# Cardiovascular system:
## Biophysics of circulation
## Cardiac biophysics

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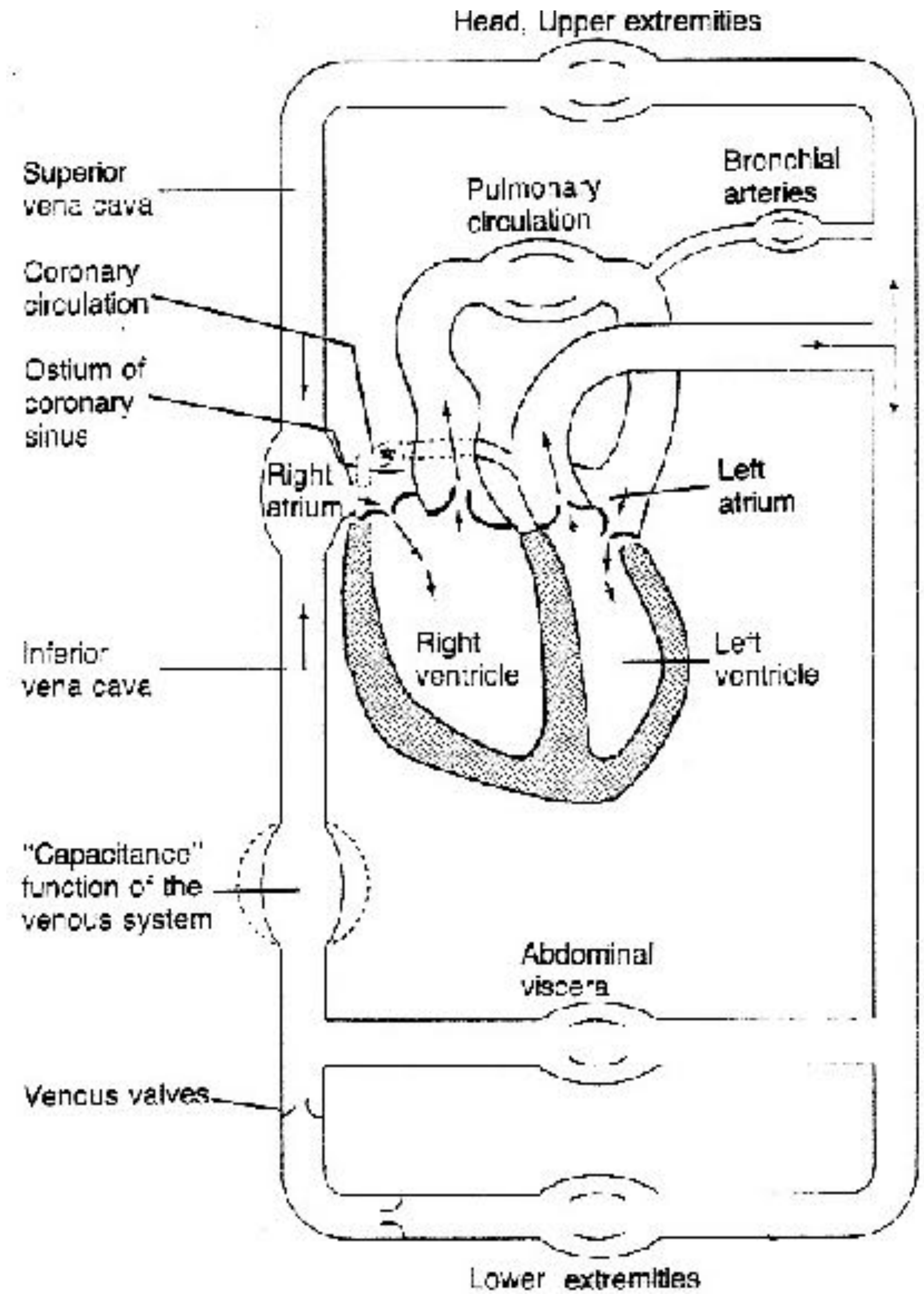
# The vascular system is a closed vessel system returning into itself

**A. Function:**

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

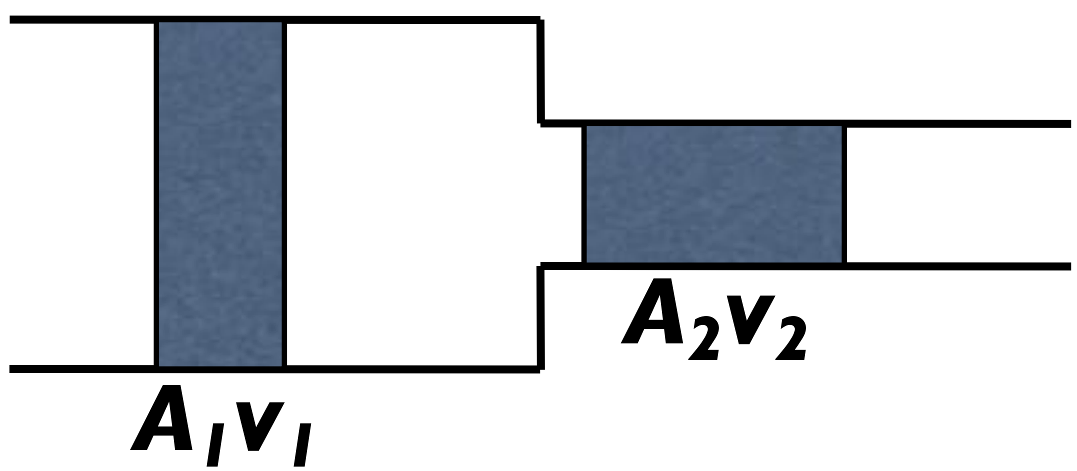
**B. Hemodynamic requirements:**

Slow (matches diffusion-driven processes)
Steady (no fluctuations)
Unidirectional



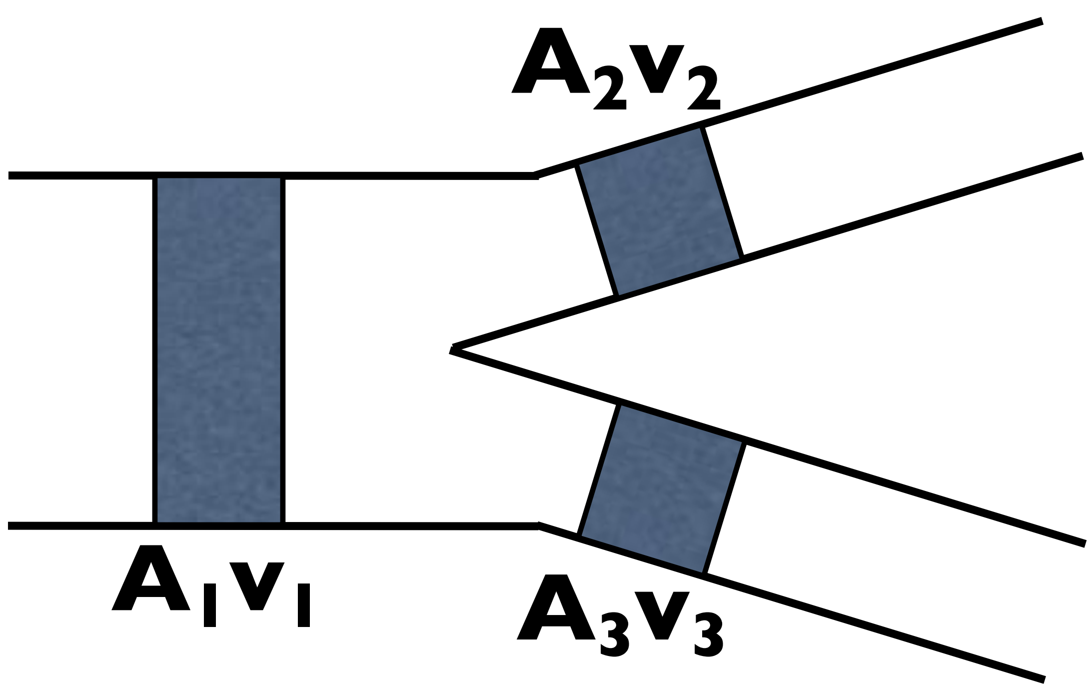
# Fluid flow in bifurcating vessel system

## Continuity equation




$$A_1 v_1 = A_2 v_2 = const$$

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




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

$A_\Sigma$ = 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*) | $J_E = -l \frac{\Delta T}{\Delta x}$ | Fourier |
| Volumetric flow | Pressure (*p*) | $J_V = -\frac{R^2}{8h} \frac{\Delta p}{\Delta x}$ | Hagen-Poiseuille |
| Electric current | Electric potential (φ) | $J_Q = -\frac{1}{r} \frac{\Delta j}{\Delta x}$ | Ohm |
| Material transport (diffusion) | Chemical potential (μ) | $J_n = -D \frac{\Delta c}{\Delta x}$ | Fick |

# Laws of flow in viscous fluids II.

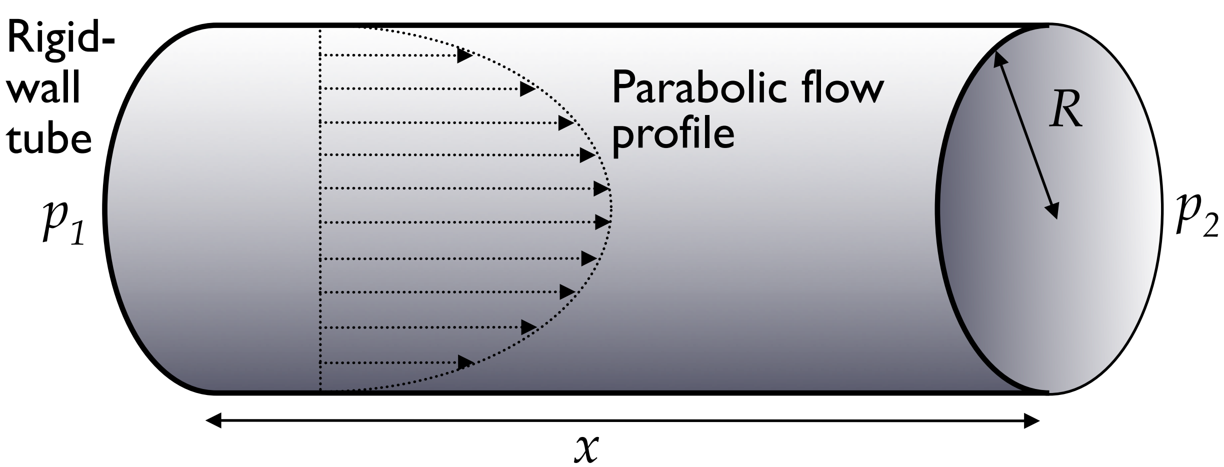
## Hagen-Poiseuille's law

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 |

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




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!

