FLUID FLOW AND CIRCULATORY SYSTEM

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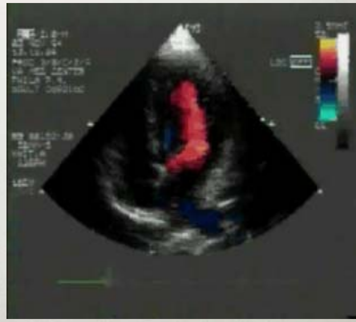
Importance of the phsics of fluids


I. Hemodynamics

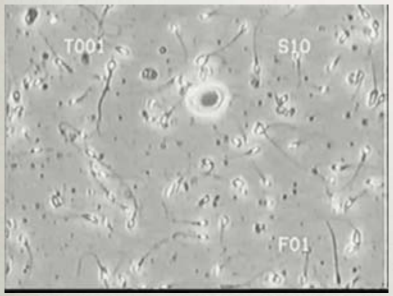
Characteristics of blood flow along the circulatory system.

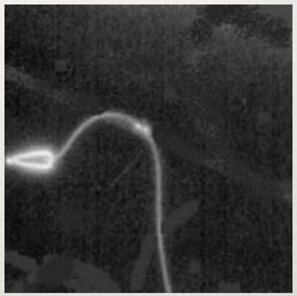
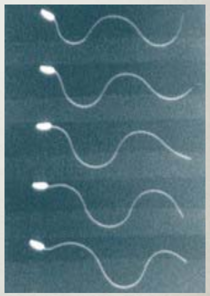



Significance of the physics of fluids

II. Motion in fuids

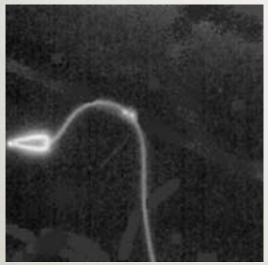
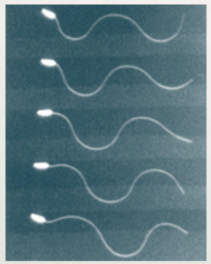
Force exerted by a single spermatocyte during its motion.



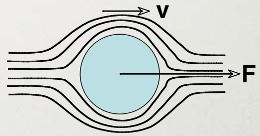



Drag coefficient of the spermatocyte

How much force is required for spermatocyte propagation?

Stokes' Law:



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

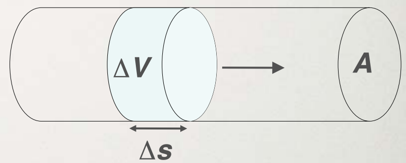
$$F = \gamma v = 3 \times 10^{-8} Ns/m \cdot 5 \times 10^{-5} m/s = 1.5 \times 10^{-12} N = 1.5\, pN$$

Biophysics of fluids

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

Basic principles I.

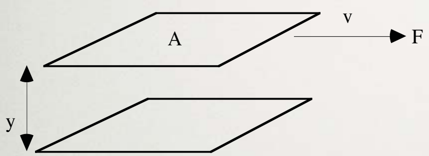
Volumetric flow rate (Q):

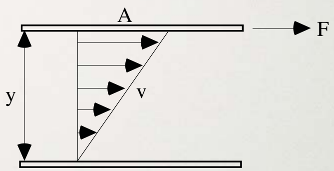


$$Q = \frac{\Delta V}{\Delta t} = A\frac{\Delta s}{\Delta t} = A\bar{v}$$

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

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)
$\Delta v/\Delta y$	= 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.

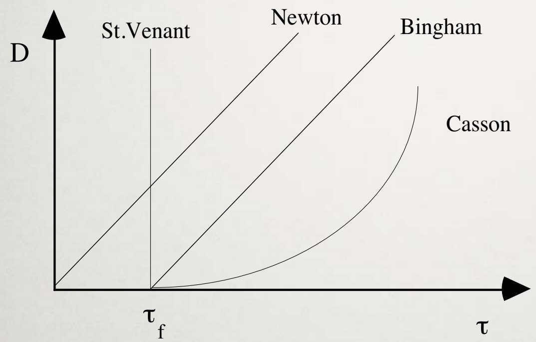
1. Ideal
frictionless, uncompressible
ρ = constant, $\eta = 0$

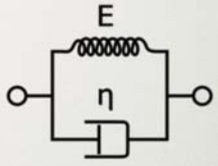
2. Non-ideal (real)
a. Newtonian (viscous)
η independent of shear stress

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

Types of fluids II.

