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:

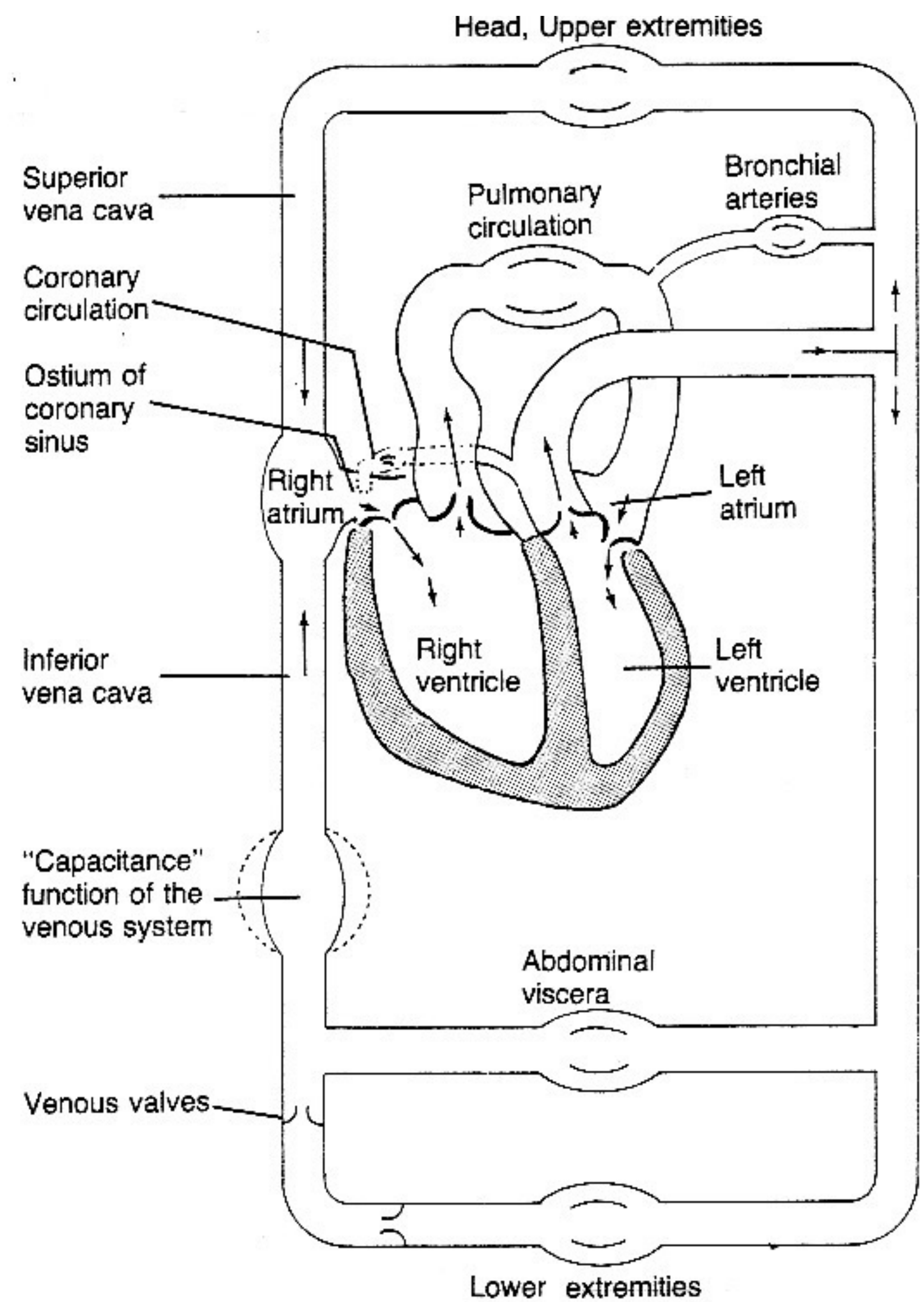
- Gases
- Metabolites
- Hormones, signal transmitters
- Immunoglobulins
- Heat

B. Hemodynamic requirements:

Slow (matches diffusion-driven processes)

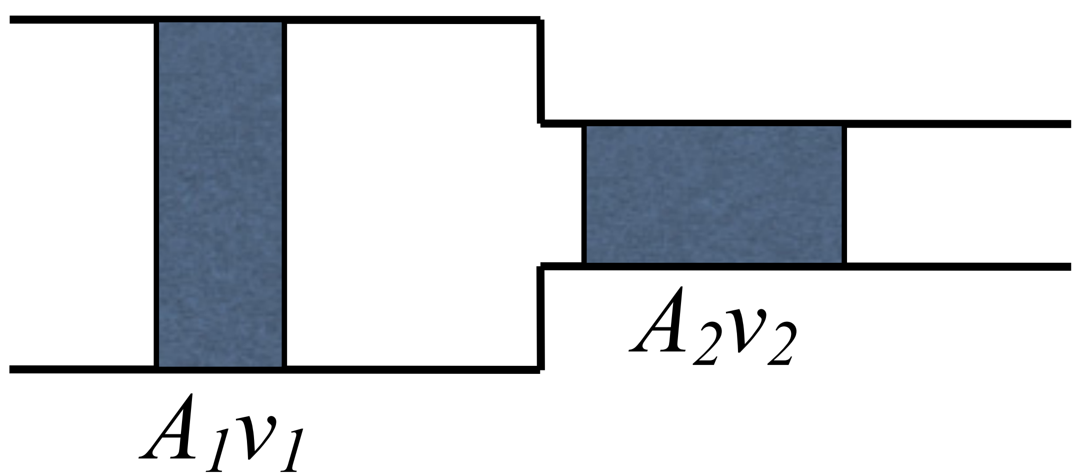
Steady (no fluctuations)

Unidirectional (but not open-ended)



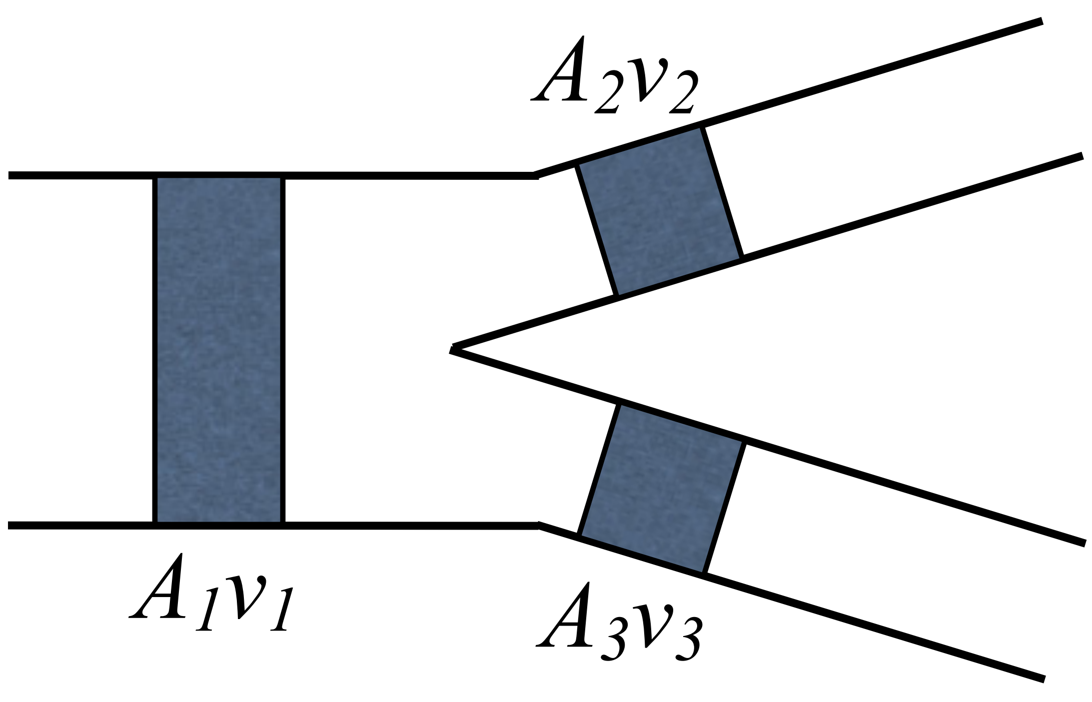
Fluid flow in bifurcating vessel system

Continuity equation



$$A_1 v_1 = A_2 v_2 = const$$

A = cross-sectional area
v = flow rate



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

A_Σ = 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 (φ)	$J_Q = -\frac{1}{\rho} \frac{\Delta \varphi}{\Delta x}$	Ohm
Material transport (diffusion)	Chemical potential (μ)	$J_n = -D \frac{\Delta c}{\Delta x}$	Fick

Laws of flow in viscous fluids II.

