Complex flows of cellular suspensions in microtubes at different temperatures

Natalya Kizilova
Institute of Aeronautics and Applied Mechanics, Warsaw University of Technology, Warsaw, Poland

Liliya Batyuk
Kharkov National Medical University, Kharkov, Ukraine

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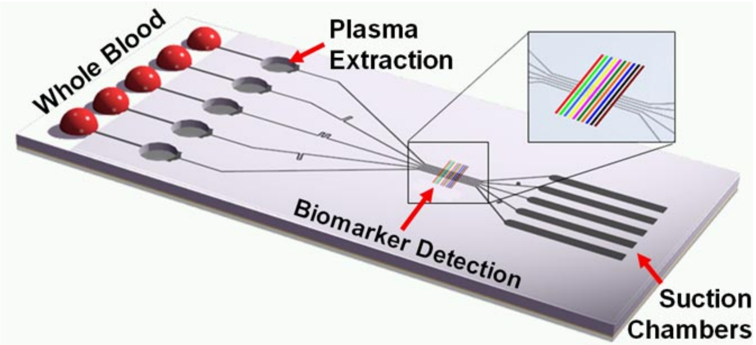
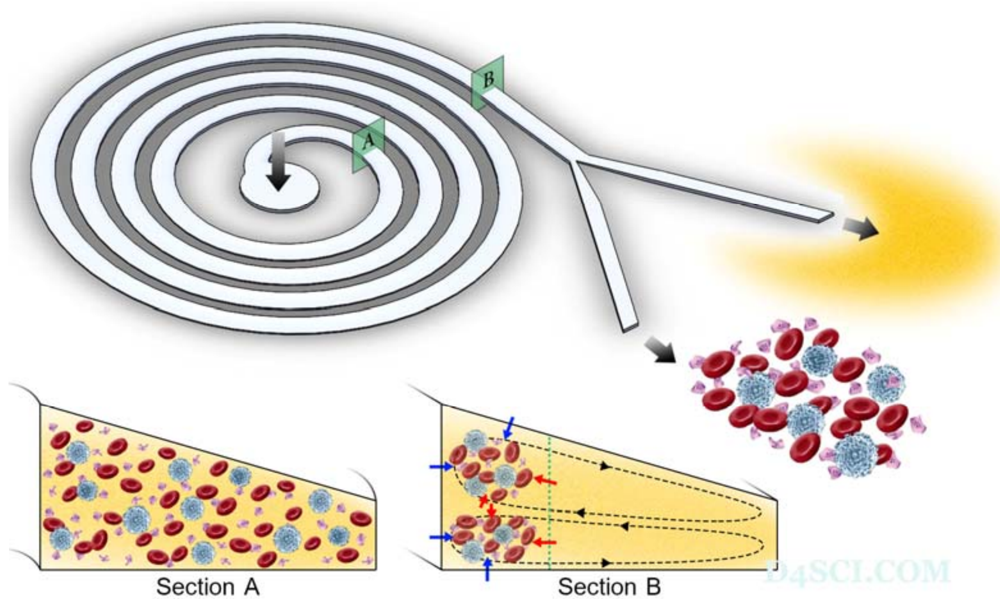
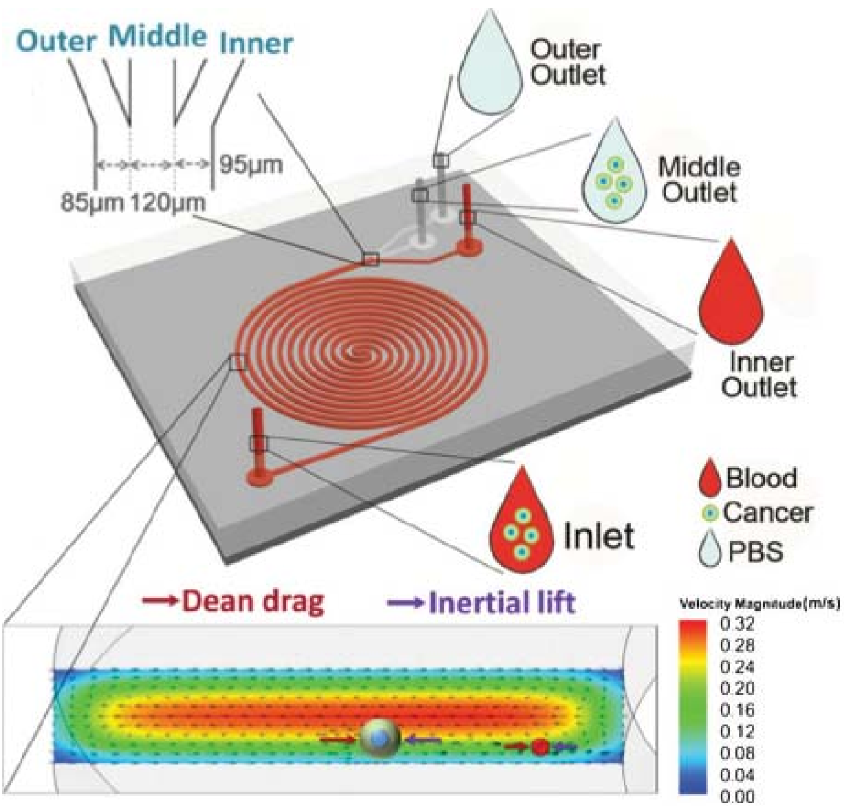
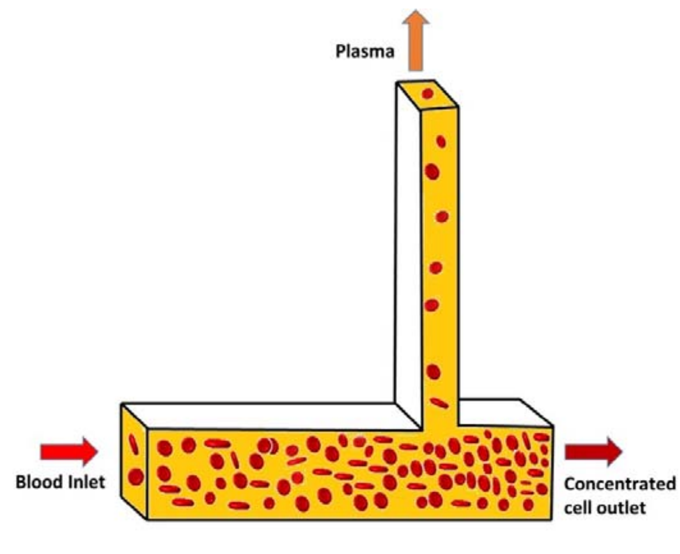
Microfluidic systems for blood processing









