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DEPENDENCE OF THE VISCOSITY ON THE CONCENTRATION OF PARTICLES BY THE EXAMPLE OF BLOOD AND ERYTHROCYTIC SUSPENSIONS

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A model of the dependence of the relative viscosity of blood and suspensions of erythrocytes on their volume concentration is proposed. Both parameters of the model correlate differently with each other in three regions of erythrocyte concentrations (for man: Hct < 0.3, Hct = 0.3–0.7, Hct > 0.7). They change abruptly when going through the boundaries of the regions. It is suggested that one of them reflects the intensity of interaction of particles in a suspension and the other is related to the effective radius of hydrodynamic resistance. The model adequately describes the experimental data on the rheology of protein solutions and other suspensions.

The problem was originally formulated in the following way: how does the viscosity of a suspension of erythrocytes depend on their dimensions and shape? Professor S. Chien and co-workers and other researchers of the rheology of blood had been deeply involved in solving this question [1–5], but then interest in it decreased and the problem remained unsolved.

Modeling of the viscosity of suspensions is closely associated with an analogous problem for protein solutions. Protein molecules are capable of aggregating and being deformed, and their dimensions are much larger than the dimensions of the solvent molecules. The curves of flow of protein solutions and an erythrocytic suspension are qualitatively the same: the viscosity decreases with increase in the rate of shear and tends to the lower limit. However, it is known that at the same molecular weight and concentration, solutions of globular proteins are less viscous than solutions of elongated proteins [6]. On the contrary, the viscosity of a suspension of erythrocytes decreases in the case of their elongation (deformation) under the action of shear forces. These facts must be remembered, even though in analyzing the viscosity of protein solutions one should also take into account the indeterminacy of the rate of shear [6] — it is entirely possible that at low rates of shear filamentous protein molecules aggregate more intensely in solution than those coiled. Moreover, the shape of the protein molecules was judged from the data of the x-ray structural analysis carried out on crystals of the substance studied, whereas the shape of a molecule in solution can be different.

It should be noted first of all that Hct (ratio of the length of the column of erythrocytes precipitated in the centrifuge to the length of the column of a liquid in the capillary) is a characteristic of a suspension, which has a rather indirect bearing to the concentration of particles. This quantity depends on the rotational velocity and geometry of the centrifuge, the time of centrifuging, and the temperature; in the case of standardization of these characteristics, it depends on the density of packing of erythrocytes, which in turn depends, for example, on the pH of the medium and the concentration of fibrinogen in the blood plasma. A simple experiment shows that when fibrinogen is added to the blood plasma, Hct measured on a special microhematocrit centrifuge (MGTs-8) decreases significantly at a constant concentration of cells in the samples (Fig. 1). Since about 0.5 g% of fibrinogen has already been contained in the blood plasma of a healthy donor, the Hct (measured on a centrifuge) of a sample containing the same amount of erythrocytes will be even higher in a physiological salt solution. As the curves of the dependence of η/η_m on Hct show, the viscosity of erythrocytes in the physiological salt solution is always lower than that of whole blood. At the same time, the curves of flow of the samples in which a constant concentration of erythrocytes was maintained show that for high rates of shear the values of η/η_m are the same in these two media (Fig. 2).

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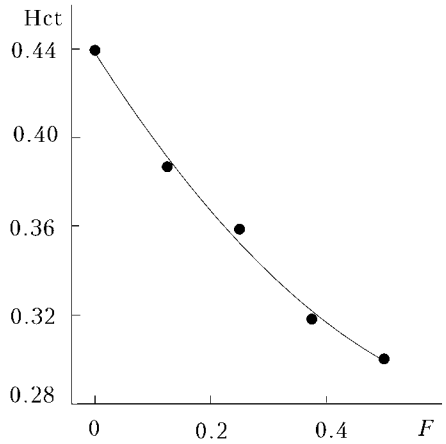

