EXPERIMENTAL RELATIONSHIPS BETWEEN THE BLOOD CONDUCTIVITY AND BLOOD RHEOLOGICAL PROPERTIES

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Abstract: The study represents a concurrent measurement system (MS) for determination electrical and rheological properties of blood by measuring the conductivity at different shear rates and at different local structure of the flow. Contraves Low Shear 30 rotational viscometer was used as a base unit. The concurrent MS includes a pair of platinum electrodes in cylindrical ring shape, embedded into the wall of resin made replica of the Couette type flow chamber of the rheometer. It includes also and a device, developed by the conductometric method and a software for measurement of conductivity of biological fluids and natural biological mixtures (Data acquisition system). The electrorheological (ER) properties of whole human blood and plasma at different shear rates and different local structure of the flow field have been studied by the system. The relationship between the blood conductivity was studied in parallel with the changes in the rheological behaviour of the whole human blood. The time variation of blood conductivity at different flow regimes and its dependence on the RBC concentration and shear rates were determined. Blood and plasma apparent viscosity were investigated under electric field and without electric field of 2 kHz. The results show that the blood conductivity and apparent viscosity are strongly dependent on the considered blood and flow factors.

Introduction

The phenomenon of electrorheology represents changes in the rheological behavior due to imposition of electric field [1,2]. The electrorheological (ER) properties of blood are determined by a variety of factors including the electrical properties of blood cells and plasma, the fractional volume concentrations of the blood cells as well as the shape and orientation of the cells. When blood flows, all these complex factors may change and contribute in a different way to the overall impedance of the flowing blood. Blood electrical properties (impedance, permittivitty, conductivity etc) and their measurement have a wide range of applications in biomedical field [3,4]. However the relationship between the blood impedance and conductivity is not well studied despite the importance of the knowledge to a full understanding and interpreting of the results in terms of cardiovascular circulation and hemorheology. The aim of the study is to determine electrorheological properties of blood using rotational Low Shear 30 Contraves viscometer by means of measurement of conductance of blood at different shear rates and at different local structure of the flow field. The aim of the study is to investigate the change of viscosity during motion at constant frequency of the applied electric field. For the purpose a concurrent measurement system (MS), using a Contraves Low Shear 30 (LS 30) rotational viscometer as a base unit was developed. It includes a pair of platinum electrodes in cylindrical ring shape, embedded into the wall of resin made replica of the Couette type flow chamber of the rheometer. The developed system is capable of concurrently measuring electrical and rheological properties of blood by measuring the blood conductivity and the apparent viscosity and shear stresses at different shear rates and at different local structure of the flow. Using this system, we have investigated the relationship between the electrical conductivity – the active main component of the electrical impedance and the hemorheological determinants as hematocrit as well as on the flow and on the regime of the applied shear rates in time.

Materials and Methods

Measuring and data acquisition system

Two different methods for characterising of electrical and rheological properties of blood are known

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in the literature: impedancometric [5] and conductometric [6]. As the impedancometric method needs an expensive apparatuses, the conductometric method has been applied to develop measuring and data acquisition system for determination electrorheological properties of blood.

The concurrent measurement system (MS), using a Contraves Low Shear 30 rheometer (Zurich, Switzerland) as a base unit was developed [7] (Figure1, Figure 2). A resin made replica of the Couette type flow chamber of the LS 30 rheometer was made. It includes a pair of platinum electrodes in cylindrical ring shape, embedded into the wall. The electric field lines in cylinder-cylinder rotational viscometers with different kinds of outer and inner cylinder proceed radially between the surfaces of the measuring cylinders. It can be assumed that the field is be homogeneous since the width of the flow slit is very small compared with the cylinder diameters [6]. Both measuring systems MS 1/1 have equal geometrical dimensions: diameter of the measuring cup is 12 mm; diameter of the measuring bob is 11 mm and its height is 8 mm. The width of the gap between cylinders is 1 mm.

