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Analysis of Complex Viscosity in a Group of Patients with Circulation Disorders

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Rheology of viscoelastic fluids is a complex phenomenon. Full blood is an example of a body fluid of non-Newtonian character with pronounced viscoelastic properties. Blood flow in the circulatory system depends not only on the physical and physico-chemical properties of blood but also on the structure and properties of the vascular system. Blood viscosity is one of the most important factor determining the blood flow. Its value depends on the shear rate, hematocrit, erythrocyte aggregability and deformability, and on the plasma viscosity and composition. In the course of the investigation we utilized oscillatory methods, called also dynamic mechanical analysis. The technique principle is based on the measurement of the amplitude and phase of oscillations of the sample subject to a harmonic force with certain amplitude and frequency. The results of dynamic mechanical analysis were used to determine the viscoelastic properties of blood samples. We performed also the standard flow curve measurements of the blood plasma samples, that is shear stress as a function of shear rate in the rotary mode. All measurements were performed by means of a Contraves LS-40 rheometer on blood samples taken from two groups of patients. One group contained patients after heart attack, while the second one — after cerebral infarction. In none of the groups the patients were in an acute state. Information obtained from oscillatory measurements indicate increased erythrocyte aggregability in both groups of patients.

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1. Introduction

Rheological characterization of any material includes determining of its two major properties: viscosity which defines its resistance to flow and elasticity which defines its resistance to deformation. With respect to the response to shearing, materials whose response to shear is constant in time are called rheostable, those which change in time are called rheo-unstable, and those which share the properties of liquids and solids are called viscoelastic media. Hemorheology is a part of rheology dealing with the flow properties of blood. The rheological properties of blood depend both on the rheological and physiological characteristics of the circulatory system and on the physico-chemical properties of blood. Features related to the blood flow in blood vessels are called blood fluidity [1].

Blood is an inhomogeneous liquid — a suspension of red cells in plasma, which is often compared to emulsion [2]. Blood red cells, like droplets of emulsion, contain liquid enclosed by the lipid membrane, but are much more durable and deformable. In favorable conditions erythrocytes can form aggregates. Observing the blood flow in the smallest blood vessels one can see the erythrocytes deform when the vessel diameter reduces to the cell size. In turn, blood flow in large vessels is accompanied by the phenomenon of axial accumulation of red cells. The factors influencing the blood flow are: hematocrit value, erythrocytes aggregability, deformability and orientation in flow, plasma viscosity η_{p} and shear stress τ [3]. According to the experiment of Chien, in the range of low shear rate γ' the dominant phenomenon is the aggregation of erythrocytes, while in the range of high shear rate — their deformation [4].

A classical rotational viscometry measurement aims at determination of so called flow curves (shear stress–shear rate relation), the degree of thixotropy, and the yield point. Hemorheological study in a great deal is based on the measurements of whole blood viscosity and plasma viscosity. In the case of non-Newtonian liquids, like blood, their viscosity depends on the shear rate. The plasma viscosity does not depend on the shear rate — plasma is a Newtonian liquid.

Apart from standard viscometric techniques there exist non-viscometric methods like oscillatory techniques, also referred to as dynamical mechanical analysis (DMA). The operating principle is based on determination of the amplitude and phase of the oscillations of the sample subjected to a harmonic force with certain amplitude and frequency. In an oscillatory experiment one determines viscoelastic properties of the liquid under consideration by calculating the elastic modulus G', the loss modulus G'', the complex viscosity η^* (Eq. (1)) as a function

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of the circular frequency ω, deformation amplitude γ, temperature T, and time t,

$$\eta^* = \eta' + \mathrm{i}\eta'', \qquad (1)$$

where η' and η'' are the viscous and elastic components of the complex viscosity η^*, respectively. Interpretation of the results obtained from DMA measurements for blood samples is usually qualitative [5–8]. Despite the fact that different mathematical models properly describe the viscoelastic properties of many non-Newtonian liquids, like polymers melts and colloidal suspensions, applicability of such models to blood samples turned out to be rather poor [8]. Therefore, in this study we restrict the analysis of DMA measurements to simple comparison of the viscous and elastic components of η^* measured at different values of the shear rate amplitude γ_0'.

2. Materials and methods

Measurements of the blood complex viscosity η^* have been performed by means of a rotary-oscillating rheometer Contraves LS-40 applying constant frequency oscillations of frequency $f = 0.5$ Hz and decreasing shear amplitude γ_0. Two groups of patients were included in the study. The first group consisted of 42 patients, aged 37 to 56, after transmural myocardial infarction experienced 6 to 10 years before the study, in the period of clinical stability. The second group consisted of 28 patients, aged 41 to 84, after ischemic stroke which took place up to 6 h before the uptake of the blood sample. The measurements were performed at the temperature of 37 °C. The blood was taken to vials containing 1.6 mg EDTA per ml of blood. For each blood sample the hematocrit value was measured using the standard method. Blood plasma viscosity was determined from a regular rotary measurement of a flow curve. The value of η_p was calculated from the linear regression of the $\tau(\gamma')$ dependence.

3. Results

The oscillatory experiments allowed for estimation of the viscous and elastic components of the complex viscosity in the two groups of patients. The values of the blood viscosity components at several chosen values of γ_0' together with mean hematocrit values and plasma viscosities have been presented in Table. Graphical representation of the complex viscosity shear rate dependence has been shown in Figs. 1 and 2 for group 1 and 2, respectively.

