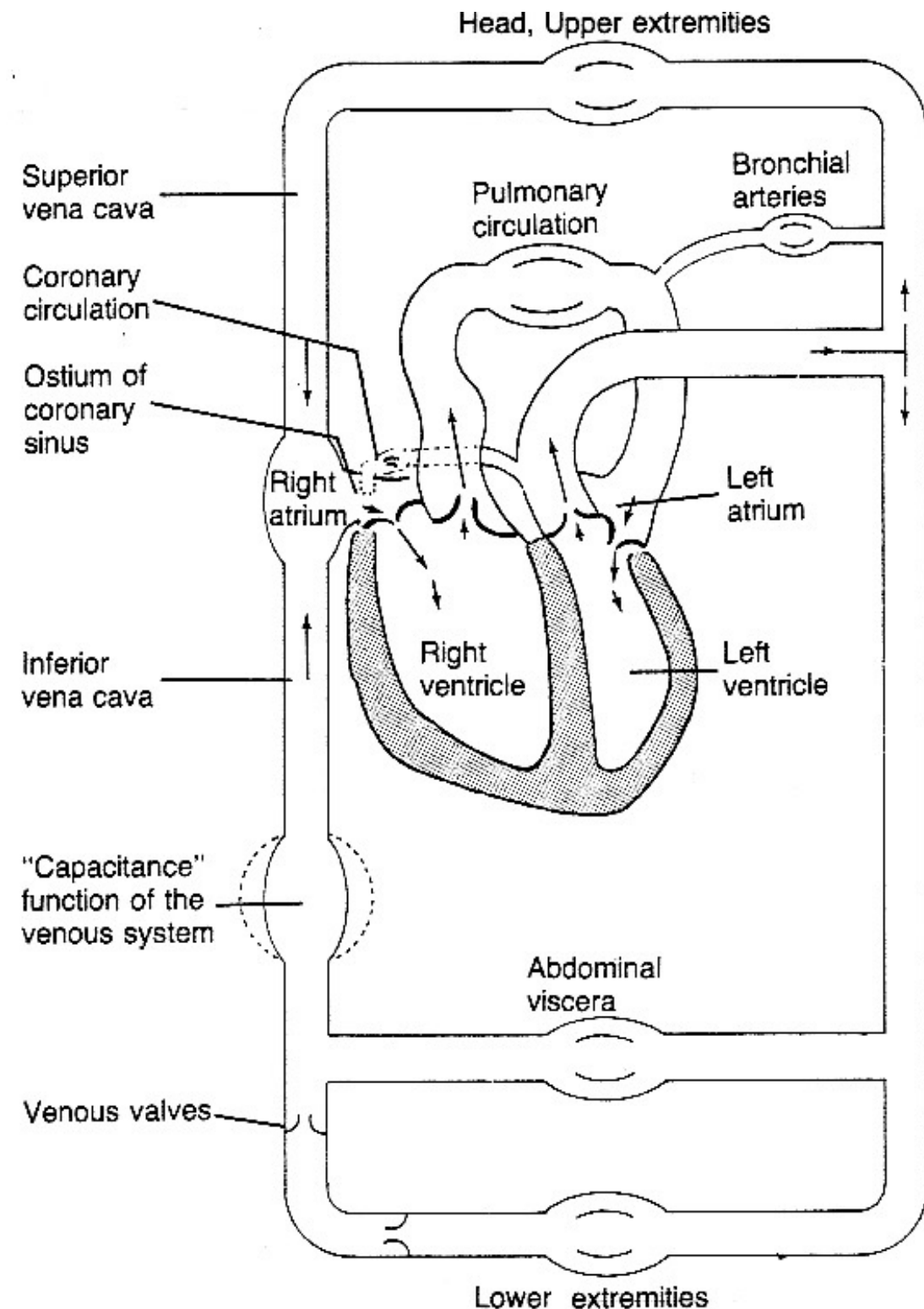
Heat

## B. Hemodynamic requirements:

Slow (matches diffusion-driven processes)

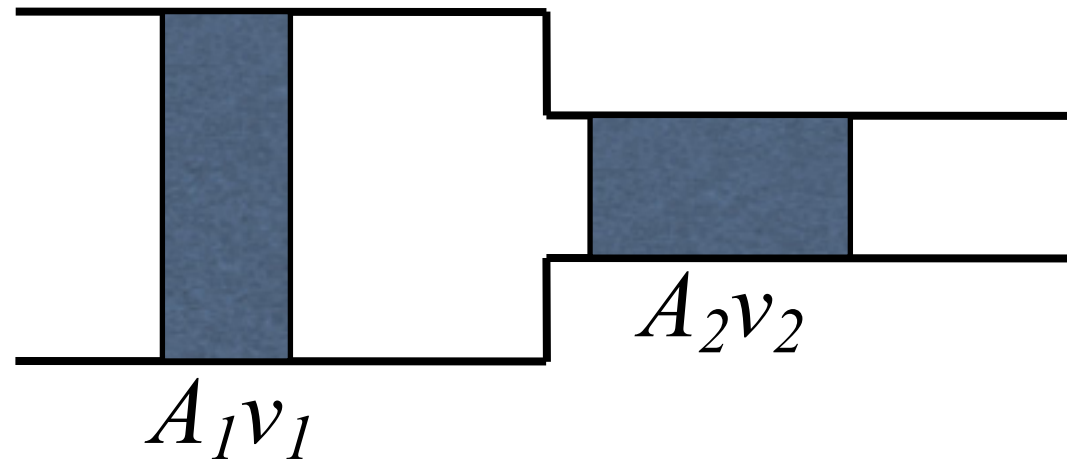
Steady (no fluctuations)

Unidirectional (but not open-ended)



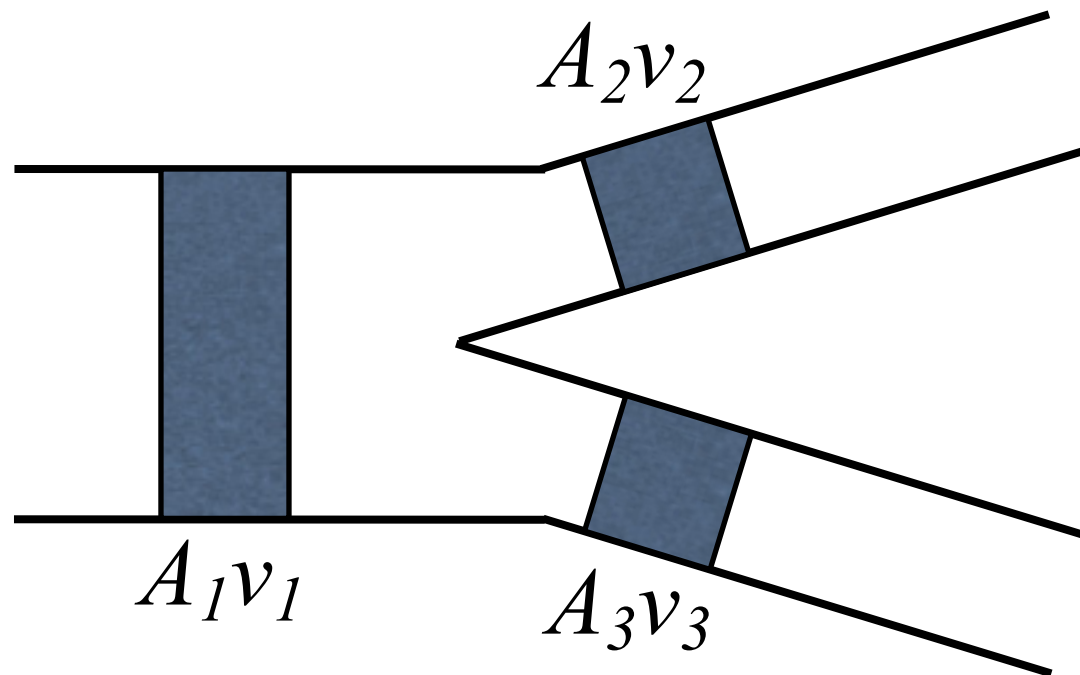
# Fluid flow in bifurcating vessel system

## Continuity equation



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

$A$  = cross-sectional area  
 $v$  = flow rate



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

$A_{\Sigma}$  = total cross-sectional area

# Thermodynamic Currents

- Natural processes are rarely reversible.
- If there are inequalities in the intensive variables at different locations within the system, thermodynamic currents arise.
- Thermodynamic currents aim at the restoration of equilibrium.
- Extensive variables flow.

