Complex flows of cellular suspensions in microtubes at different temperatures

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Introduction

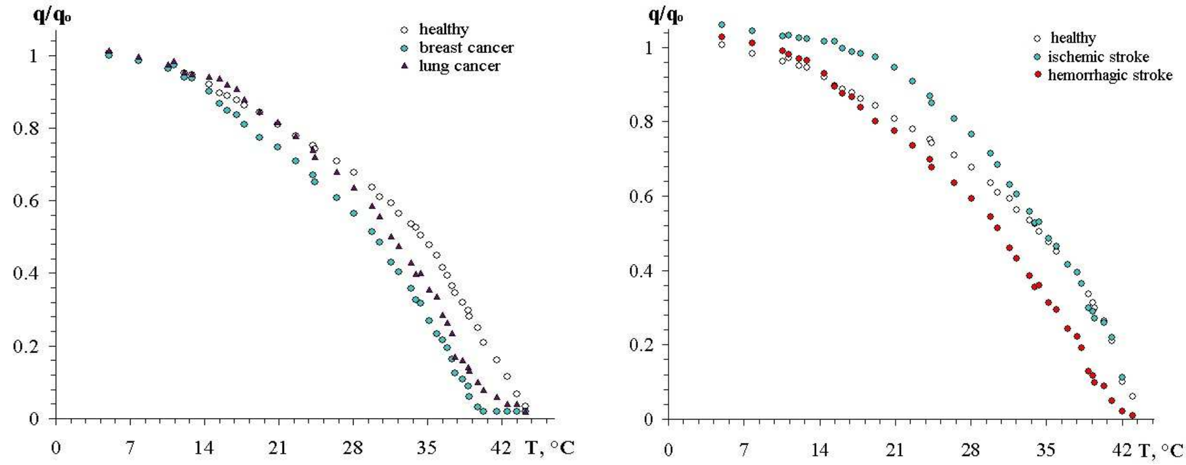
Recently different microfluidic systems have been proposed for separation of blood cells based on their mechanical, optical, electric, magnetic, adhesive and other properties which are different in the blood samples of healthy donors and patients with different pathology [1,2]. The systems are based on the blood flow through one or a system of microtubes or channels in the external field(s) or in interaction with bioactive receptor-sensing nanoparticles. Mathematical modeling of the flows of suspensions of microparticles through the microtubes with diameters $d = 100 - 500\ \mu m$ is based on the Navier-Stokes equations with velocity slip boundary conditions [1], but for the flows of suspensions the Fåhræus–Lindqvist and Copley-Scott Blair phenomena are also essential. The Fåhræus–Lindqvist effect is the decrease of the apparent viscosity with decrease in the diameter of the capillary within the values $3\ \mu m < d < 500\ \mu m$ due to formation of a thin boundary layer with lower concentration of particles and, thus, with lower viscosity [3]. This layer serves as the lubricating one and promotes the higher flow rates in comparison to the Poiseuille flow of a uniform liquid. The Copley-Scott Blair phenomenon relates to the decrease in the apparent viscosity with decrease in the diameter due to specific interaction and adhesion of some components at the capillary wall. For instance, when the blood, blood plasma or serum are moved through a tube their apparent viscosity depends on the material of the inner wall [4]. The two effects were found to have different origins [5], and the electric double layer at the wall [6] and related electrokinetic phenomena [7] have been proposed for explanation of the Copley-Scott Blair phenomenon.

Materials and methods

Volumetric rate of steady flow of the suspensions of human red blood cells (RBCs) through a thin tube ($d = 500\ \mu m$, $L = 10\ cm$) at different ambient temperatures ($T = 0 - 43^{\circ}C$) has been measured. The RBCs of healthy volunteers and patients with stroke and cancer have been used. The blood samples have been collected and stabilized by heparin. The RBCs have been washed out with saline in the centrifuge at ω=3500 min^{-1}, and the RBC (35%) suspensions with saline have been prepared. The blood samples of patients with lung cancer (32 persons), breast cancer (40 persons), ischemic stroke (22 persons), hemorrhagic stroke (18 persons), and healthy donors (25 persons) have been studied. The measured dependencies q / q_0 on T are presented in Fig.1a,b. Here q is the measured volumetric rate, q_0 is one computed for the Poiseuille flow.

Mathematical model

Incompressible Navier-Stokes equations of a viscoplastic fluid with first order velocity slip boundary conditions have been solved for a tube with actual diameter $d_a = d - 2h(T)$, where $h(T)$ is the thickness of the Copley-Scott Blair layer have been solved. The outer Fåhræus–Lindqvist layer with lower viscosity has been introduced as an immiscible fluid. The temperature dependences of viscosity $\mu(T)$ and yield stress $\tau_0(T)$ have been taken into account. The dependences $h(T)$ and $\tau_0(T)$ are determined by gradual denaturation of the membrane proteins at higher temperatures $T > 39^{\circ}C$. The sets of material parameters when $q / q_0 < 1$ have been found.



a b

Fig.1. Relative flow rates of the RBC suspensions of cancer (a) and stroke (b) patients in comparison to healthy donors (empty circles).

Results and discussions

In 84% of the measured samples the severe diseases (cancer, hemorrhagic stroke) exhibit higher apparent viscosity μ_{app} measured by the capillary viscosimeter and lower q values than those for the healthy donors (Fig.1a,b). In the less dangerous cases (ischemic stroke) μ_{app} may be higher at low temperatures $T \in [0; 20^{\circ}]\mathrm{C}$ and q is bigger or equal to those for the healthy donors (Fig.1b).

The Fåhræus–Lindqvist effect promotes increase of q in comparison to q_0 at the same temperatures, while Copley-Scott Blair effect promotes decrease of q due to adsorption of the proteins and cells at the surface of the tube and decrease of d_a. With temperature growth different types of membrane proteins become denaturated that change adhesive properties of the cell surfaces and protein extraction. Therefore, the decreasing dependence $\mu(T)$, and increasing ones $h(T)$ and $\tau_0(T)$ contribute significantly to the fluid flow. Due to the above discussed complex properties of the cellular suspensions, their physical behaviour differs from uniform liquids.

Conclusions

Steady flow of a viscoplastic suspension of RBCs through a microtube at different temperatures has been studies. The temperature dependencies of the material parameters as well as the Fåhræus–Lindqvist and Copley-Scott Blair phenomena have been taken into account. The measurement data have been discussed based on the theoretical results.

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