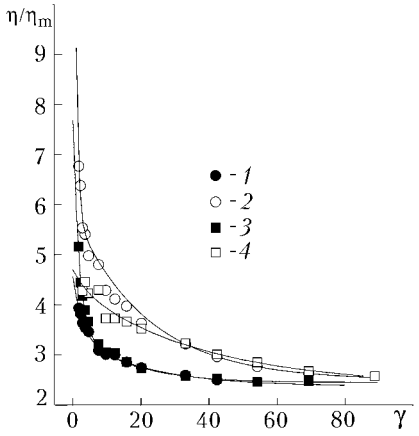

Fig. 1. Dependence of the hematocrit Hct (MGTs-8) on the concentration of fibrinogen added to the plasma. *F*, g%.

Fig. 2. Dependences of the relative viscosity of the erythrocytic suspension of man on the rate of shear: 1) in the plasma + 0.96 g% of fibrinogen, 2) in the plasma, 3) in the 0.85% NaCl + 0.96 g% of fibrinogen, and 4) in the 0.85% NaCl. In all the samples the same erythrocyte concentration ($3.17 \cdot 10^{12}$ 1/liter) was maintained.

Since practically in all the works the portion of the entrained medium is not given, it should be remembered that simple division of Hct by V_{er} gives a regular mistake in the concentration of cells in the direction of increasing values.

In modern clinical laboratories, the concentration of erythrocytes and their volume can be measured on Micros-type apparatus and the true hematocrit Hct (Micros) — the sum of the volumes of all the cells in a unit volume of a suspension — can be determined. Parallel experiments have shown that for the blood plasma of a healthy donor we have

$$\text{Hct (Micros)} \approx 0.89 \text{ Hct (MGTs–8)} . \tag{1}$$

At most, the aforesaid should be taken into account when the data of different works are compared. All other things being equal, Hct is proportional to the concentration of particles in the suspension.

As for the relative viscosity, it is more convenient to use the viscosity of the relative carrying medium and not the viscosity of water (η/η_m) in order that this quantity be equal to unity at the zero concentration of cells.

At low rates of shear, we have the disaggregation of erythrocytes in the blood samples; in this case, the number of particles (aggregates) increases and their size decreases until individual erythrocytes are left. This takes place at rates of shear of the order of 1 sec^{-1}. Then erythrocytes begin to deform and elongate, which also decreases the viscosity of the suspension; in this case, their number is constant but the shape changes. For erythrocytes in the plasma and for other cases where we have the aggregation and disaggregation of particles in the suspension (protein solutions and electrorheological liquids), it is more convenient to use the volume concentration of particles since in the process of disaggregation the concentration of particles in the suspension and their volume change, while the value of Hct remains constant.

The dependences of the relative viscosity of erythrocytic suspensions on the concentration of cells are described by the formula

$$\ln (\eta/\eta_m) = a\text{Hct}^b . \tag{2}$$

There is reason to assume that into (2) we should substitute the effective packed cell volume