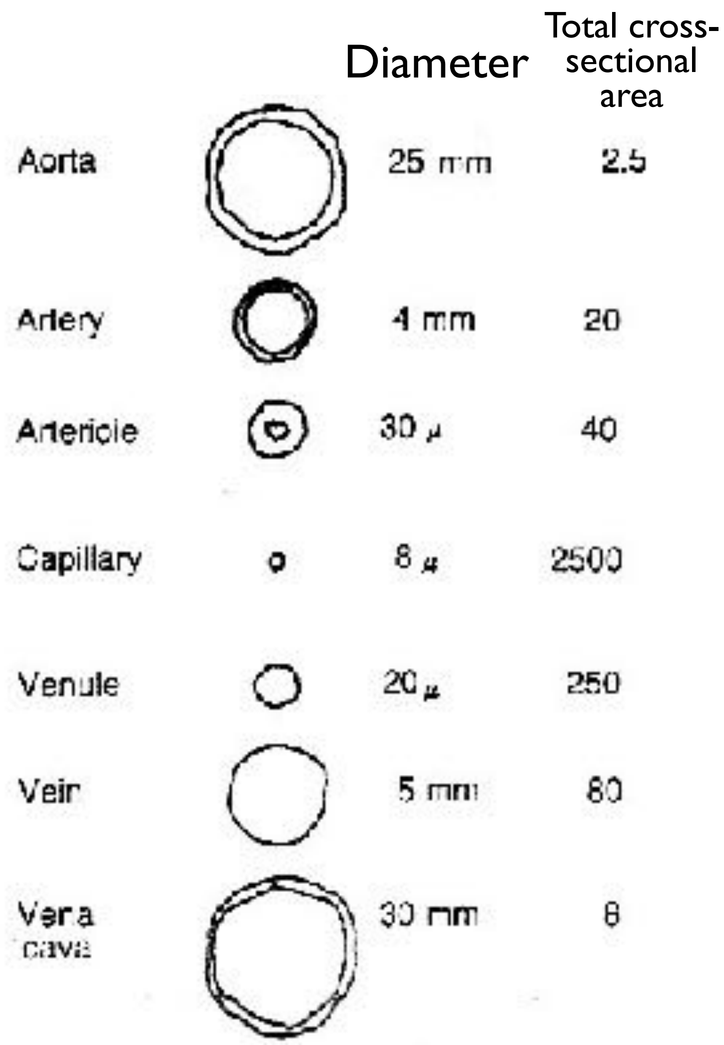
N.B. 3: $\frac{\Delta v}{\Delta r} \sim r \Rightarrow \left(\frac{\Delta v}{\Delta r}\right)_{max} = R \Rightarrow \tau_{max} = R$

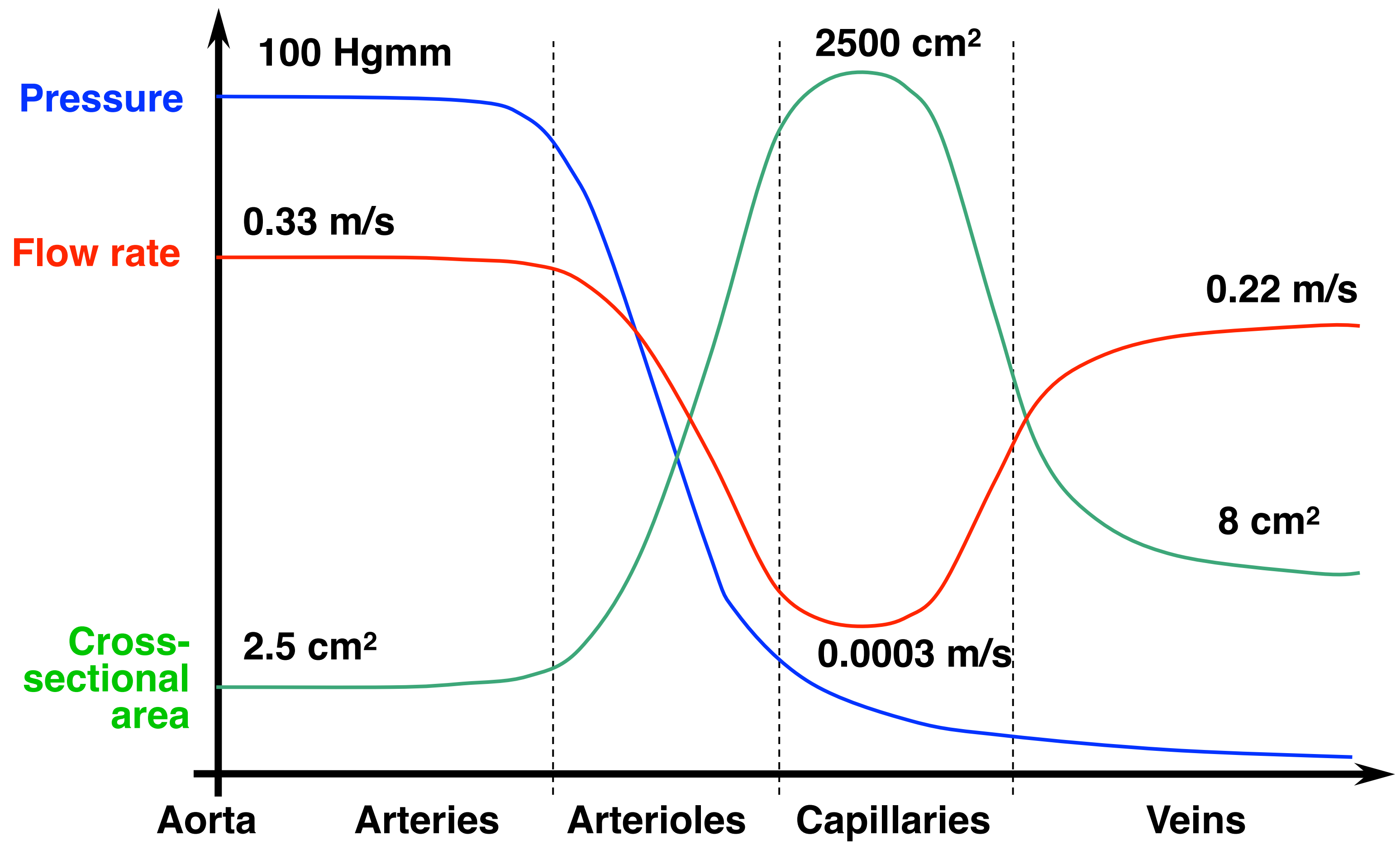
Shear stress is maximal at the tube wall because of the parabolic flow profile.

$V$ = volume
$t$ = time
$R$ = tube radius
$\eta$ = 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

# Structure and physical properties of the vascular system



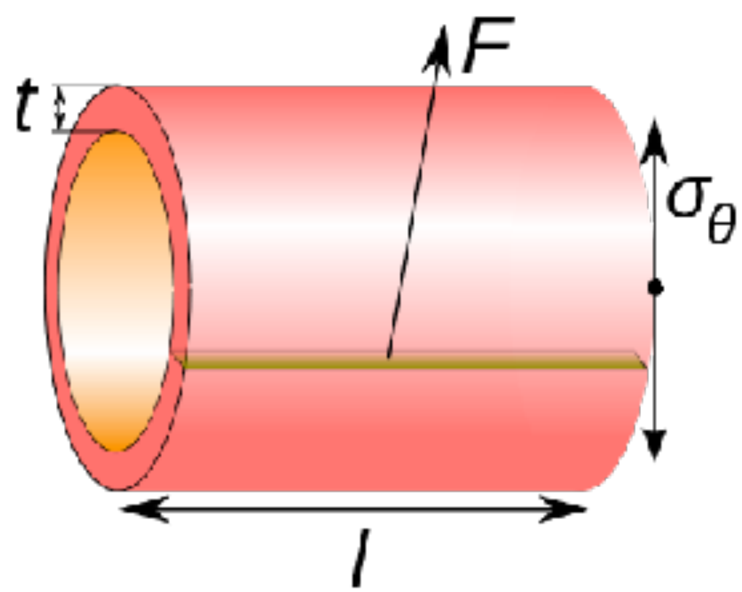

- **Pressure** on blood vessel wall: ***"blood pressure"***. Pressure drop along vessel maintains blood flow.
- Reason of **pressure drop**: flow resistance - most of energy is converted to heat.
- **Flow rate** and total **cross-sectional area** change inversely (based on equation of continuity, $Av$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

