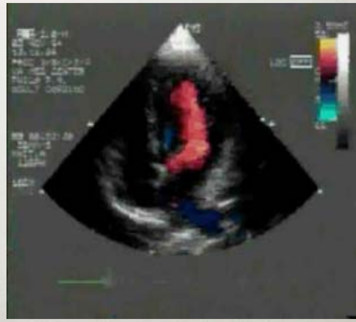
Biophysics of fluids, Blood flow and Heart function

Importance of the phsics of fluids

I. Hemodynamics

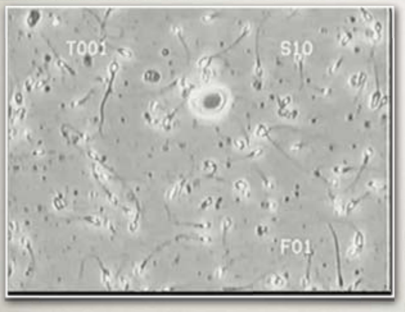
Characteristics of blood flow along the circulatory system.

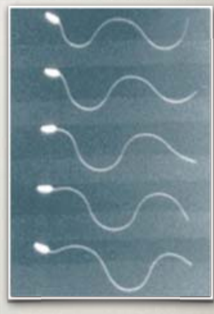


Significance of the physics of fluids

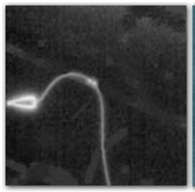
II. Motion in fuids

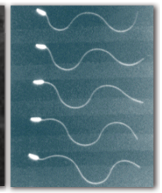
Force exerted by a single spermatocyte during its motion.



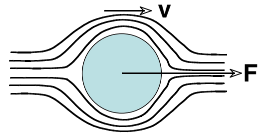


Drag coefficient of the spermatocyte





Stokes' Law:



$$\gamma = 6r\pi\eta = 6 \cdot 1.6\times10^{-6}(m) \cdot \pi \cdot 10^{-3}(Pas) = 3\times10^{-8} Ns/m$$

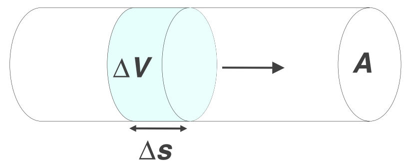
$$F = \gamma v = 3\times10^{-8} Ns/m \cdot 5\times10^{-5} m/s = 1.5\times10^{-12} N = 1.5\, pN$$

Biophysics of fluids

- Basic principles
- Types of fluids
- Types of fluid fow
- Laws of fluid flow
- Biomedical importance

Basic principles I.

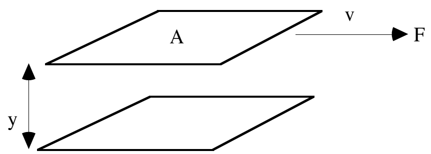
Volumetric flow rate (Q):

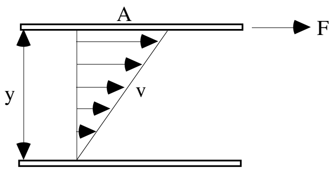


$$Q = \frac{\Delta V}{\Delta t} = A\frac{\Delta s}{\Delta t} = A\bar{v}$$

Average velocity: $\bar{v} = \frac{Q}{A}$

Basic principles II. Viscosity (internal friction)





F =shear force
A =area of fluid layer
η =viscosity
v =flow velocity
y =distance between fluid layers

F/A =shear stress (τ)
Δv/Δy =velocity gradient (D)

$$\frac{F}{A} = \eta\frac{\Delta v}{\Delta y}$$

$$\eta = \frac{\tau}{D}$$

Units of viscosity: $1Pas = 1\frac{Ns}{m^2} = 10P(poise)$

Types of fuids I.

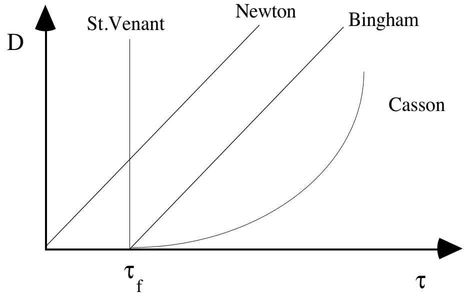
1. **Ideal**
   frictionless, uncompressible
   ϱ=constant, η=0

2. **Non-ideal (real)**
   a. Newtonian (viscous)
   η independent of shear stress

   b. Non-newtoni (anomalous)
   η varies with shear stress

Types of fluids II.