TABLE

The values of the viscous and elastic components of the complex viscosity in the group of patients with acute cerebral ischemic episode and in the group after myocardial infarction. Parameter p indicates the limiting value of confidence level when the difference between the groups becomes statistically significant.

Rheological parameter	Patients after myocardial infarction ($n = 42$)	Patients with cerebral ischemic episode ($n = 28$)	p
hematocryte	44.0 ± 0.5	43.0 ± 0.5	–
plasma viscosity	1.275 ± 0.014	1.503 ± 0.047	< 0.001
value of η' at $\gamma_0' = 0.2$ s^{-1}	7.0 ± 0.3	9.8 ± 0.8	< 0.001
value of η' at $\gamma_0' = 1$ s^{-1}	6.9 ± 0.2	9.6 ± 0.5	< 0.001
value of η' at $\gamma_0' = 10$ s^{-1}	5.4 ± 0.2	6.6 ± 0.4	< 0.005
value of η' at $\gamma_0' = 20$ s^{-1}	5.0 ± 0.2	5.9 ± 0.4	< 0.04
value of η'' at $\gamma_0' = 0.2$ s^{-1}	7.1 ± 0.4	7.3 ± 0.6	–
value of η'' at $\gamma_0' = 1$ s^{-1}	4.7 ± 0.3	5.1 ± 0.4	–
value of η'' at $\gamma_0' = 10$ s^{-1}	0.8 ± 0.1	1.4 ± 0.3	< 0.04
value of η'' at $\gamma_0' = 20$ s^{-1}	0.4 ± 0.1	0.7 ± 0.2	–

4. Discussion

The analysis of the measurements results showed that the hematocrit values in both groups were not significantly different in the statistical sense. Such result allows to exclude the influence of hematocrit value on other estimated rheological parameters.

Observed statistically significant difference in the plasma viscosity between the two groups (higher value in the group of patients in the acute phase of the ischemic stroke) is in agreement with the literature data. Many publications point to the increase of plasma viscosity in the acute state of ischemic stroke [9–11].

Analysis of the viscous and elastic components of blood viscosity allows not only for estimation of blood viscosity but also for estimation of erythrocytes aggregability and deformability. Aggregation and deformation of red cells

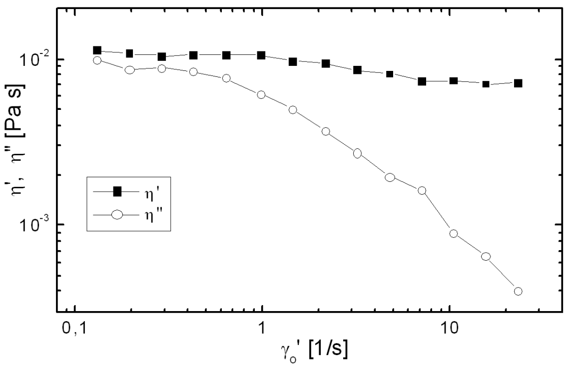

Fig. 1. Dependence of the viscous and elastic components of the complex viscosity on the amplitude of shear rate γ_0' (for oscillation frequency of 0.5 Hz) in the group of patients after myocardial infarction.

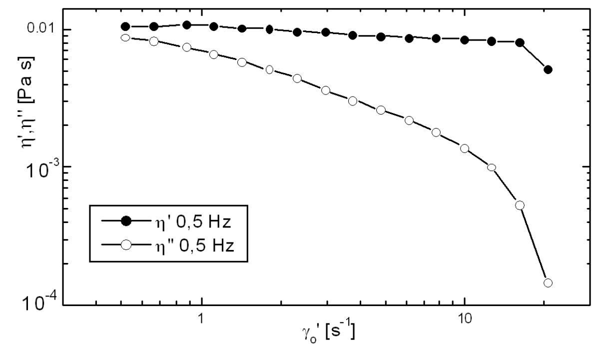

Fig. 2. Dependence of the viscous and elastic components of the complex viscosity on the amplitude of shear rate γ_0' (for oscillation frequency of 0.5 Hz) in the group of patients in the acute phase of cerebral ischemic stroke.

in big extent influences the blood flow in the circulatory system [1].

Comparison of the results obtained for the viscous component η' of the complex blood viscosity shows its higher mean values at all shear rate values listed in Table in the group of patients in the acute phase of ischemic stroke compared to the group of patients after myocardial infarction. These results corroborate with other our results obtained for this group of patients [9]. Comparison of current results with the data obtained for patients with remote ischemic episode [12] indicates an increase of plasma viscosity and whole blood relative viscosity in the group of patients in the acute phase of ischemic stroke with respect to the patients with remote ischemic episode.

Comparison of the elastic components of the complex viscosity for the two studied groups of patients shows higher values in the group of patients in the acute phase of the ischemic stroke. It is also in agreement with some literature data [12] where increased red cells aggregability accompanied by decreased deformability was reported. Such combination may lead to creation of unordered packets of red cells which can result in hindered blood flow.

5. Conclusions

Comparison of the obtained viscous and elastic components of the blood complex viscosity in the two groups of patients shows a significant increase of both components in the group of patients in the acute phase of stroke with respect to the patients after myocardial infarction experienced at least 6 months before the study.

The comparative analysis was possible thanks to equal hematocrit values in both groups and identical procedures applied in both series of measurements.

The plasma viscosity was higher in the group of patients in the acute phase of ischemic stroke.

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