Figure 1: Couette type flow chamber of the rheometer Low Shear 30 Contraves between the coaxial cylinders – pair of electrodes

The resin flow chamber isolates the measuring unit electrically from the base unit - Contraves Low Shear 30 rheometer. The inner cylinder (measuring bob) is electrically isolated by varnish holding (cover). The platinum electrodes of the resin flow chamber are connected by sliding golden contacts to a conductometric device especially developed for measurement the conductivity of biological fluids and natural biological mixtures as a function of shear rates (Figure.1-2).

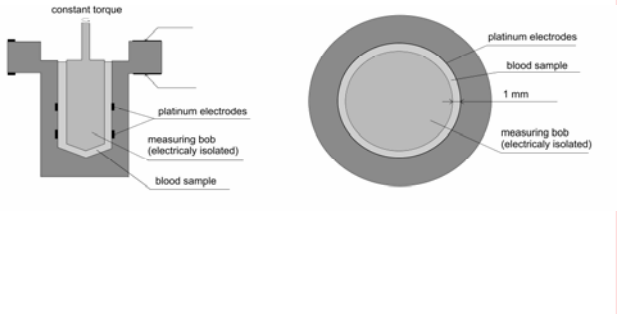

Figure 2: Principal scheme of the concurrent measurement system (MS) of the Couette type of the rheometer Low Shear 30 Contraves between the coaxial cylinders – pair of electrodes

The conductometric method is based on the measurement of the AC current response resulting from a small amplitude (200 mV p-p) sinusoidal (2 kHz) AC voltage applied between a pair of platinum electrodes. The AC current is converted in voltage with the aim of a controlled gain I/E converter. The low frequency noise (50/60 Hz) is eliminated by a two stage Butterworth High Pass Filter. Then the 2 KHz AC voltage signal is processed by a precise linear rectifier and then by a low pass filter in order to obtain a DC signal proportional to the measured electrical conductivity of the blood or other biological sample.

This DC signal could be recorded by means of X-Y recorder or by a PC using a specially developed device and software for collection and processing of data from the rotational viscometer Contraves Low Shear 30 (Data acquisition system). The microprocessor module has been managed by the program, which has been installed in the PC, through interface RS 232. By means of appropriate graphic interface in the program the frequency of data acquisition has been given. The rate of data acquisition could be given from 256 μs to 15 min period between two measurements. These data graphically are visualized on the desktop of the PC as a function of time. The developed concurrent measurement system (MS), the device and software were used as a basis for series of experiments.

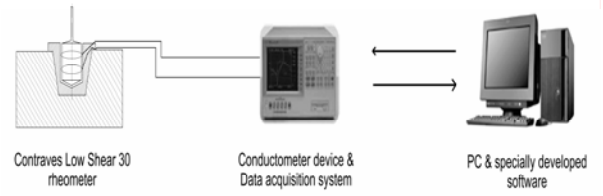

Figure 3: Principal electronical scheme of the device for acquisition and processing of data (Data acquisition system) from the rotational viscometer Contraves Low Shear 30

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The developed concurrent measuring system MS 1/1 was calibrated by means of the physiological solution (0, 9% NaCl) at T=37°C and statistically significant difference between the values of the apparent viscosity of the physiological solution, obtained by the standard and by the concurrent measuring system was not found.

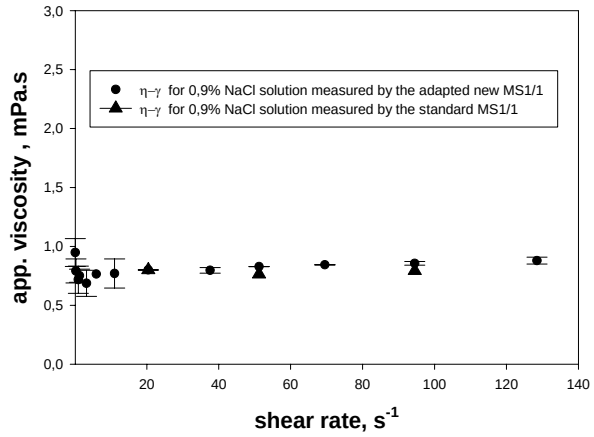

Figure 4: Comparison of the apparent viscosity, determined by the standard and the concurrent new measuring cup with 0,9% NaCl solution at 37 ˚C (n=5)

The calibration of the device and the constant of the measuring cell was determined on the basis of the measurements with 0,5%, 0, 9% and 1% NaCl at T=25°C and comparison with the literature conductivity data. The results show no changes in time of the conductivity of the NaCl solutions (Figure 5).

