MOVEMENT OF THE BLOOD AND CHANGES IN ITS ELECTRICAL CONDUCTIVITY

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Like other biological fluids, the blood of man and animals has a relatively high electrical conductivity by comparison with the remaining tissues of the body. For this reason the electrical conductivity of any area of the body and organ depends on the quantity of blood present in it. This relationship between the electrical conductivity of the tissues of the body and their blood content is at the basis of electroplethysmography [3, 6 and others]. However, the electrical conductivity of the blood is not constant in physiological conditions, but depends on the rate of its movement; this introduces errors during investigation of the circulation of the blood by electroplethysmographic methods.

Sigman, Kolin, Katz et al. [7] found that the electrical conductivity of circulating blood changes in relation to changes in the rate of the circulation: as the linear velocity of the blood flow rises from 0 to 40 cm/sec, the electrical conductivity of the blood increases by 5-10%. These workers suggested that this phenomenon was due to agglutination. Changes in the electrical conductivity of a column of blood in the aorta of a rabbit when the blood flow was suddenly arrested were observed by Weeks and Alexander [8]. A. A. Kedrov and A. I. Naumenko [1], from studies of the pulse variations in the cranial cavity by the method of electroplethysmography, point out that the resistance of the blood is a function of its movement.

In this connection there is undoubted interest in the study of the relationship of changes in the electrical conductivity of the blood and its movement and the frequency of the alternating current used to measure it.

EXPERIMENTAL METHOD

Measurement of the electrical conductivity of the blood while moving was carried out by means of a special apparatus [3] producing alternating current of various frequencies between a range of 20 cps to 500 kcps. The blood to be tested passed at a determined velocity through glass tubes 8 mm in diameter and 600 mm long. In the lower part of the tubes were fused platinum electrodes in such a way that a line joining the centers of the electrodes formed a definite angle with the direction of movement of the blood. This arrangement of the electrodes enabled the relationship between the direction of an externally applied electric field and the change in electrical conductivity of the blood during movement to be investigated. In the experiment we used three types of tubes, in which the angle between the tube axis and the line joining the centers of the electrodes was 90°, 45° and 0°. Experiments were carried out on citrated and defibrinated blood from human subjects, dogs and cats. In the majority of cases an alternating current of frequency 300 kcps was used in the investigations.

To enable the results of the different experiments to be compared and analyzed, we used the relative change in the electrical conductivity of the blood, equal to the quotient obtained by dividing the change in electrical conductivity of the blood by the electrical conductivity of the blood at rest. Both measurements were taken in the same units (mhos). In this way we could make allowance for errors in individual experiments, since the effect of any factor applied equally to both the initial value of the conductivity and to the change in this value.

In all the experiments the relative conductivity of the blood was within limits of 0.005 to 0.008 mho, and its changes with movement amounted to 2 to 5% of the initial value.

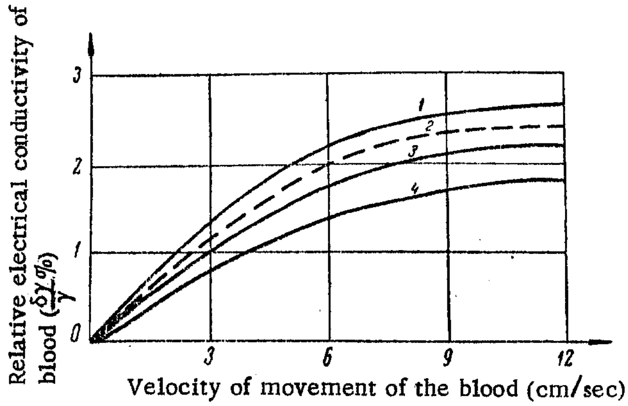

Fig. 1. Relationship of the change in the relative electrical conductivity of blood and its velocity of movement (frequency 300 kcps).
1) Defibrinated blood of a dog; 2) calculated curve; 3) citrated blood of a dog; 4) citrated of a dog, partially agglutinated.

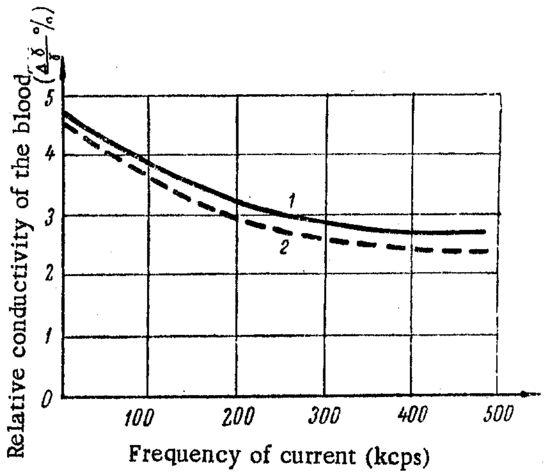

Fig. 2. Change in the relative electrical conductivity of blood in relation to the frequency of the current passing through it.
1) Experimental curve; 2) theoretical curve.