Thermodynamic current	Relevant intensive variable (its difference maintains current)	Current density	Physical law
Heat flow	Temperature ( $T$ )	$J_E = -\lambda \frac{\Delta T}{\Delta x}$	Fourier
Volumetric flow	Pressure ( $p$ )	$J_V = -\frac{R^2}{8\eta} \frac{\Delta p}{\Delta x}$	Hagen-Poiseuille
Electric current	Electric potential ( $\phi$ )	$J_Q = -\frac{1}{\rho} \frac{\Delta \phi}{\Delta x}$	Ohm
Material transport (diffusion)	Chemical potential ( $\mu$ )	$J_n = -D \frac{\Delta c}{\Delta x}$	Fick



# Laws of flow in viscous fluids II.

## Hagen-Poiseuille's law

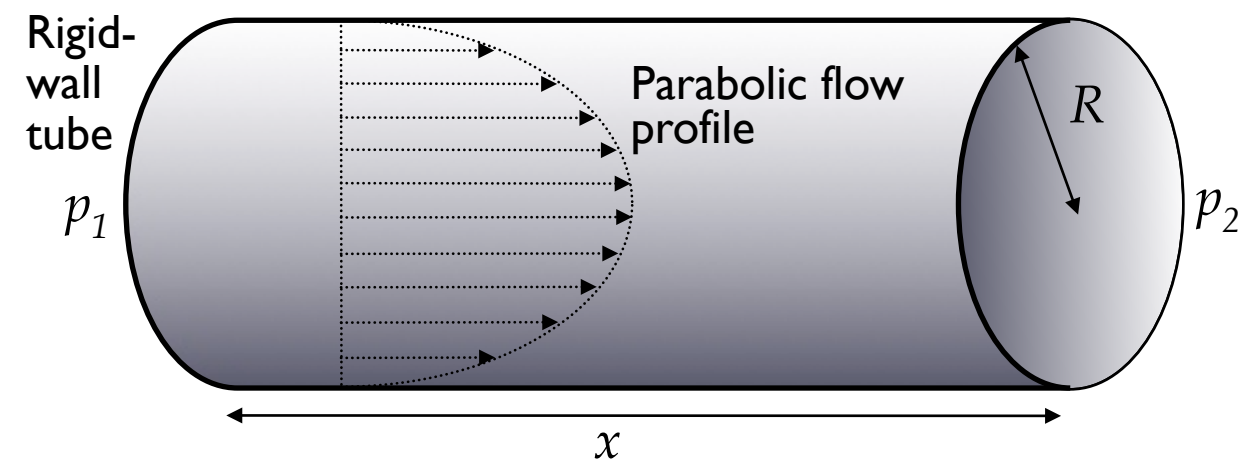


G.H.L. Hagen  
(1797-1884)



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  
 $\eta$  = 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

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

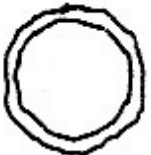






N.B. 1:  $A = R^2 \pi \Rightarrow I_V = \frac{V}{t} = -\frac{R^4 \pi}{8\eta} \frac{\Delta p}{\Delta x}$

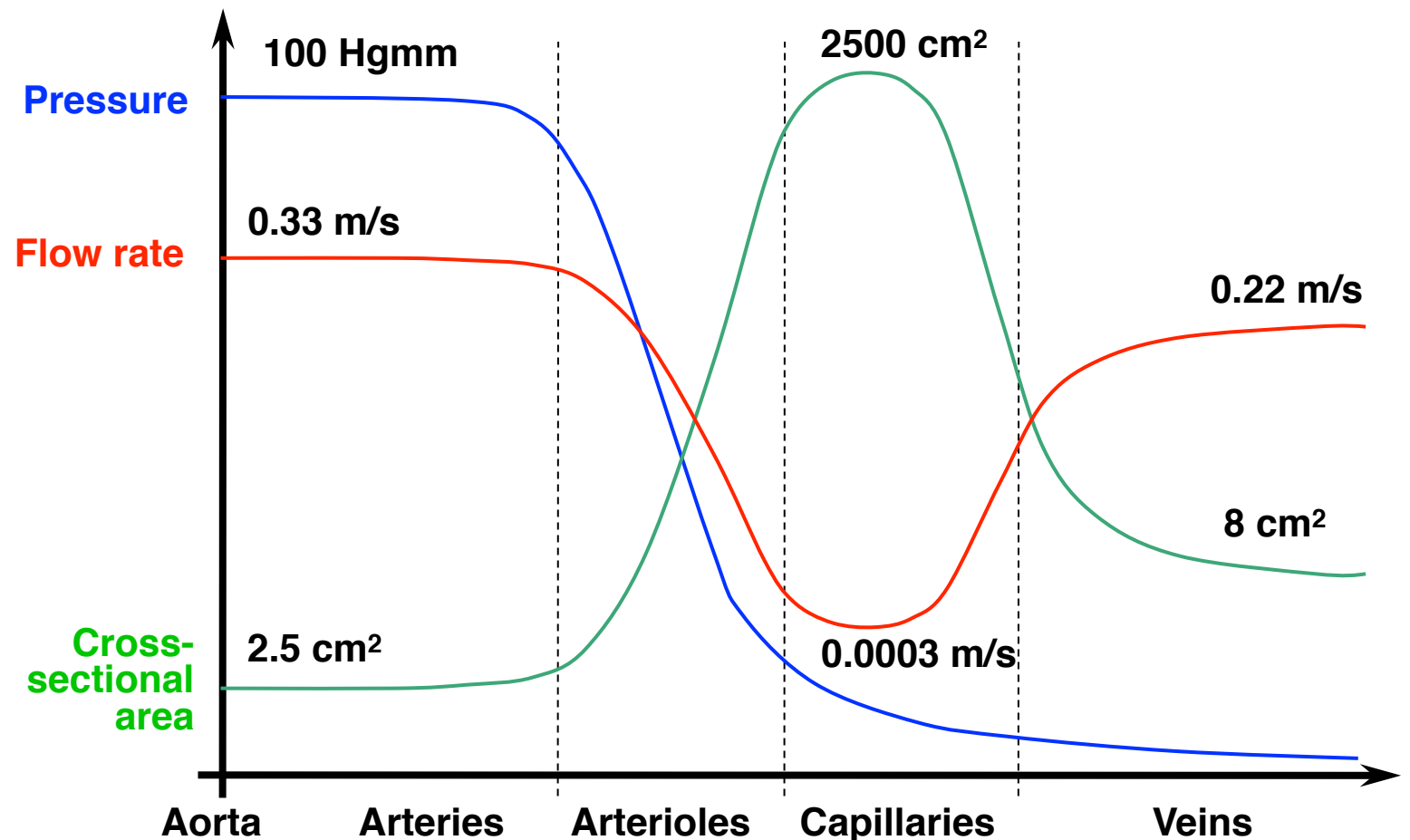
N.B. 2:  $I_V = -\frac{R^4 \pi}{8\eta \Delta x} \Delta p \Rightarrow -\Delta p = R_{tube} \cdot I_V \Rightarrow U = R \cdot I$   
 Ohm's law!

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 $\mu$	40
Capillary		8 $\mu$	2500
Venule		20 $\mu$	250
Vein		5 mm	80
Vena cava		30 mm	8



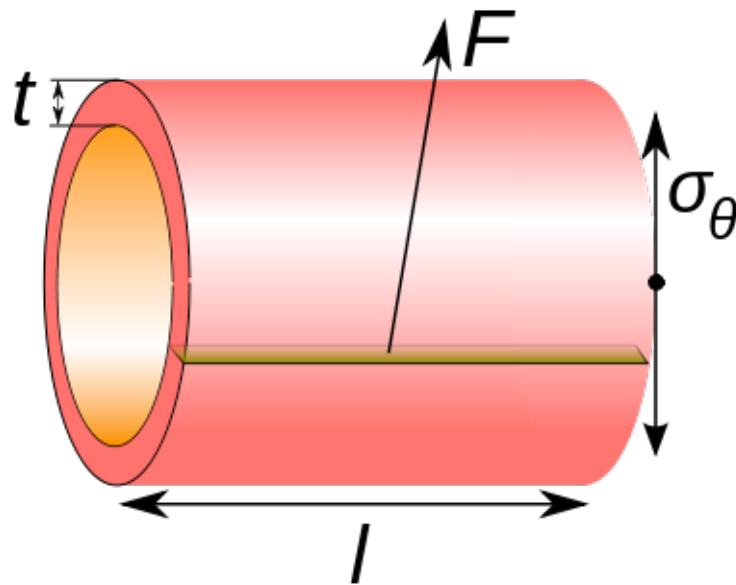
- **Pressure** on blood vessel wall: "**blood pressure**". Pressure drop along vessel maintains blood flow.
- Reason of **pressure drop**: flow resistance - most of energy is converted to heat.
- **Flow rate** and total **cross-sectional area** change inversely (based on equation of continuity,  $A_v = \text{constant}$ ).
- 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 ( $\sigma_\theta$ ) depends on blood pressure:  
(Young-Laplace - equation)

