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Study of the thermoelectrokinetic effect in the animal's blood

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The paper presents the results of experimental measurements of the thermoelectrokinetic EMF of animal blood samples. The cross thermoelectrokinetic effect that occurs in aqueous solutions of ionic compounds under the action of three thermodynamic forces has been studied in cases where the kinetic and temperature parameters of the studied samples corresponded to the real conditions of functioning of living organisms. It was found that the EMF generated is commensurate in magnitude with the known values of human biopotentials. In order to study the effect of the ionic composition on the electrical and thermoelectric properties of blood, measurements were carried out on samples with a changed ratio of concentrations of potassium and sodium ions compared with the normal initial ones. The influence of the ion balance on the value of the formed thermal EMF has been revealed. The obtained dependencies can be used to diagnose electrolyte disorders, including hypo- and hyperkalemia.

Keywords: thermoEMF, blood plasma, hyperkalemia, hypokalemia.

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Introduction

The study of the physico-chemical properties of animal blood, including human blood, is of considerable interest for solving diagnostic problems. The study of kinetic effects occurring in blood plasma samples makes it possible to determine its ionic composition. Electrochemical [1,2] and photometric [3] methods are broadly used in human medicine [4] and veterinary medicine [5].

The paper [6] showed earlier that thermoelectric and thermoelectrokinetic EMF can be formed in liquid systems of living organisms under conditions of flow and temperature drop. Measurements were carried out on model blood plasma solutions.

The thermoelectric properties and electrical conductivity of animal blood plasma were studied in Ref. [7], as well as the effect of dilution with Ringer's solution and distilled water on the measured characteristics. A hypothesis was proposed about the impact of thermoelectric EMF, commensurate in magnitude with the known values of human biopotentials, on the course of biochemical processes in the body, as well as on the mechanism of thermoregulation. This confirms the relevance of the topic of the study and the need for its continuation.

The purpose of this work is an experimental study of thermoelectric effects in conditions *in vitro* simulating cross-phenomena occurring in the circulatory system of warm-blooded animals.

1. Experimental results and discussion

The thermoelectrokinetic EMF in animal blood plasma samples was measured using an experimental setup based on a U-shaped tube described in Ref. [8]. The setup is schematically shown in Fig. 1.

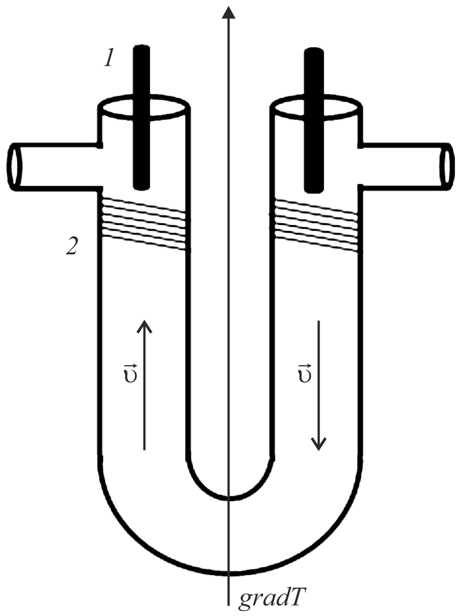

Figure 1. Scheme of an experimental setup for measuring thermoelectrokinetic EMF in liquid electrolyte solutions: *1* — reference electrodes, *2* — wire heater.

1.1. Measurement of thermoelectrokinetic EMF in pig blood samples

Measurements of the thermoelectrokinetic effect in pig blood plasma were performed for the first time in this paper. The impact of the mass transfer rate and temperature difference on the value of thermoelectrokinetic EMF was studied.

Fresh collected within max. 24 h, cooled pig and nutria blood was used as samples. Large coagulate fractions were removed from the samples by mechanical filtration before the measurement.

The choice of pig's blood for the study is attributable to the similarity of the ionic composition of its plasma with human blood plasma. The discrepancy in the content of the main defining elements is insignificant [9.10]:

— Na^+ in humans 135−155 mmol/l, in pigs 180 mmol/l.
— K^+ in humans 3.6−5.0 mmol/l, in pigs 7 mmol/l.
— Ca^{2+} in humans 2.25−2.75 mmol/l, in pigs 3 mmol/l.
— Cl^- in humans 97−108 mmol/l, in pigs 100 mmol/l.

The thermoelectrokinetic effect, as a cross-process, is formed in liquid dispersed systems in the presence of three thermodynamic forces — gradients of thermodynamic parameters (pressure, electric potential, temperature), causing a deviation from the equilibrium state.