EXPERIMENTAL RESULTS

The experiments showed that both citrated and defibrinated blood change their electrical conductivity on movement (Fig. 1), and citrated blood rather less so than defibrinated. The electrical conductivity is most sharply altered when the velocity of movement of the blood increases from 0 to 15 cm/sec. Increase in the velocity of movement of the blood above 20 cm/sec causes no appreciable change in the resistance.

Keeping the velocity of movement of the blood constant (12 m/sec), we altered the frequency of the current. During the change in frequency from 20 cps to 500 kcps, the curve of the resistance of the blood fell by 30-35%. The resistance of the blood was altered most when a constant current was passed through it (Fig. 2).

To ascertain the causes of the decrease in the resistance of the blood, 30 experiments were carried out with ionized colloidal solutions and blood components, and also with hemolysed blood. These experiments showed that a change in the resistance is observed only in the blood or component of the blood in which the red cells are present as integral structural elements. Neither blood plasma nor hemolysed blood changes its resistance on movement. In experiments with suspensions of red cells it was shown that their resistance decreases on movement according to the same law as that obeyed by whole blood, but in contrast to whole blood, the change in the resistance of the suspensions is rather smaller. The magnitude of the change in the resistance of a suspension of red cells depends on their concentration (Fig. 3).

It was found that the relative change in the electrical conductivity depends on changes in the surface of the red cells. In fact, from a comparison of the physicochemical data on the composition of the blood of the dog and cat it may be seen that the surface of the cat's red cells is 30% smaller than the dog's. The relative change in the resistance of the blood of these animals during movement at the same velocity differs by the same degree (Fig. 4). Red cells, placed in isotonic saline, acquire a spherical shape, and hence their surface area decreases. From a comparison of the findings obtained in the experiment with whole blood and with the suspension of red cells, it may be seen that the latter changes its resistance less on movement.

It follows from the experiments with hemolysed blood that disturbance of the structure of the red cell deprives the blood of this property.

It may be concluded from the results obtained that the relative electrical conductivity of the blood is greatly influenced by its chemical composition as a system; exclusion of one factor from it results in a change in the entire system. This is confirmed by a comparison of the results obtained in experiments with citrated and defibrinated blood. In trying to understand this relationship it is important to realize that the blood plasma, although it does not change its electrical conductivity on movement, nevertheless has a considerable effect on the change of electrical conductivity of the whole system.

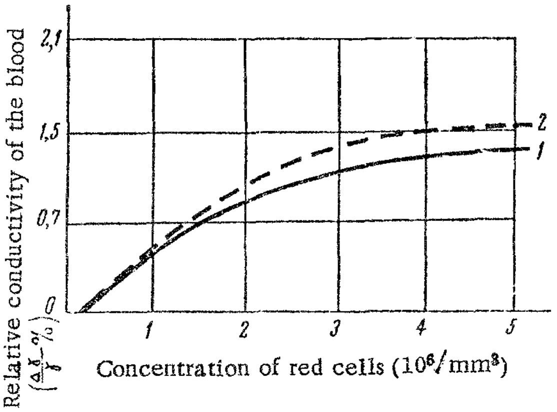

Fig. 3. Relationship between the change in relative electrical conductivity and the concentration of red cells in a suspension (velocity of movement 12 cm/sec).
1) Experimental curve; 2) theoretical curve.

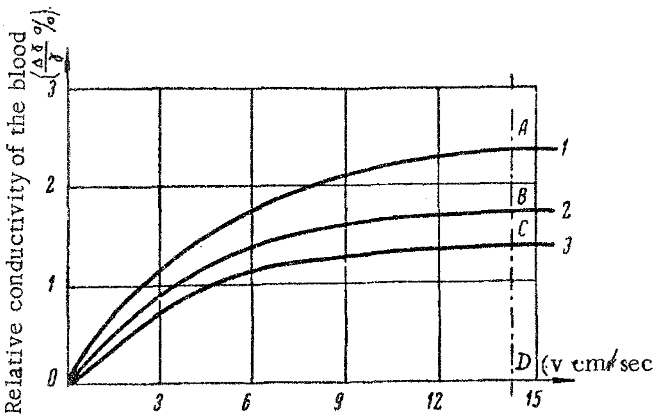

Fig. 4. The importance of increase in the surface area of red cells in changes in the electrical conductivity of the blood on movement.
1) Citrated blood of a dog; 2) citrated blood of a cat; 3) suspension of cat's red cells (concentration $4 \cdot 10^6$/mm^3). The ratios AD/BD and BD/CD correspond to the ratio of the surface areas of the red cells of dogs and cats and of cats' red cells in plasma and isotonic solution.

The effect of agglutination was elucidated in special experiments with blood in which the red cells were agglutinated to different degrees (the degree of agglutination was altered by allowing the blood to stand before the experiment). The experiments showed that the change in the electrical conductivity of the agglutinated blood was 1.2 times smaller than in the unagglutinated. Agglutination changes the electrical conductivity of the blood on movement only quantitatively, without altering the general law (see Fig. 1, 4). This is due to the fact that the active surface of the red cells is diminished by agglutination.