T-shaped Microchannel for blood plasma separation

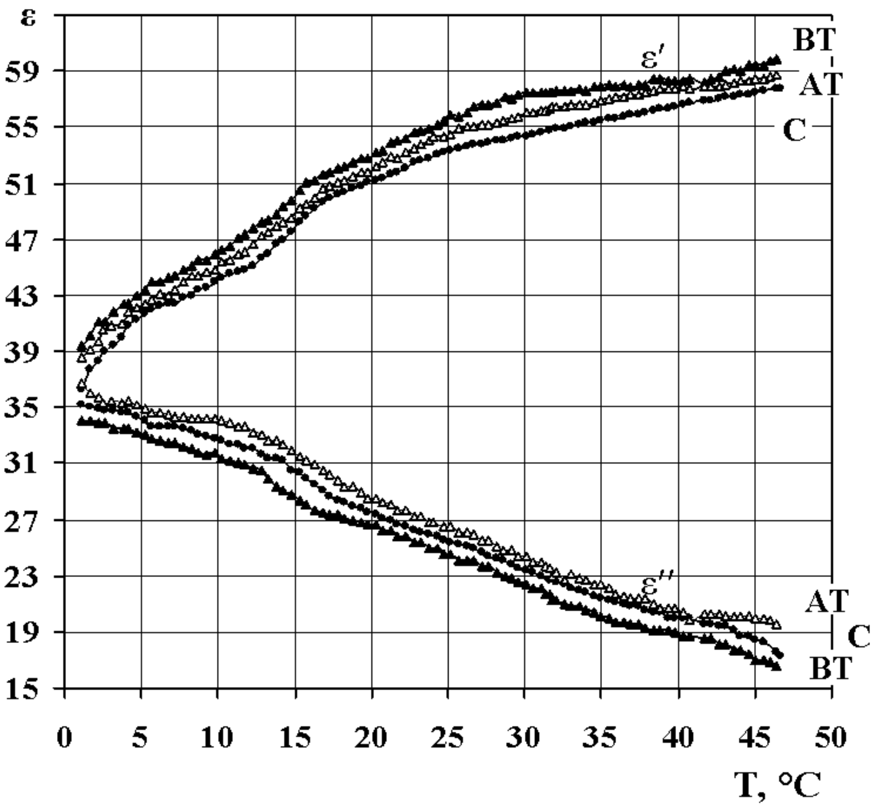
Treatment/separation are based on

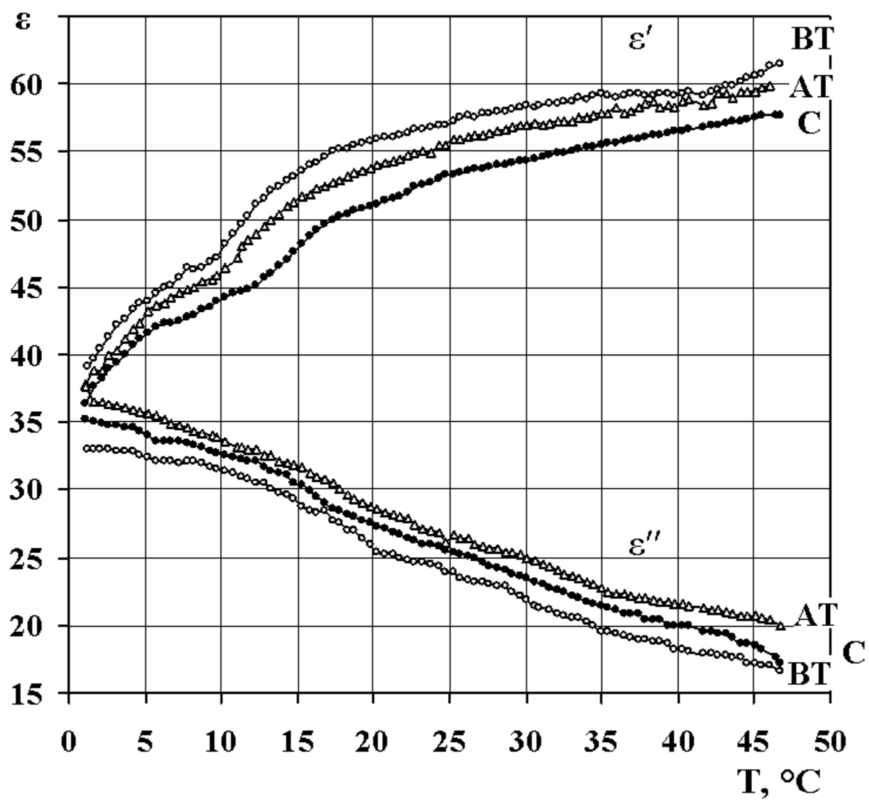
- Mechanical properties: density, elasticity, flexibility;
- Eelectric properties: charge, dielectric permittivity;
- Magnetic properties: magnetic moment, magnetic permittivity;
- Biochemical properties: adhesiveness, biomarkers.