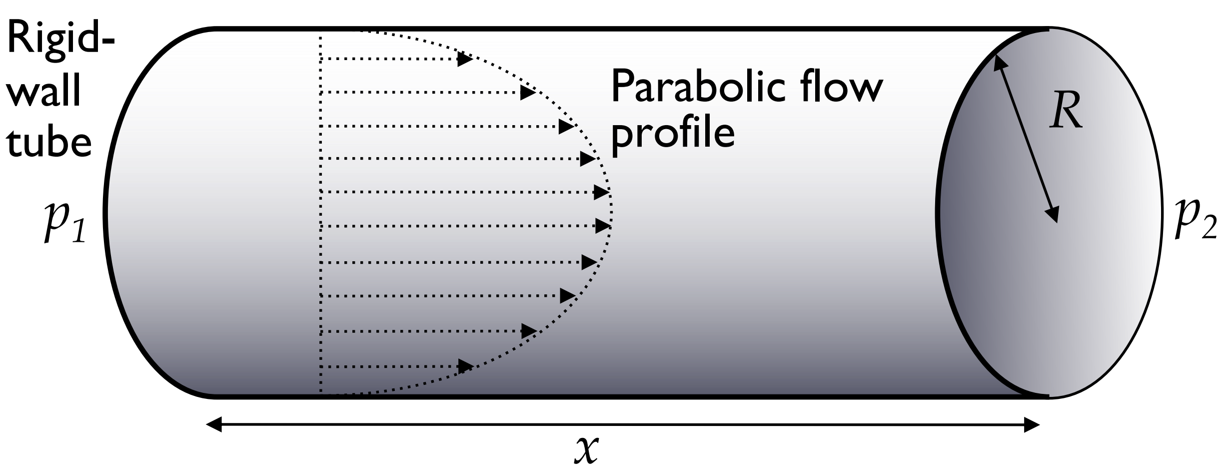
Hagen-Poiseuille's law

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

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



V = volume
t = time
R = tube radius
η = viscosity
p = pressure
x = tube length

$V/t = I_V$ = volumetric vlow 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

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: $I_V = -\frac{R^4\pi}{8\eta\Delta x}\Delta p \Rightarrow -\Delta p = R_{tube}\cdot I_V \Rightarrow U = R\cdot I$

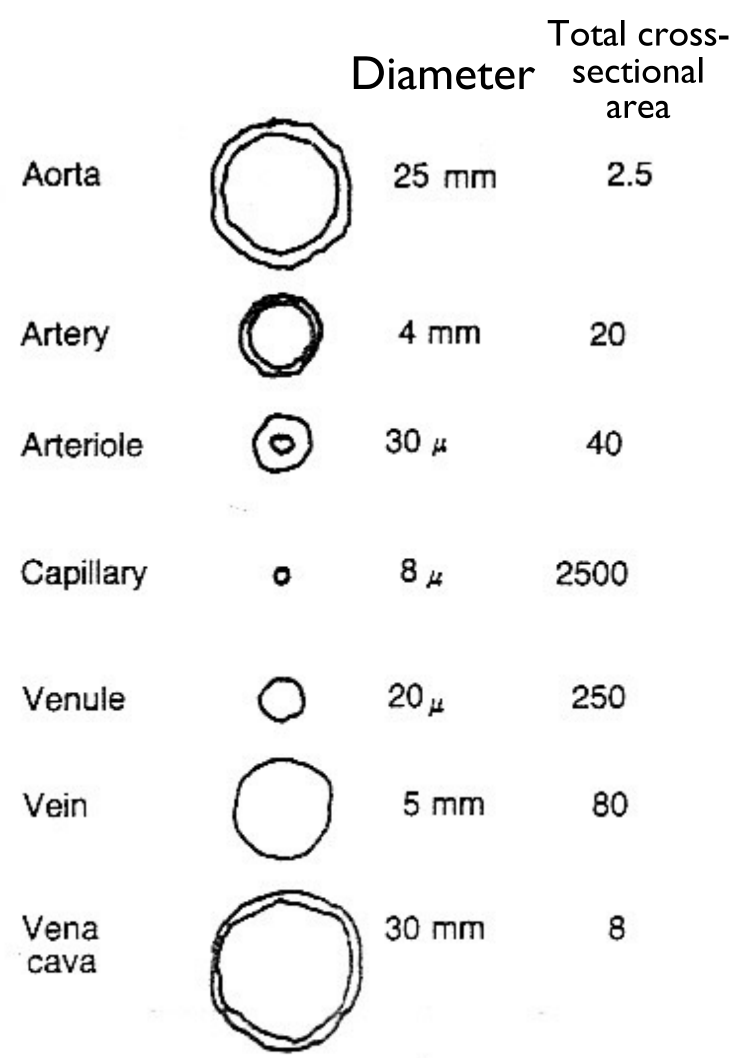
$1/R_{tube}$

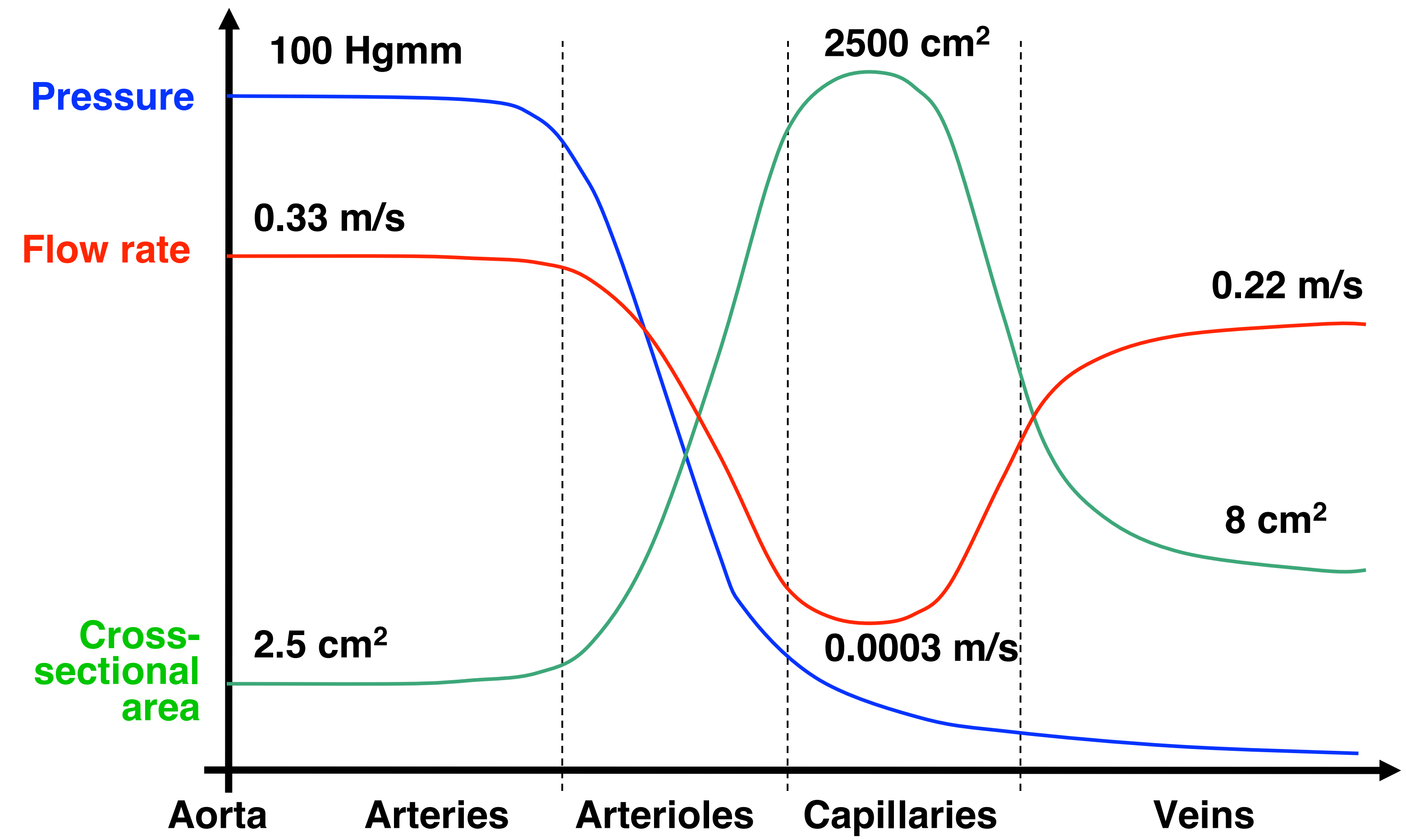
Ohm's law!

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





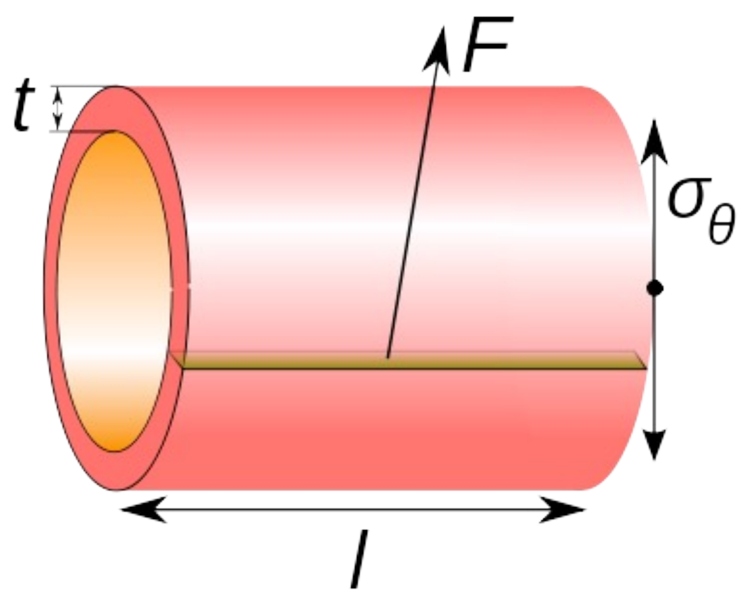
- **Pressure** on blood vessel wall: ***"blood pressure"***. Pressure drop along vessel maintains blood flow.
- Reason of **pressure drop**: flow resistance - most of energy is converted to heat.
- **Flow rate** and total **cross-sectional area** change inversely (based on equation of continuity, Av = 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 bood 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