Relationship between velocity gradient and shear stress in real fluids



τ_f=flow threshold

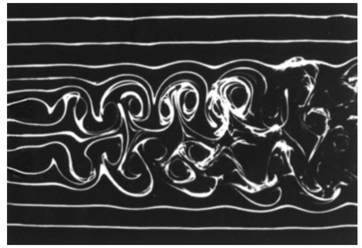
Viscoelastic materials: combination of elastic and viscous properties (e.g., polymer solutions)

Stress-relaxation: decay of shear stress in viscoelastic material following sudden stretch.

NB: Blood is non-newtonian fluid!

Types of fluid flow

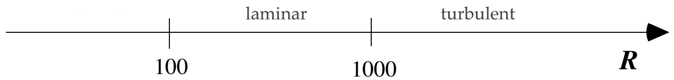
1. **Stationary**
   Flow intensity stays constant.
2. **Laminar**
   Fluid layers do dot mix.
3. **Turbulent**
   Fluid layers mix.



Reynolds number:

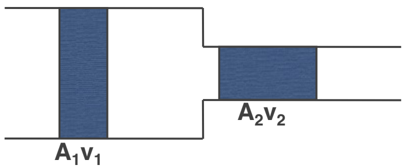
$$R = \frac{vr\rho}{\eta}$$

v=flow rate (m/s)
r=tube radius (m)
ϱ=density of fluid (kg/m³)
η=viscosity (Ns/m²)



Laws of flow in ideal fluids I.

Continuity equation



$$A_1v_1 = A_2v_2 = konst$$

A=cross-sectional area
v=flow rate

Laws of flow in ideal fluids II.

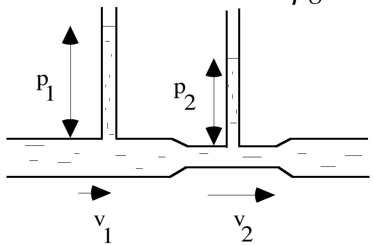
Bernoulli's law

$$p + \frac{1}{2}\rho v^2 + \rho gh = konst$$

p=static pressure

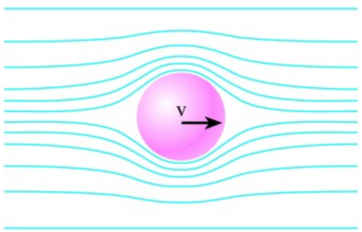
$\frac{1}{2}\rho v^2$ = dynamic pressure

ρgh = hydrostatic pressure



Laws of flow in viscous fluids I.

Stokes' law

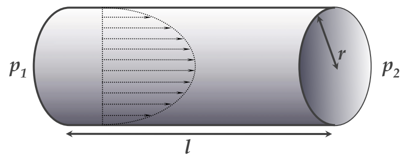


$$F = \gamma v = 6r\pi\eta v$$

F = force
γ = drag coefficient (shape factor)
v = flow rate
r = radius of sphere
η = viscosity

Laws of flow in viscous fluids II.

Hagen-Poiseuille's law

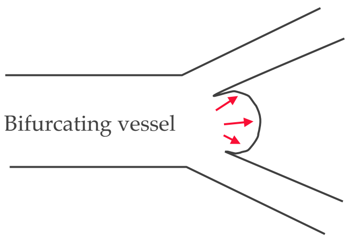


$$\frac{V}{t} = \frac{\pi r^4}{8\eta}\frac{dp}{dl}$$

V=volume
t=time
(V/t=Q = flow intensity)
r=tube radius
η=viscosity
p=pressure
l=length of tube
(dp/dl=pressure gradient, maintained by p_1-p_2)

Biomedical significance

Bernoulli's law:



aneurysm:
➡ flow rate decreases (accoring to continuity equation)
➡ pressure increases
➡ aneurysm increases