UltraHighFrequency dielectrometry

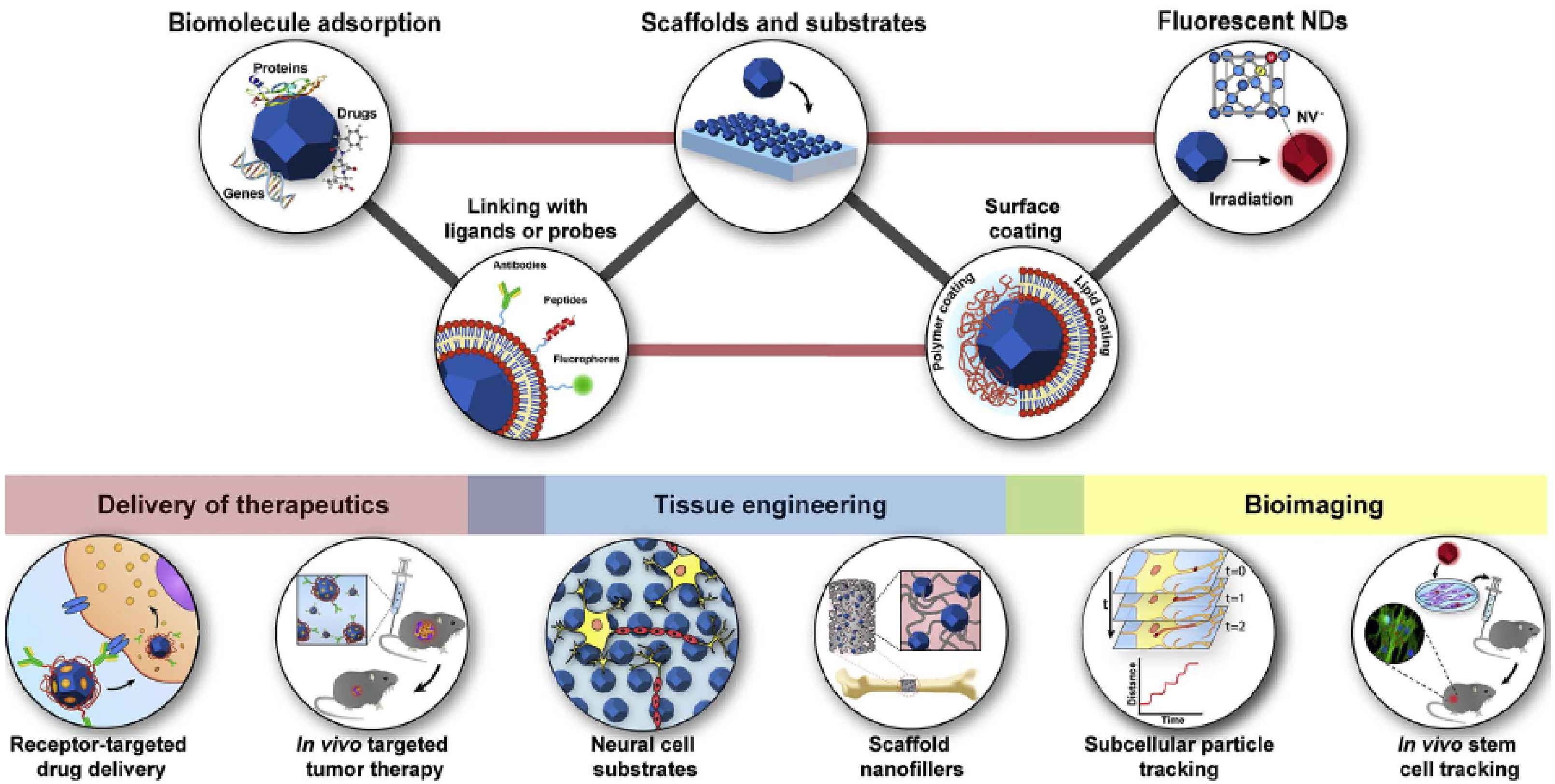
Erythrocytes of venous blood was washed out in 0.9% NaCl and diluted to 35% suspension.

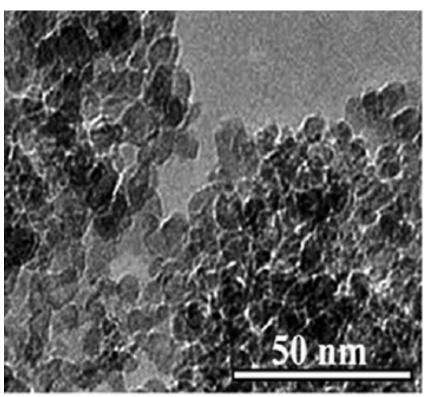
HF dielectrometer with $f = 9.2\ HHz, T = 0 - 47^{\circ} C$