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

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

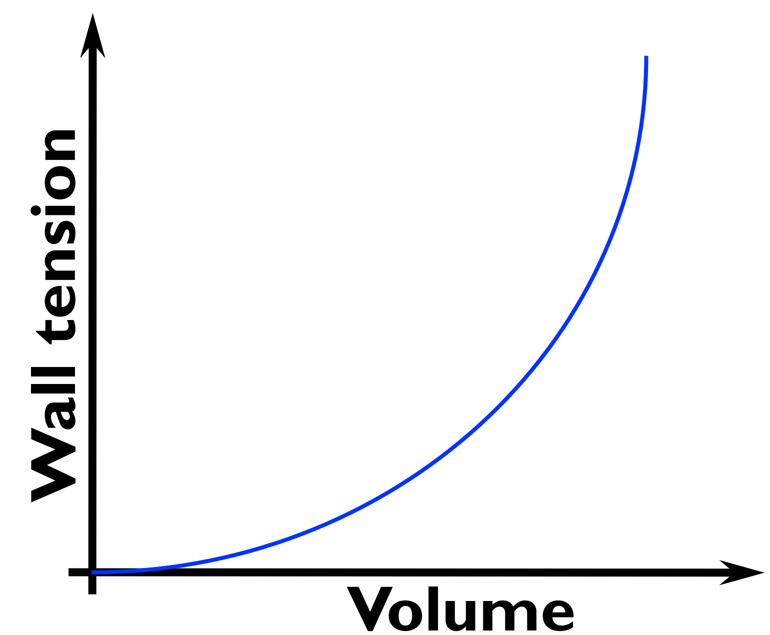



$$\sigma_\theta = \frac{F}{t \cdot l}$$

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:**

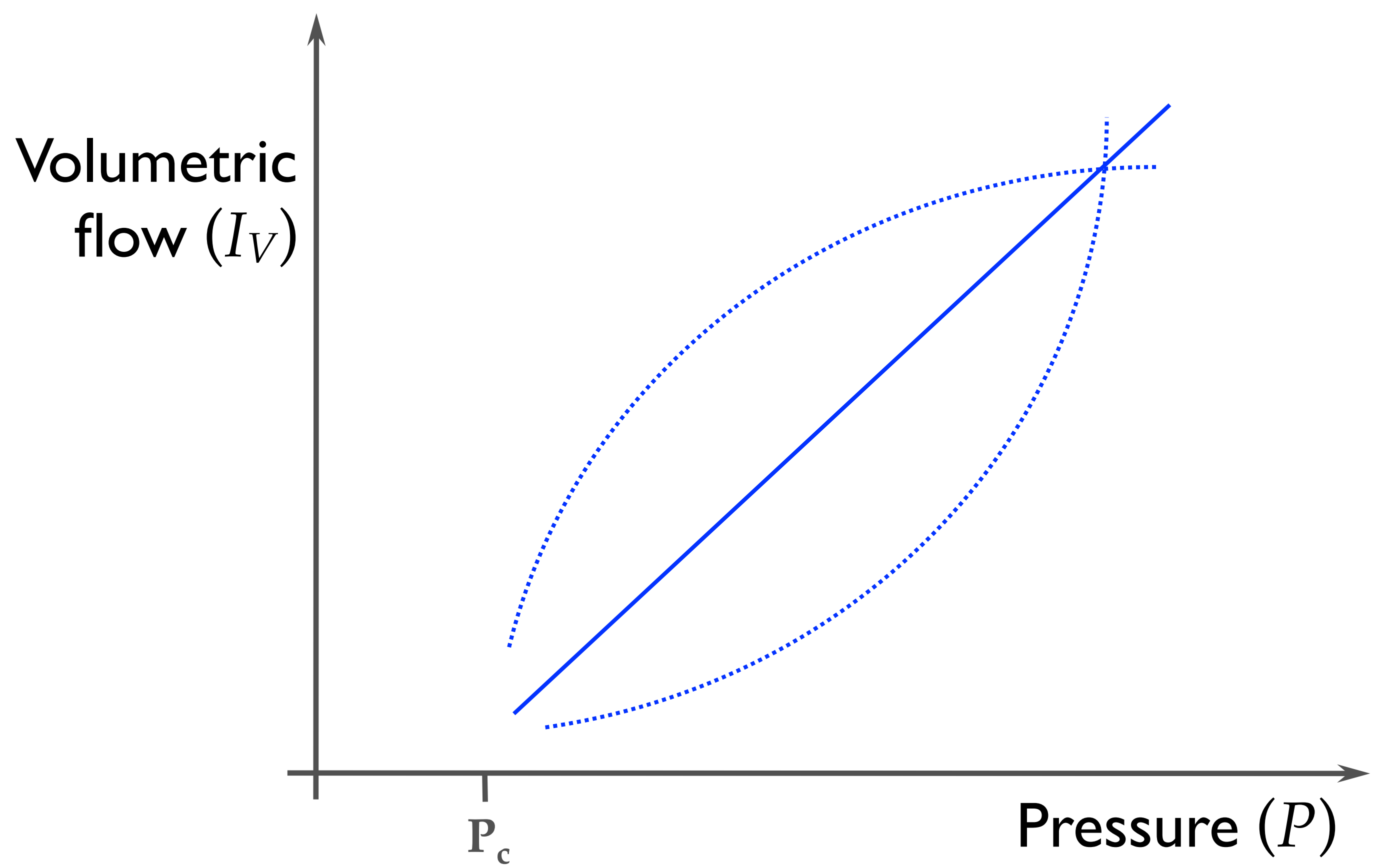
Elastin
Collagen
Smooth muscle

**Implications of vascular easticity:**

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

# Relationship between flow intesity and pressure

Below certain pressure vessels collapse and flow ceases



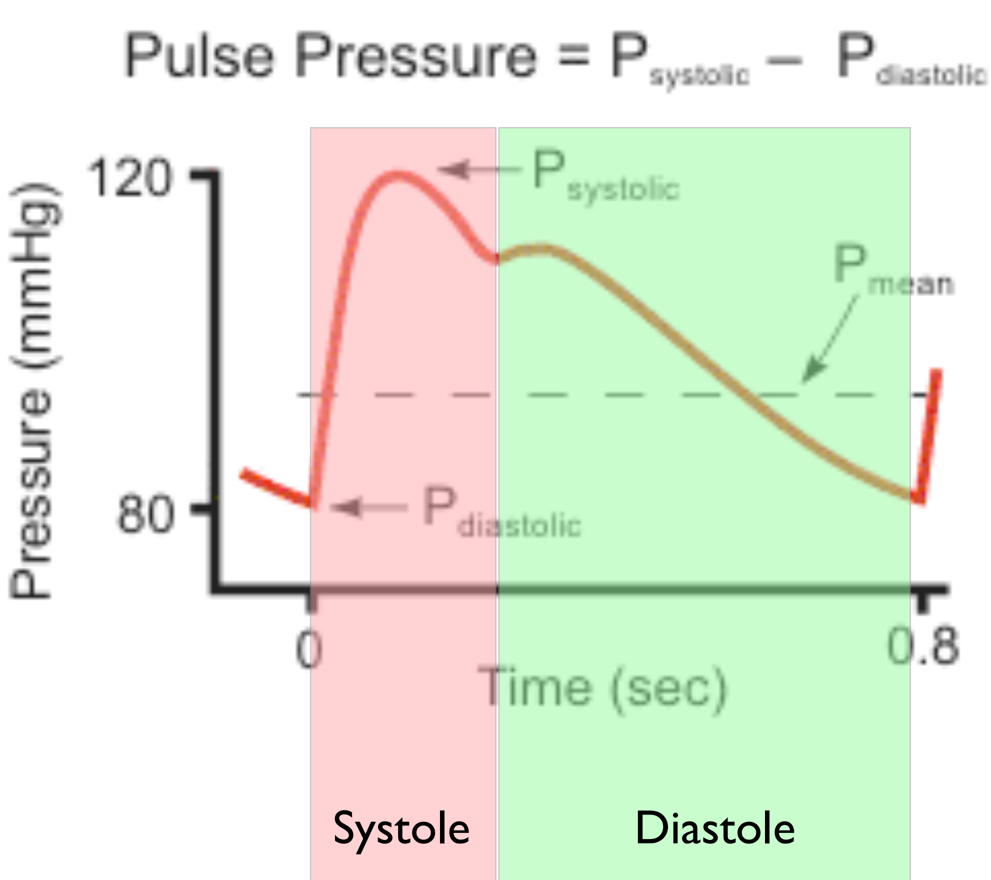

**N.B.:**

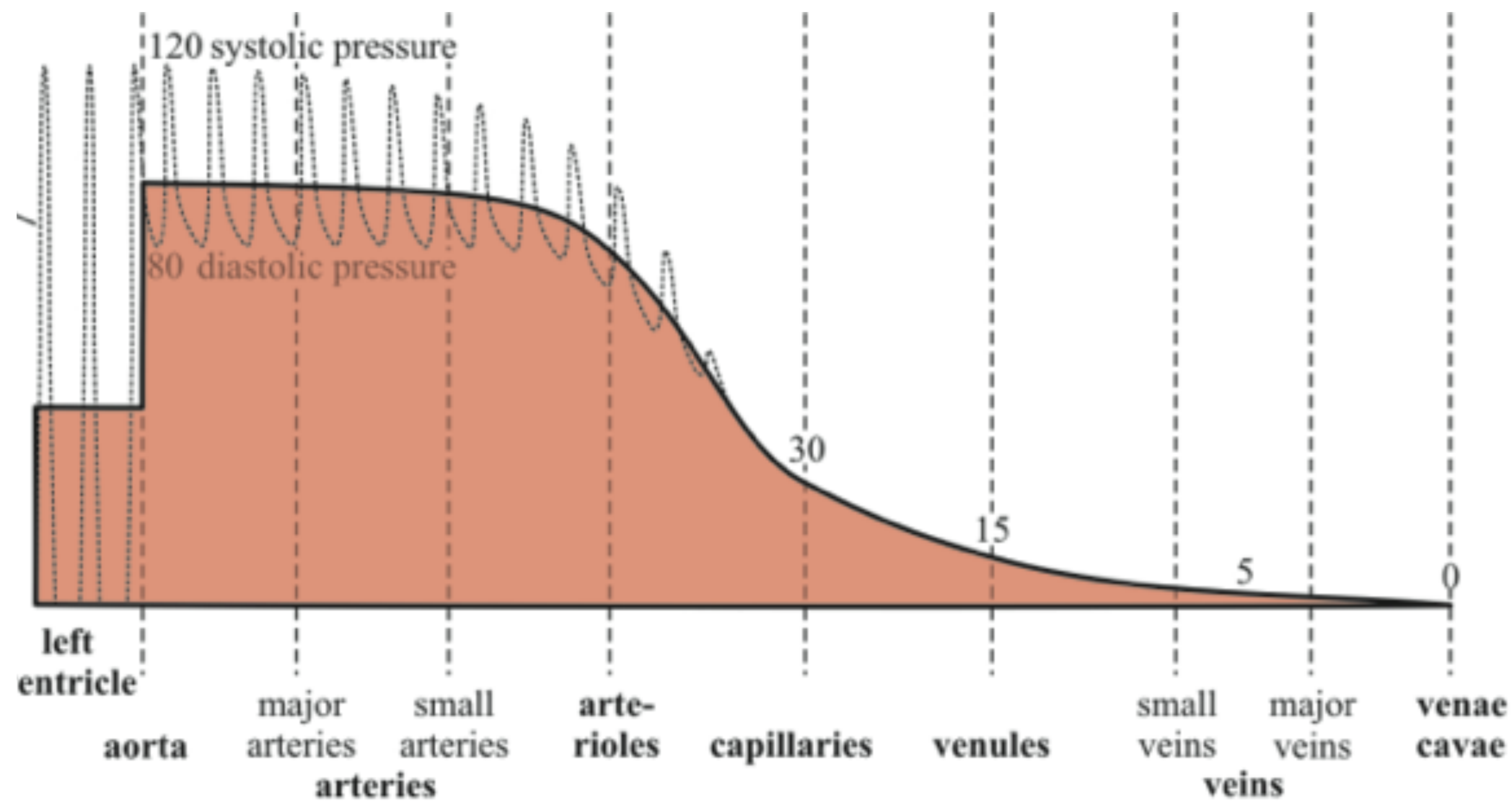
-The curves intersect the pressure axis at values greater than 0 (critical closing pressure, $P_c$).