Hagen-Poiseuille's law:

$$\frac{V}{t} = \frac{\pi r^4}{8\eta}\frac{dp}{dl}$$

Flow intensity may be **drastically reduced** in certain pathological conditions:

-constriction of blood vessels
(e.g., diabetes, Bürger's disease)

-change in blood viscosity
(e.g., fever, anaemia)

BIOPHYSICS OF BLOOD FLOW

1. Blood as fluid
2. Determinants of blood viscosity
3. The vascular system
4. Blood vessels as elastic tubes
5. Auxiliary forces of circulation

BLOOD AS FLUID

55-60% of body mass is water 42 kg (70 kg body mass)		
2/3 intracellular 28 kg	1/3 extracellular 14 kg	
	1/3 plasma 4-5 kg	2/3 intersticium 9-10 kg

Blood

Average volume: 5 l
Average viscosity: 5 mPas
Average density: 1.05 g/cm³
Composition: 40-45 % corpuscular, 55-60 % plasma

Determinants of blood viscosity I.

1. Hematocrit (htc, ϕ):

$$htc = \frac{V_{cells}}{V_{total}}$$

Normal range: 0.4-0.5.

Viscosity of blood as suspension
(in the physiologically relevant htc range):

$$\lg \eta_s = A + B\phi$$

η_s=suspension viscosity
A, B=empirical constants

Determinants of blood viscosity II.

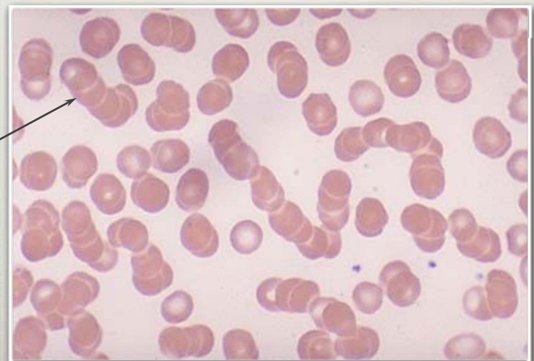
2. Plasma viscosity
Depends on plasma proteins.
In paraproteinaemias (e.g. myeloma multiplex or plasmocytoma) the concentration of immunoglobulins is high, leading to increased viscosity.

3. Plasticity of red blood cells
65% suspension of blood-cell-size particles is rock hard.
In contrast, a 95% blood suspension if fluid, with viscosity of ~20 mPas!
Deformation of red blood cells: droplet, parachute, arrowhead shapes.

Determinants of blood viscosity III.

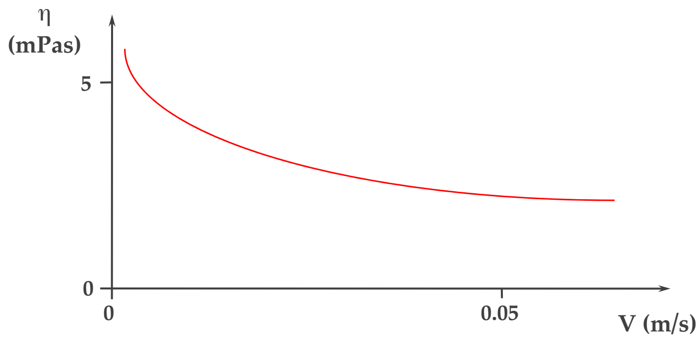
4. Aggregation of red blood cells
Stack or roleaux formation.
More pronounced at low flow rates.

Roleaux



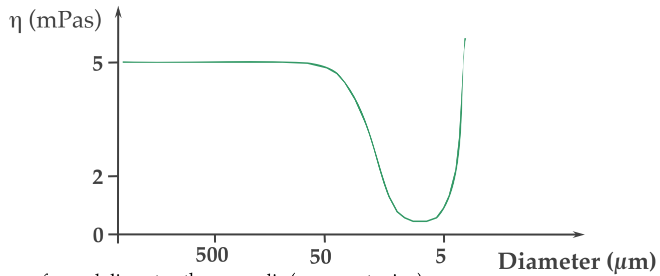
Determinants of blood viscosity IV.

5. Flow rate, velocity gradient



Determinants of blood viscosity V.