The methodology of its experimental study is presented in the early paper of the authors [8]. A setup consisting of a U-shaped tube filled with the test solution, the flow rate of which is regulated by a peristaltic pump, is described. The electrical signal is read from the open ends of the U-shaped tube using electrodes of the second kind and transmitted to a computer via an interface. As a result, a data table is generated: time, voltage, temperature. The temperature of the liquid in the areas of the electrodes and the bending area of the tube can be adjusted and measured in this setup. This configuration makes it possible to measure the thermoelectrokinetic EMF, measure and subsequently take into account the accompanying thermoelectric effect, the EMF of which increases or decreases the measured signal. The installation allows changing: the direction and magnitude of the temperature gradient created, the direction and magnitude of the flow velocity of the studied solution — the most important factors forming the kinetic inhomogeneity in the U-shaped tube.

The measured EMF value consists of thermoelectric E_{TE} and thermoelectrokinetic E_{TEK} components: $E = E_{TE} + E_{TEK}$.

Therefore, it is necessary to take into account the thermoelectric effect that occurs between the open ends of the U-shaped tube for finding the value of the actual thermoelectrokinetic EMF. Its formation is attributable to the fact that a solution with a temperature higher than the solution rising along the left arm from the fold at the melting temperature of ice flows into the right arm. The temperature of the liquid regions in which the electrodes are placed is equalized using additional heaters, the temperature field distribution was controlled using the FLIR EXTECH i5 thermal imager.

Experimental limitations related to heat transfer and measurement errors in the temperatures of flowing liquids limit the possibilities for reducing the temperature difference between the arms to a value of 1−2°C. The thermoelectric EMF was measured in animal blood plasma in Ref. [7] and the thermal EMF coefficient $\alpha = -26.6\,\mu$V/K was obtained. This value allows calculating and taking into account the associated thermoelectric EMF.

Figure 2 shows the experimental dependence of the potential difference arising in a sample of pig blood plasma on time. The temperature difference of the solution between the heated and cooled parts of the tube was 30°S, the mass flow rate varied from 1.5 to 3 ml/min, which corresponded to mass transfer rates of 0.09 and 0.18 mm/s.

Let us describe the characteristic stages of the experimental measurement.

1−2: the bend of the U-shaped tube is immersed in water at a temperature close to 0°C. There is no fluid flow. Transients occur, a stationary, background potential difference is established, close to 0 MV (on the graph — level I).

2−3: a fixed flow velocity is set, corresponding to a mass flow rate of 1.5 ml/min.

3−4: a stationary potential difference is established corresponding to the sum of E_{TEK} and E_{TE}.

4−5: the temperatures of the solution areas in which the electrodes are installed are equalized using additional heaters for minimizing the contribution of the accompanying thermoelectric effect.

5−6: a stationary potential difference (level II) is established corresponding to the sum of E_{TEK} and E_{TE}. At $\alpha = -26.6\,\mu$V/K and $\Delta T = 2$ K, the value of the thermoelectric EMF is 0.05 mV. As can be seen from the graph, the magnitude of the thermoelectrokinetic EMF

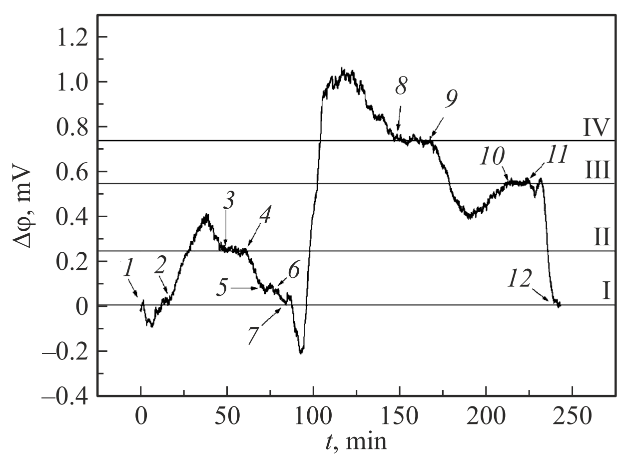

Figure 2. Dependence of the thermoelectric potential difference on time for pig blood plasma samples. The temperature of the cooled area is 5°C, the maximum temperature of the heated part is 35°C.

Table 1. The results of measurements of the thermoelectrokinetic EMF of pig blood plasma in dependence on the mass transfer rate υ. Confidence probability for all measurements is 0.95

№ No.	Sample	υ, mm/s	E, mV	Relative error,%
1	Pig blood plasma	0.09	0.05	±10%
2	Pig blood plasma	0.11	0.15	±10%
3	Pig blood plasma	0.18	0.44	±10%

and thermoelectric EMF at a given mass transfer rate are comparable in magnitude.