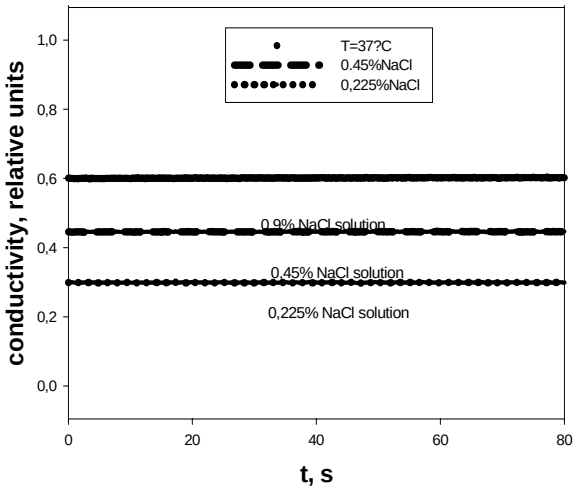

Figure 5: Conductivity of 0.9% , 0.45% and 0.225% NaCl solutions at rest, determined by the device and data acquisition system at 37˚C

Blood Samples

32 whole heparinized blood samples (H ranging from 38% up to 53%) and 6 blood plasma samples from patients with two different pathologies were collected with heparinized tubes and rheological measurements were completed within 3 hours after preparation. Whole blood viscosity was measured using a rotational Couette viscometer Contraves Low Shear 30 with the standard measuring system MS 1/1 at a steady flow over a shear rate range of 0.0237 s^{-1} to 128.5 s^{-1}; under transient flow conditions at rectangular changes of shear rates and under trapezium-liked changes of shear rates, given by the Rheoanalyzer to the LS 30 Contraves viscometer.

In parallel the conductivity of blood as a function of shear rate as well as a function of time at constant frequency (2 kHz) was measured simultaneously with blood viscosity measurements by means of the developed concurrent measurement system (MS 1/1) and device with data acquisition system.

Results and Discussion

The developed concurrent measuring system MS 1/1 was calibrated by means of measurements with physiologic 0, 9% NaCl solution at T=37°C. The apparent viscosity values of the physiologic solution, obtained by the standard and by the new are identical. The same results have been obtained and for apparent viscosity of blood, measured by the both measuring systems, shown on Figure 6.

The results of the study show, that the applied electric field with a constant frequency of 2 kHz influences the rheological properties of blood, increasing its apparent viscosity, but does not influence the rheological properties of human blood plasma (Figure 6), measured in vitro.

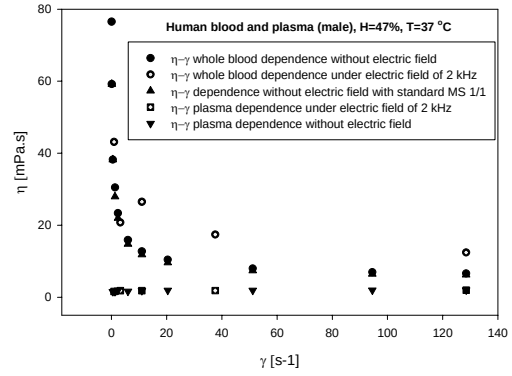

Figure 6: Apparent viscosity – shear rate dependences from human blood and plasma (male), H=47%, T=37°C. Measurements are carried out by Low Shear 30 rotational viscometer under steady shear with the standard and the concurrent measuring systems and under electric field at frequency of 2 kHz.