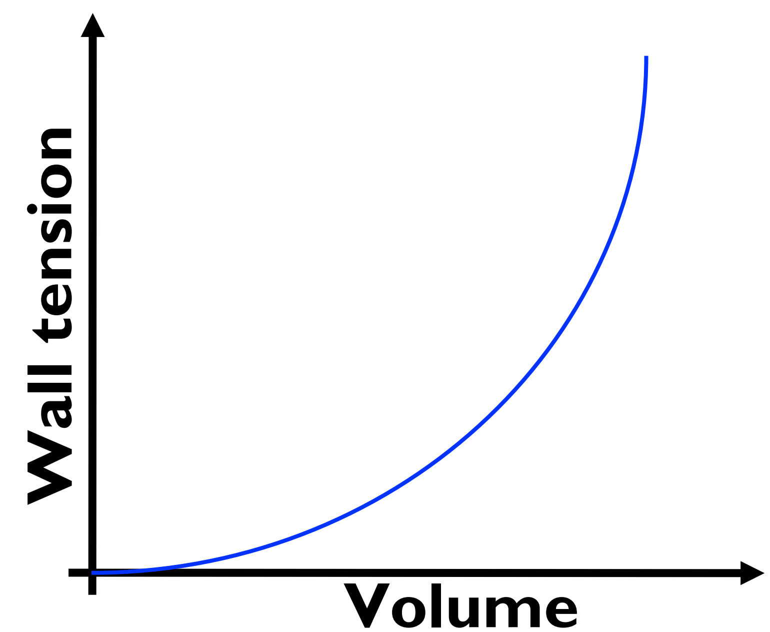


$$\sigma_\theta = \frac{F}{t \cdot l}$$

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

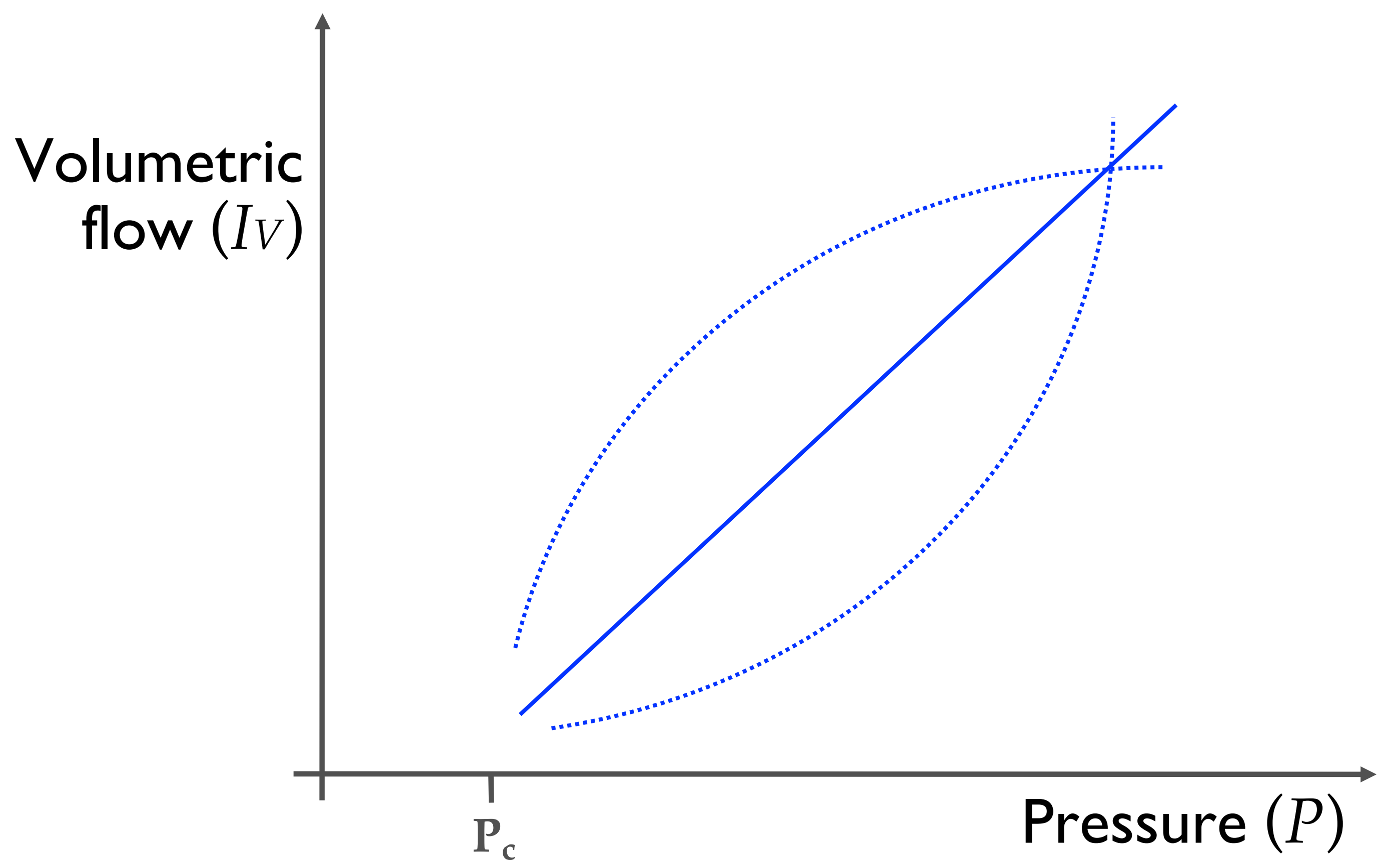


Determinants of vascular elasticity:
- Elastin
- Collagen
- Smooth muscle

Implications of vascular easticity:
- Storage of potential (elastic) energy
- Dampening of pressure pulses
- Constant flow rate

Relationship between flow intensity and pressure

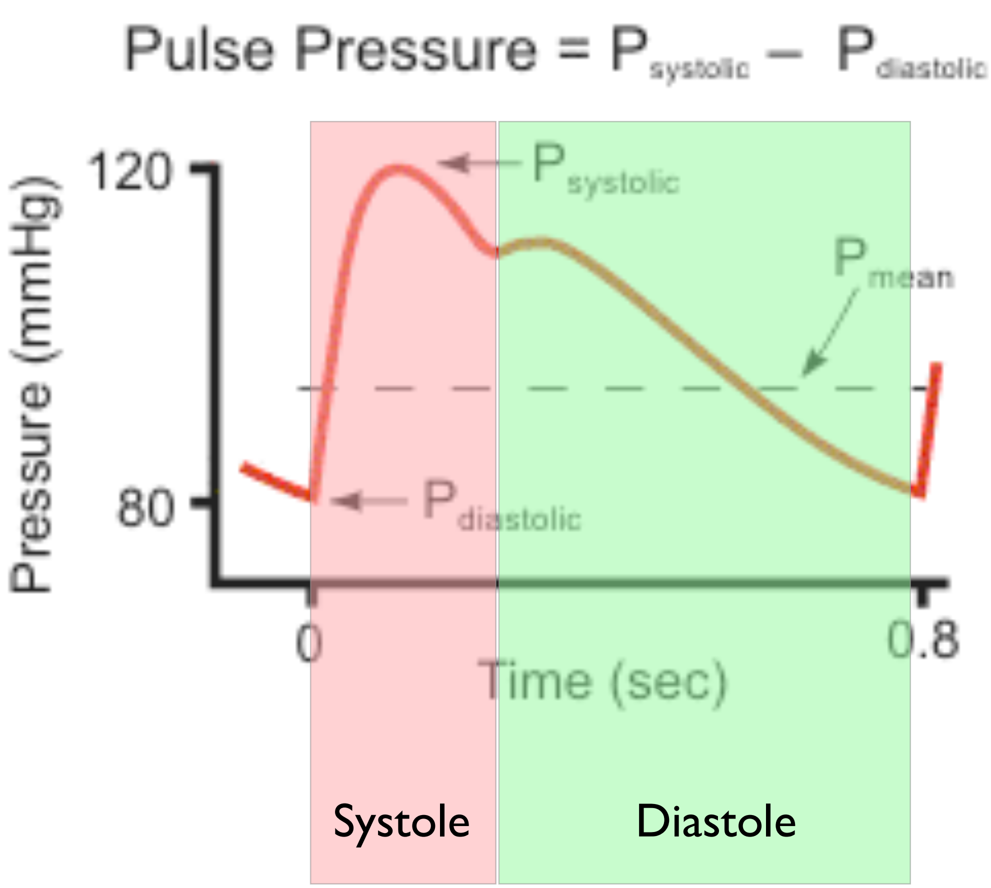
Below certain pressure vessels collapse and flow ceases

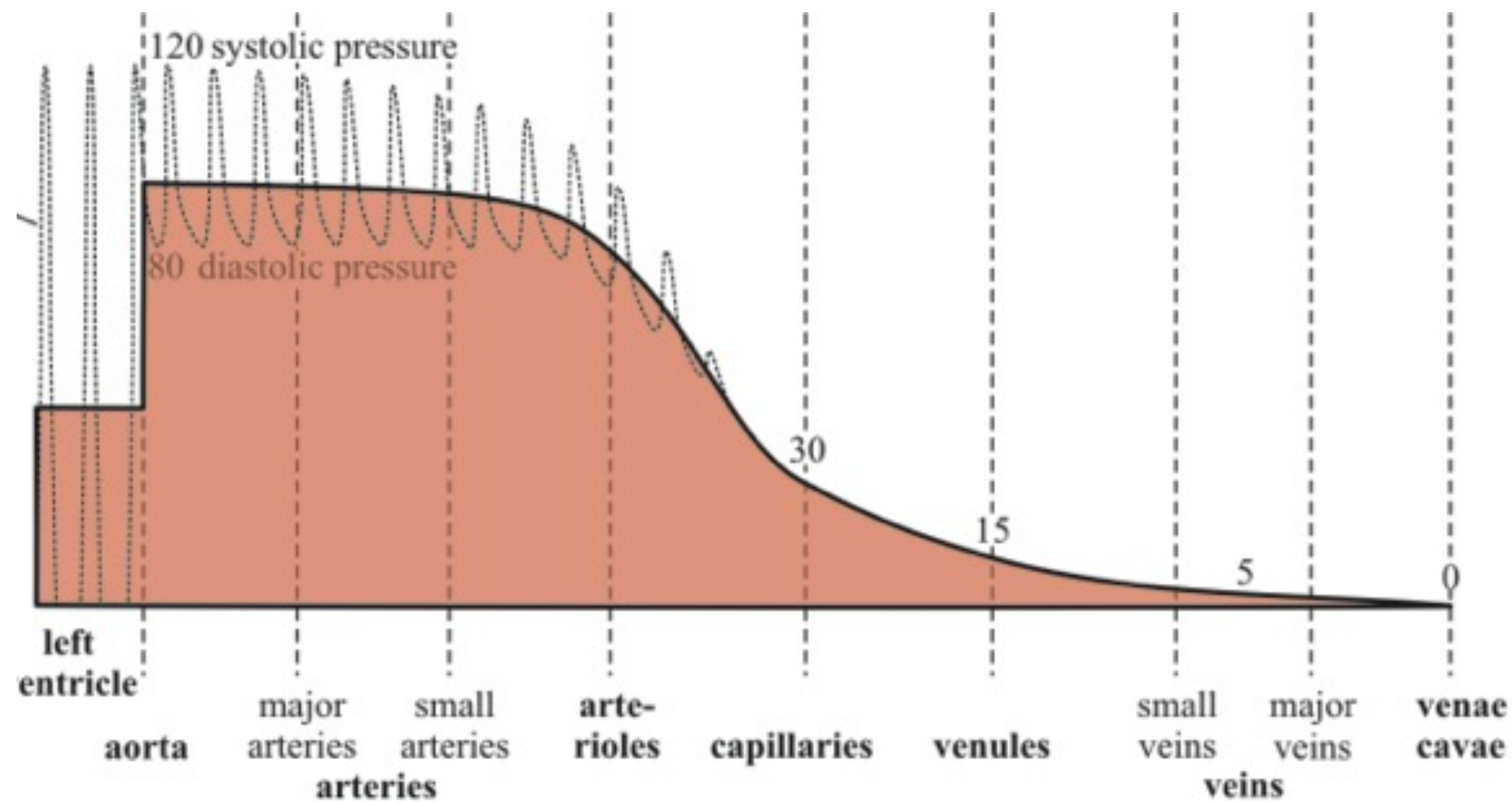


N.B.:

-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

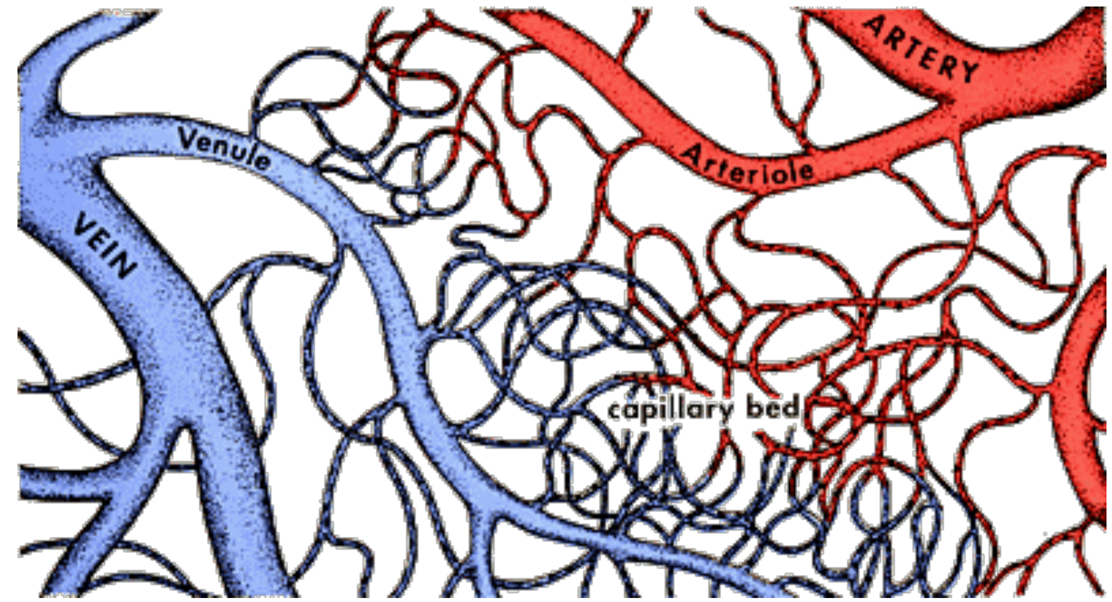




Because of vessel wall elasticity, pressure fluctuations are dampened.

Capillary circulation, fluid exchange

1. Capillaries:
Length: 400-700 μm
Diameter: 0.5 μm



2. Open state depends on function
Number of open caillaries in muscle:
Rest - 5/mm^2
Activity - 200/mm^2

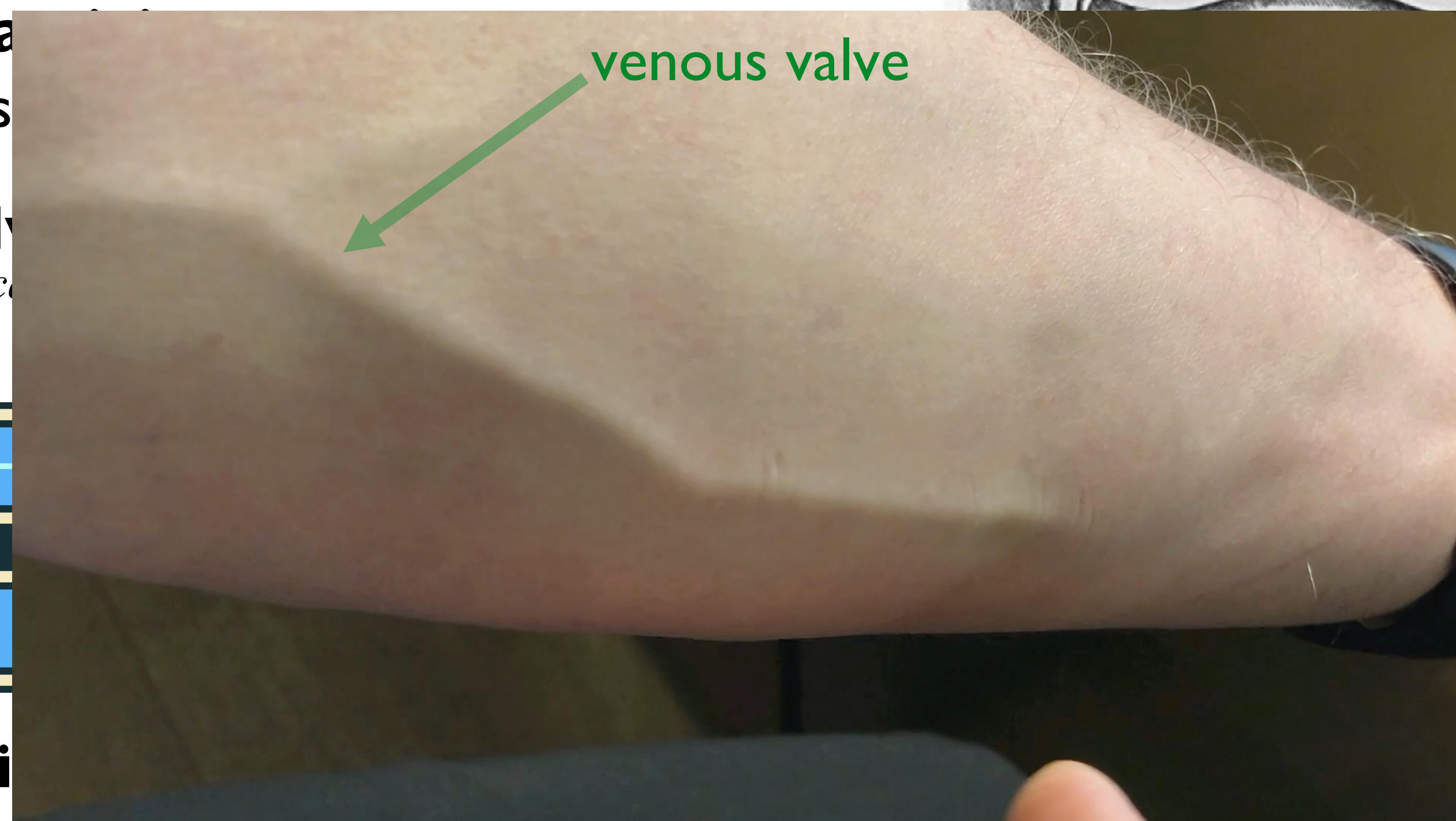
3. Capillary fluid exchange
fluid movement between blood plasma and interstitium
driven by: difference in blood pressure and colloid osmotic pressure
Colloid osmotic (oncotic) pressure:
osmotic pressure caused by the presence of colloidal proteins (2.6 kPa)

	Arterioles	**Capillaries**	**Venules**
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