6–7: switching off the peristaltic pump, the potential difference decreases to a value close to background.

7–8: a constant flow velocity corresponding to a mass flow rate of 3 ml/min is established.

8–9: a stationary potential difference (level IV) is established corresponding to the sum of E_{TEK} and E_{TE}. The value of the thermoelectric EMF is 0.1 mV at $\alpha = -26.6\,\mu$V/K and $\Delta T = 4$ K. As can be seen from the graph, the value of the thermoelectrokinetic EMF exceeds the value of the thermoelectric EMF at a given mass transfer rate.

10–11: a stationary potential difference (level III) is established corresponding to the sum of E_{TEK} and E_{TE}. At $\alpha = -26.6\,\mu$V/K and $\Delta T = 2$ K, the value of the thermoelectric EMF is 0.05 mV.

11–12: switching off the mass transfer, the potential difference decreases to a value close to background.

The results of measurements of thermoelectrokinetic EMF in pig blood plasma samples for various mass transfer rates are listed in Table 1.

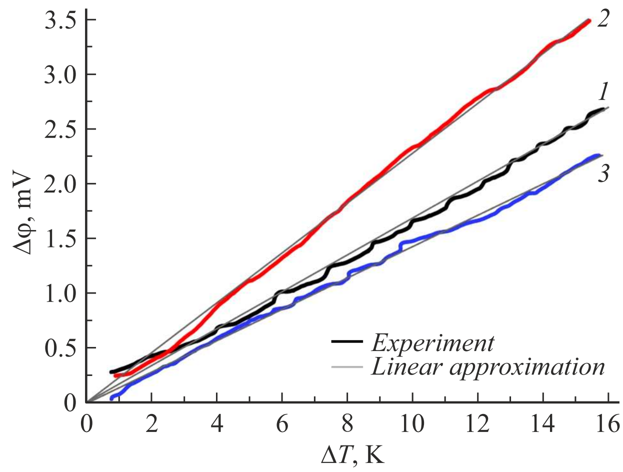

Figure 3. Dependence of the thermoelectric potential difference on the temperature difference for Ringer's solution samples with different potassium ion content. *1* — standard balance (4 mmol/L), *2* — excess ions (5.5 mmol/L), *3* — lack of ions (3 mmol/l). The temperature of the colder region is 18°C.

1.2. Investigation of the effect of ion balance on thermoelectric properties of blood

A series of experiments were conducted on Ringer's medical solution for detection of the effect of the concentration of potassium ions on the value of the thermal EMF coefficient with different percentages of components. At the same time, it was taken into account that the standard composition of Ringer's medical solution (147.2 mmol/l NaCl, 4 mmol/l KCl and 2.25 mmol/l $CaCl_2$) [9] is isotonic with respect to human blood plasma, and deviations from the initial proportions allow simulating cases of ion imbalance. Figure 3 shows the experimental dependences of the thermoelectric EMF of three samples of the modified Ringer solution on the temperature difference. A comparison of the graphs confirms the dependence of the thermal EMF coefficient on the ion balance.

At the next stage, the thermoelectric effect was studied in pig blood plasma samples with a modified ionic composition.

The thermoelectric potentials were measured as close as possible to the conditions of functioning of warm-blooded organisms, taking into account the blood temperature of 38°C in the heart area and blood temperature of 25°C in the limbs. The temperature of the cold part of the tube was equal to room temperature of 18°C and did not change throughout the experiment, while the maximum temperature of the hot part was limited by the protein coagulation temperature and was reduced to 40°C.

Experimental dependences of the thermoelectric EMF of two samples of pig blood plasma on the temperature difference between the heated and cold regions are presented in Fig.4. Sample No.1 represented the original blood plasma, sample No.2 modeled the deviation of the ionic composition from the physiological norm due to the addition of an additional amount of potassium chloride. The differences in the measured values of the thermal EMF coefficient are significant, and exceed the experimental error.