-$P_c$ in arteries, at resting conditions, is ~20 Hgmm.

During blood pressure measurement we compress the limb by raising the cuff pressure above the local $P_c$.

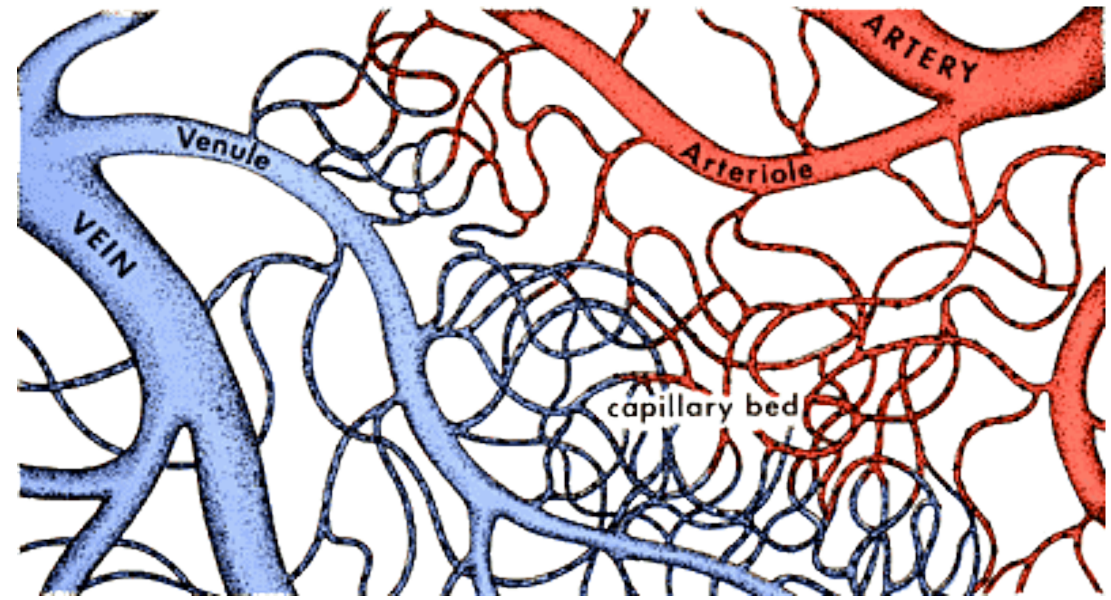
# Dynamic pressure-changes in the arterial system




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$^2$

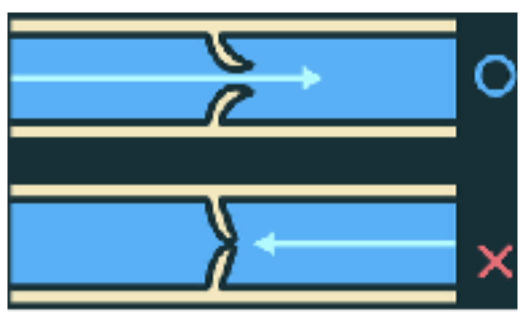
**3. Capillary fluid exchange**
fluid movement between bloof plasma and interstitium
driven by: difference in blood pressure and colloid osmotic pressure
Colloid osmotic (oncotic) pressure:
osmotic pressure caused by the presence of colloidal proteins (2.6 kPa)

| | **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 elasticity**
elastic fibers ➣ storage of potential energy