1. Arterial ela
elastic fibers ➛ s

2. Venous val
“Exercitatio anatomic
animalibus” (1628)

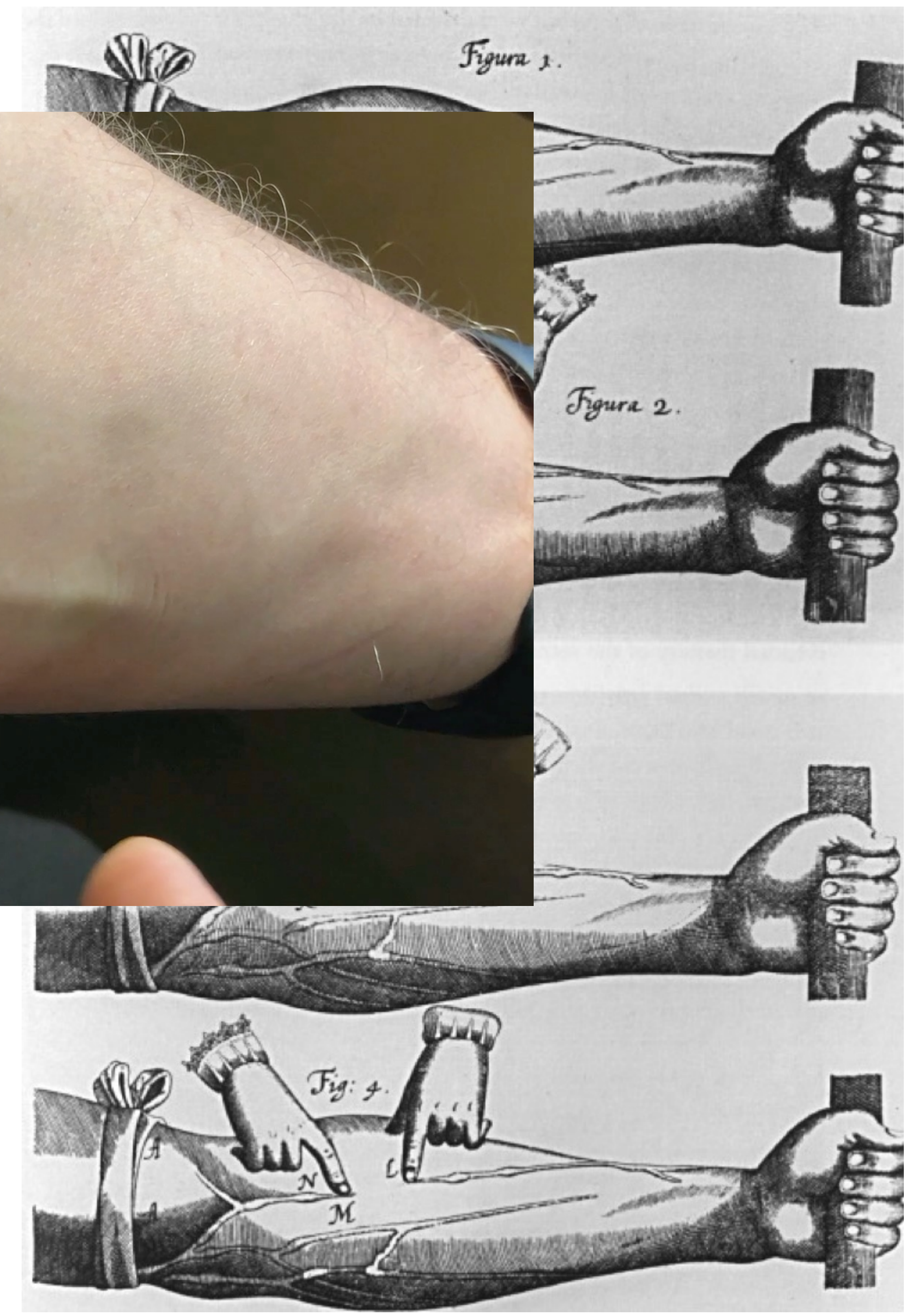


3. Muscle acti

4. "Negative" intrathoracic pressure

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

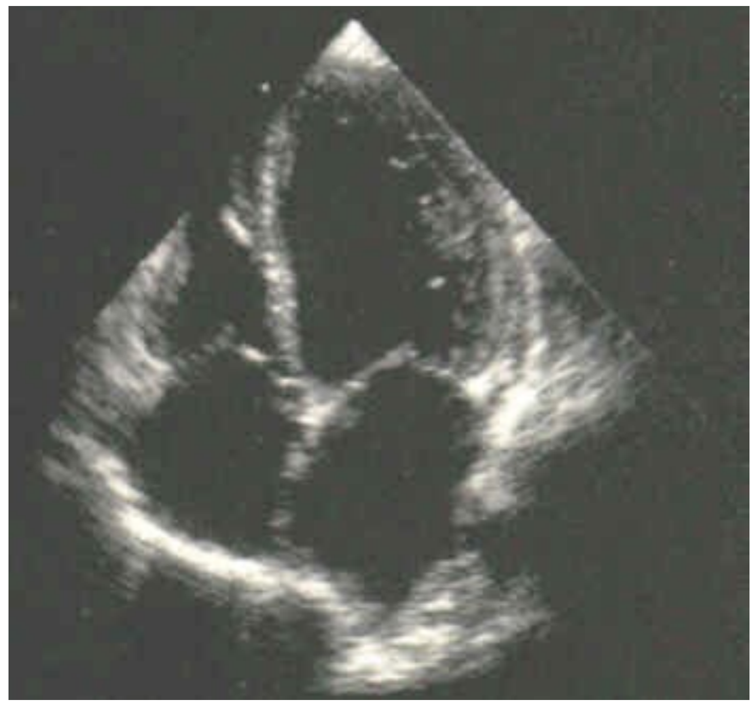
Harvey’s experiment (1628)



Cardiac biophysics

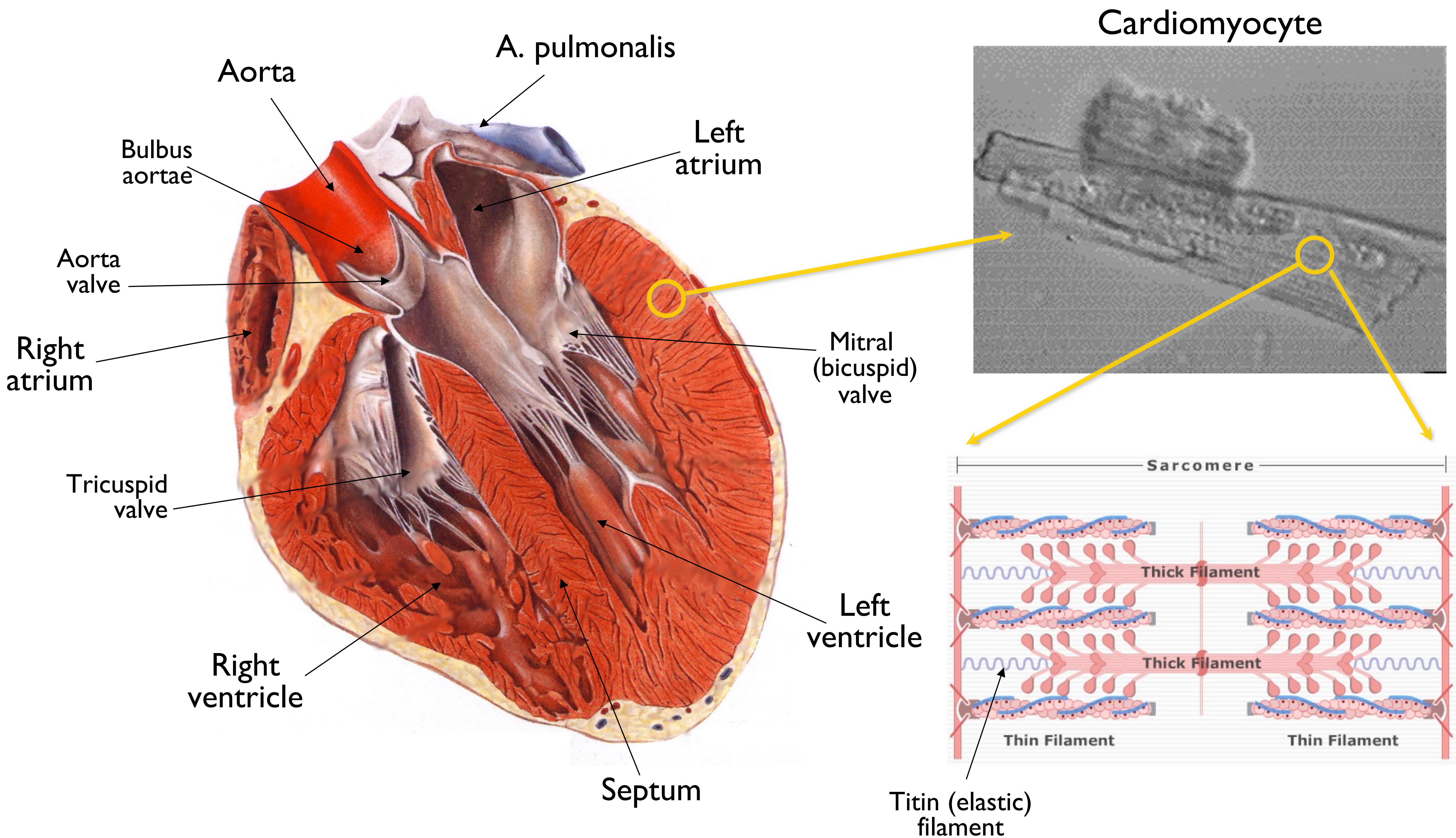
Heart:

Pump of the circulatory system

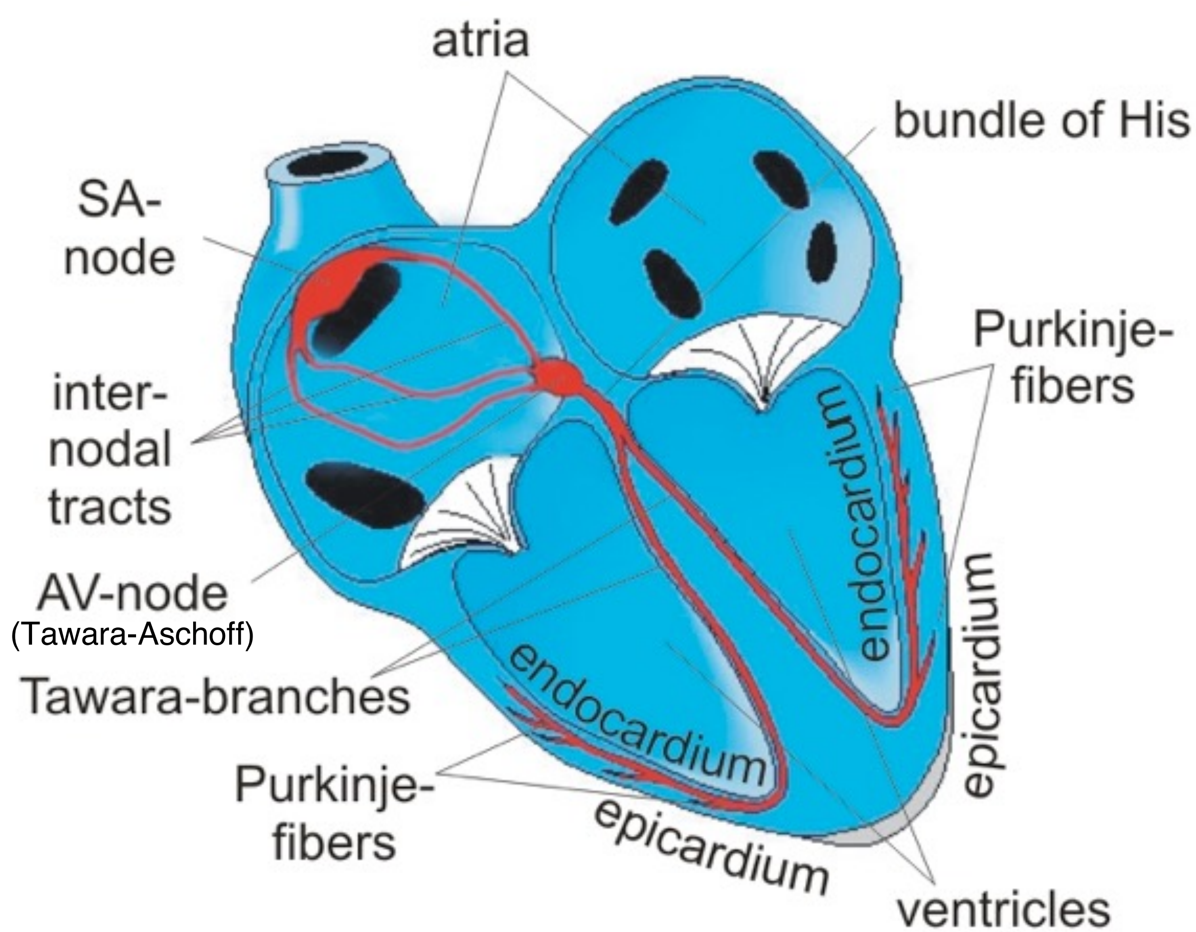


	Number of contractions	Expelled blood volume
1 min	~70	~6 l
1 day	~100.000	~8600 l
Life (70 yrs)	~2.5 x 10^9	~220 x 10^6 l