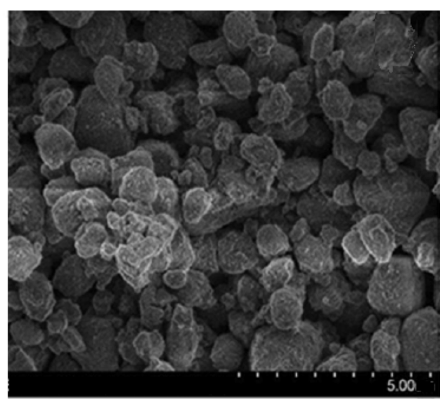


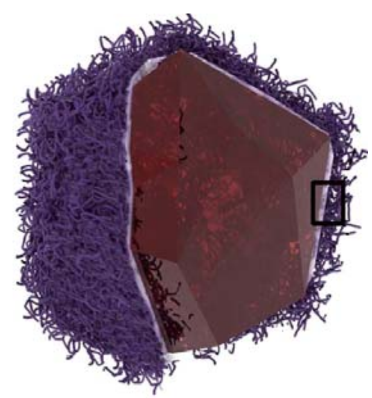


Nanodiamonds in medicine

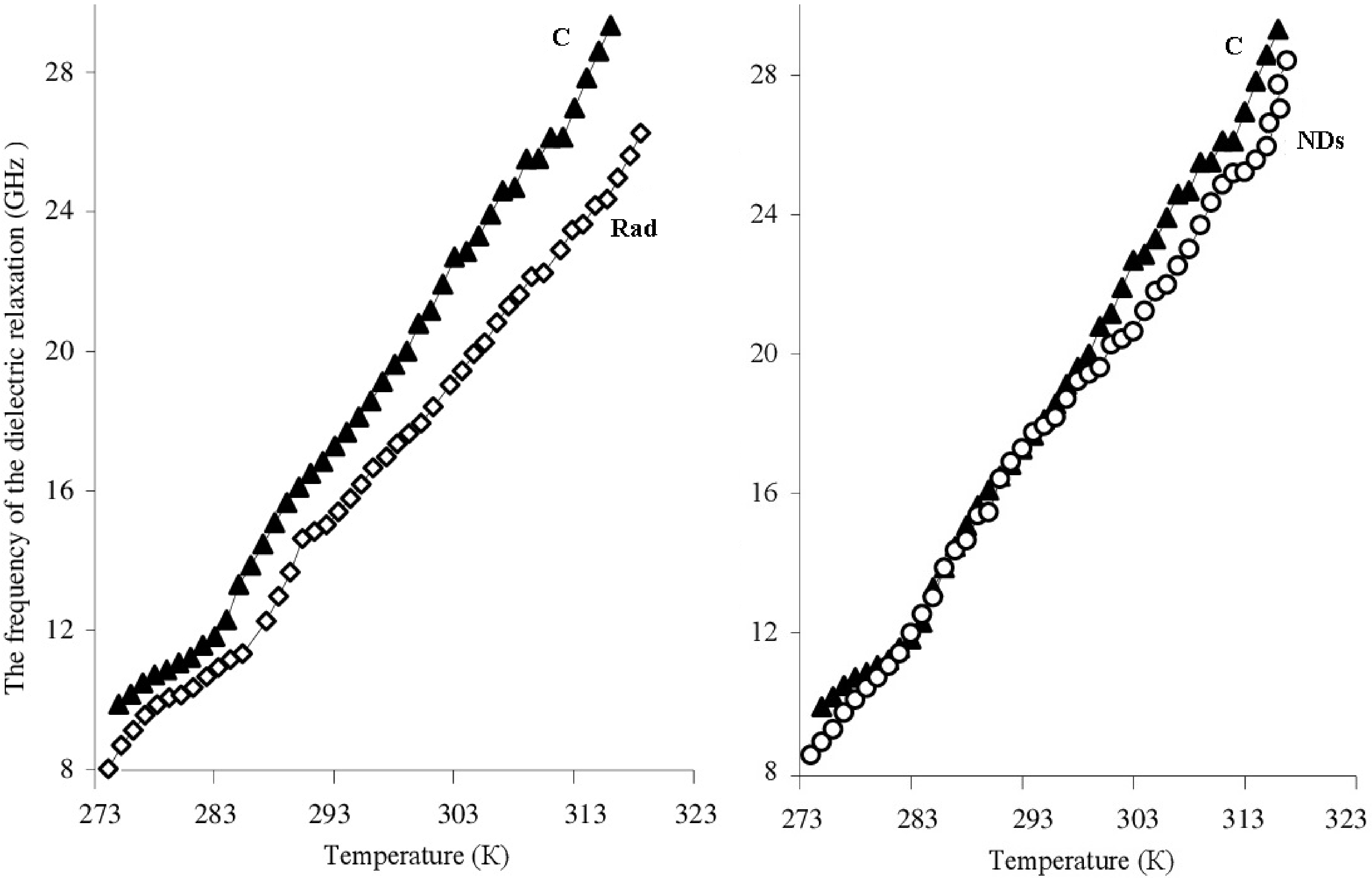




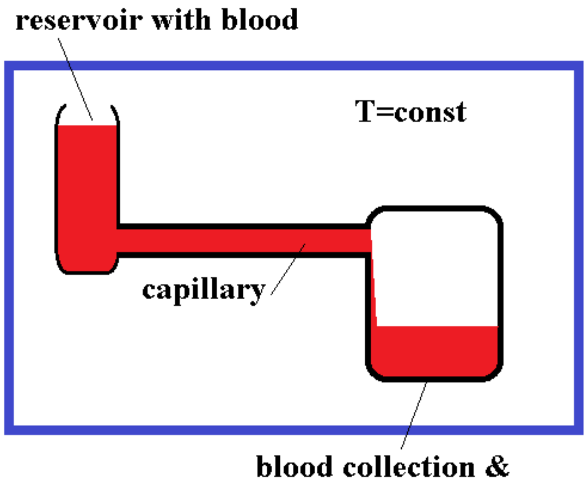




Radioprotective action of NDs



Blood flow measurements



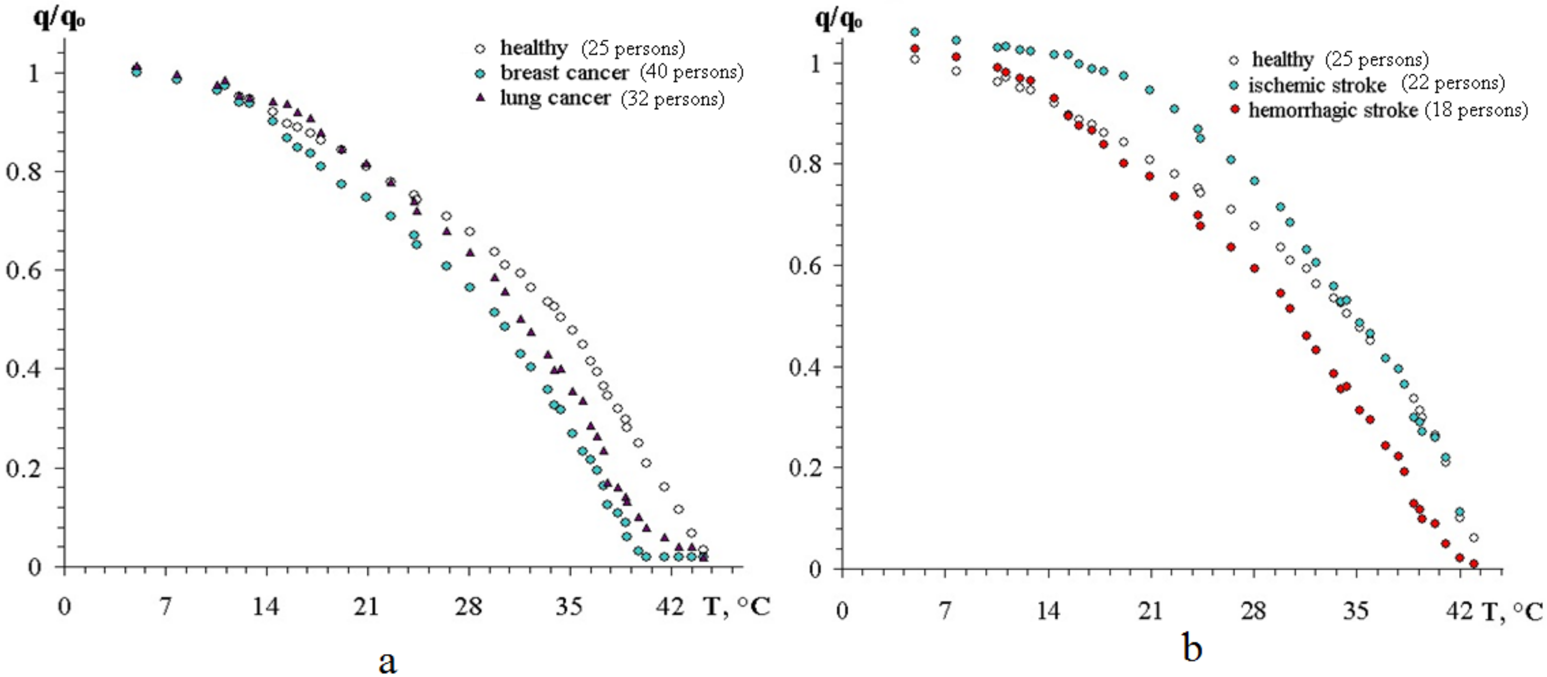
$$Tubes: \quad d = 100, 300, 500\ \mu m, \quad L = 1, 2, 3\ cm$$