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It has been observed that the blood conductivity depends on the applied shear rates; due to flow the blood conductivity increases, when measured from 0,945 s^{-1} to 94,5 s^{-1} (Figure 7). It was determined that varying shear rates from 0,945 s^{-1} to 94,5 s^{-1} the conductivity of blood samples with hematocrit between 42 % and 52 % increases from 0,36 % at 0,945 s^{-1} to 3,4 % at 94,5 s^{-1}. The reason for the change of the flow properties has not yet been fully explained, but the most likely explanation would seen to be that the particles (RBCs) are electrically charged and are surrounded by a diffusive cloud of counter ions. The interface of the suspended cells and blood plasma is the site of complex phenomena as the ionisation of solid phase molecules. Resulting spatial charge distribution induces the electric potential which plays a decisive role in determining cell rheological properties and cell interaction. In the flowing blood the red blood cells deform and rotate in plasma. When an electric field is applied, the ion clouds are distorted and there is interaction [8-11].

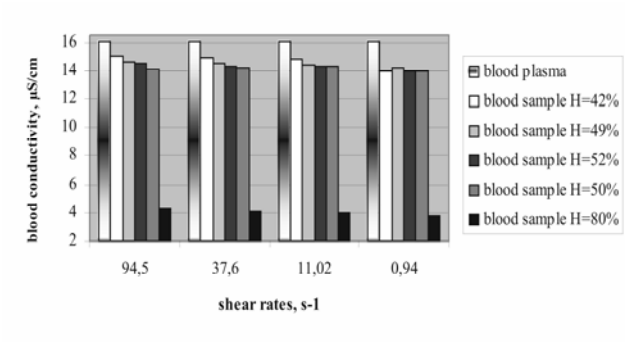

Figure 7: Experimental relationship between the blood conductivity and shear rates from 94,5 s^{-1} to 0,945 s^{-1} for whole human blood samples, measured by LS 30 Contraves, T=37^{0}C

On the other hand the results show that the hematocrit or the relative volume RBC concentration also influences on the blood conductivity. It was experimentally observed that the conductivity increases in the whole shear rate range from 0,945 s^{-1} to 94, 5 s^{-1} when the native hematocrit of investigated blood samples decreases, measured under steady flow (Figure 8). Changes of conductivity are between 4,4 % and 11,7 % for different blood samples with hematocrit values from 42 % to 80 % at one and the same shear rate from 0,945 s^{-1} to 94,5 s^{-1} .

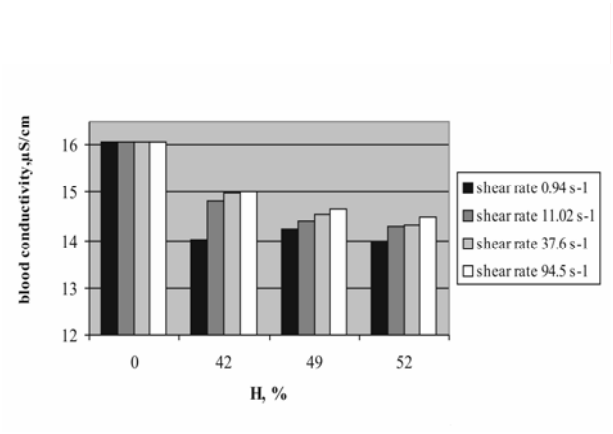

Figure 8: Experimental relationship between the blood conductivity and hematocrit at shear rates from 94,5 s^{-1} to 0,945 s^{-1} for whole human blood samples with different native hematocrit, measured by LS 30 Contraves, T=37 ^{0}C