6. Blood vessel diameter



N.B.:
-With a decrease of vessel diameter, the anomalic (non-newtonian) behavior of blood becomes more pronounced.
-*Axial migration*:
the red blood cells line up in the axis of the vessel.
In the axis the velocity gradient decreases,
and near the vessel wall it increases.
Increase in velocity gradient decreases apparent viscosity (Fåhraeus-Lindquist effect).

CIRCULATORY SYSTEM

A. Function:

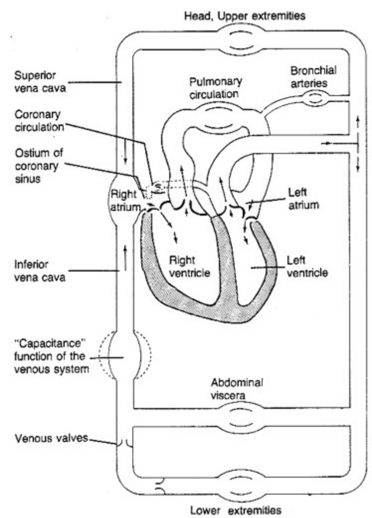
- Maintenance of environmental parameters of cells
- "Steady state"
- Transport:
  - Gases
  - Metabolites
  - Hormones, signal transmitters
  - Immunoglobulins
  - Heat

B. Hemodynamic requirements:

- Slow (low flow rate)
- Steady (no fluctuations)
- Unidirectional

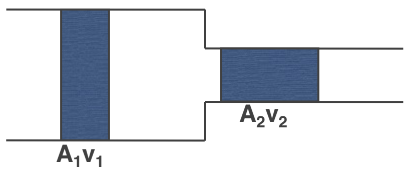
C. The vascular system is a closed vessel system returning into itself

The vascular system is a closed vessel system returning into itself



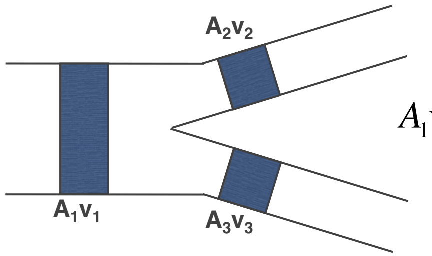
Fluid flow in vessel

Continuity equation – reminder



$$A_1v_1 = A_2v_2 = const$$

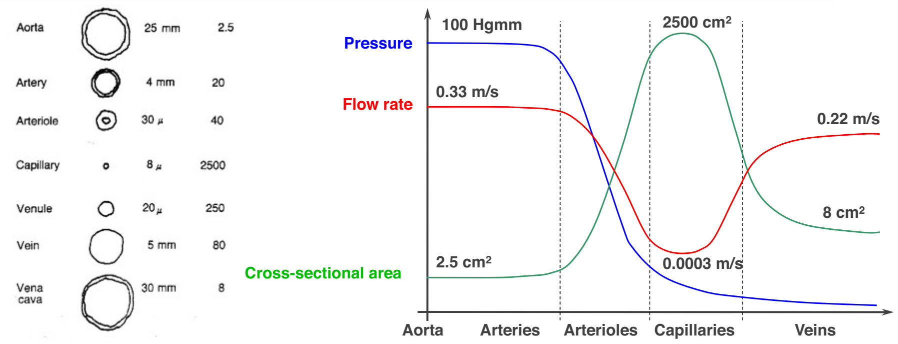
A=cross-sectional area
v=flow rate



$$A_1v_1 = A_\Sigma(v)_{average} = const$$

A_Σ=total cross-sectional area

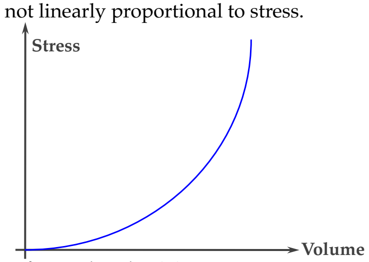
Structure and physical properties of the vascular system



Pressure> pressure that sustains flow, *"blood pressure"*.
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. (But: 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."*

Blood vessels as elastic tubes

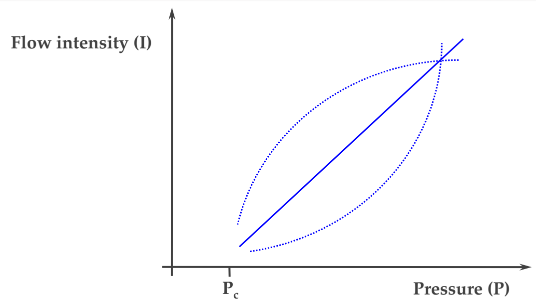
Non-liear elasticity
Strain is not linearly proportional to stress.