$$Temperature: \quad T = 5 - 43^{\circ}C, \ \ \Delta T = 1^{\circ}C$$

$$Capillary\ viscosimeter (d = 1.15\ mm): \mu(T)$$

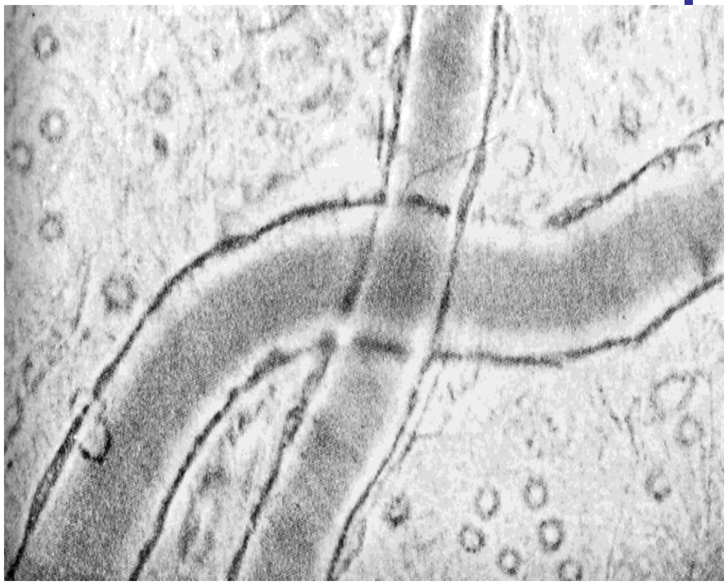
$$q_0 = \frac{\delta p \cdot \pi R^4}{8L\mu_{bl}(T)}$$

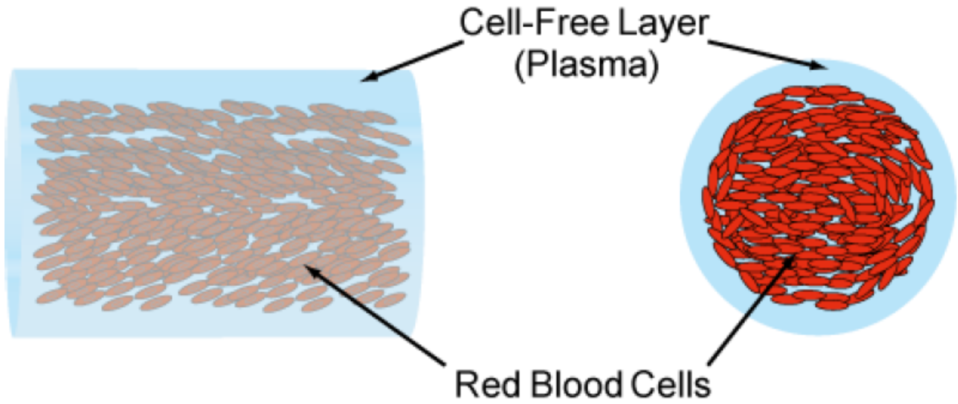
$$q - measured\ volumetric\ rate$$



Relative flow rates of the RBC suspensions of cancer (a) and stroke (b) patients
in comparison to healthy donors

Fåhræus-Lindqvist effect in suspensions

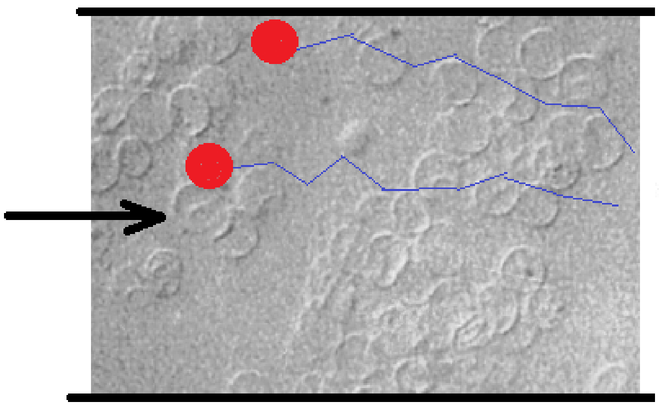


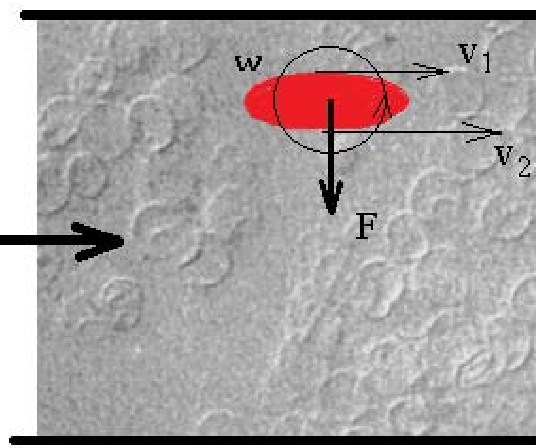


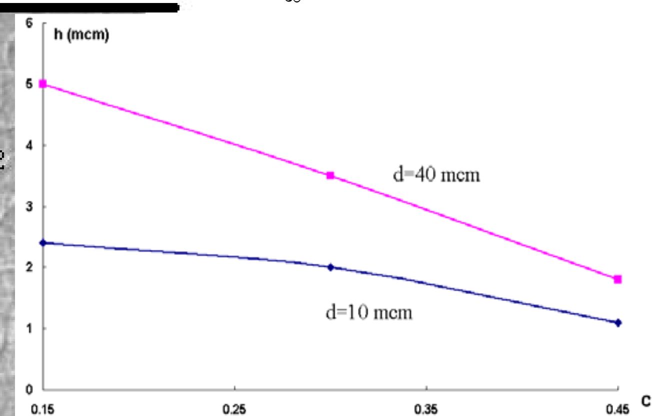
$$5\ \mu m < d < 500\ \mu m$$

Stokes force, flow non-uniformity, inertia, Magnus force, unsteady viscous phenomena

$$\vec{F} = k\mu R(\vec{v}-\vec{v}_\infty) + k_1\mu\Delta\vec{v}_\infty - k_2\rho R^3 \frac{d}{dt}(\vec{v}-\vec{v}_\infty) + k_3\rho R^3(\vec{\omega}-\vec{\omega}_\infty)\times(\vec{v}-\vec{v}_\infty) + k_4\sqrt{\mu\rho}R^2\int_{-\infty}^{t}\frac{d}{d\tau}(\vec{v}-\vec{v}_\infty)\frac{d\tau}{\sqrt{t-\tau}}$$