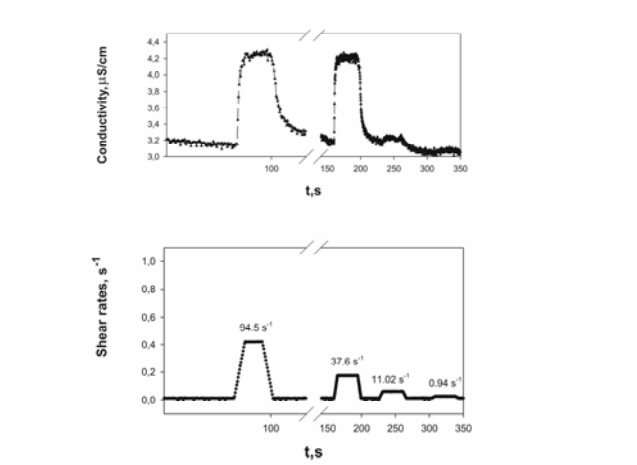

Figure 9: Experimental relationship of changes of conductivity with time (upper curve) under trapezium-shaped changes of shear rates from 0,945 s^{-1} to 94,5 s^{-1} in time (lower curve) for RBC mass (H=80%), measured by LS 30 Contraves, T=37^{0}C

The time dependent changes of blood conductivity at different changes of shear rates were investigated (Figure 9). It is established that the blood conductivity is dependent on the regime and time of the applied shear rates in the Couette viscometric flow. These dependences reflect the structuring of the blood flow under different shear rates changes and should be able to detect the aggregation-disaggregation processes in the blood. The results show as well that valuable information could be received about the mechanical properties of blood, in particular about the kinetics of "rouleaux formation". The time dependences of the blood conductivity follow the morphological transformations of RBC aggregates during the aggregation-desaggregation processes. These results

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suggest that this technique may be used to clarify the mechanism of dynamics of RBC aggregates.

Conclusion

The study represents a developed concurrent measurement system (MS), using a Contraves Low Shear 30 (LS 30) rotational viscometer as a base unit for determination electrical and rheological properties of blood by measuring the conductivity at different shear rates and at different local structure of the flow. The concurrent MS includes also and a device, developed by the conductometric method and a software for measurement of conductivity of biological fluids and natural biological mixtures (Data acquisition system).

They could be successfully used for determination of ER properties of blood and other natural biological mixtures.

It was found in this study that rheological properties of whole human blood have been changed under electric field with constant frequency (2 kHz) when measured in vitro. Blood conductivity is dependent on the changes of the shear rates and the hematocrit. While in the same time it was found that rheological properties of human blood plasma have not been changed under electric field with a constant frequency (2 kHz). Plasma conductivity is not dependent on the changes of the shear rates and on the regime of the flow.

The results of this study show the blood conductivity relationship to some hemorheological determinants as the relative volume of red blood cells and the parameters of the steady and transient viscometric flow. It is found, that when subjected to shear steady flow, the blood conductivity is determined mainly by the shear rate. An increase due to flow was found from 0, 36 % at 0.945 s^{-1} and about 3, 4 % at 94.5 s^{-1}. Blood conductivity dependences on the hematocrit have been determined, showing conductivity decrease when the relative RBC concentration volume increases. The results of our study support previous data for the cow blood conductivity increases in 1 MHz to 1 GHz frequency range [12].

The time dependent changes of blood conductivity at different changes of shear rates were investigated. It is established that the blood conductivity is dependent on the regime and time of the applied shear rates in the Couette viscometric flow. These dependences reflect the structuring of the blood flow under different shear rates changes and should be able to detect the aggregation-disaggregation processes in the blood. The results show as well that valuable information could be received about the mechanical properties of blood, in particular about the kinetics of "rouleaux formation". The time dependences of the blood conductivity follow the morphological transformations of RBC aggregates during the aggregation-desaggregation processes. These results suggest that this technique may be used to clarify the mechanism of dynamics of RBC aggregates. Thus the results of the study expand the experimental approach based on electrical properties of RBCs to study the effect of the size and morphology of aggregates [13,14].

It follows from the study, that the blood conductivity is strongly dependent on the above conditions which also determine the blood flow properties. When blood conductivity is applied to cardiovascular circulation phenomena a more rigorous analysis as well as a careful calibration of the impedance measurement technique versus the multiple determinants should be need. These results in combination with previous ones [7] suggest that this technique can be used for studies of kinematics and dynamics of blood rheological properties and RBC aggregation and probably for diagnostic and therapeutic purposes.

Acknowledgements

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