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

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

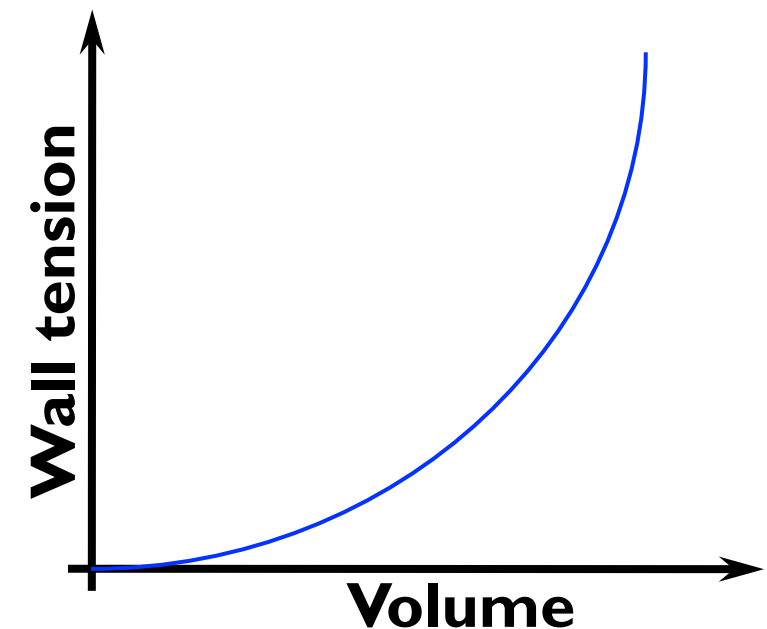


$$\sigma_\theta = \frac{F}{t \cdot l}$$

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

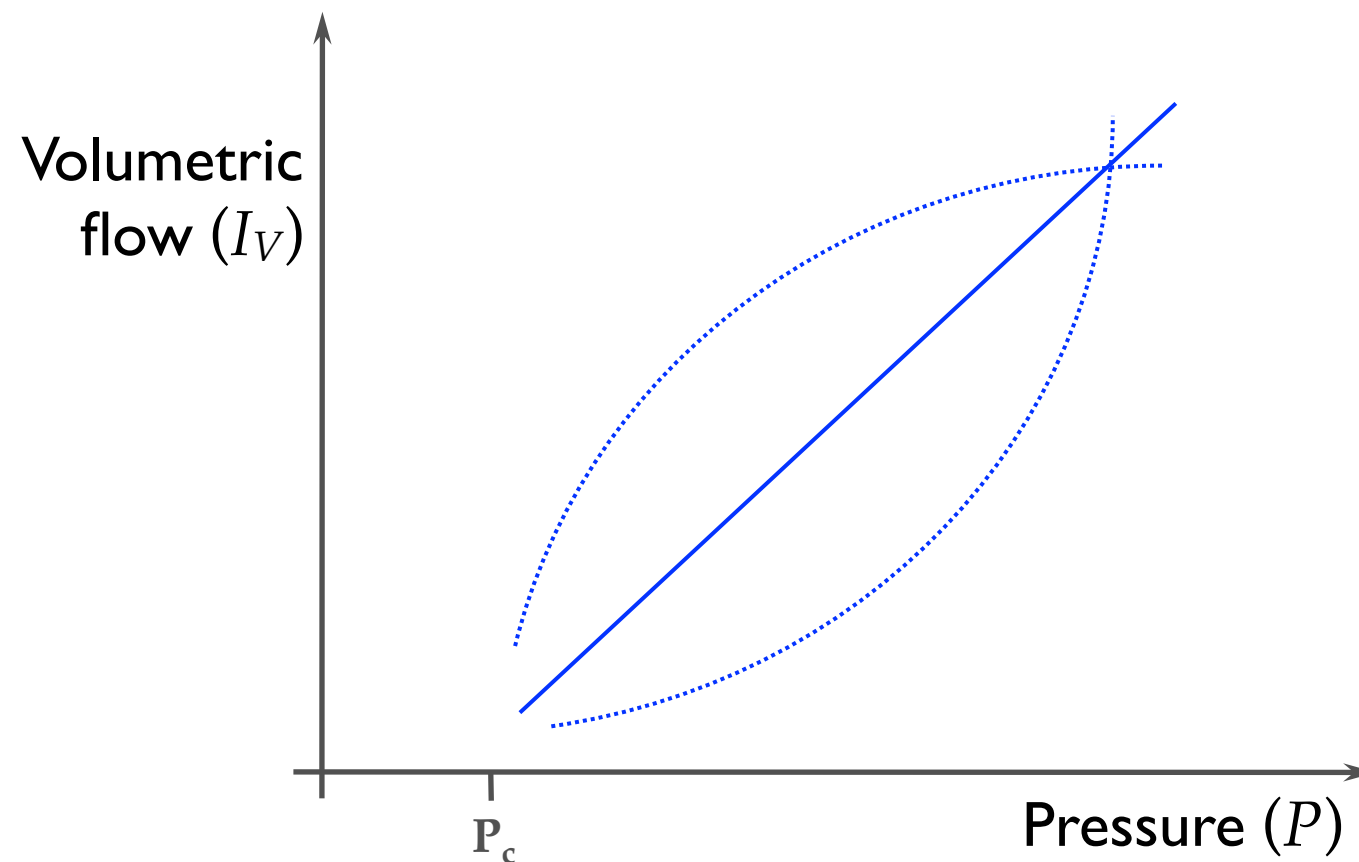
## Implications of vascular elasticity:

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

# Relationship between flow intensity and pressure

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Below certain pressure vessels collapse and flow ceases



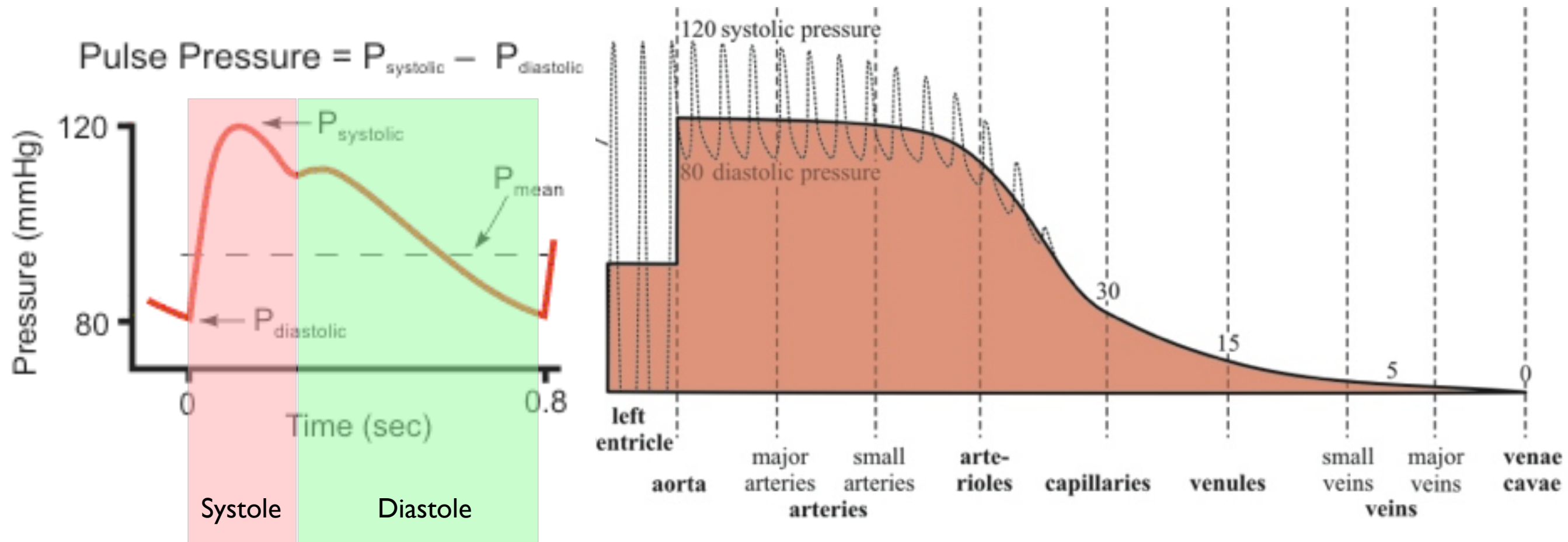
**N.B.:**

- The curves intersect the pressure axis at values greater than 0 (critical closing pressure,  $P_c$ ).
- $P_c$  in arteries, at resting conditions, is  $\sim 20$  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  $\mu\text{m}$   
Diameter: 0.5  $\mu\text{m}$

## 2. Open state depends on function

Number of open capillaries in muscle:  
Rest - 5/mm<sup>2</sup>  
Activity - 200/mm<sup>2</sup>



## 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

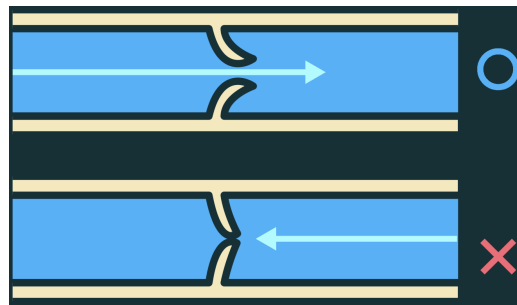
Harvey's experiment (1628)

