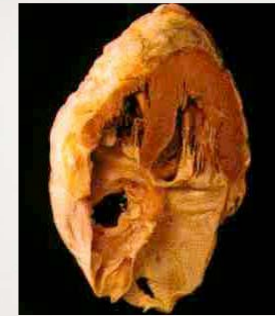# FLUID FLOW AND Circulatory system

Miklós Kellermayer

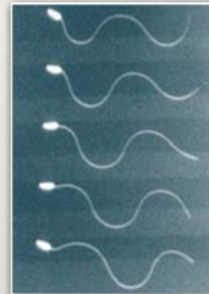
Importance of the phsics of fluids
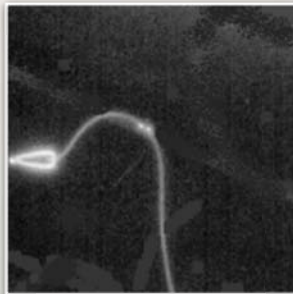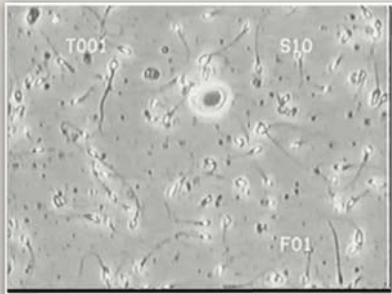
I. Hemodynamics

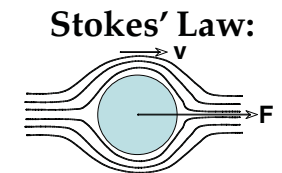Characteristics of blood flow along the circulatory system.

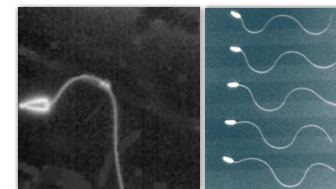## Significance of the physics of fluids

II. Motion in fuids

Force exerted by a single spermatocyte during its motion.

Drag coefficient of the spermatocyte

Stokes' Law:

$$\gamma = 6r\pi\eta = 6 \cdot 1.6 \times 10^{-6}(m) \cdot \pi \cdot 10^{-3}(Pas) = 3 \times 10^{-8} Ns/m$$
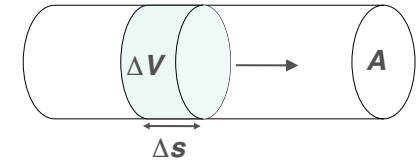
$$F = \gamma v = 3 \times 10^{-8} Ns/m \cdot 5 \times 10^{-5} m/s = 1.5 \times 10^{-12} N = 1.5\, pN$$

Biophysics of fluids

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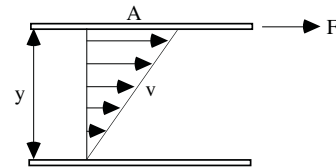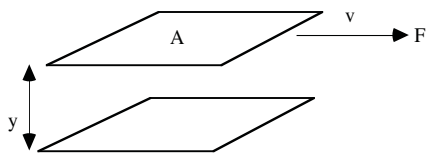- Biomedical importance

---

Basic principles I.

Volumetric flow rate (Q):

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

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

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: $\quad 1Pas = 1\dfrac{Ns}{m^2} = 10P(poise)$

Types of fuids I.

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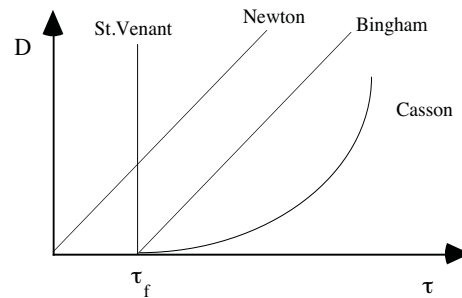   frictionless, uncompressible
   ϱ=constant, η=0