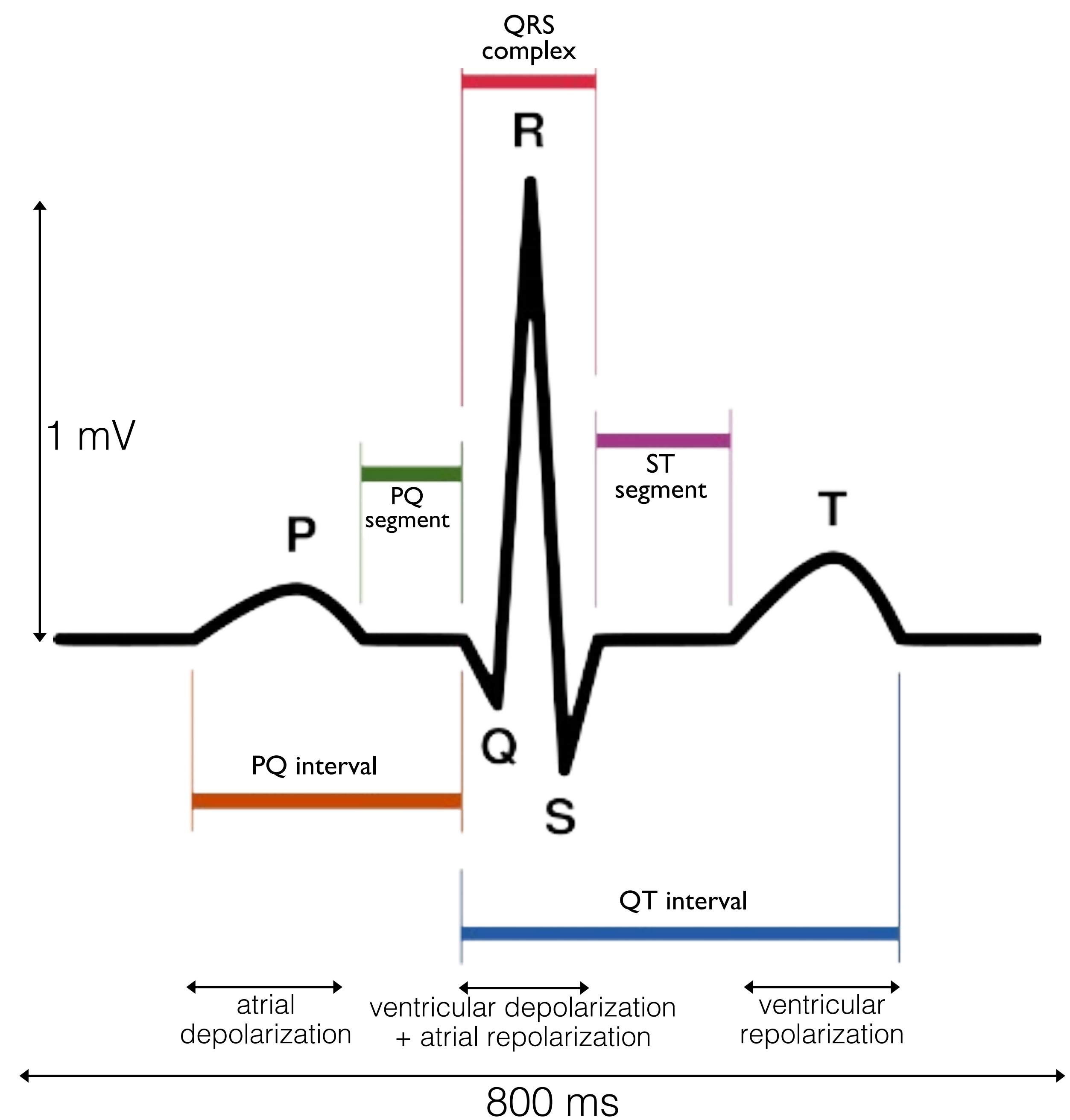
Schematic structure of the human heart



Activation of coordinated cardiac contractions

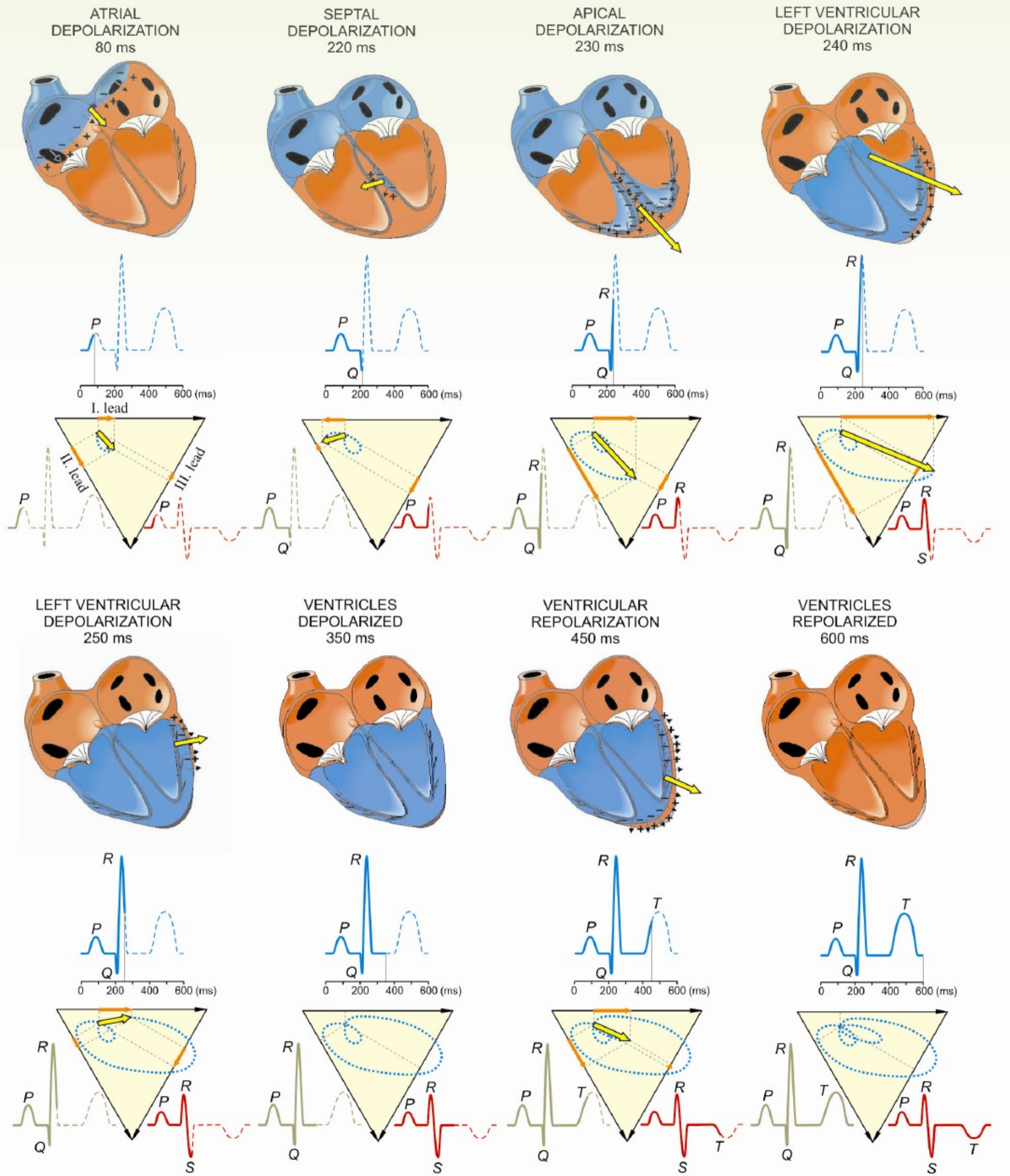


Electrocardiogram (ECG)



EKG:

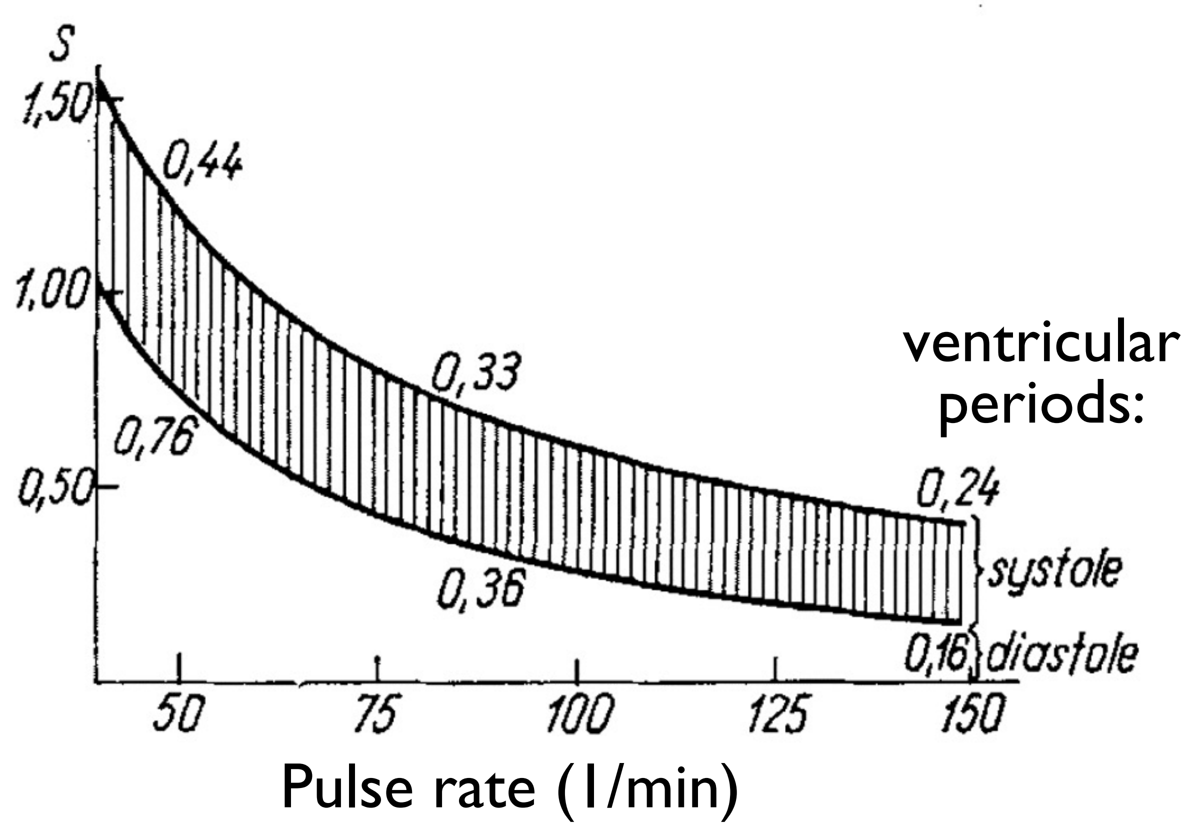
Vectorial projections (according to leads) of the resultant dipole (integral vector) that changes in time and space during myocardial depolarization and repolarization.