## 1. Arterial elasticity

elastic fibers → storage of potential energy

## 2. Venous valves (Harvey's experiment)

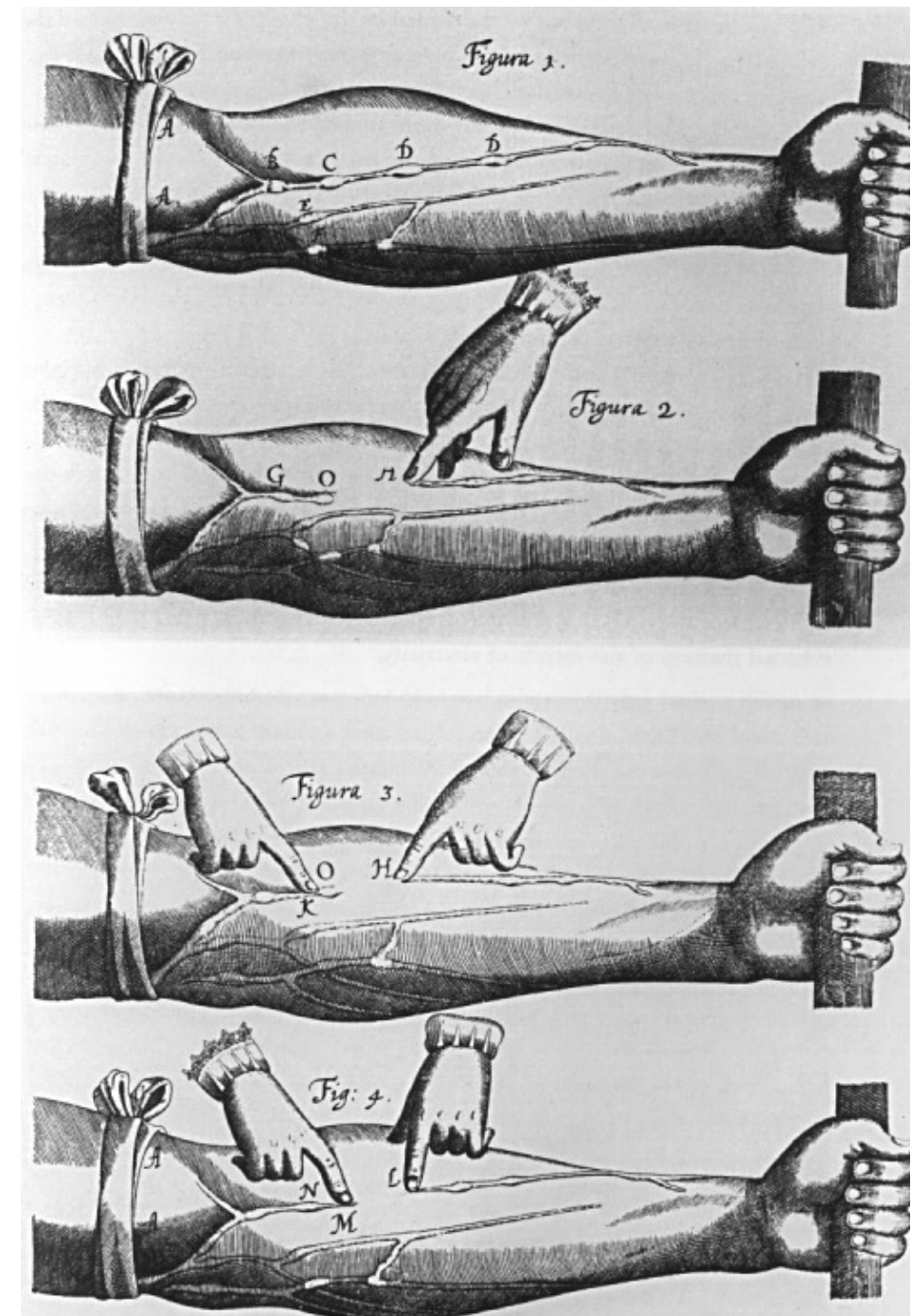
*"Exercitatio anatomica de motu cordis et sanguinis in animalibus"* (1628)