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.
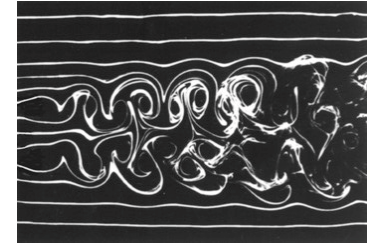
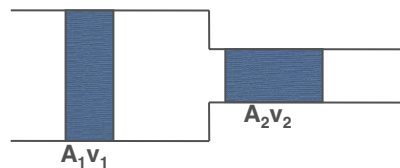**Reynolds number:** $$R = \frac{vr\rho}{\eta}$$

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

laminar | turbulent

100   1000 R

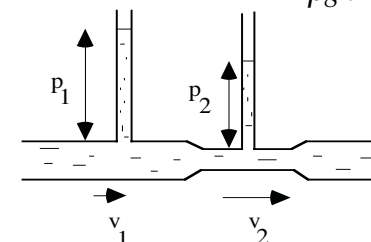# Laws of flow in ideal fluids I.

Continuity equation

A_2v_2

A_1v_1

$$A_1v_1 = A_2v_2 = konst$$

A=cross-sectional area
v=flow rate

Laws of flow in ideal fluids II.

Bernoulli's law

p=static pressure

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

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

ρgh = hydrostatic pressure

P_1 P_2

v_1 v_2

Laws of flow in viscous fluids I.

Stokes' law

$$F = \gamma v = 6r\pi\eta v$$
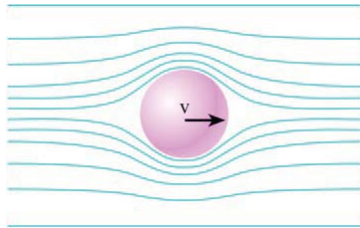
F = force
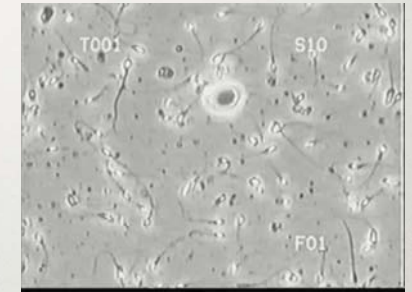γ = drag coefficient (shape factor)
v = flow rate
r = radius of sphere
η = viscosity

Stokes Force

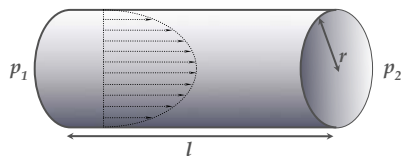Hydrodynamic drag force (Stokes force): $F = \gamma v = 6r\pi\eta v$

Affects stationary particles in moving fluid

Affects moving particles in stationary fluids

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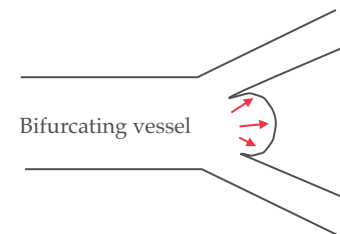t=time
(V/t=Q = flow intensity)
r=tube radius
η=viscosity
p=pressure
l=length of tube
(dp/dl=pressure gradient, maintained by p_1-p_2)

Biomedical significance

Bernoulli's law:

Bifurcating vessel

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
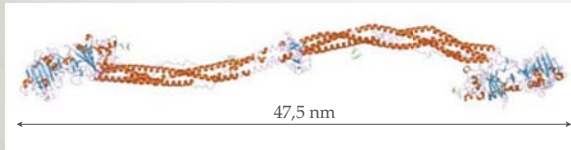
Determinants of blood viscosity II.

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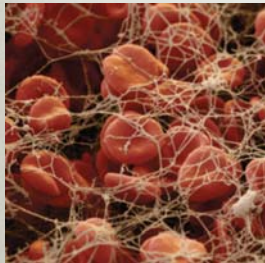   leading to increased viscosity.