The cardiac cycle

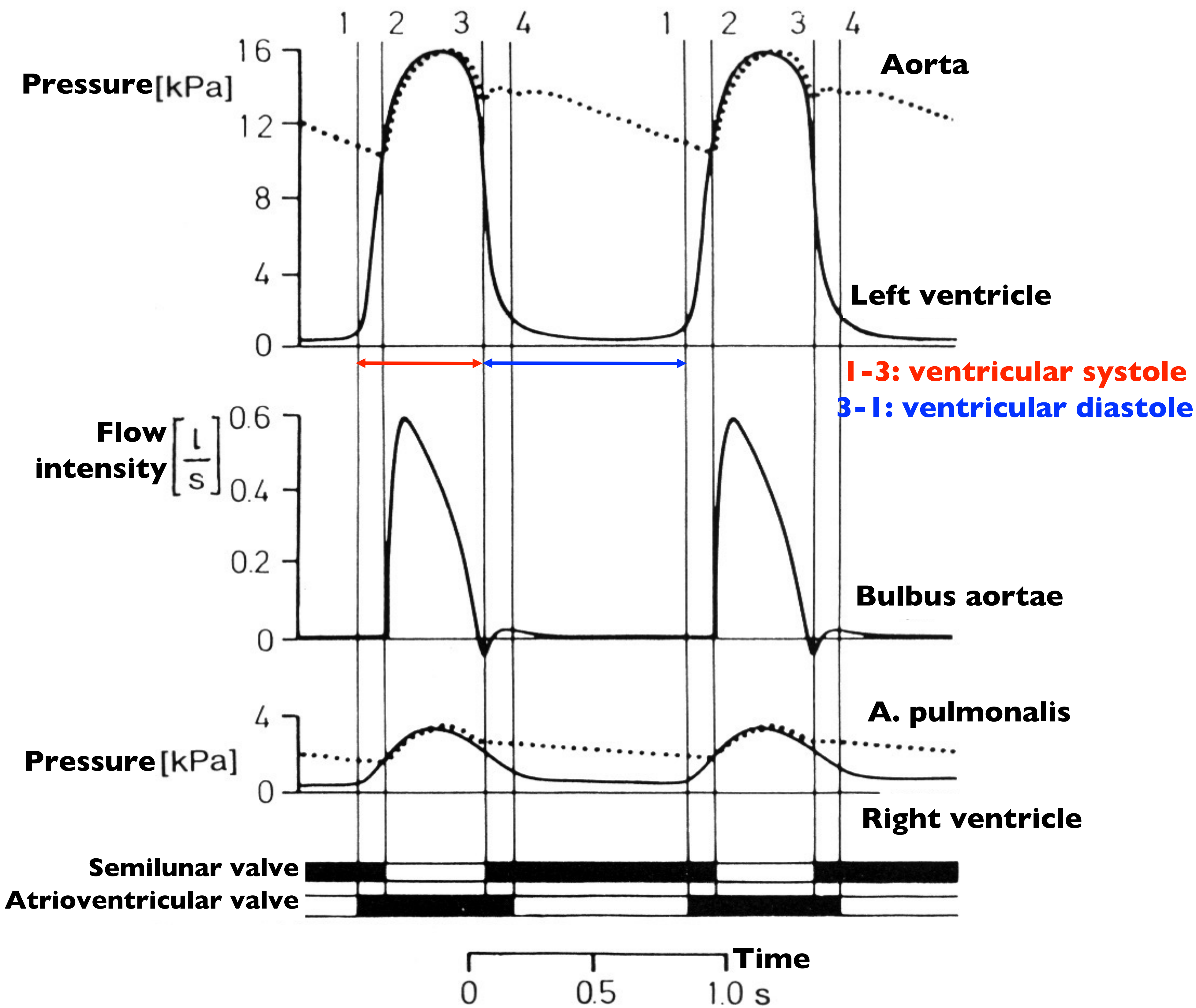
Contraction (systole) - relaxation (diastole) cycle of the heart

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

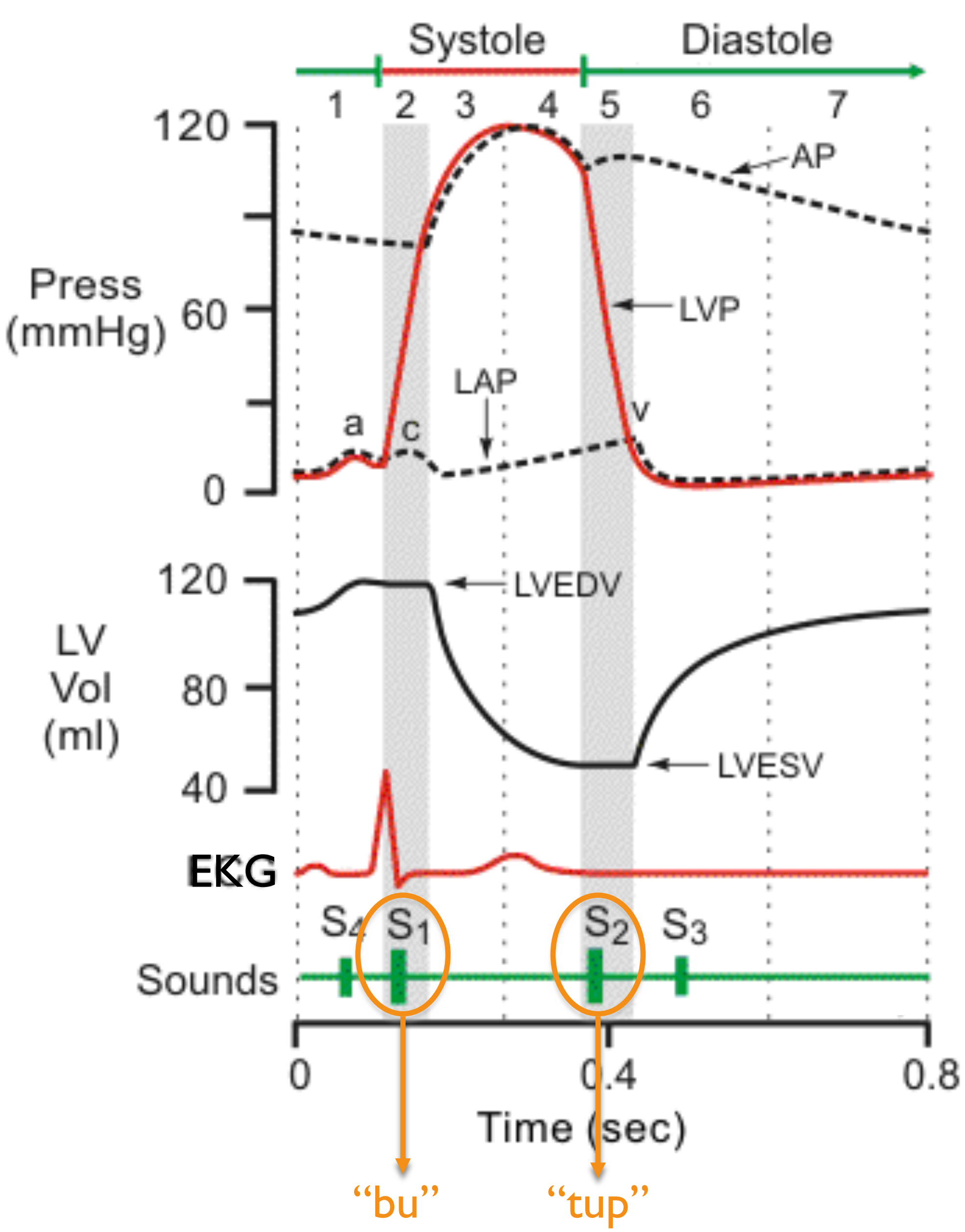


Events of the cardiac cycle 1.

