Computer analysis of the thermal state of the object after cryotherapy

D Yerezhep¹, A Yemelyanov², Y Kuznetsov³, A Perminov³, V Pronin¹, A Minikaev¹ and A Yerezhep⁴

¹ITMO University, Kronversky Ave., 49, St. Petersburg, 197101, Russian Federation
²LLC «Dokon», Predportovy, 4, lit.I, St. Petersburg, 196240, Russian Federation
³JSC Scientific Production Association «Compressor», Bolshoy Sampsonievsky Ave.,
64, St. Petersburg, 194044, Russian Federation
⁴Ufa State Petroleum Technological University, 1, Kosmonavtov street, Ufa, 450062,
Russian Federation

E-mail: darhan_13@corp.ifmo.ru

Abstract. In this work, experimental data are presented that allows one to estimate the relative amount of heat release. It also provides the opportunity to state the general tendency of its change over time for patients with various individual characteristics of the organism. An important indicator of safety and effectiveness of cryotherapy is the temperature of the skin surface $T_k$, which should not fall below -2 °C during exposure. It is also planned to propose a method for studying the dynamics of $T_k$ and heat flux from the human body using a thermoelectric module (TEM). The paper evaluates the experimental data on the TEM current changes during and after cryotherapy. Also, dynamics assessment of heat flow during cryotherapy is given and the possibility of evaluating $T_k$ will be shown. It is planned to get an overall picture of the process of heat exchange of the measuring device with the skin of the test object. The results allow us to make recommendations regarding the duration and intensity of cryotherapy.

1. Introduction
For the treatment of a wide range of diseases, cryotherapy - exposure to low temperatures - is used. The evaluation of the temperature state of human skin under conditions of low ambient temperatures is a difficult technical problem. Experimental measurement of the temperature of the skin surface with a thermometer during a session is impossible, since this requires a tight fit of soft tissues around the surface of the thermometer. The use of pyrometers also does not work, as the skin appears to be transparent to the device. This paper considers the possibility of using thermoelectric devices to solve this problem.

Thermoelectric devices produce direct conversion of thermal energy into electrical and electrical into thermal. They are used for low-power generation of energy, cooling and as measuring devices, for example, heat meters - devices for measuring heat fluxes [1]. The field of application of thermoelectric heat meters can be the analysis of heat fluxes from the surface of the human body for the diagnosis of local inflammatory processes, oncological diseases, diseases of the joints, the cardiovascular system, etc. [2]. The paper considers the possibility of using thermoelectric converters for diagnostics of heat fluxes and temperatures of the upper layers of the skin under conditions of exposure to extremely low temperatures.
Cryotherapy is a physiotherapy procedure, the main effect of which is the effect of cold on the receptor layer of the skin (skin overcooling). However, the thermal processes taking place during a therapeutic session have not yet been fully investigated. In particular, the dynamics of the temperature field on the surface of the skin and in the tissues as a whole is not known. This parameter is of great importance to ensure greater efficiency and safety of the procedure, since overcooling of the epidermis to a temperature below \(-2.5^\circ C\) \([3, 4]\) leads to irreversible destruction of tissue. The rate of change of the temperature field will allow us to calculate the appropriate temperature of nitrogen vapor and the exposure to cryotherapeutic effects. The exposure of most installations is 2 to 4 minutes, and the gas temperature varies in the range from 90 to 190 K. The speed of the coolant, as a rule, does not exceed 1.0 m/s \([5-7]\).

The cryotherapeutic procedure (WBC) starts the mechanisms of self-testing and correction in the human body, stimulates the improvement of metabolic processes in damaged organs and speeds up the process of treatment \([8-11]\). Cryotherapy is widely used as a universal remedy for the prevention of socially significant diseases, oncology, rheumatoid arthritis, pollinosis, osteoporosis, etc. \([11-14]\). This determines the high social significance, providing medical facilities in Russia with efficient and safe cryotherapy equipment.

However, due to the inhomogeneous distribution of the gas temperature in the cryochamber, there is a risk of overcooling of the local cover \([2]\). Consequently, one of the current problems of the WBC is to measure the temperature of the skin during therapy, because the problems associated with the analysis of temperature fields, both on the surface and inside the skin of the WBC object, have not been solved yet. To study the temperature fields in the skin layers of the WBC object, modeling of this process was applied, since measuring the temperature fields in the skin layers of the object, both during cryotherapy and after it is difficult \([15]\). Now, as we know, there are no works that would investigate the temperature distributions inside the skin of an object when exposed to cryogenic temperatures on a given object. In this paper, attempts are made to apply modeling using the finite element method, the skin of an object of general cryotherapeutic impact. The complexity of the process consists of several aspects, such as solving a non-stationary problem, which includes the processes of effective thermal conductivity of the fabric and entailing a distortion of the physical picture of non-stationary heat transfer through a multilayer object containing an internal heat source.