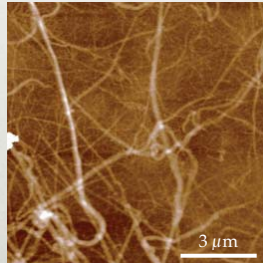| Plasma protein	Normal concentration	% ratio	Function
Albumin	35-50 g/l	55%	maintenance of colloind osmotic pressure, transport
Globulins	20-25 g/l	38%	Part of the immune system
Fibrinogen	2-4.5 g/l	7%	Blood coagulation

Fibrinogen, fibrin

Fibrinogen:
MW = 340.000 Da
In plasma: 2-4 g/l ≈ 10 μM
Average nearest-neighbor
distance ≈ 55 nm

47,5 nm

Red blood cells in fibrin meshwork

Fibrin polymerized in vitro (AFM)
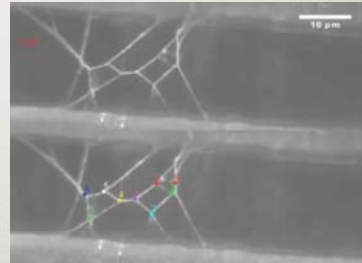
Extensibility of fibrin fibrils
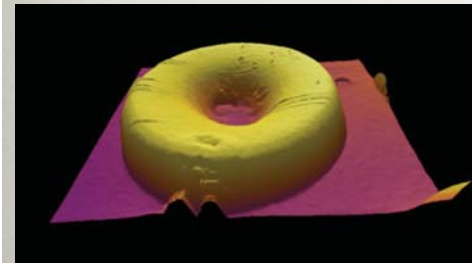
3 μm

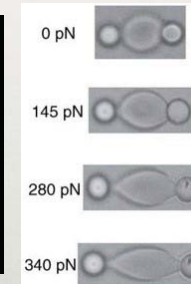# Determinants of blood viscosity III.

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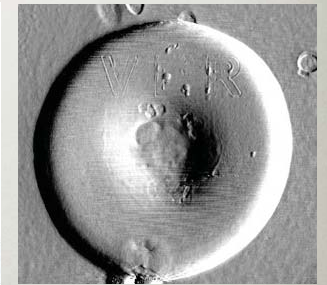By contrast, a 95% blood suspension if fluid, with viscosity of ~20 mPas!
Deformation of red blood cells: droplet, parachute, arrowhead shapes.

Disc-shaped cell with 7-11 μm diameter

0 pN
145 pN
280 pN
340 pN

Deformation of a RBC with optical tweezers

Fixed RBC maintaining impression (AFM)

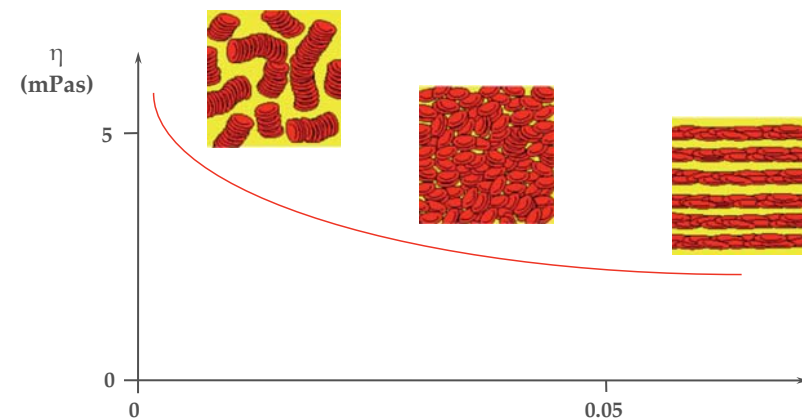# Determinants of blood viscosity III.

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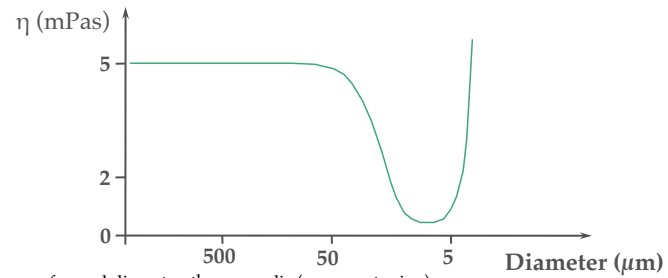Stack or roleaux formation.
More pronounced at low flow rates.

Roleaux

Determinants of blood viscosity IV.

5. Flow rate, velocity gradient

η (mPas)

5

0

0   0.05

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).