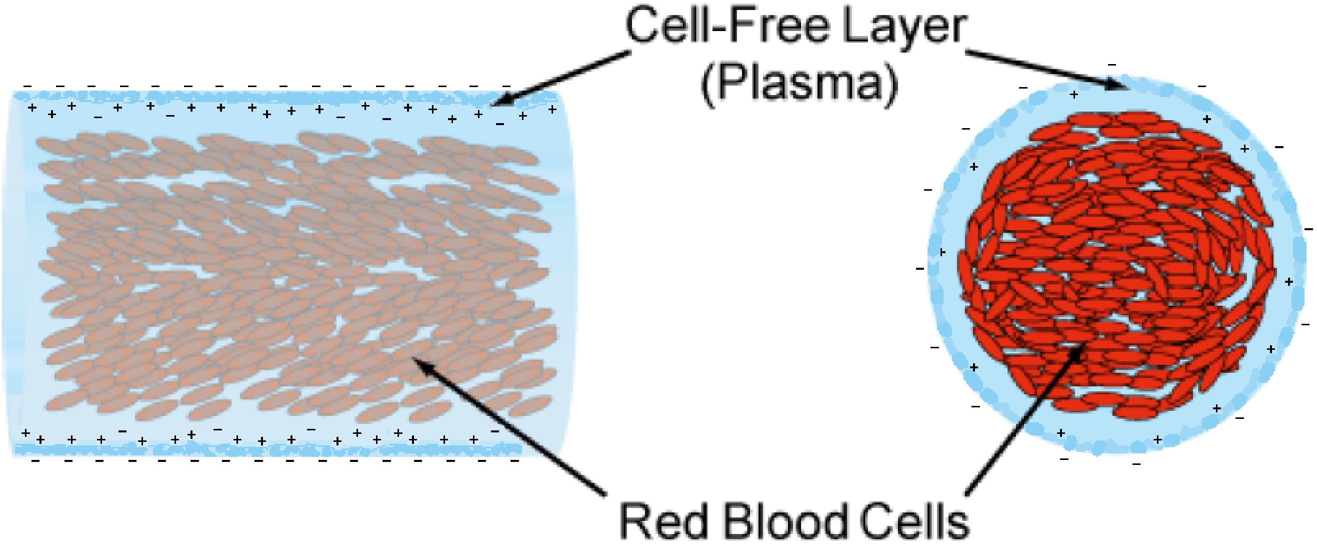




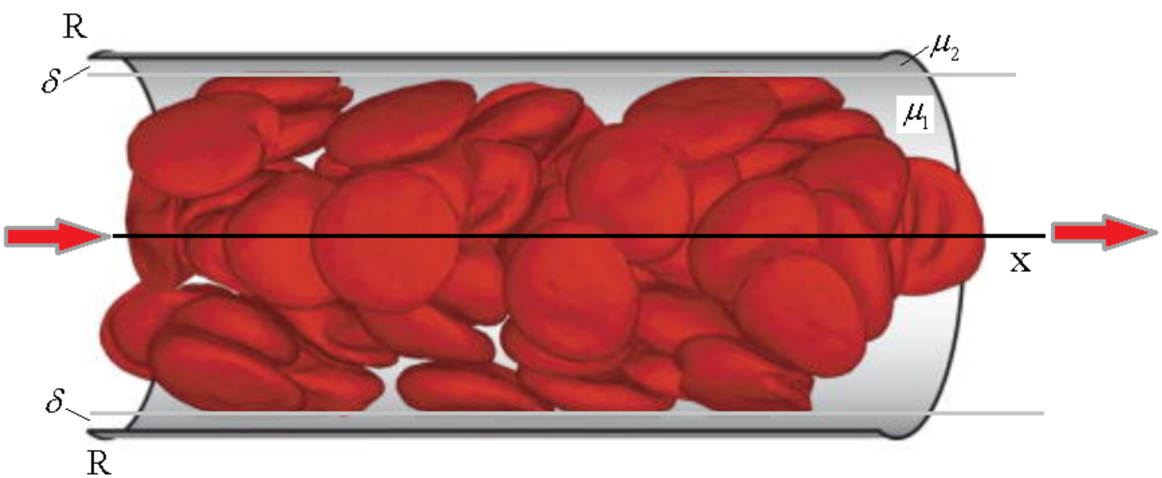


Copley-Scott Blair effect

- Specific material-dependent adhesion at the inner wall of the tube;
- Double electric layer and related electrokinetic phenomena;
- Decrease in the apparent viscosity with decrease in the diameter and electrostatic forces.



Problem formulation



- Fåhræus-Lindqvist effect (boundary layer free of cells)
- Copley-Scott Blair effect (h-layer of adsorbed molecules/ions)
- Velocity slip boundary conditions (in microtubes)
- Temperature dependencies of material parameters

$$\frac{1}{r}\frac{d}{dr}\left(r\frac{dv_{1,2}}{dr}\right)=\frac{\delta p}{\mu_{1,2}L}$$