2. Problem definition

Measurement of energy expended in the process of vital activity of an organism is one of the priority tasks not only for medical and research institutes, but also for an ordinary person. However, accurate measurement of the total amount of energy expended by the body is quite a difficult task. A detailed description of all types of calorimeters existing now is given in \([16-19]\). Currently, there are many wearable devices that allow you to calculate the number of calories expended, but almost all of them determine energy consumption by measuring one or more replacement parameters. Among the many methods for measuring energy costs in medicine, there are two main areas: measuring oxygen consumption (indirect calorimetry) and direct heat generation (direct calorimetry). Indirect calorimeters are the most common type of calorimeter. They are called indirect because the assessment of consumed energy is based on data on oxygen consumption and carbon dioxide production that occurs during metabolism. The measuring device, which operates on the principle of direct calorimetry, is designed to directly measure the heat generated during metabolism. In the past, most direct calorimetry systems were complex systems for measuring all forms of heat exchange between the human body and the environment. Now, direct calorimetry systems, despite all their advantages, are largely superseded by indirect calorimeters due to a number of practical advantages. It should be noted that none of the above methods (direct and indirect calorimetry) is currently possible for use in everyday life, therefore their use has been limited mainly by clinical studies.

3. Experiment

To study the possibilities of using a thermoelectric heat meter to solve the problem of estimating heat generation from the surface of a human body, a number of measurements were carried out in various environmental conditions: at room and extremely low temperatures.
Under the influence of the temperature difference between the surface of the human body and the environment, the thermopower arises on the cold and hot sides of the thermoelectric module. The magnitude of the thermopower measured in the idling mode of the converter and the current measured in a closed circuit can be used as a response to assess the temperature regime of the surface layers of a biological object.

In an external electrical circuit connected to the module, a current appears, determined by the ratio:

\[ I = \frac{n \cdot \alpha \cdot \Delta T}{R + R_n}, \]

where \( n \) is the total number of thermoelements, \( \alpha \) is the thermopower coefficient, \( \Delta T \) is the temperature difference between the cold and hot sides of the thermoelectric module, \( R \) is the internal electrical resistance of the converter, \( R_n \) is the electrical resistance of the load (external circuit connected to the module).

Using the results of measurements made using a thermoelectric converter by studying the characteristics of the electrical circuit, attached to it, allows one to obtain data on the temperature change of the skin of the body and heat fluxes.

For the experiment, the thermoelectric generator module TGM-127-1.0-1.3 was used, the geometrical parameters of which are shown in Fig. 1. Before conducting studies, a calibration was carried out for the module used in the experiments, the results of which are shown in Fig. 2. The obtained dependence agrees well with the passport data of the module. In the area from zero to 45 degrees, the dependence is linear, which will significantly simplify further calculations. When conducting experiments to fix the magnitude of the current, a multimeter was connected to the module in the mode of current measurement. The cold side of the module was maintained at a temperature of 0 °C by application of a container with melting ice. The hot side of the module was applied to the skin in the chest of the subjects. A schematic model of the experiment is presented in Fig. 3.

**Figure 1.** Schematic representation of the TGM-127-1.0-1.3 module.

**Figure 2.** Experimental dependence of the generated current on the temperature difference on the sides of the module.

**Figure 3.** The scheme of the experiment. \( Q_1 \) is the heat removed from the cold side of the module, \( Q_2 \) is the heat supplied to the hot side of the module from the surface of the human body.
Results and Discussion

To determine the possibility of using this thermoelectric module as a heat meter, a control measurement of the heat flux density from the human body was carried out. The module was placed on the skin surface. The electrical leads of the thermoelectric module were connected to the microammeter. The load resistances in the circuit were not connected, thus, the generator module worked in the short circuit mode. At room temperature, a primary measurement of the magnitude of the short-circuit current at various time intervals was made. In Fig. 4 shows that the maximum current value is reached in 3-5 seconds of measurement. Then the value of the generated current begins to decrease and after 60 seconds reaches a steady-state value. This behavior of the current dependence is explained by the fact that in the first moments of time the temperature difference between the surfaces of the heat meter is maximum. After the fifth second of measurement, the heat from the human body begins to spread along the module and reaches the opposite side. It can be concluded that the inertia of such heat meter is quite large and equal to 60 seconds, but as the main indicator describing the heat flux from the body, you can use the maximum current value at a time instant equal to 3-4 seconds. After several attempts to carry out the measurement of heat flux in a row, it became clear that the heat absorbed at the time of the first measurement has not had time to be distributed uniformly in modulus, so that all subsequent measurements showed too low current.