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

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

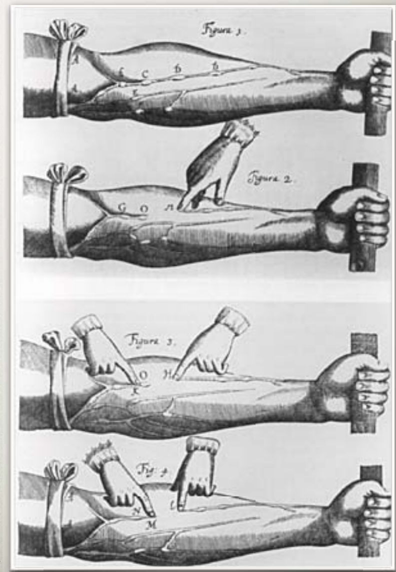
Relationship between flow intesity and pressure



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

Auxiliary factors of circulation

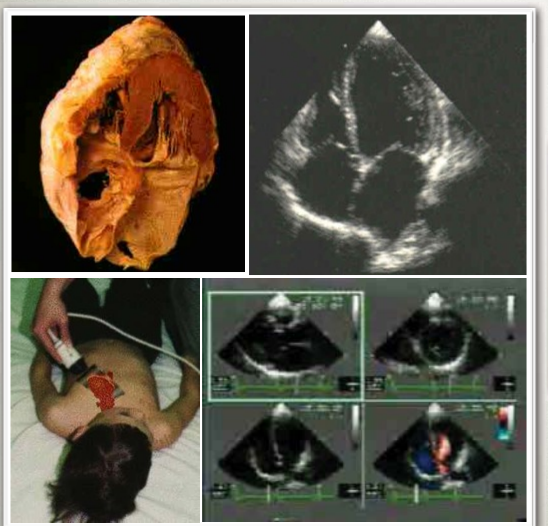
1. **Arterial elasticity**
   (storage of potential energy)
2. **Venous valves** (Harvey's experiment)
   "On the Circulation of the Blood" (1628).
1. **Muscle action**
2. **Negative intrathoracic pressure**
3. "Up-and-down" movement
   of **atrioventricular plane**



Harvey's experiment

Cardiac Biophysics

Heart:
Pump of the circulatory system

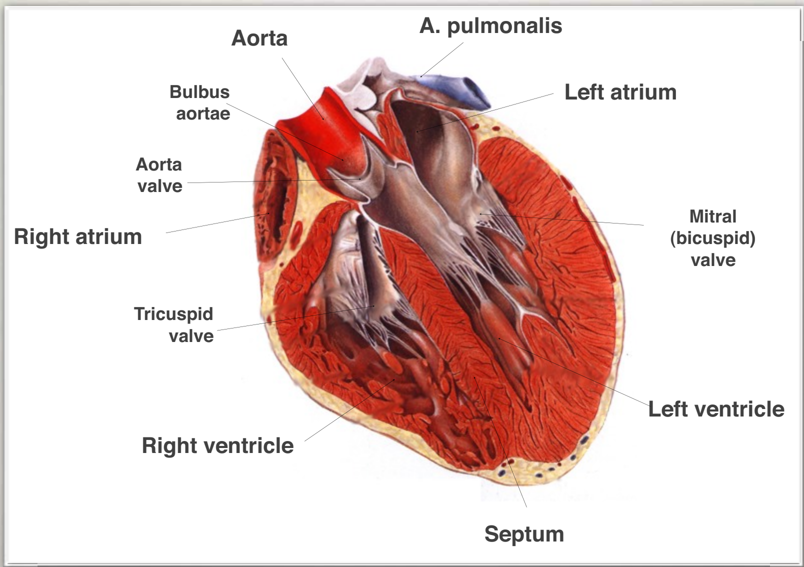


	Number of contractions	Expelled blood volume
1 min	~70	~6 l
1 day	~100.000	~8600 l
Life (70 yrs)	~2.5 x 10^9	~220 x 10^6 l