$$r=0: \quad \frac{dv_1}{dr}=0$$

$$r=R: \quad v_2(R)-\alpha\frac{\partial v_2}{\partial r}(R)=0$$

$$r=R-\delta: \quad v_1=v_2$$

$$\frac{dv_1}{dr}=\frac{\tau-\tau_0}{\mu_1} \text{ – Bingham fluid}$$

$$\mu(T): \quad d\mu/dT<0$$

$$\delta(T): \quad d\delta/dT<0$$

$$h(T): \quad dh/dT>0$$

$$\tau_0(T): \quad d\tau_0/dT>0$$

$$\alpha(T): \quad d\alpha/dT>0$$

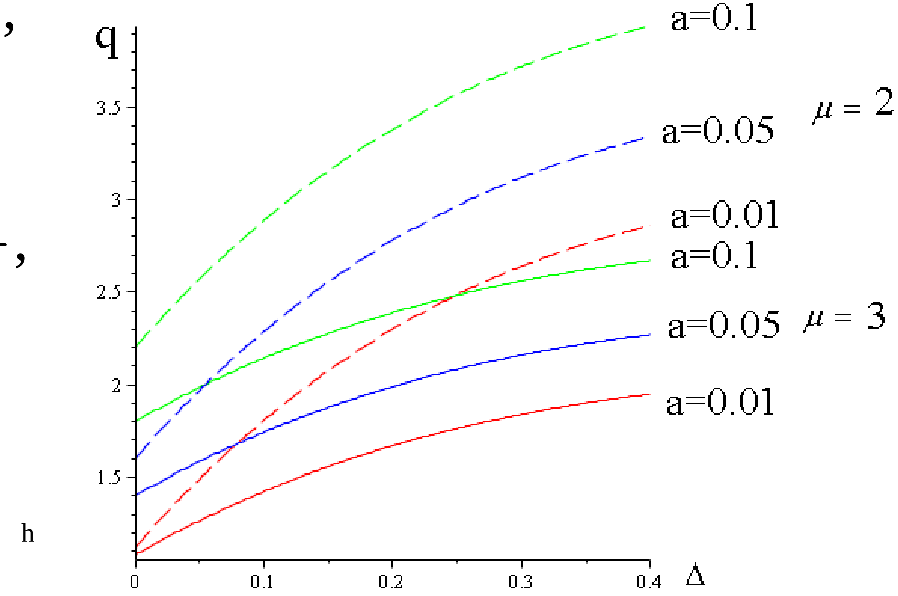
Fåhræus-Lindqvist for Newtonian fluids

$$\tilde{v}_1(\tilde{r}) = \mu(1-2a) + (1-\mu)(1-\Delta)^2 - \tilde{r}^2,$$

$$\tilde{v}_2(\tilde{r}) = \mu(1-2a) - \mu\,\tilde{r}^2,$$

$$\tilde{v}_{1,2} = \frac{v_{1,2}}{v^*}, \qquad v^* = \frac{R^2}{4\mu_1}\frac{\delta p}{L}, \quad \mu = \frac{\mu_1}{\mu_2},$$

$$a = \frac{\alpha}{R}, \qquad a = C \cdot Kn, \qquad Kn = \lambda / R.$$



$$q = \int_0^{\Delta} \tilde{v}^{(1)}\,\tilde{r}d\tilde{r} + \int_{\Delta}^{1} \tilde{v}^{(2)}\,\tilde{r}d\tilde{r} = \mu(1+4a) - (\mu-1)(1-\Delta)^4$$

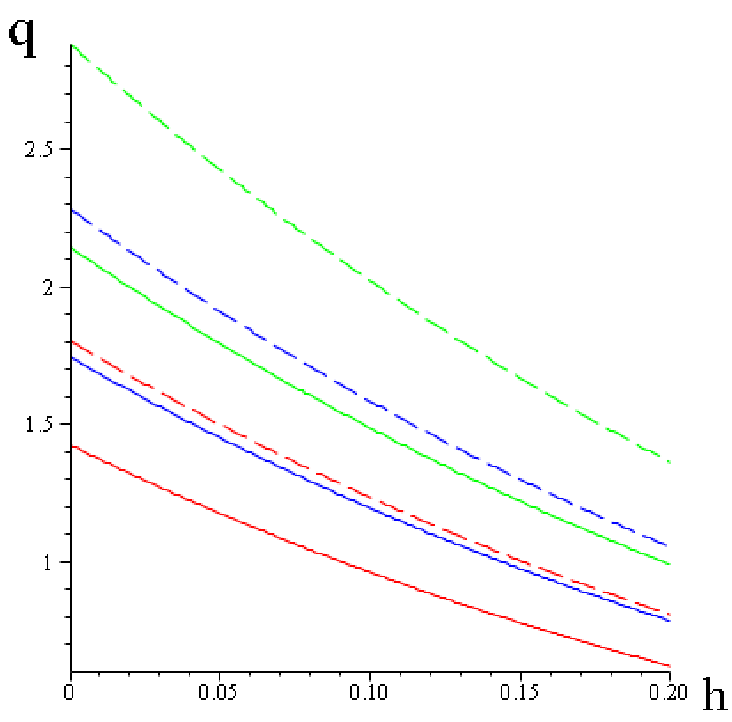
$$q(T) = q(\mu(T), \Delta(T), a(T))$$

For a Boltzmann gas $Kn = \dfrac{k_B T}{\sqrt{2}\pi d^2 p R}, \quad \mu' < 0, \quad \delta' < 0, \quad a' > 0.$

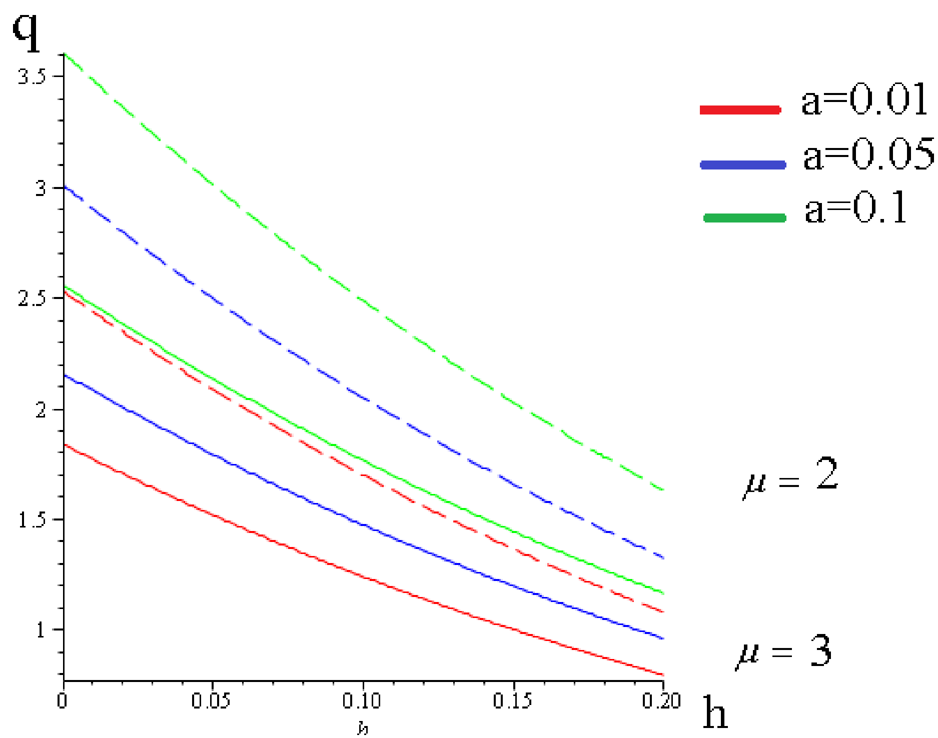
Copley-Scott Blair + Fåhræus-Lindqvist for Newtonian fluids