The increase in the electrical conductivity of the blood on movement may be explained on the assumption that the red cells carry an electric charge on their surface; their movement in a definite direction then produces a convection current. The red cell obtains its electric charge as the result of adsorption of polar protein molecules on its surface [5].

On the assumption that the red cells have an electric charge, it may be considered that on movement of the blood in relation to the electrodes a current is produced, whose intensity can be expressed by the formula:

$$\overline{I} = \rho \overline{V}, \qquad (1)$$

where ρ is the volume charge of one unit volume of blood, equal to the product of the number of red cells n in this volume and their electrical charge q; V is the velocity of movement of the blood.

Since in a laminar flow of fluid the velocity of its layers at different distances from the center is not the same, V is the integral velocity of movement of the blood. The current density between the electrodes during movement is expressed in the following form:

$$\overline{\delta} = \overline{\delta}_{movement} + \overline{\delta}_{rest} \qquad (2)$$

In formula (2) the item $\delta_{movement}$ is dependent on the appearance of a convection current, and δ_{rest} is the sum of the current of conductivity and the current of displacement:

$$\overline{\delta}_{movement} = qn\overline{V} \qquad (3)$$

$$\overline{\delta}_{rest} = \gamma \overline{E} \sin \omega t + \frac{\epsilon \omega}{4\pi} \overline{E} \cos \omega t \qquad (4)$$

where γ is the electrical conductivity of the blood at rest; E is the voltage of the electric current between the electrodes.

Thus the total current density between the electrodes during movement of the blood is expressed by:

$$\overline{\delta} = \gamma \overline{E} \sin \omega t + \frac{\epsilon \omega}{4\pi} \overline{E} \cos \omega t + qn\overline{V} \quad (5)$$

But the modulus of current density is equal to:

$$\delta = \gamma E \cos\alpha + \frac{\omega \epsilon}{4\pi} E \sin\alpha + qnV \quad (6)$$

where α – the angle between the vectors $\underline{E}$ and $\underline{V}$ on the assumption that the electric field is linear. In fact this assumption introduces a small error into the final formula.

The change in the electrical conductivity of the blood on movement is equal to:

$$\Delta\gamma = \frac{\delta \text{ movement}}{E} = \frac{qnV}{E} \quad (7)$$

From formulae (6) and (7), the relative change in electrical conductivity is expressed by:

$$\frac{\Delta\gamma}{\gamma} = \frac{qnV}{(\gamma + \frac{\epsilon\omega}{4\pi} \tan\alpha) E + qnV} \quad (8)$$

(the minus sign does not appear in front of the expression since the negative charge of the red cells must be considered).

Substituting the numerical values in the formula gives a relationship to the velocity and frequency of the current which differs from the experimental findings by 10-15%.

We carried out a calculation for a frequency of the applied field of 400 kcps. At this frequency the dielectric permeability of the blood has a value of 55 and the electrical conductivity γ – 0.0054 mho (2).

Formula (8) was also applied to a suspension of red cells; under these circumstances the electrical conductivity of the suspension may be calculated by the formula given in the paper by K. S. Trincher [4]:

$$\gamma_{susp.} = \lambda \frac{1 - S}{1 - \frac{1}{2} S} \quad (9)$$

where $\gamma_{susp.}$ – the electrical conductivity of the suspension; $\underline{S}$ – the volume occupied by the red cells (concentration); λ – the electrical conductivity of the isotonic solution.

From formula (8) it may be seen that the blood plasma does not change its resistance on movement, since $\rho = nq$ for the plasma ,is equal to zero.

The red cell obtains its charge as a result of the adsorption on to its surface of polar protein molecules, and for this reason the magnitude of the change in the electrical conductivity of the blood must depend on the surface area of the red cell. We can see that this relationship holds good in the data presented above.

Thus the statement by Sigman, Katz et al. [7], that the change in the electrical conductivity of the blood on movement, to a constant current, is due to agglutination, is not confirmed.

SUMMARY

The electroconductivity of the blood changes with its flowing. This rise in the electroconductivity of citrated and defibrinated blood, as well as in the erythrocyte suspension follows the same law. The curves of the changes in electroconductivity of citrated and defibrinated blood, as well as of the erythrocyte suspension follows the same law. The curves of the changes in electroconductivity of these fluids differ only quantitatively. Blood plasma, as well as other ionic and colloidal solutions and hemolyzed blood do not change their resistance in flowing. The change of blood electroconductivity is caused by the presence of erythrocytes, the carriers of a negative charge, the value of which depends on their surface. The change in the electroconductivity depends on the fre-

quency of the passed current, the number of erythrocytes in the blood, the protein colloidal and ionic content of the blood plasma. The change in the blood electroconductivity characterizes the velocity of blood flow in the vessels and may also denote the value of the charge of erythrocytes. The phenomenon of the change of the blood electroconductivity should be taken into consideration in analyzing the data obtained by the method of electroplethysmography.

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