## 3. Muscle action

## 4. Negative intrathoracic pressure

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



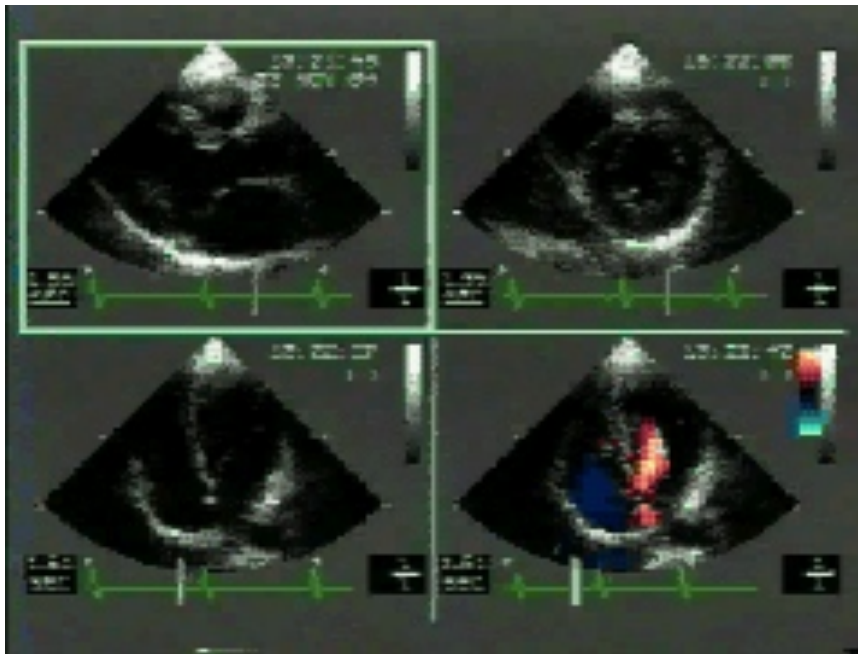


# CARDIAC BIOPHYSICS



# Heart:

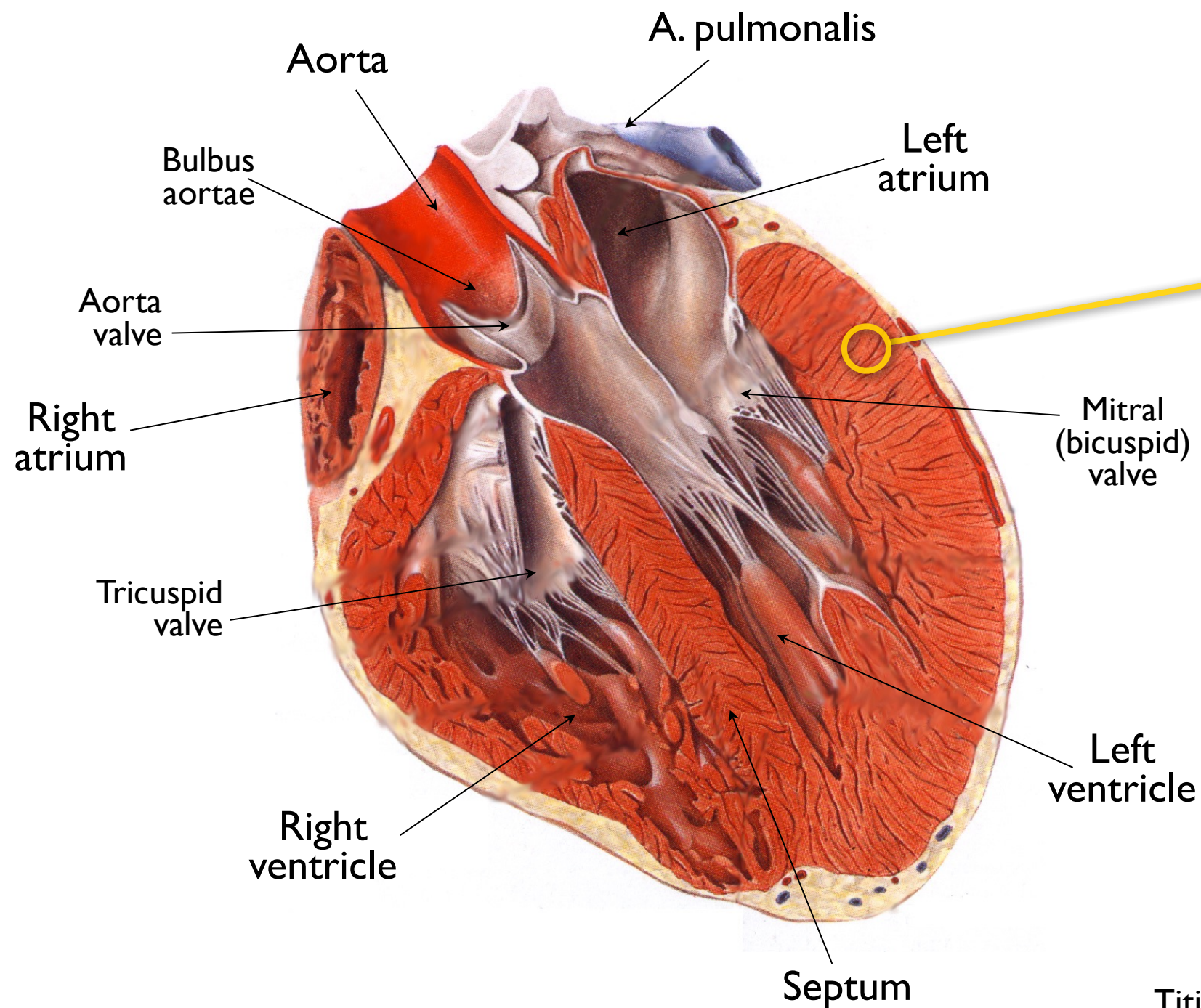
## Pump of the circulatory system



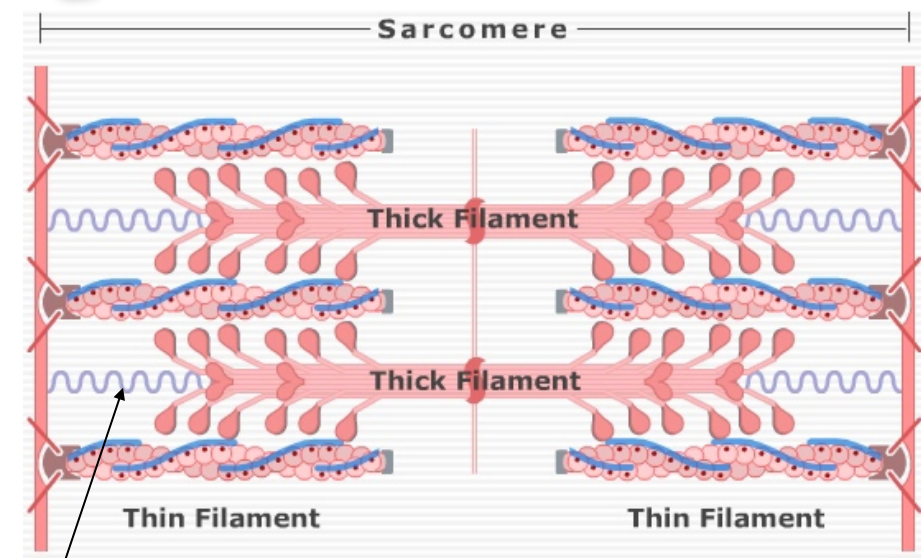
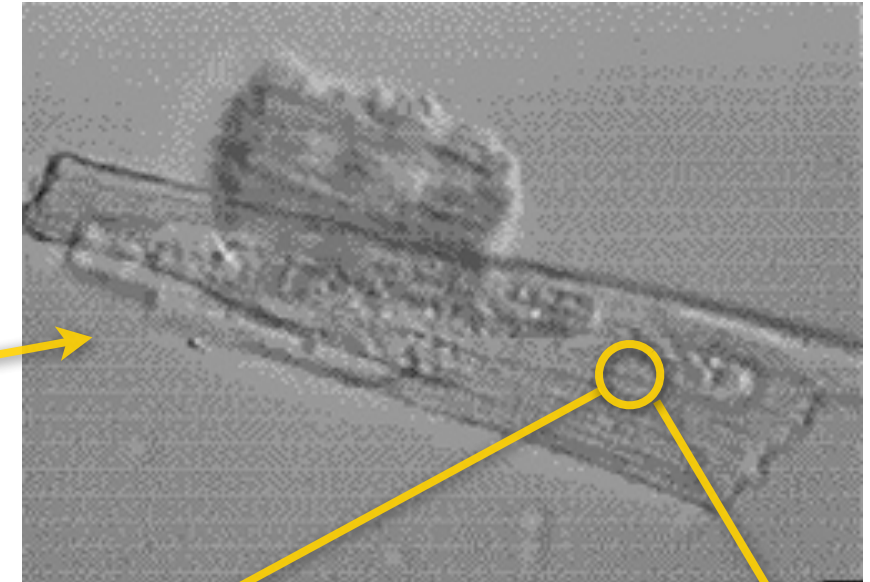
	Number of contractions	Expelled blood volume
1 min	~70	~6 l
1 day	~100.000	~8600 l
Life (70 yrs)	$\sim 2.5 \times 10^9$	$\sim 220 \times 10^6 \text{ l}$



# Schematic structure of the human heart

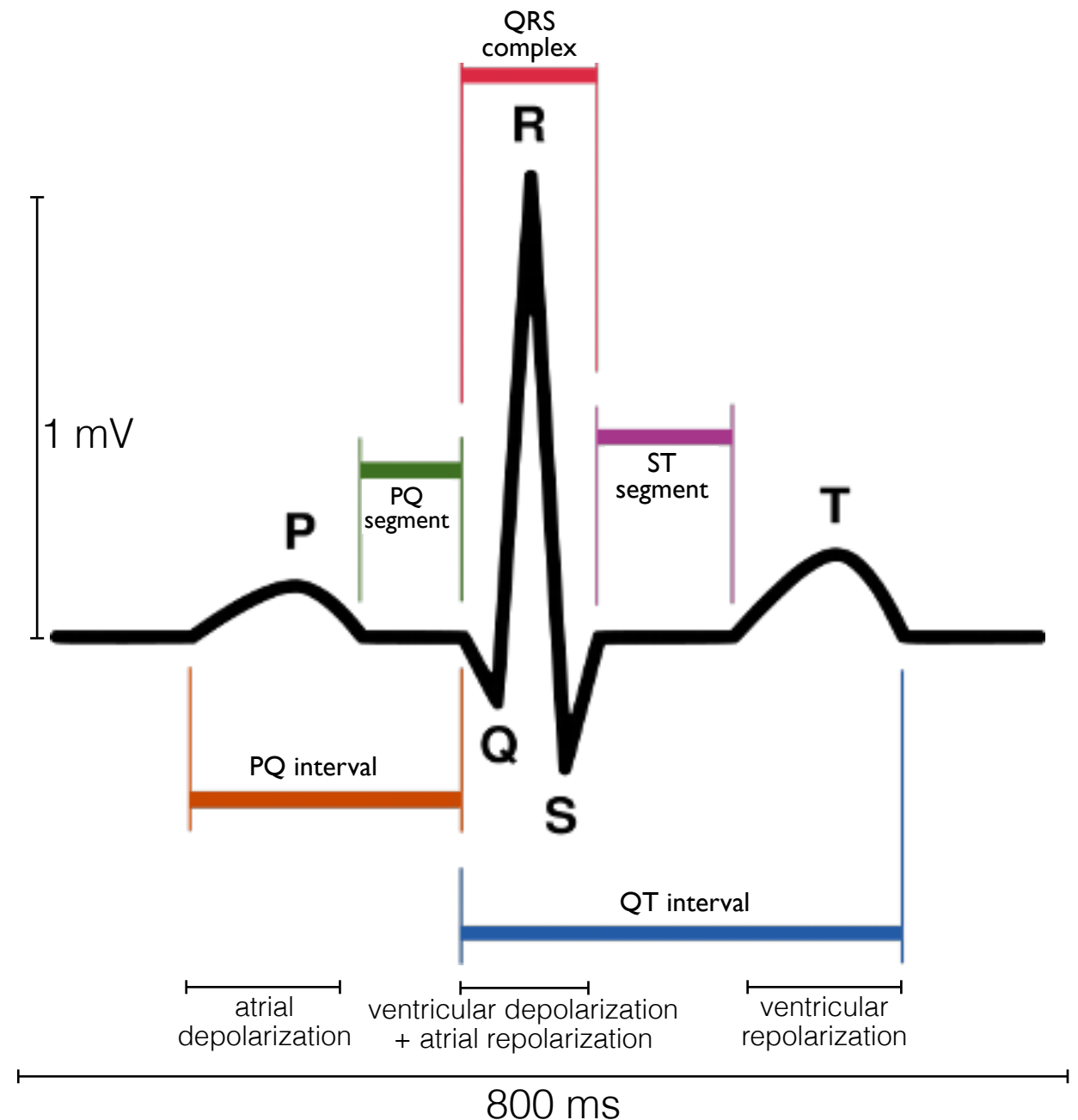
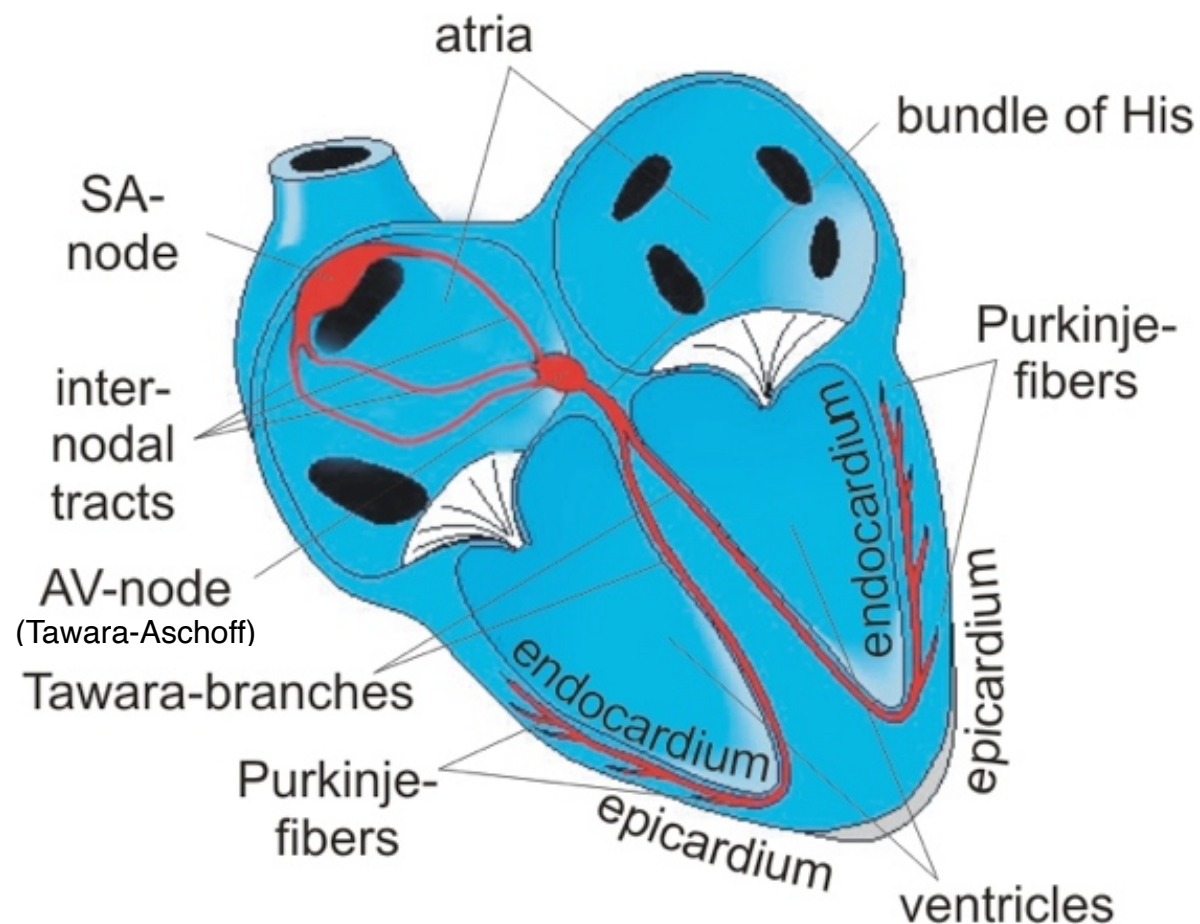