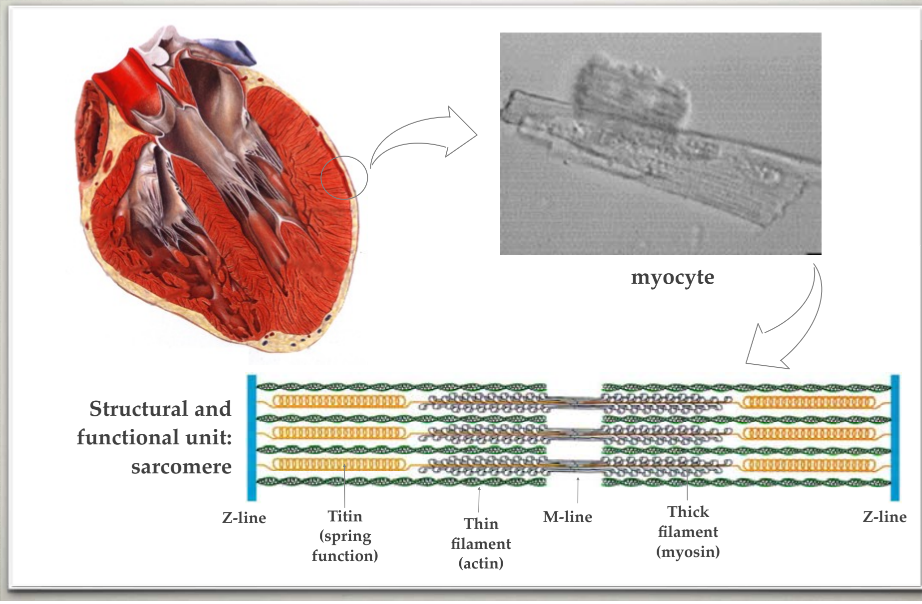
Cardiac biophysics

1. Structure of the heart
2. Coordinated contraction
3. The cardiac cycle
4. Work of the heart

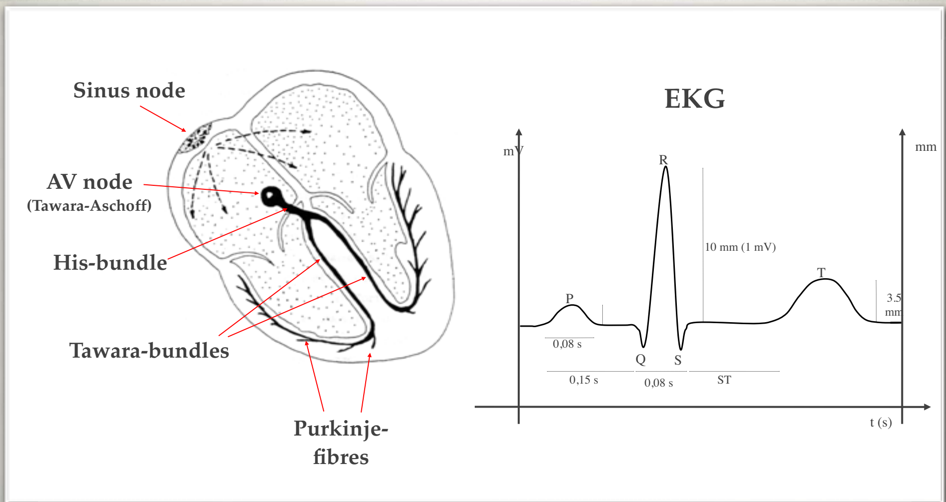
Structure of the human heart



Functional structure of the heart



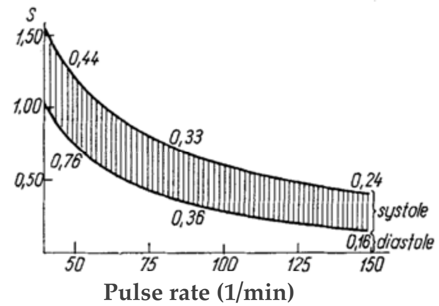
Activation of coordinated contractions



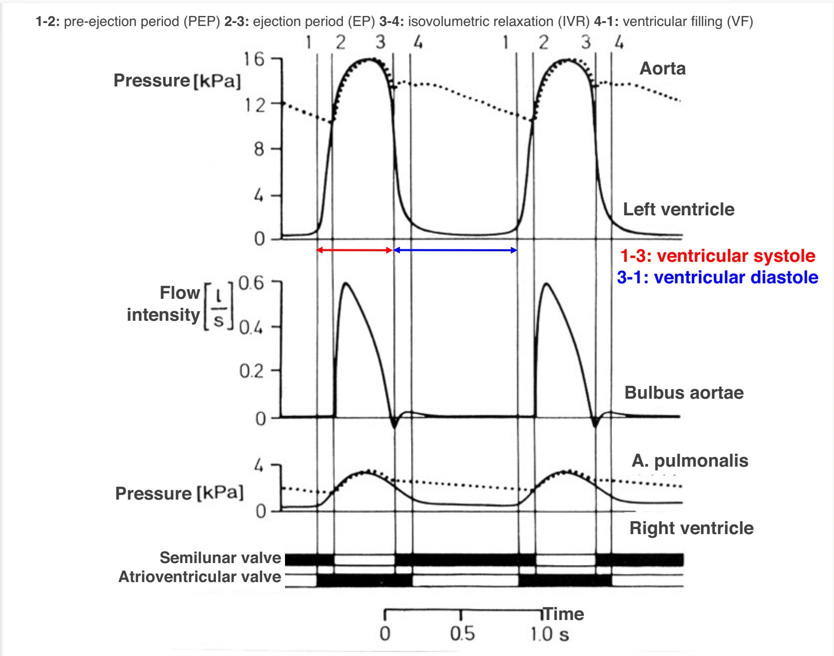
The cardiac cycle