$$\text{Hct}_{ef} = \text{Hct (Micros)} + V_m ,$$

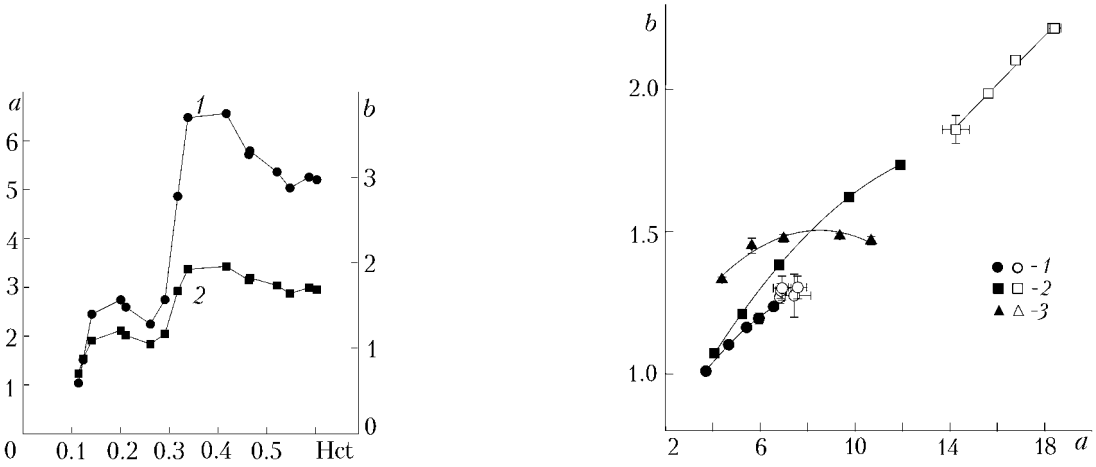

Fig. 3. Dependences of the parameters of (2) *a* (curve 1) and *b* (curve 2) on the hematocrit. The data of [1], the erythrocytes of the camel and the llama in the plasma. $T = 37^{o}$C and $\gamma = 100$ sec^{-1}.

Fig. 4. Correlations of the parameters of (2) *a* and *b* with each other [1) Hct < 0.3, 2) Hct ≈ 0.5, and 3) Hct > 0.7]. The data of [4], human erythrocytes in the 0.85% NaCl. The dark points are normal erythrocytes; the light points are erythrocytes treated with acetaldehyde. $T = 37^{o}$C and $\gamma = 0.01 - 52$ sec^{-1}.

i.e., a quantity that is larger than the sum of the volumes of cells by the relative volume of the medium entrained by the cells. Actually, as is seen in Fig. 2, the concentrations of erythrocytes are the same in all the samples. However, the viscosity in the samples with fibrinogen is much lower, especially at low rates of shear when the erythrocytes with fibrinogen are strongly aggregated in comparison with the samples with a low content of fibrinogen. This fact can be explained only on the assumption that the viscosity depends on Hct_{ef}, since the volume of the increased medium abruptly decreases with increase in the degree of aggregation of particles. It is rather difficult to determine V_m experimentally; moreover, this quantity for a suspension differs from that for shear flow. In actual practice, one has to use the measured packed cell volume, which changes the value of *a* in calculations and not the value of *b*.

To understand the physical sense of the parameters *a* and *b*, we processed our data and the literature data on the blood rheology by formula (2) with the use of the software of the SigmaPlot Windows program. We calculated the values of the parameters *a* and *b* for five neighboring points of the dependence of η/η_m on Hct; the values obtained were assigned to the central point of the five points. To calculate the dependences of *a* and *b* on Hct, we successively shifted the selected five points along the curve. The method described was used for processing the data in [1], where the concentration dependences of the viscosity of erythrocytes of the goat (V_{er} = 18.2 μm^3), the sheep (V_{er} = 46 μm^3), the dog (V_{er} = 66 μm^3), the camel and the llama (V_{er} = 56.7 μm^3), and man (V_{er} = 88 μm^3) were thoroughly investigated in three media: 1) plasma, 2) 9.7 g% of albumin + 0.85% NaCl solution, and 3) physiological salt solution (0.85% NaCl). The measurements in [1] were carried out on an Ostwald capillary viscosimeter at $T = 37^{o}$C and $\gamma = 100$ sec^{-1}, i.e., at a rate of shear at which erythrocytes were completely disaggregated and practically ultimately deformed. The erythrocytes of the camel and the llama were shaped as an elongated spheroid with dimensions of the axes 7.5 × 3.8 μm; the other erythrocytes were shaped as biconcave disks.

We carried out the experiments on human blood usually at $T = 30^{o}$C or $T = 37^{o}$C with the use of a VIR-78 coaxial-cylindrical viscosimeter.