Cardiomyocyte



# Activation of coordinated cardiac contractions

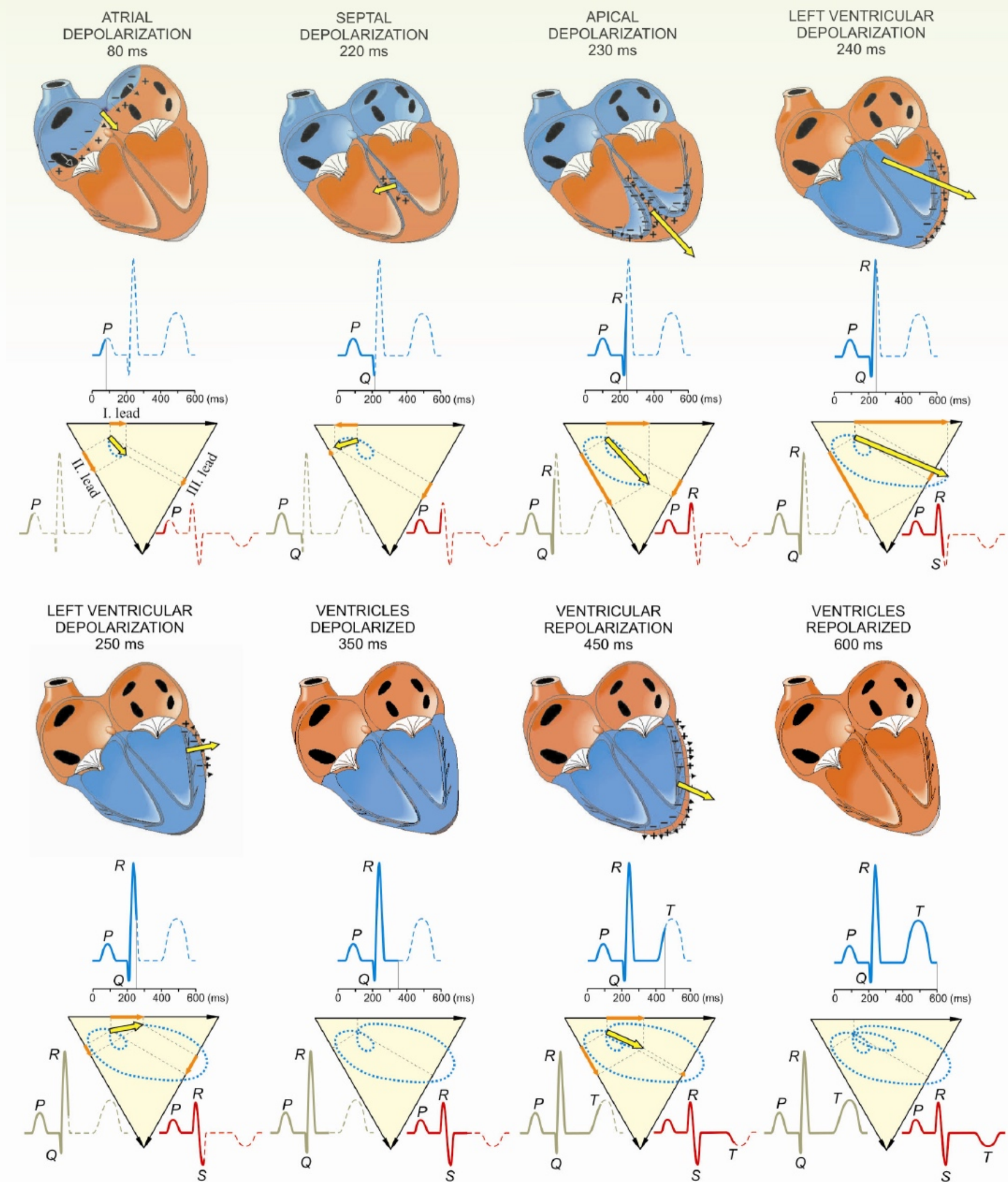
## Electrocardiogram (ECG)





# EKG:

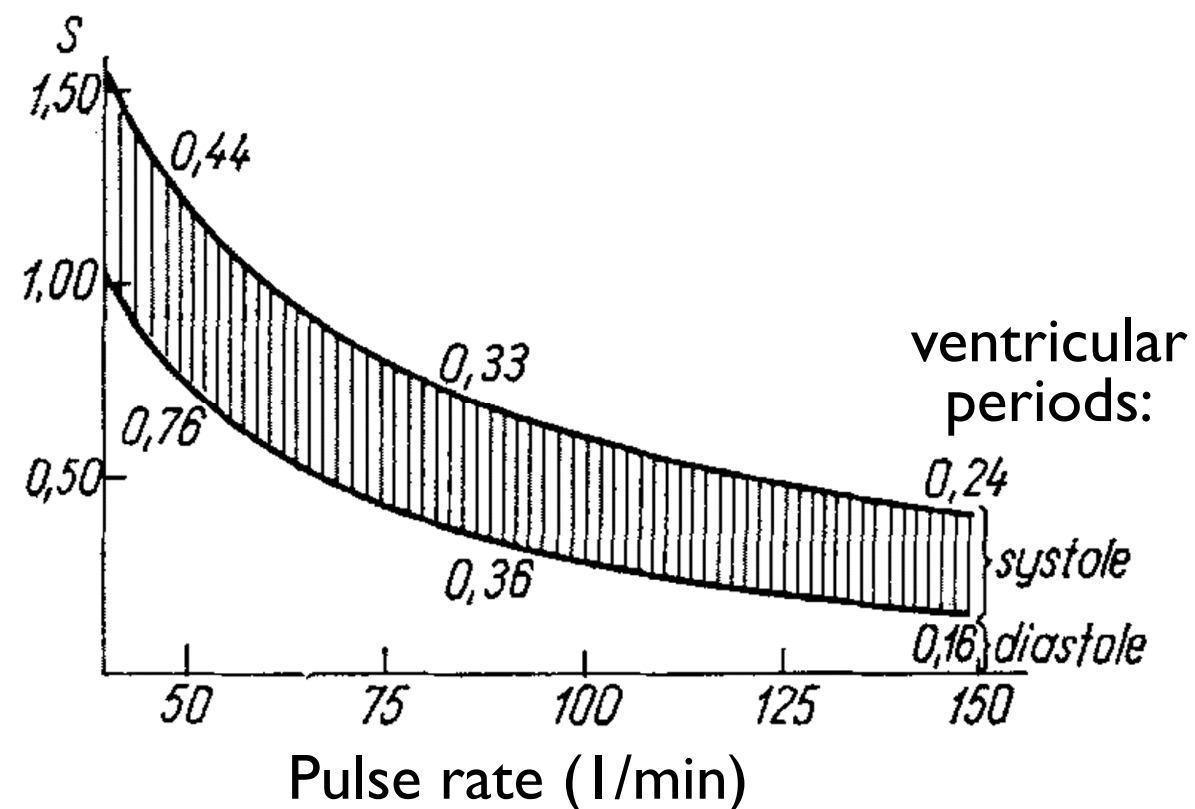
Vectorial projections (according to leads) of the resultant dipole (integral vector) that changes in time and space during myocardial depolarization and repolarization.