**2. Venous valves** (Harvey's experiment)
*"Exercitatio anatomica de motu cordis et sanguinis in animalibus" (1628)*

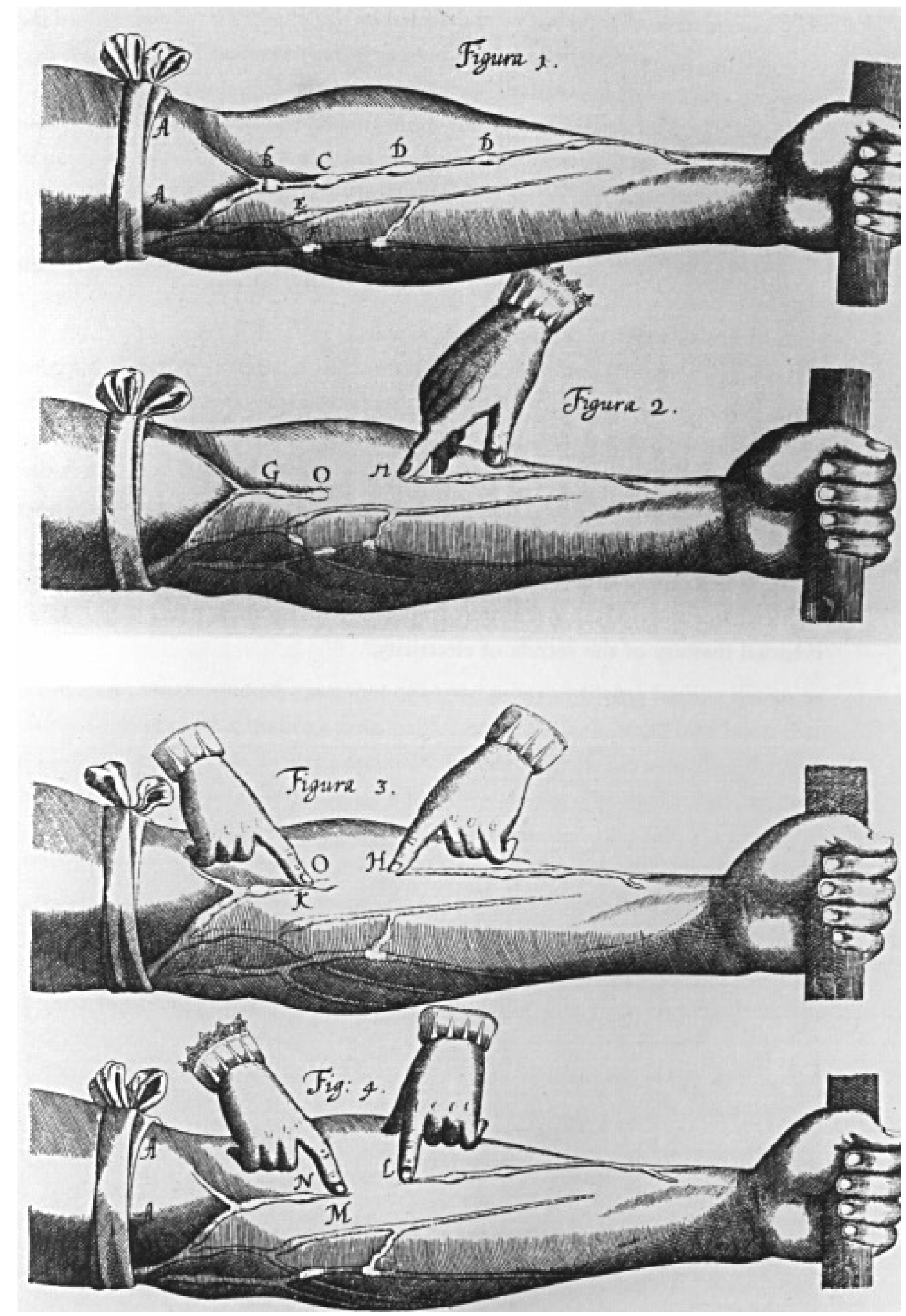


**3. Muscle action**

**4. Negative intrathoracic pressure**

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

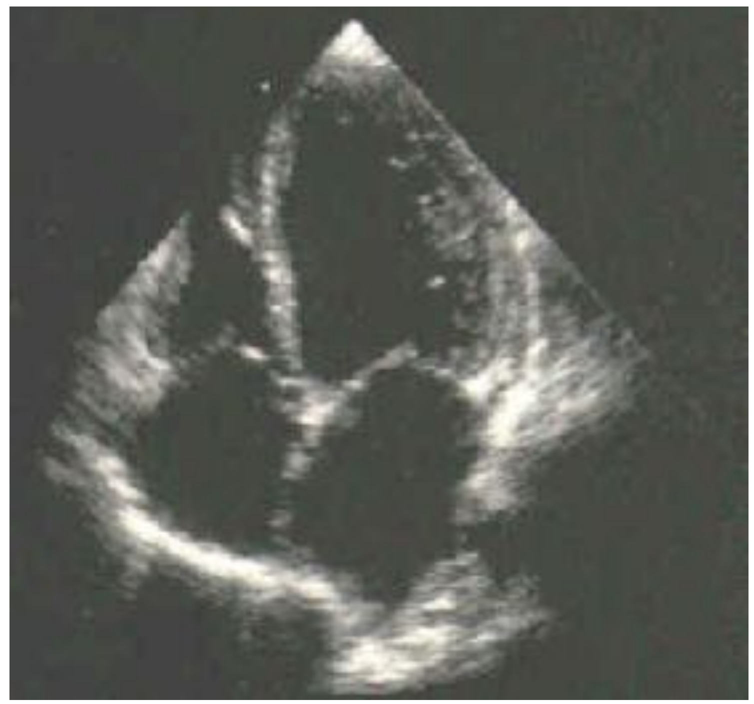
*Harvey's experiment (1628)*

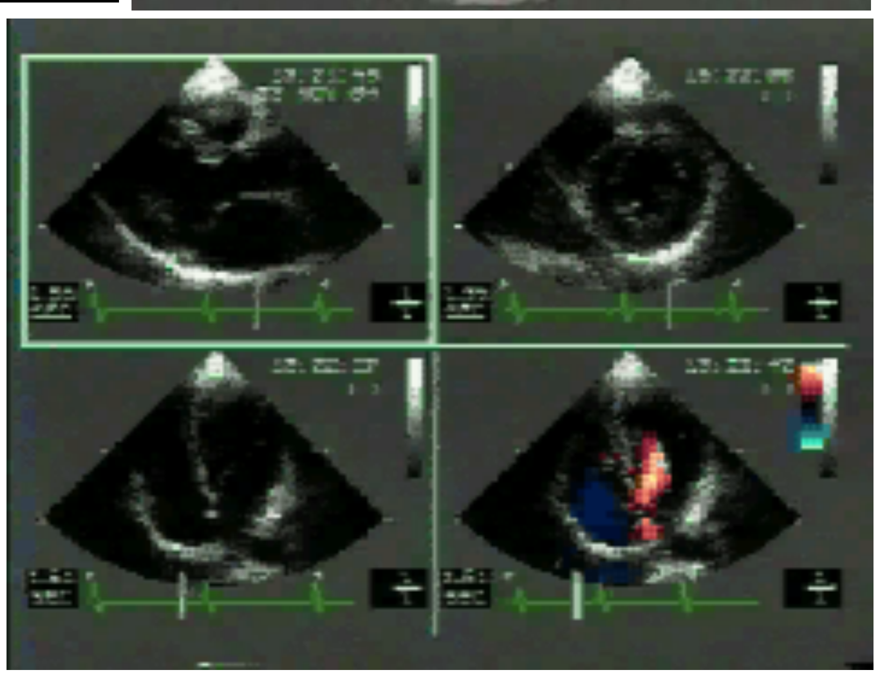


# Cardiac biophysics

# Heart:

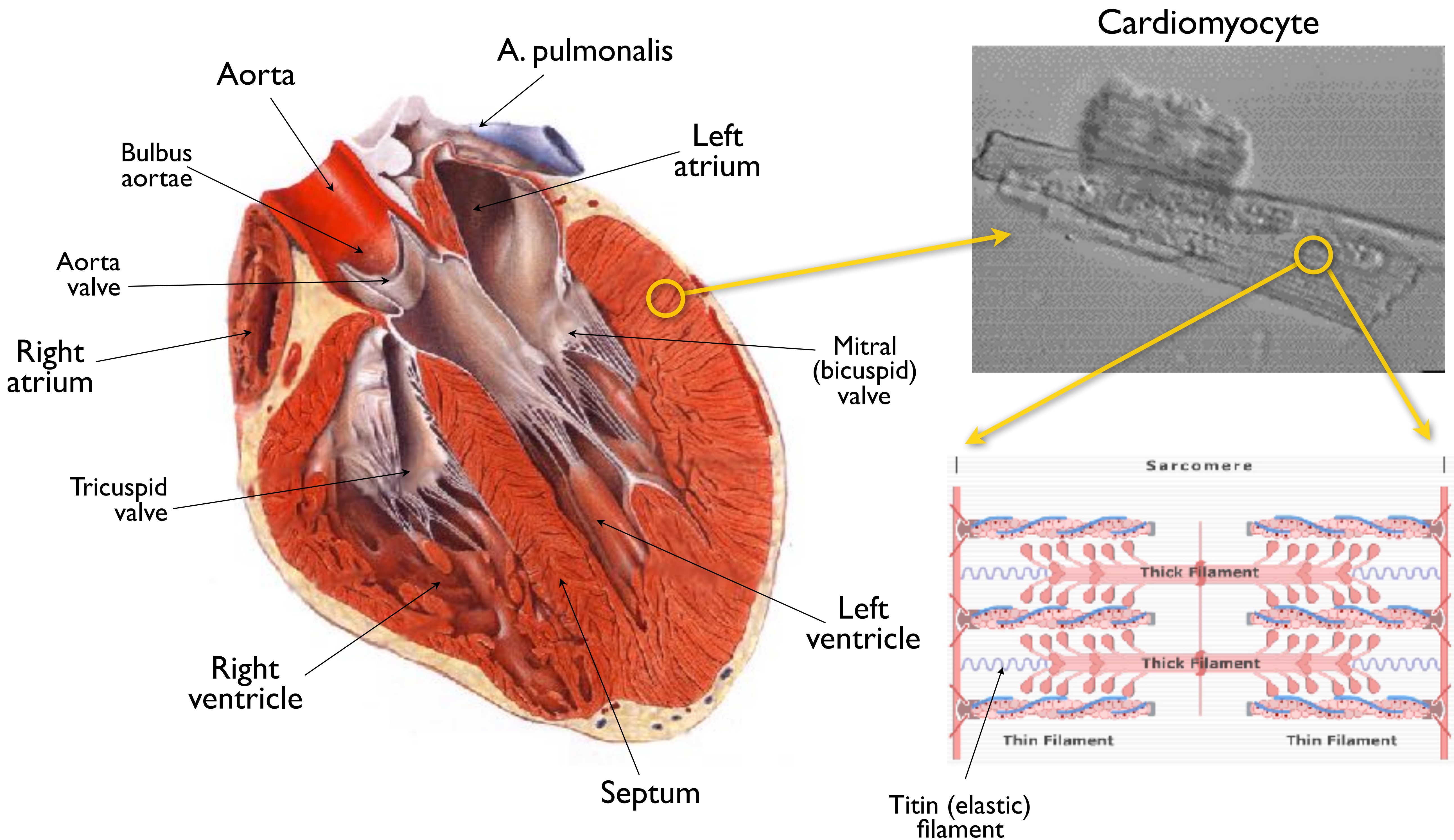
## Pump of the circulatory system



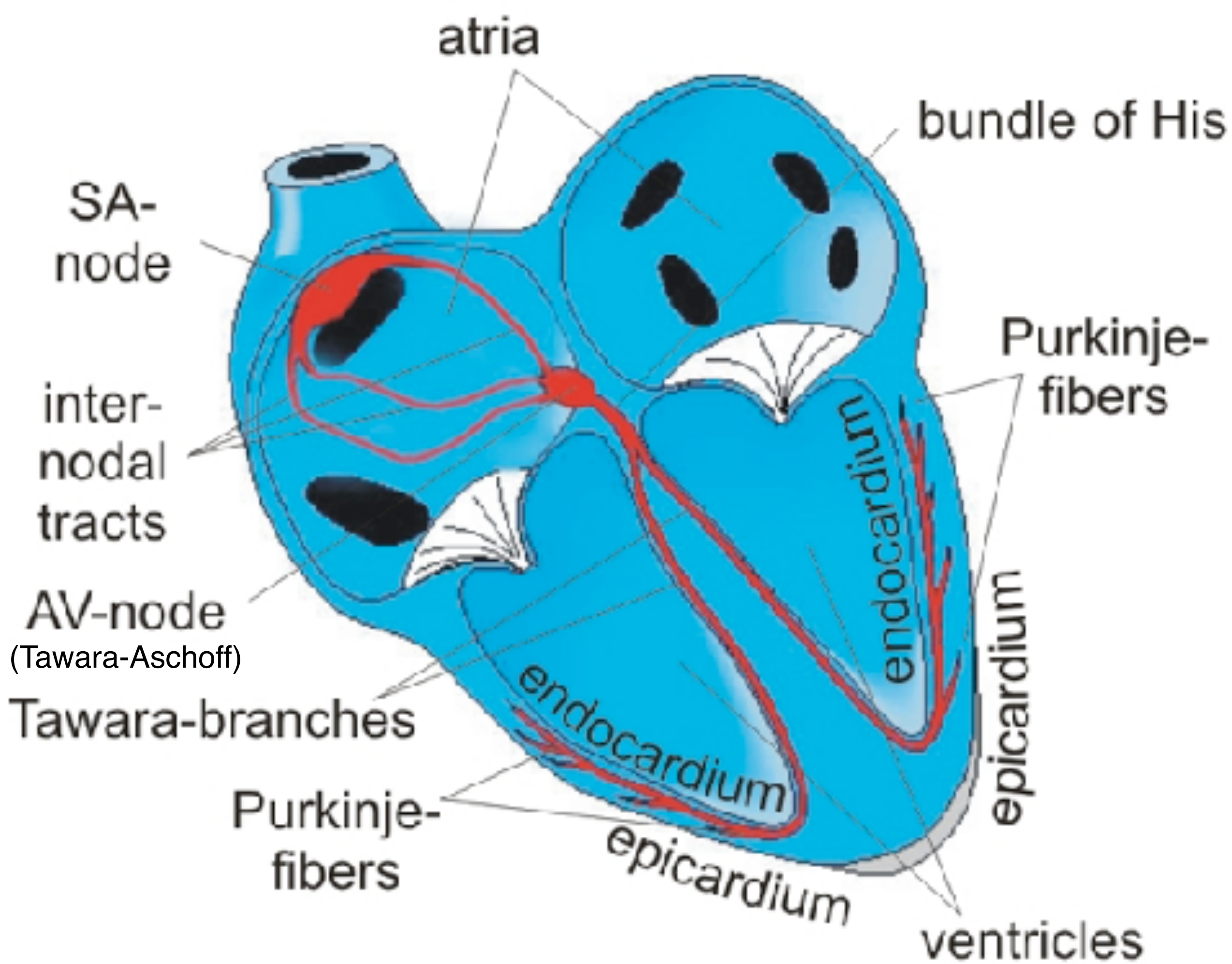


| | Number of contractions | Expelled blood volume |
|---|---|---|
| 1 min | ~70 | ~6 l |
| 1 day | ~100.000 | ~8600 l |
| Life (70 yrs) | ~2.5 x $10^9$ | ~220 x $10^6$ l |