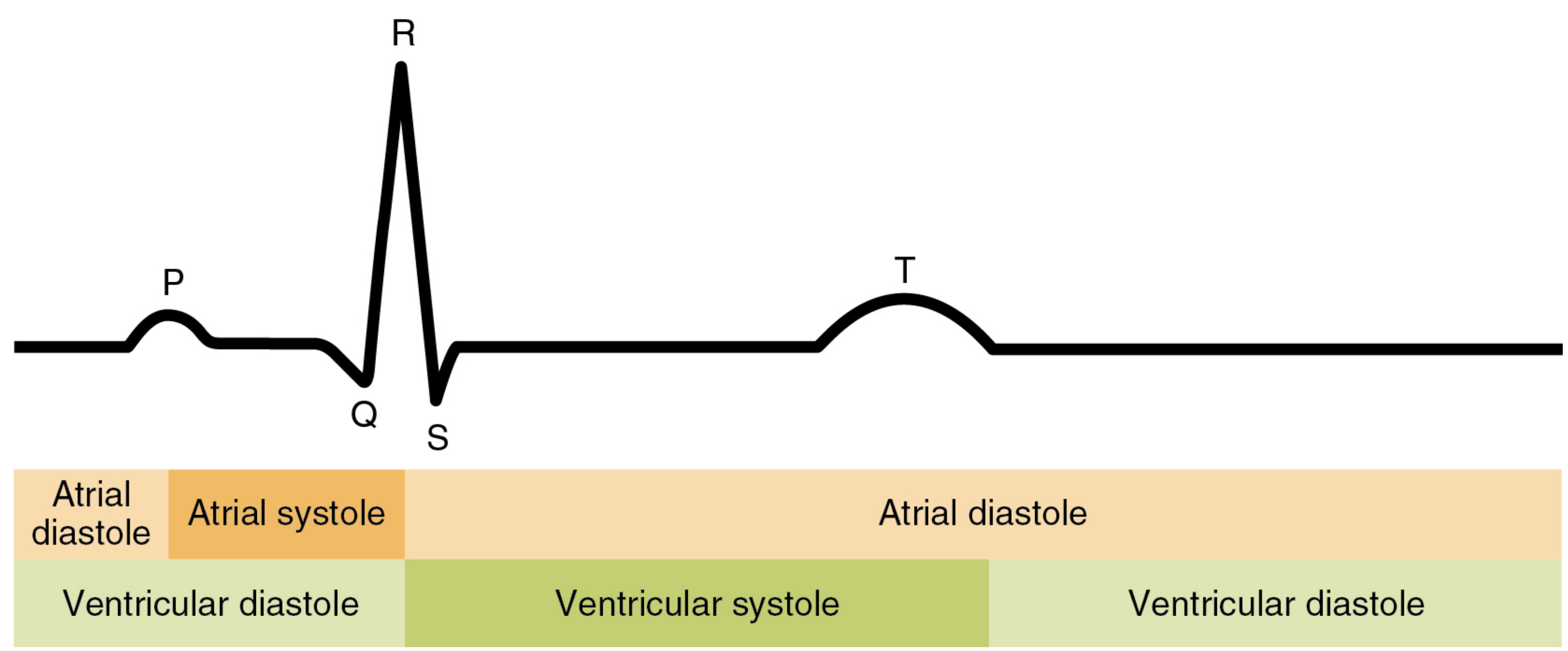
1-2: pre-ejection period (PEP) **2-3:** ejection period (EP) **3-4:** isovolumetric relaxation (IVR) **4-1:** ventricular filling (VF)



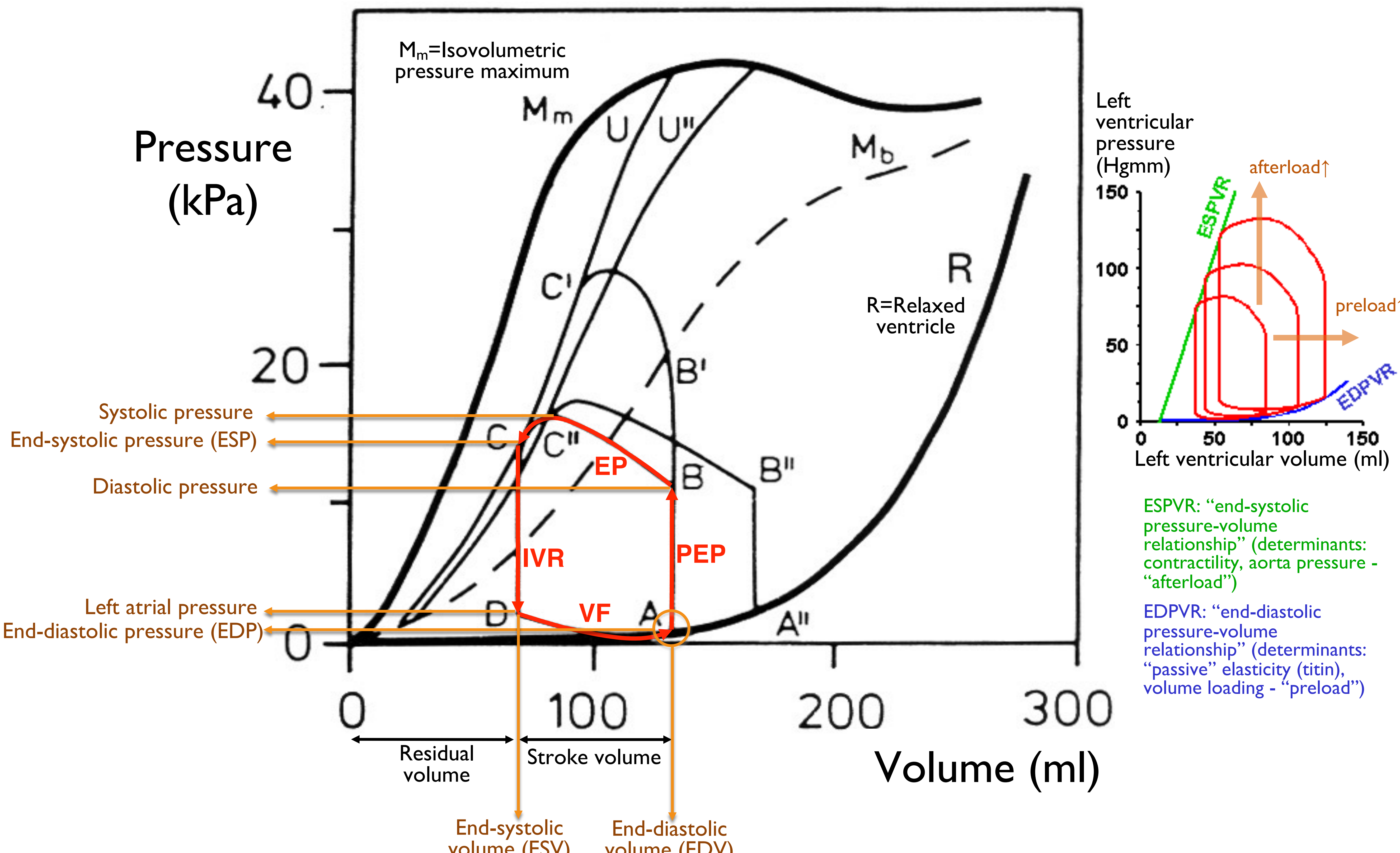
Events of the cardiac cycle 2.



Electrocardiogram (ECG)



Pressure-volume diagram of left ventricle



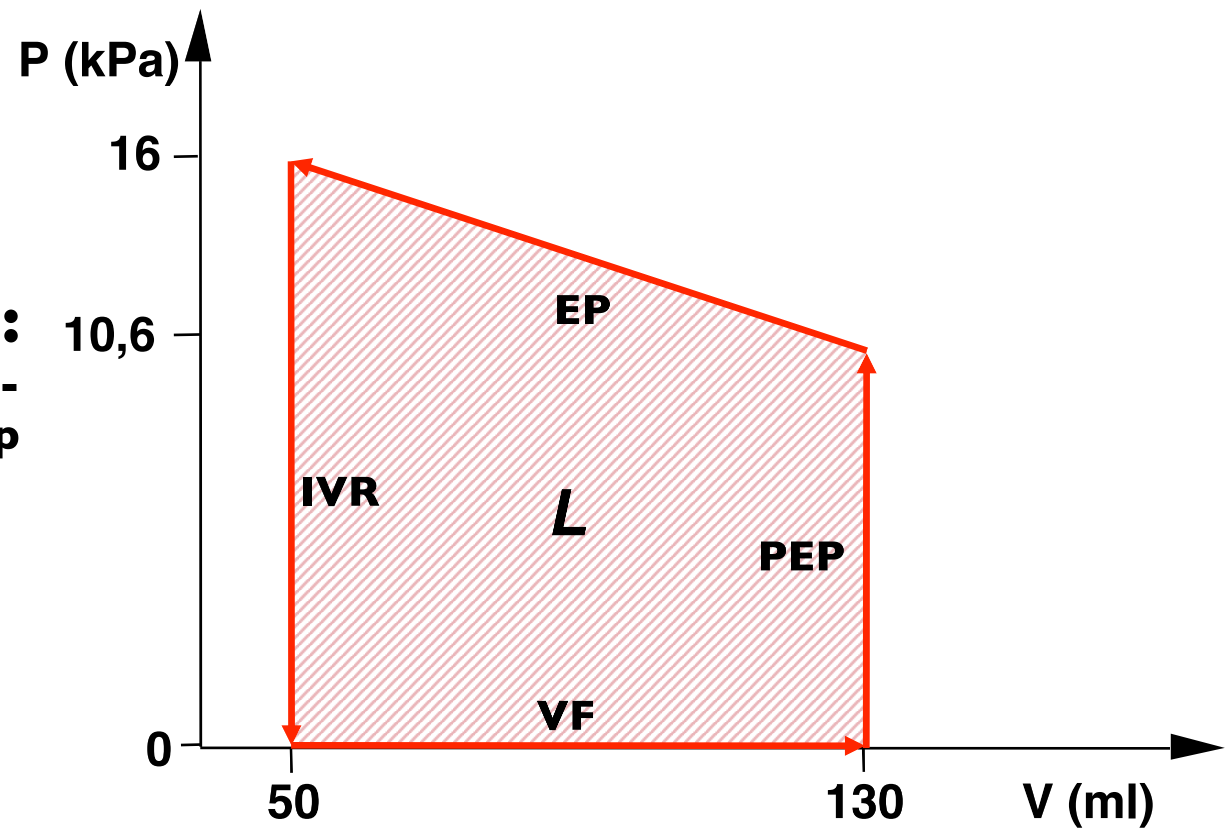
ESPVR: "end-systolic pressure-volume relationship" (determinants: contractility, aorta pressure - "afterload")

EDPVR: "end-diastolic pressure-volume relationship" (determinants: "passive" elasticity (titin), volume loading - "preload")

Work of the heart

(work of the left ventricle)

Indicator diagram:
Simplified pressure-volume relationship



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

pΔV=static (volumetric) component
1/2mv²=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

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