Relationship between velocity gradient and shear stress in real fluids





Model of viscoelastic body - Kelvin-body: spting and dashpot coupled in parallel

τ_f=flow threshold

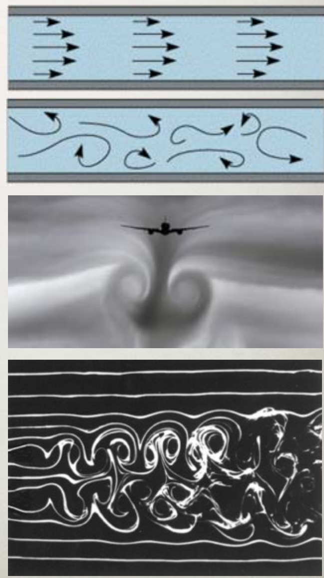
Viscoelastic materials: combination of elastic and viscous properties (e.g., polymer solutions)

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

N.B.: Blood is non-newtonian fluid. It possesses viscoelastic properties!

Types of fluid flow

1. **Stationary**
   Volumetric flow rate 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)

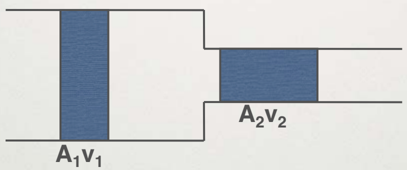
laminar | *turbulent* → R

$R_c \approx 2000$

"When I meet God, I am going to ask him two questions: Why relativity? And why turbulence? I really believe he will have an answer for the first." (Werner Heisenberg)

Laws of flow in ideal fluids I.

Continuity equation



$$A_1v_1 = A_2v2 = \text{constant}$$

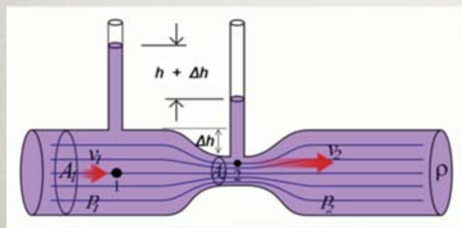
A = cross-sectional area
v = flow velocity

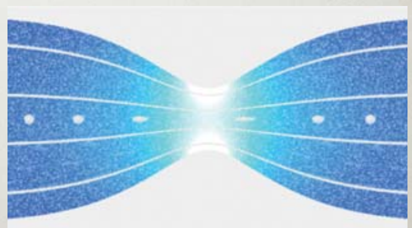
Laws of flow in ideal fluids II.

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

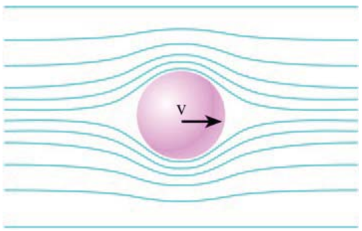




Venturi effect

Laws of flow in viscous fluids I.

Stokes' law

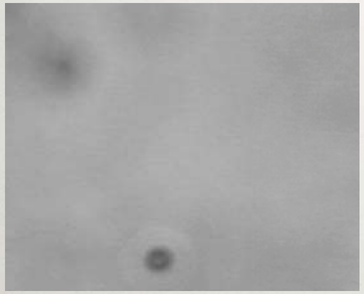


$$F = \gamma v = 6r\pi\eta v$$

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

Stokes Force

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

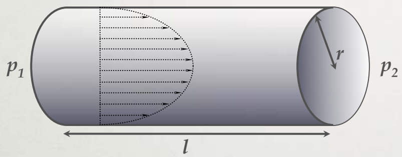


Affects stationary particles in moving fluid

Affects moving particles in stationary fluids

Laws of flow in viscous fluids II.

Hagen-Poiseuille's law

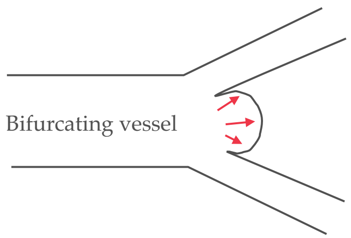


$$\frac{V}{t} = \frac{\pi r^4}{8\eta}\frac{dp}{dl}$$

V = volume
t = time
($V/t = Q$ = volumetric flow rate)
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/cm^3
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

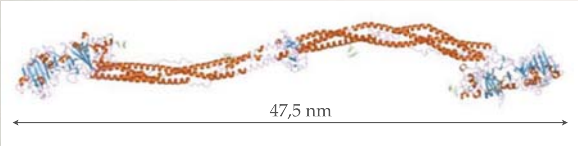
Determinants of blood viscosity II.