# The cardiac cycle

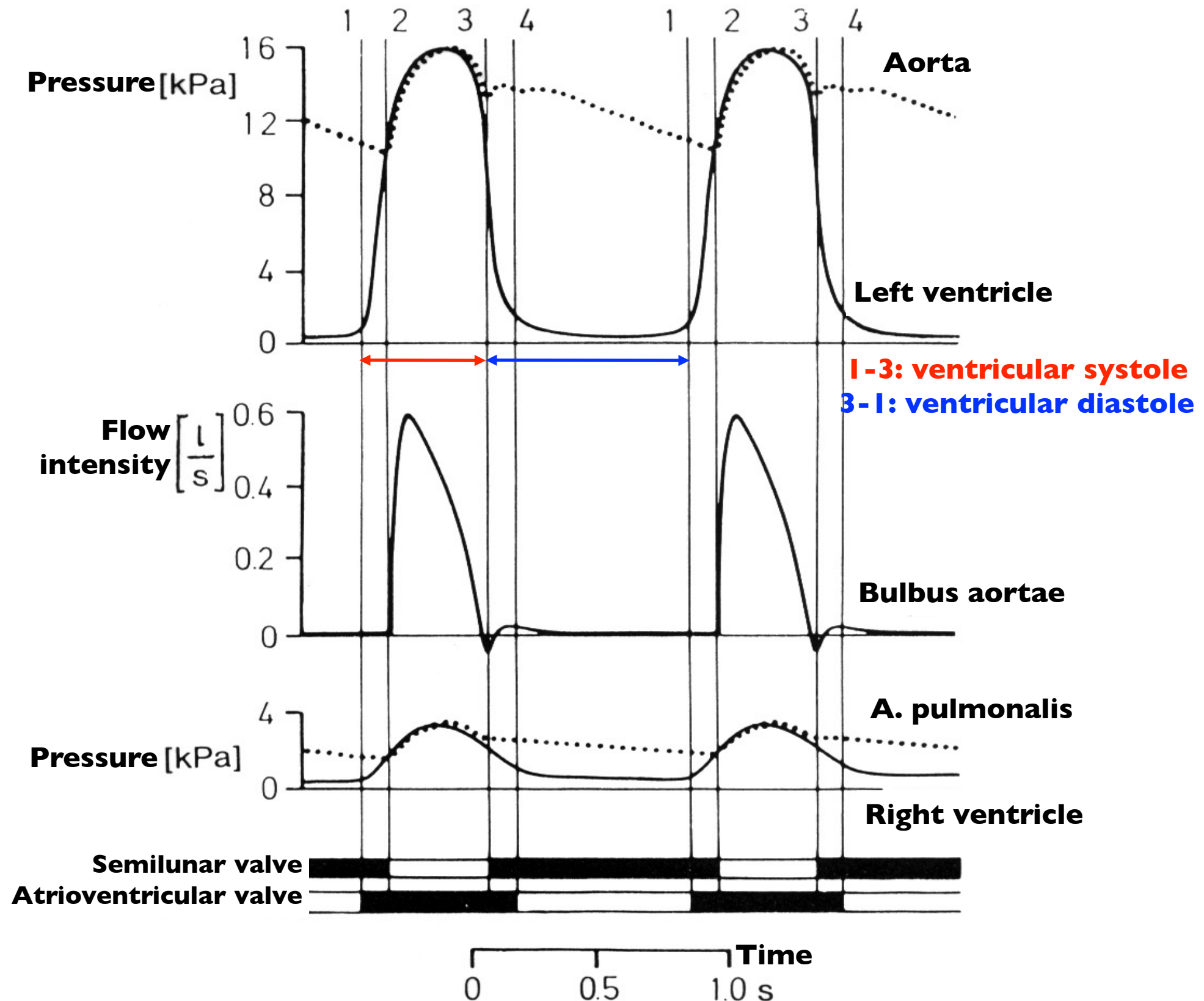
Contraction (systole) - relaxation (diastole) cycle of the heart

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



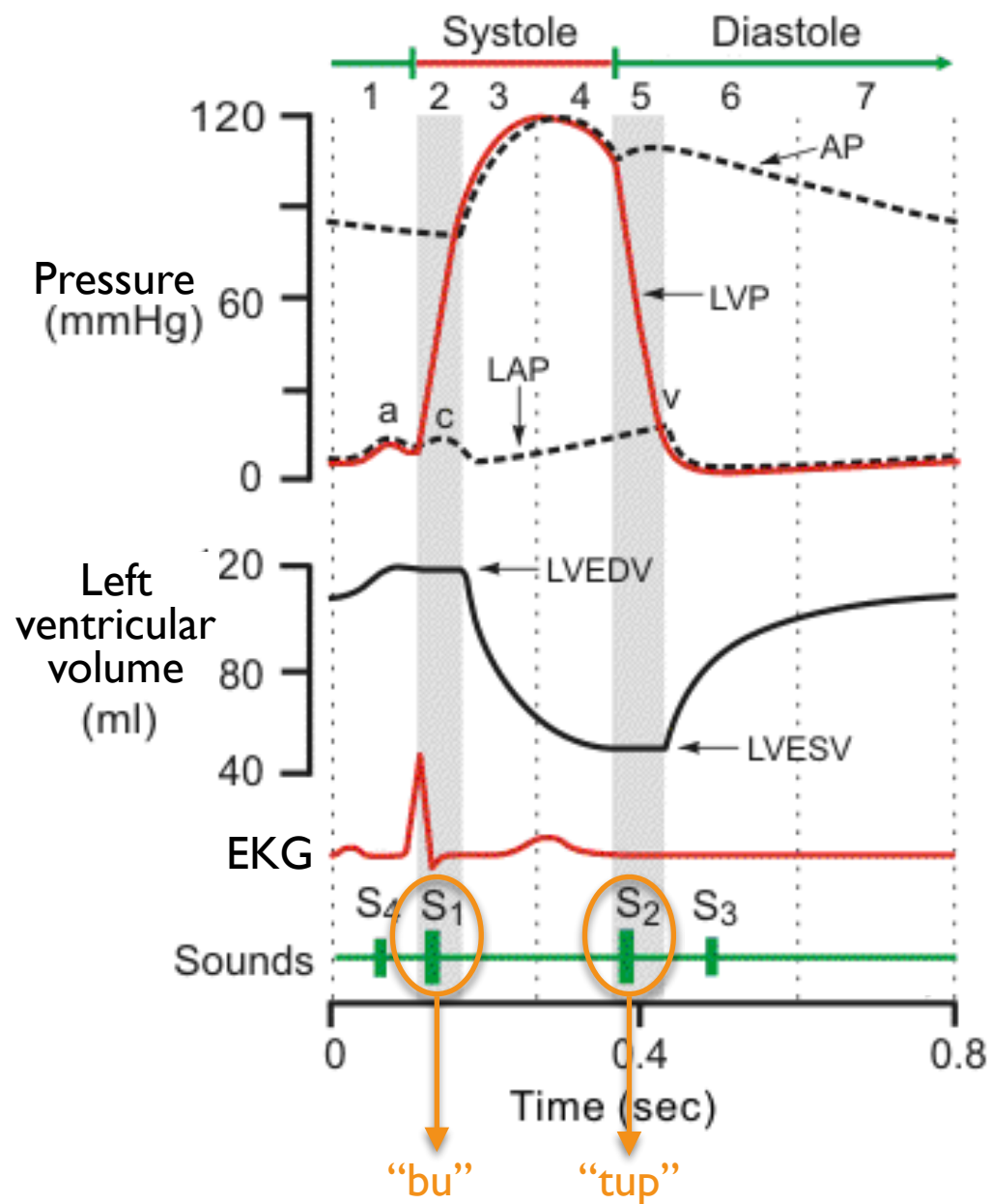
# Events of the cardiac cycle I.