As a solution to this problem, it was proposed to stabilize the temperature on the reverse side of the module by melting ice. This solution allows several measurements in a row with one module and increases the maximum value of the detected short-circuit current. In Fig. 5 shows the dependence of the current in the measurement process. The curve has a characteristic maximum of $I_{m}$.

The maximum electric power $P_{ma}$ produced by the generator module is determined according to the Joule-Lenz law, and is equal to:

$$P_{ma} = I_{ma}^2 \cdot R$$

(2)

The value of electrical resistance will be considered constant, respectively, the value of power will depend only on the square of the maximum current. Thus, the value of heat flux from the skin surface will directly depend on the square of the current generated by the module.

For the physical assessment of the processes occurring during the stay the human body in an environment with extremely low temperature, apply the analysis of the thermal field in the tissues of the human body. In parallel, it is possible to solve a number of important applied tasks, such as calculating the appropriate temperature and the rate of nitrogen vapor supply, exposure to cryotherapy, etc. 170 K, the speed of the coolant, as a rule, does not exceed 1.0 m/s [3]. In this paper, we consider a particular case of cryotherapy, in which nitrogen vapors act as a coolant. In the course of the cryotherapy session, several measurements were made. The current value was recorded by a multimeter at the following points in time:

- before the session, in the absence of cryotherapy;
- at the beginning of the session;
- during the session;
- after the end of the session;
- 30 minutes after the end of the session.

The general nature of the change in heat release, assessed by the dynamics of the current change during the cryo-exposure session, is preserved for all subjects, only deviations of absolute values are observed, caused by the individual characteristics of the test subjects. Therefore, in order to obtain a complete picture, the results of measurements carried out at various points were made to the initial value $I_{m1}$, measured before the session and corresponding to the normal heat release. The experiment involved three probationers. The averaged dependence of the reduced current value on the moment of current registration is shown in Fig. 6.
Figure 4. Time dependency graph: 1 – the temperature value in the epithelium, 2 – the value of the minimum temperature in fatty tissue.

Figure 5. The dependence of current on time in the measurement process. Measurements were taken prior to the start of the cryotherapy session.

Figure 6. Graph of current change in various time sections of a cryotherapy session. 1 – before the session, 2 – a few seconds after the start of the session, 3 – during the session, 4 – after a few seconds after the end of the session, 5 – 15 minutes after the session, 6 – 30 minutes after the session.

The behavior of heat flux $q$ from time is presented in Fig. 7. The duration of the gap A for all subjects is 2 to 4 minutes. At that time, the durations of gaps B and C depend on the individual characteristics of the organism of each patient and can vary greatly from each other.

Figure 7. Graph of change in heat flux over time. A - from the initial moment until the end of the cryotherapy session and the minimum flow $q_{min}$ is reached, B - from the end of the cryotherapy session to the maximum increase in the flow to $q_{max}$, C - from the moment $q_{max}$ is reached until the flow reaches the plateau corresponding to the initial value of the flow $q_1$.  

Time
5. Conclusion
The performed work is the initial stage in the development of methods for assessing the temperature state of the skin of biological objects as a result of exposure to extremely low temperatures. Heat flow according to the principle of electrothermal analogy has the same behavior as the current. Therefore, the analysis of the obtained dependence gives an idea about the dynamics of the heat flux from the skin surface. The flow is reduced by about a third during a cryotherapy session, which corresponds to a decrease in skin temperature and heat release. After the session, the heat release from the skin surface is intensified and becomes, on average, one and a half times higher than its initial value. These results are consistent with the sensations of the subjects from the effects of the cryochamber. Experimental data were obtained that allowed an estimate of the relative magnitude of heat release and the general trend of its change over time for patients with different individual characteristics of the organism. The overall picture of the ongoing process of heat transfer is obtained, its characteristic stages are highlighted, and a preliminary numerical and qualitative assessment of each stage is given.

6. Conflict of interest
The authors declare that they have no conflict of interest on the content of this paper.

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