$$q = (1-h)^4 + 4(\mu\Delta - \Delta + \mu a)(1-h)^3 + 6\Delta^2(1-\mu)(1-h)^2 + 4\Delta^3(\mu-1)(1-h) + (1-\mu)\Delta^4,$$

$$h = \frac{H}{R}, \quad \mu = \frac{\mu_1}{\mu_2}, \quad \Delta = \frac{\delta}{R}, \quad a = \frac{\alpha}{R}, \quad a = C \cdot Kn, \quad Kn = \lambda / R.$$

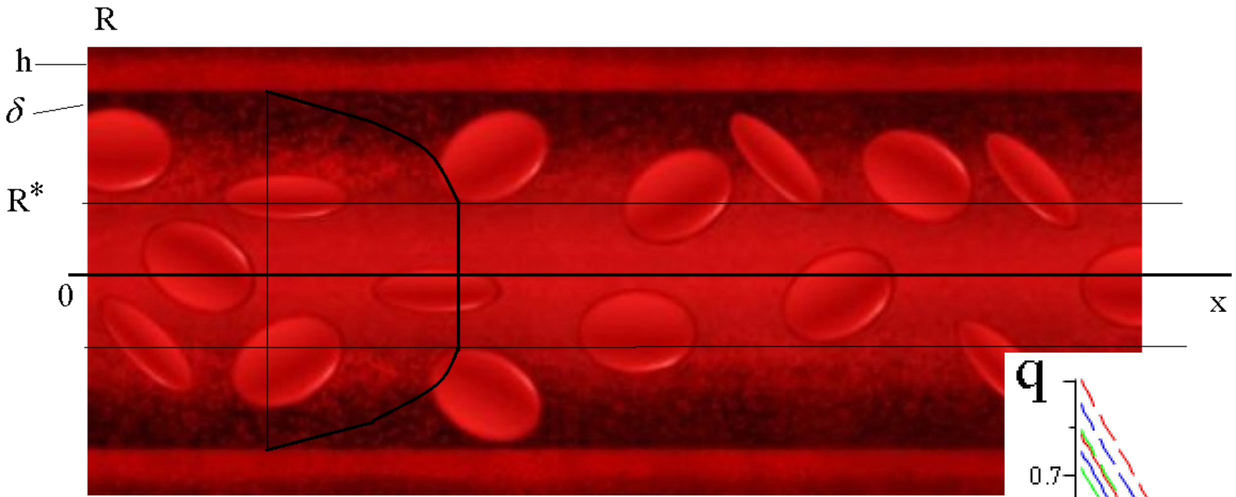


Δ =0.1

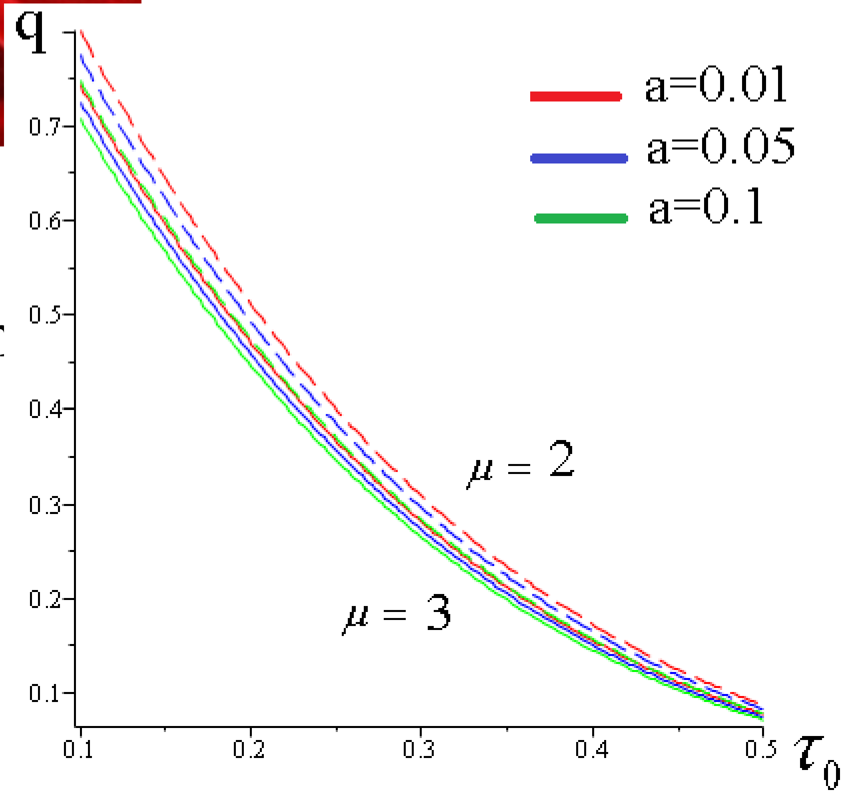


Δ =0.3

Copley-Scott Blair + Fåhræus-Lindqvist for Bingham fluids



$$v(r) = \begin{cases} v_2(r), & r \in [R-h-\delta, R-h \\ v_1(r), & r \in [R^*, R-h-\delta] \\ v_1(R^*), & r \in [0, R^*] \end{cases}$$



Conclusions

- Dielectric properties of red blood cells vary with temperature and their surfaces are influenced by serious diseases (cancer, stroke)
- Steady flow of cellular suspensions through microtubes differs from those described by Poiseuille law
- Among possible factors the transition to viscoplastic state may explain the experimentally observed temperature dependencies