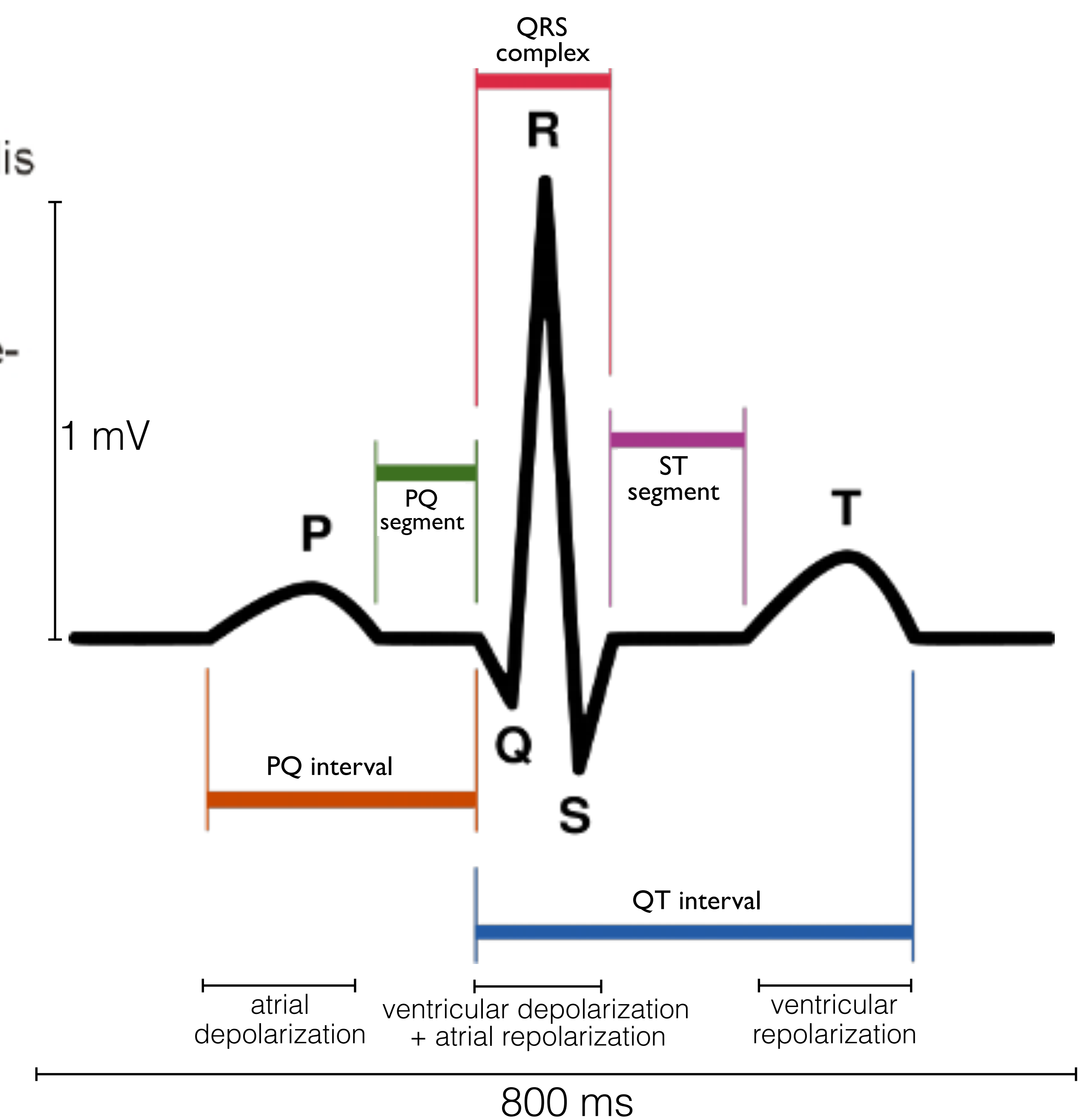
# Schematic structure of the human heart



# Activation of coordinated cardiac contractions

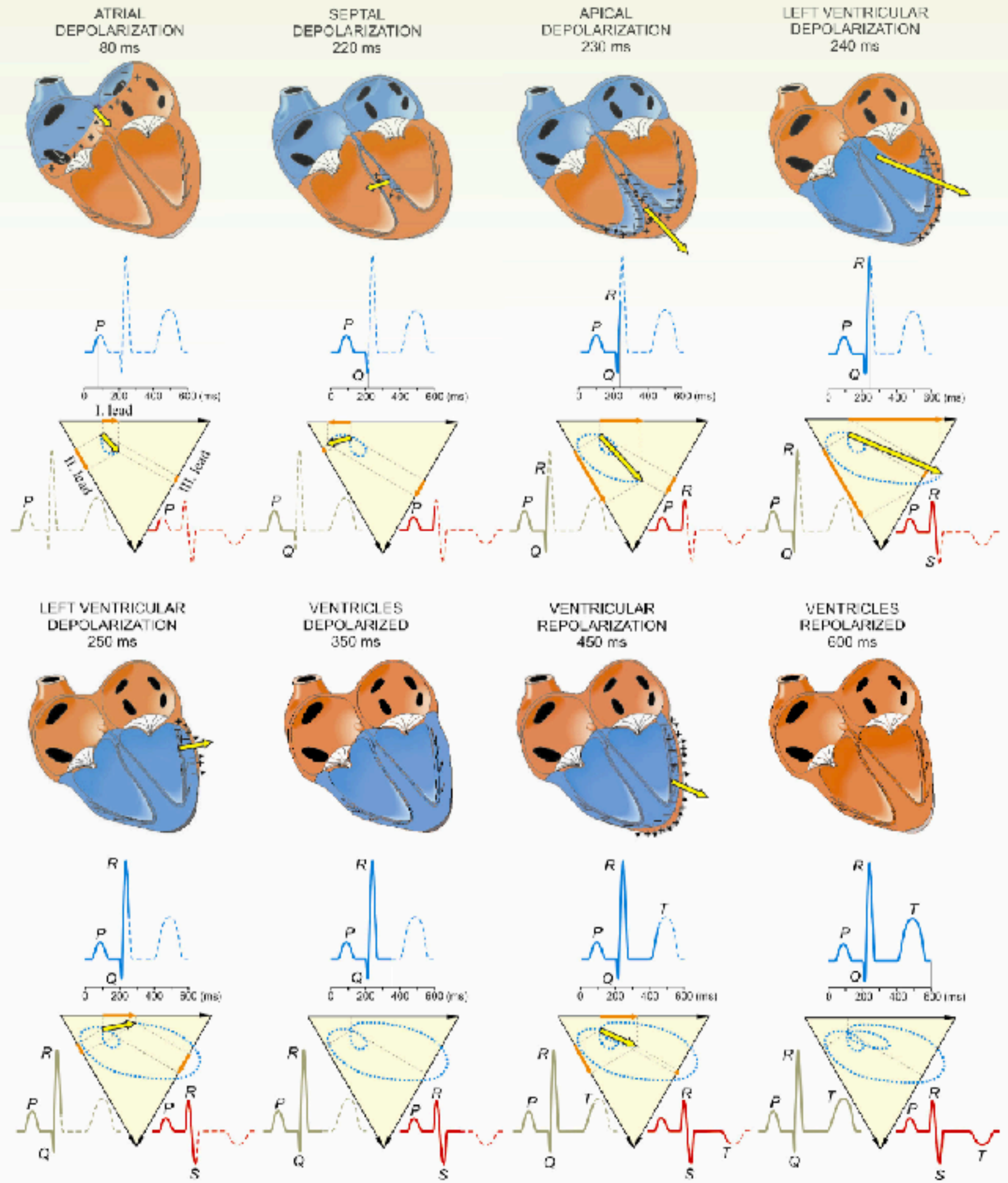



**Electrocardiogram (ECG)**



# EKG:

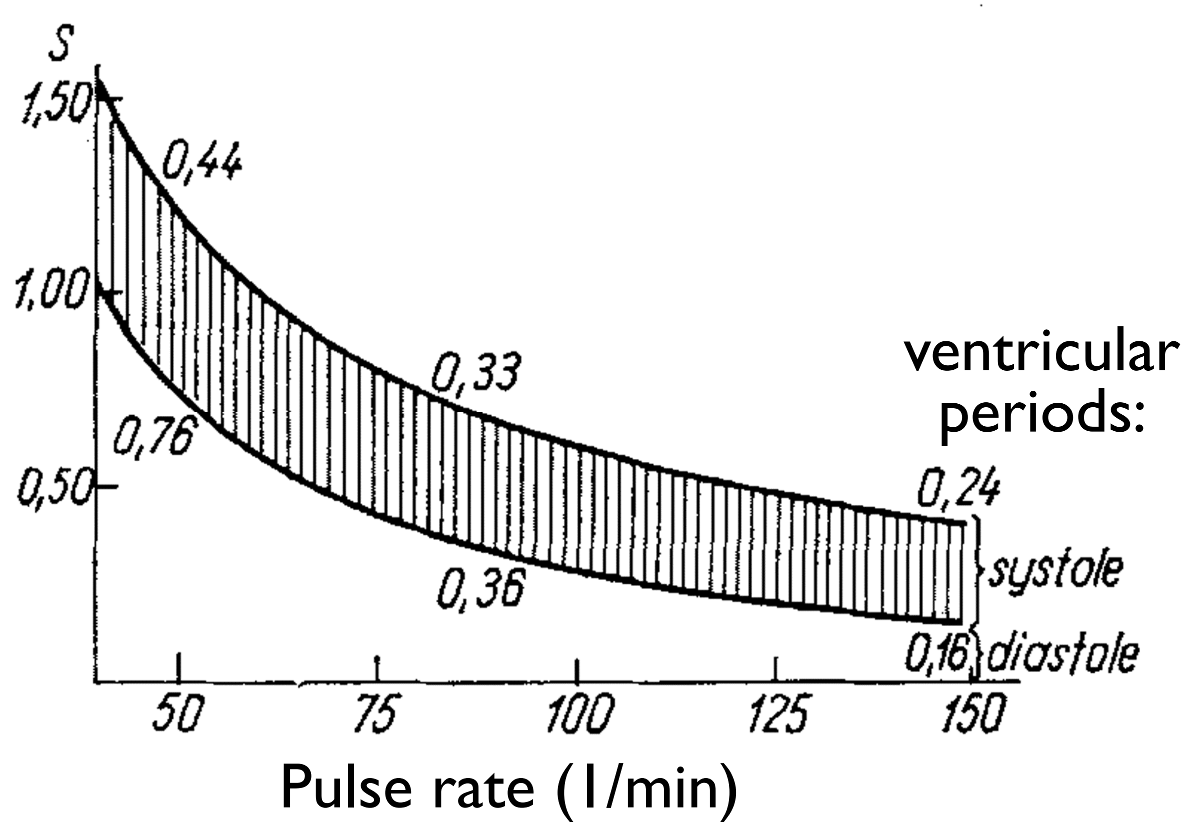
Vectorial projections (according to leads) of the resultant dipole (integral vector) that changes in time and space during myocardial depolarization and repolarization.