For all the groups of mammals we detected three regions of erythrocyte concentrations, between which there took place an abrupt change in the parameters of (2) (Fig. 3). We varied the boundaries of the regions for different species of mammals; the differences were particularly strong for the erythrocytes of the goat (they were the smallest): both transitions were shifted to the side in the direction of increasing values of the hematocrit.

The parameters of (2) *a* and *b* correlated with each other, but in different concentration regions these correlation dependences were different (Fig. 4). In the regions of low and medium concentrations (Hct < 0.7), there took place

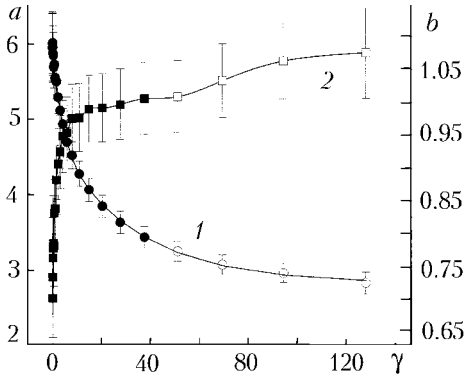

Fig. 5. Dependences of the parameters of (2) *a* (curve 1) and *b* (curve 2) on the rate of shear. Human erythrocytes in the plasma, Hct = 0.3–0.7, $T = 37^{o}$C. The region of deformation of erythrocytes is denoted by light points. γ, sec^{-1}.

a correlated decrease in the parameters with increase in the rate of shear, and in the region of higher concentrations the value of *a* decreased with increase in the rate of shear but the value of *b* remained practically constant (Fig. 4).

The analysis of the dependences of *a* and *b* on the rate of shear reveals a strong influence of the nature of the carrying medium. In the physiological salt solution, where there is no aggregation of cells, both parameters decrease with increase in the rate of shear. In the plasma, the pattern for the parameter *b* changes to the reverse: it abruptly increases in the region of the disaggregation of erythrocytes, then a plateau is observed, and then it insignificantly increases in the region of deformation of the erythrocytes (Fig. 5).

It may be suggested that the parameter *b* reflects the intensity of interaction of the suspension particles with each other — the frequency and quality of collisions (for rigid particles, *b* is larger, all other things being equal). Whatever the medium, the parameter *b* decreases with increase in the concentration of particles or in the degree of their aggregation, i.e., when the distance between the particles increases. But it is possible that the change in the fraction of the medium, entrained as a result of the aggregation of cells, plays a decisive role in this process; therefore, this question is still not understood. As for the parameter *a*, the assumption of its relation to the effective radius of hydrodynamic resistance of particles seems to be quite reasonable at the given stage of the work.

Formula (2) adequately describes the data on the rheology of solutions of proteins (hemoglobin and fibrinogen) and other suspensions, for example, a suspension containing latex particles [7].

The aim of further work is to find the relation of the parameters of (2) to the shape of the particles and the degree of their aggregation. It is impossible to understand for the present how the above-mentioned contradiction implying that the elongation of a protein molecule leads to an increase in the viscosity of the solution and the elongation of erythrocytes leads to a decrease in the viscosity of the suspension is resolved. The entire range of erythrocyte concentrations should be divided into three regions and the data obtained for each individual region should be compared. At the boundaries of the indicated concentration regions, the system experiences a qualitative jump that manifests itself as a reliable change in the values of the parameters of the model.

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NOTATION

Hct, packed cell volume (volume concentration of erythrocytes); Hct_{ef}, effective hematocrit; V_m, relative volume of the entrained medium; V_{er}, erythrocyte volume, μm^3; η, viscosity of a suspension, Pa·sec; η_m, viscosity of the carrying medium, Pa·sec; γ, rate of shear, sec^{-1}; *F*, fibrinogen concentration, g%; *T*, temperature, C; *a* and *b*, parameters. Subscripts: m, medium; ef, effective; er, erythrocytes.

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