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

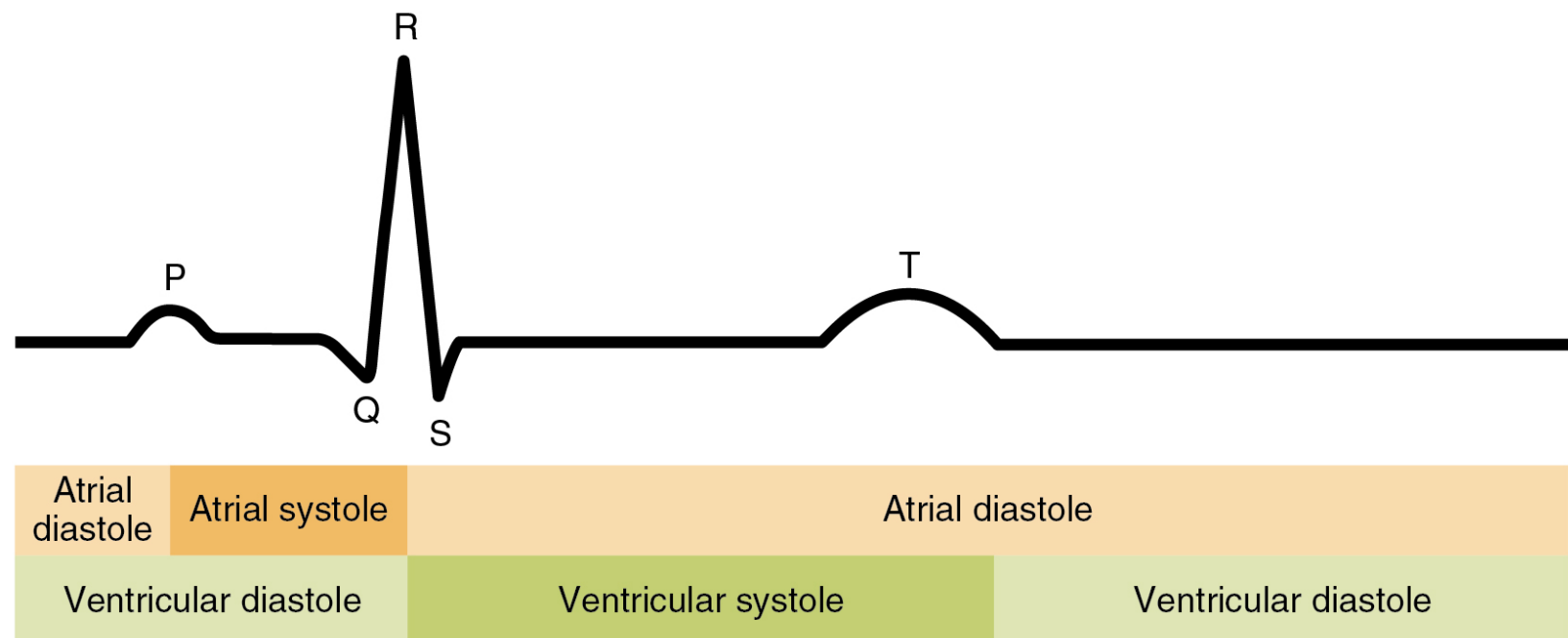




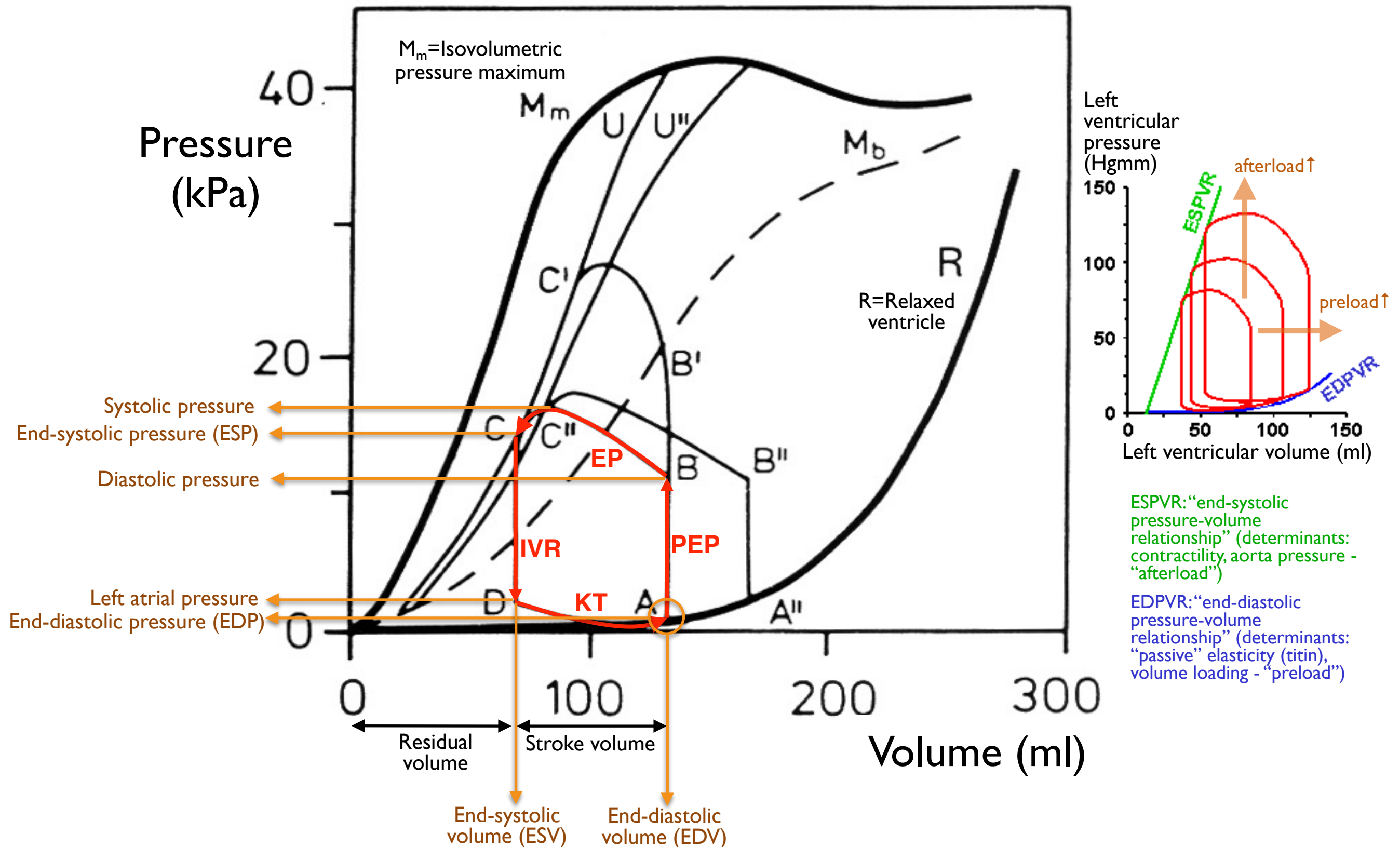
# Events of the cardiac cycle 2.



Electrokardiogram (ECG)



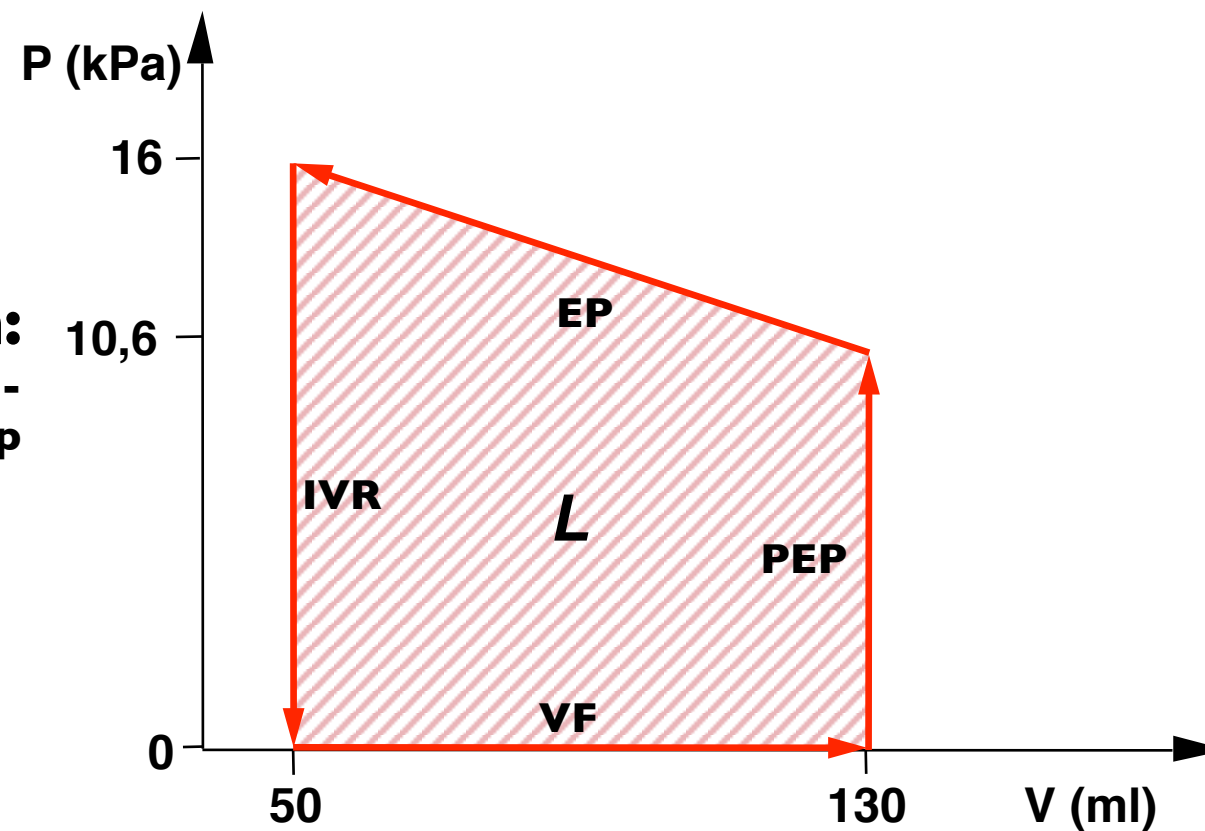
# Pressure-volume diagram of left ventricle



# 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

$\Delta V$ =**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



<http://report.semmelweis.hu/linkreport.php?qr=DODZ7V2YLR6KBWQ4>