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

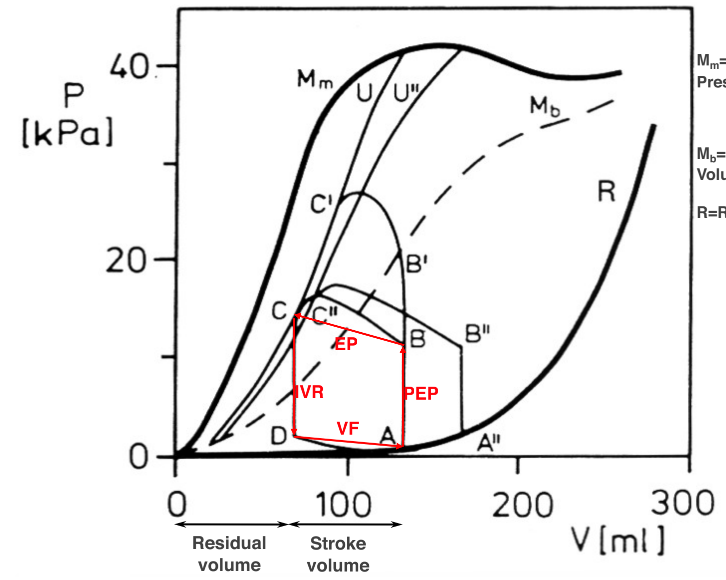
	systole	diastole
atrium	0,1 s	0,7 s
ventricle	0,3 s	0,5 s



Events of the cardiac cycle



Pressure-volume diagram of left ventricle

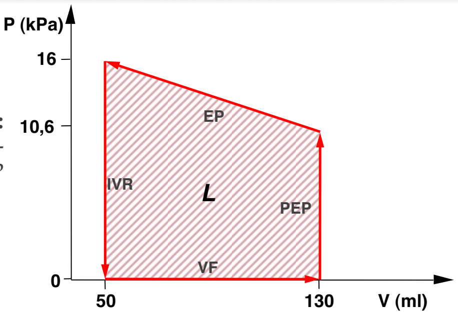


Work of the heart

(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
ΔV=**stroke volume**

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