2. Plasma viscosity

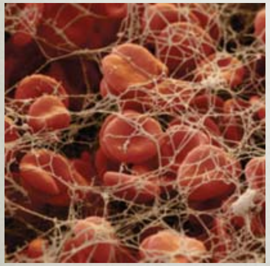
Depends on plasma proteins.
In paraproteinaemias (e.g. myeloma multiplex or plasmocytoma) the concentration of immunoglobulins is high, leading to increased viscosity.

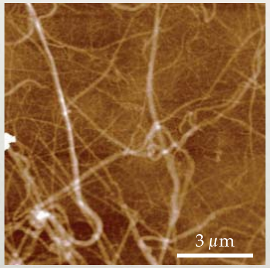
Plasma protein	**Normal concentration**	**% ratio**	**Function**
Albumin	35-50 g/l	55%	maintenance of colloind osmotic pressure, transport
Globulins	20-25 g/l	38%	Part of the immune system
Fibrinogen	2-4.5 g/l	7%	Blood coagulation

Fibrinogen, fibrin

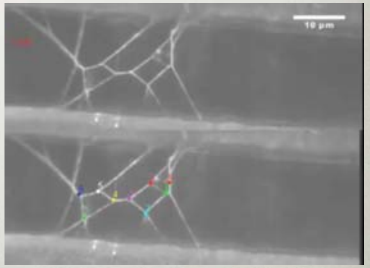


Fibrinogen:
MW = 340.000 Da
In plasma: 2-4 g/l ≈ 10 μM
Average nearest-neighbor distance ≈ 55 nm


Red blood cells in fibrin meshwork



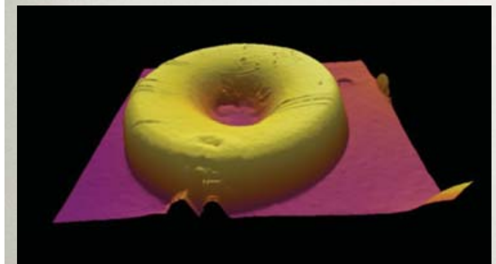
Fibrin polymerized in vitro (AFM)

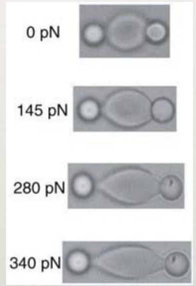

Extensibility of fibrin fibrils

Determinants of blood viscosity III.

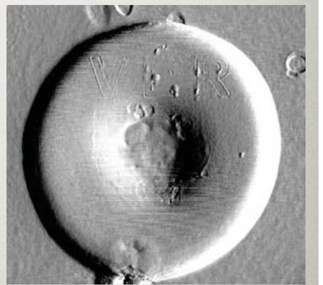
3. Plasticity of red blood cells

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



Deformation of a RBC with optical tweezers


Fixed RBC maintaining impression (AFM)

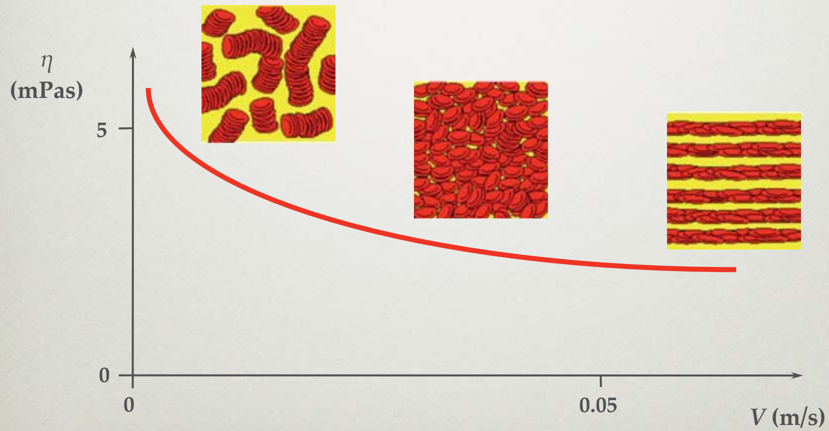
Determinants of blood viscosity III.

4. Aggregation of red blood cells

Stack or roleaux formation.
More pronounced at low flow rates.

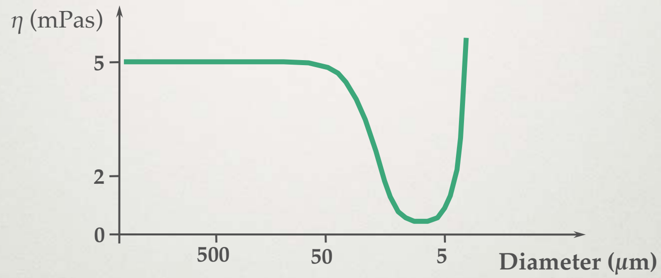
Determinants of blood viscosity IV.

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).