Some measurements were performed not only at the site of the increase of the temperature difference ΔT for increasing the relevance, but also during the cooling process, i.e. at the site of the decrease of the temperature difference ΔT. Measurements using this method were carried out on more than 40 samples of Ringer's solution, pig blood plasma, including those modified by ionic composition. Summary data on the effect of potassium ion concentration on thermoelectric properties are given in Table 2. The

Table 2. The results of measurements of the coefficient of thermoelectric EMF α of Ringer's solutions and pig blood plasma. Confidence probability for all measurements is 0.95

№ n/a	Substance	α, mV/K	$\pm\Delta\alpha$, mV/K	Relative error,%
1	Ringer's solution (4 mmol/l)	0.168	0.010	6
2	Ringer's solution with excessive K ions (5.5 mmol/l)	0.227	0.010	4
3	Ringer's solution with shortage of K ions (3 mmol/l)	0.143	0.010	7
4	Pig blood plasma (7 mmol/l)	0.271	0.010	5
5	Pig blood plasma with excessive K ions (8 mmol/l)	0.367	0.010	10

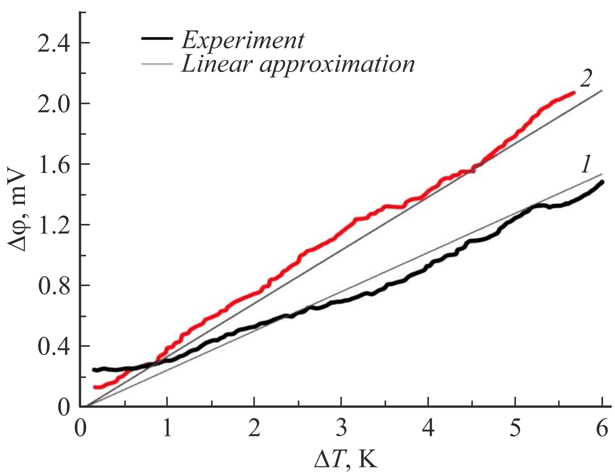

Figure 4. Dependence of the thermoelectric potential difference on the temperature difference for pig blood plasma samples with different potassium ion content. *1* — standard balance (7 mmol/l), *2* — excess ions (8 mmol/l). The temperature of the colder region is 18°C.

calculated error of measurment of the coefficient of thermal EMF α did not exceed 10%.

The data presented in Table 2 indicate that the concentration of potassium ions, which has a significant effect on the course of biochemical processes in living organisms [9,10], also has a certain effect on the magnitude of thermoelectric potentials arising in the blood under the influence of temperature gradients.

Therefore, the measured thermoelectric and thermoelectrokinetic EMF have the order of units of mV, which is comparable to values of biopotentials. The values of the biopotential parameters of human tissues and organs are in the following ranges according to [11]: heart — up to 5 mV; brain (on the surface of the scalp / on the open brain) — 0.2 and 5 mV, respectively; stomach — up to 10 mV; muscle tissues — up to 10 mV; back brain — no more than 0.1 mV.

1.3. Study of the effect of ion balance on electrical conductivity of blood plasma

Electrical conductivity measurements were carried out using laboratory conductivity meter S30-K SevenEasy (Mettler Toledo). Pig blood plasma samples were prepared according to the procedure described above for thermoelectric measurements. The measurements were performed at a constant temperature of $t = 22°$C.

The threshold concentration of potassium ions in human blood plasma diagnosed as hyperkalemia is considered to be 5.0 mmol/l [2.10]. In this regard, potassium chloride was added to pig blood plasma at the rate of 160 mg per 1 l of plasma for obtaining a sample simulating hyperkalemia.

The following electrical conductivity values were obtained for the original and modified pig blood plasma as a result, respectively:

1) normal balance $\sigma = 232 \pm 3$ mS/cm;

2) hyperkalemia $\sigma = 256 \pm 3$ mS/cm.

Conclusion

Therefore, experimental studies of the thermoelectric properties of animal blood (pigs) allowed obtaining a number of results and drawing the following conclusions.

1. The formation of thermoelectrokinetic EMF in blood plasma samples of animals within the framework corresponding to the conditions of functioning of living organisms has been experimentally detected.

2. The measured value of thermoelectrokinetic EMF (0.5 mV) is comparable to the known values of biochemical

potentials [11], while the mass transfer rate (0.1 mm/s) [9] and the temperature difference (10 K) correspond to real values of blood flow parameters.

3. The relationship of the concentration of potassium ions in blood plasma samples and electrolyte solutions modeled by it with the value measured by thermal EMF has been experimentally established.

4. Joint measurements of the value of the coefficient of thermal EMF and electrical conductivity of samples of physiological fluids (blood plasma) can be used for rapid diagnosis of electrolyte disorders.

The results obtained for the first time in the work allow evaluating the impact of thermoelectric phenomena on thermoelectromagnetic processes in the organisms of warm-blooded animals.

Statement of compliance with ethical norms and standards of work with people and animals

All applicable international, national, and/or institutional guidelines for animal care and management were observed.

This study does not include any studies involving humans as objects.

Conflict of interest

The authors declare that they have no conflict of interest.

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