# The cardiac cycle

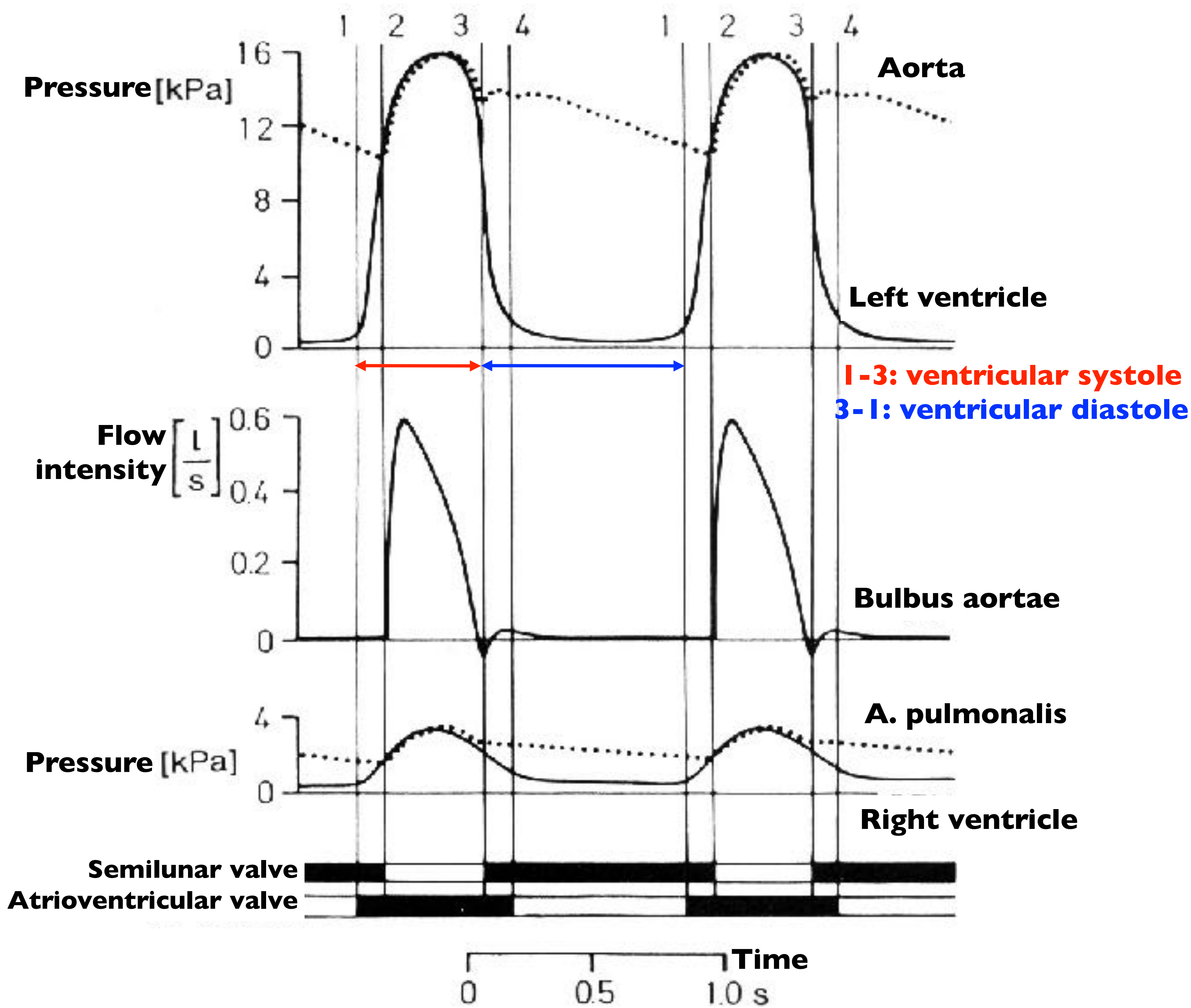
## Contraction (systole) - relaxation (diastole) cycle of the heart

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

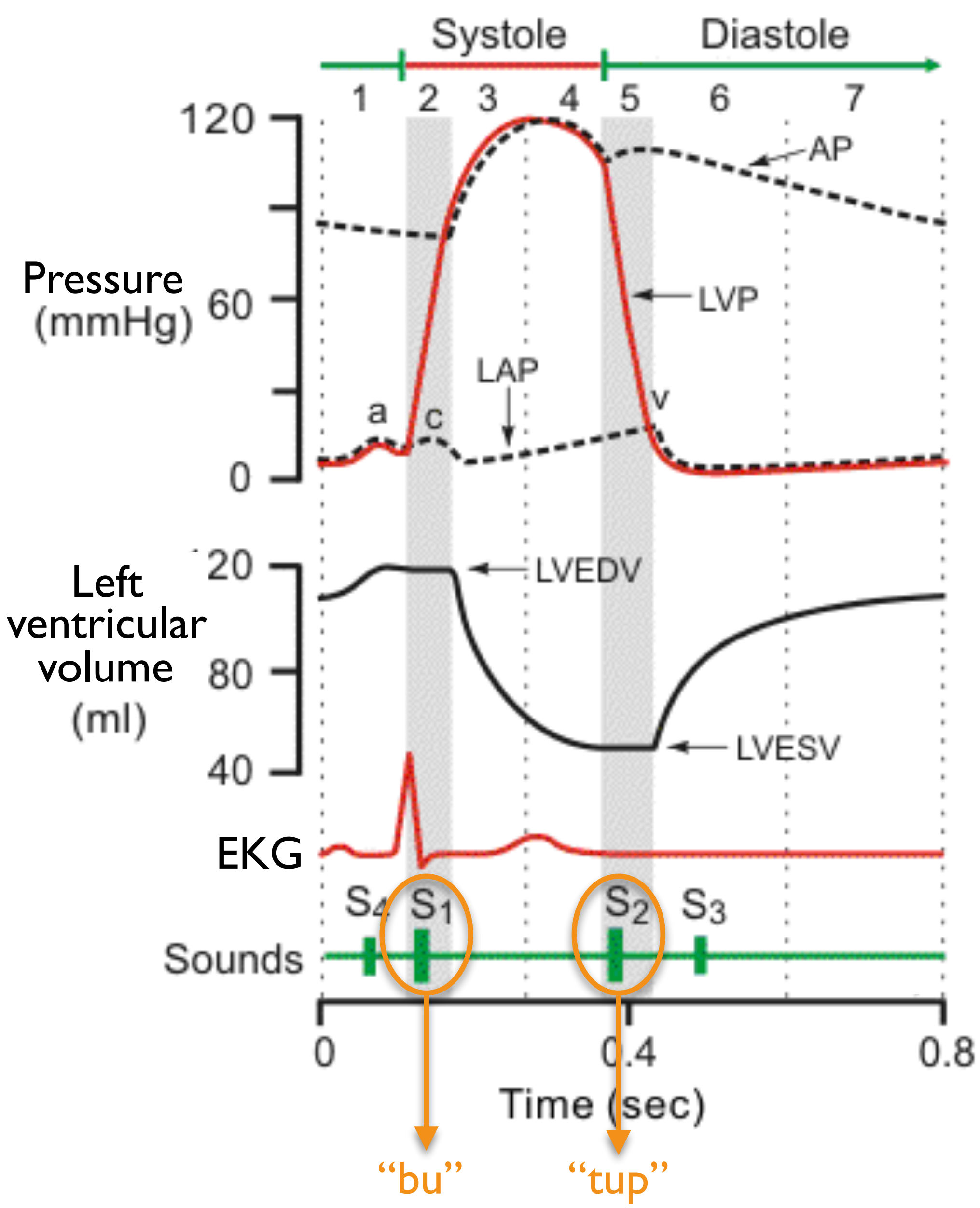


# Events of the cardiac cycle 1.

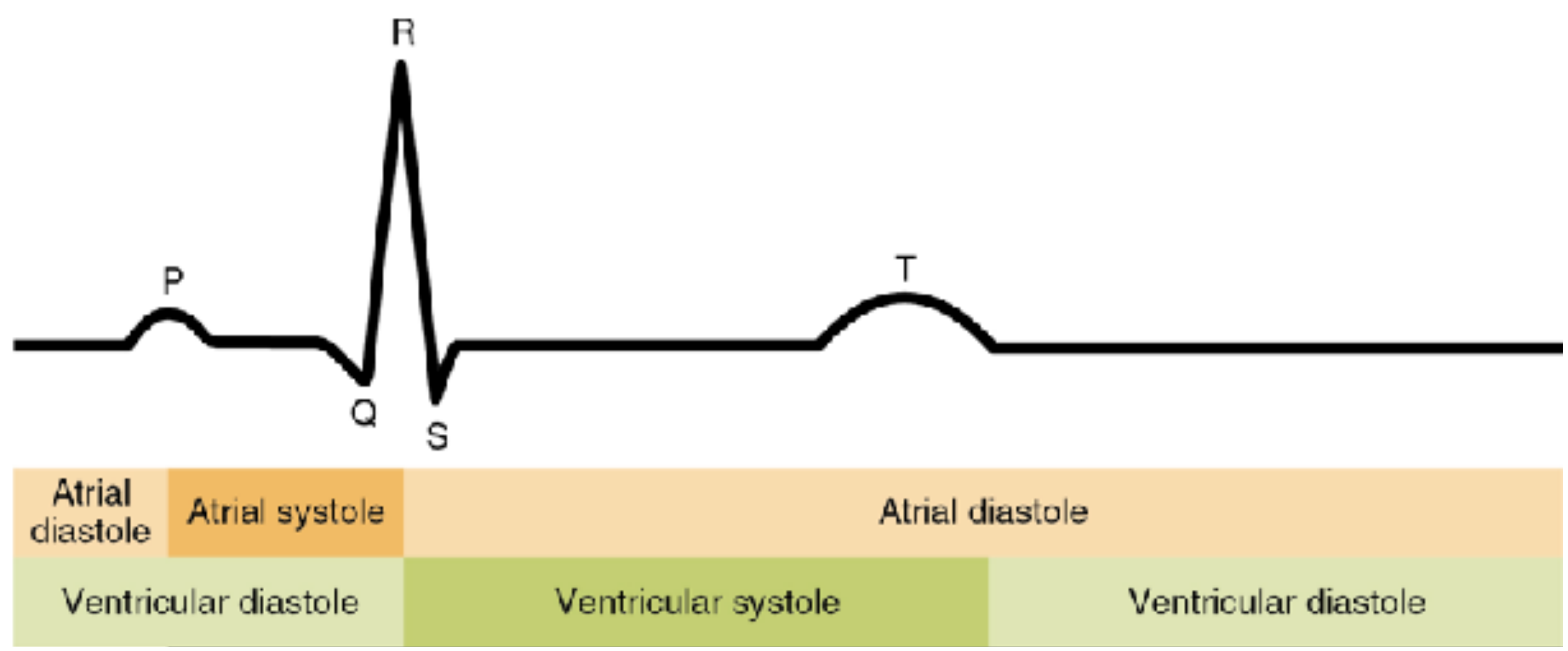
**1-2:** pre-ejection period (PEP) **2-3:** ejection period (EP) **3-4:** isovolumetric relaxation (IVR) **4-1:** ventricular filling (VF)



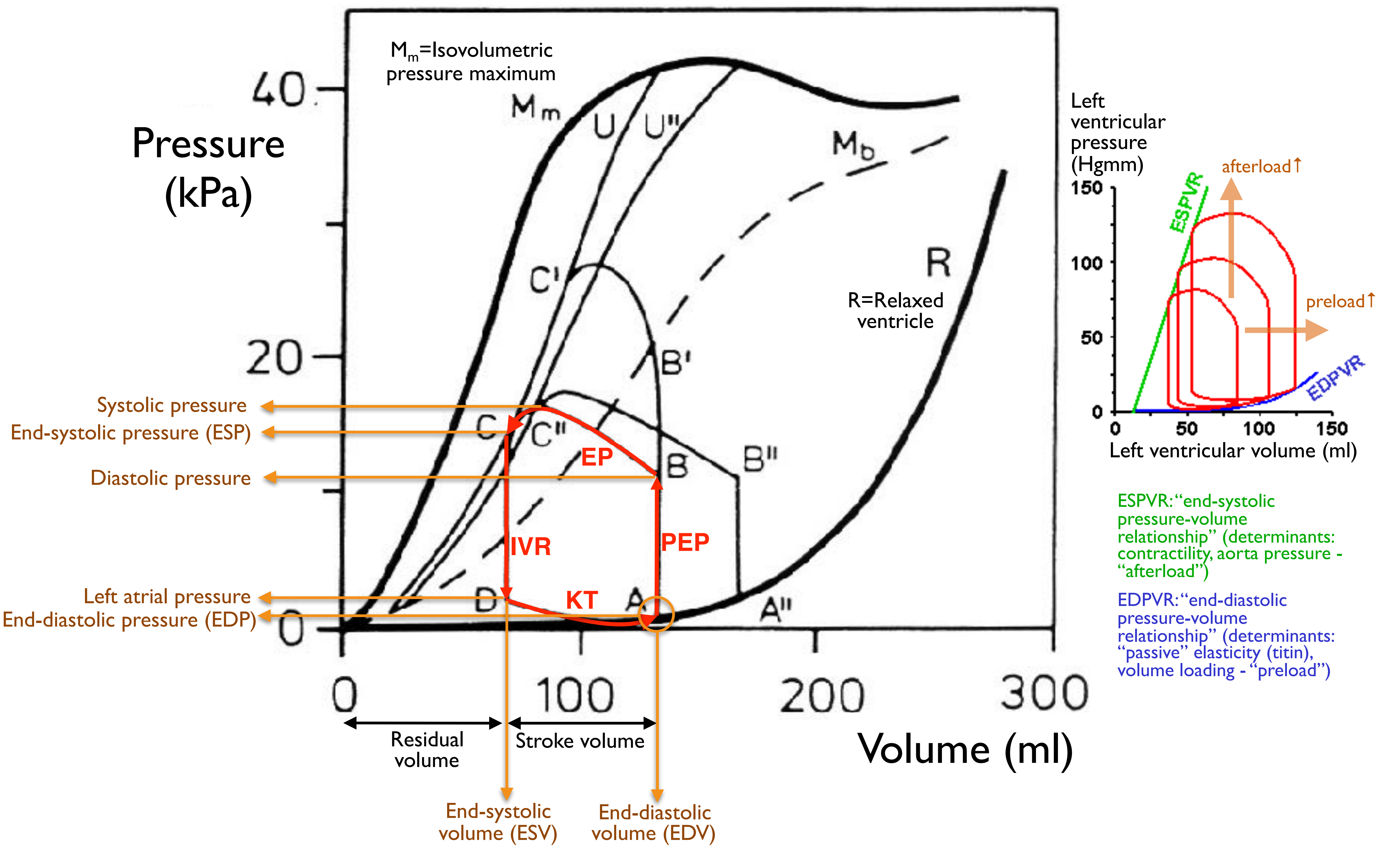
# Events of the cardiac cycle 2.




Electrokardiogram (ECG)



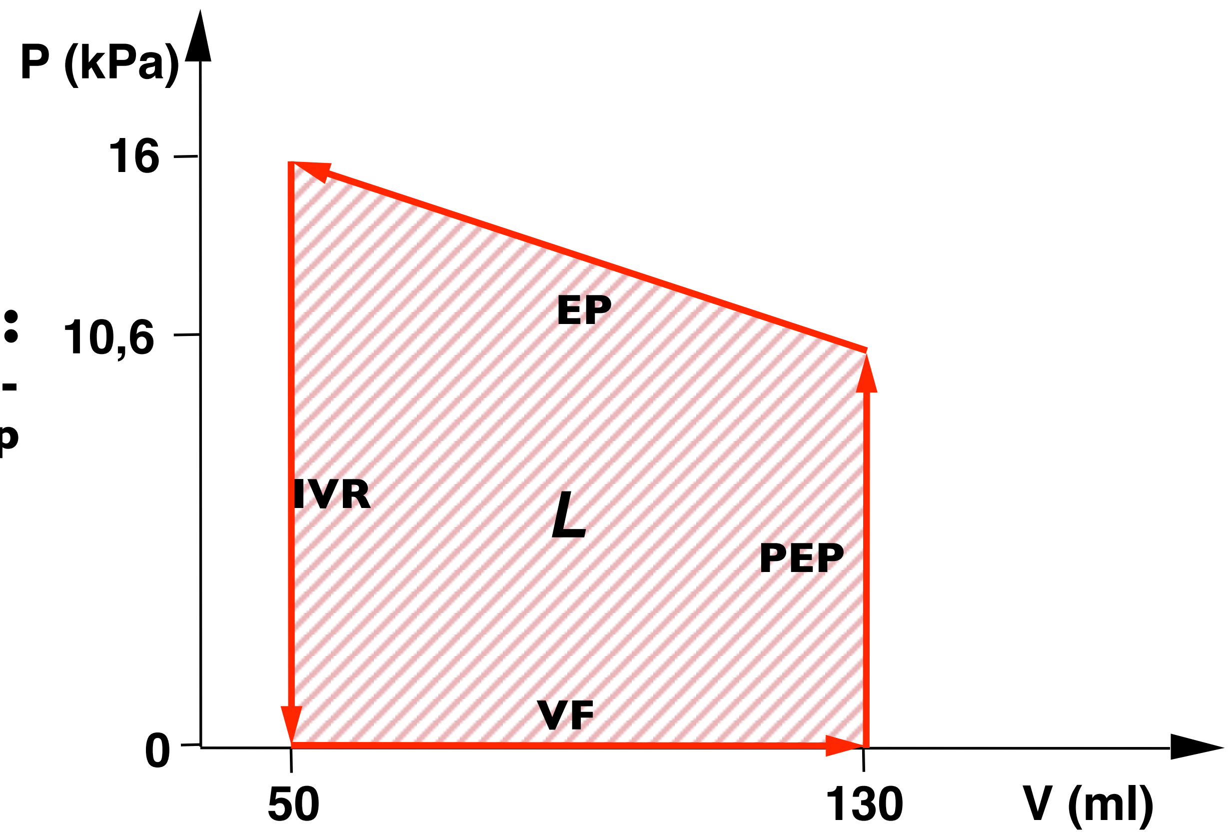
# Pressure-volume diagram of left ventricle



# 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
$1/2mv^2$=dynamic component
p=pressure
$\Delta V$=**stroke volume**

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