Infrared Thermography of Cutaneous Integument of Biological Object

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Abstract:

The work presents the results of research on thermometry of cutaneous integument of biological objects, using the method of remote infrared thermography. The process of evaporation of drops of sweat during physical loading has been simulated in imitation of evaporation of drops of water. For the first time, research resulted in time dependence of the temperature of drops of water (sweat) with convective and diffuse mechanisms of a heat and mass exchange with the ambient air. Research results can be applied in experimental medicine for controlling process of athletes training.

Keywords:

Remote Infrared Thermography, Biological Object, Thermoregulation, Gradient, Temperature

1. Introduction

The temperature of cutaneous integument of a biological object (BO) is the complex indicator of biophysical processes in the body and it is measured by a clinical thermometer, radiocapsules equipped with sensors whose signals are registered by specialized devices, as well as with the help of thermal imaging or thermography.

Infrared (IR) thermography relates to a contactless remote two-dimensional method for visualizing the spontaneous output from human skin that is caused by the processes of heat production in BO organs and tissues in the range of electromagnetic waves 0.8-50 microns long [1-5].

It is known that the training of athletes is associated with high physical loads, in which sweat is released. This phenomenon is individual for each athlete and it is difficult to establish the relationship between the athlete's health status and the intensity of sweating. Unfortunately, in this area there are few publications from which one can single out the work [6].

The obtained distribution of internal temperature provides an opportunity for the assessment of biomedical applications of the method while using thermographs as well as for a correct interpretation of the thermal image on examining abnormal thermal zones on surface of the skin integument of biological objects upon applying the method of infrared (IR) thermography. This is very important for the control of the functional status of the organism in vivo. However, in the presented works, the processes of self- regulation of temperature in a living organism were not taken into account. Exothermal biochemical processes in cells and tissues of all internals of biological object result in generation of heat that is redistributed in the organism. The said continuous process takes place within the total period of vital activity of biological object upon essential interaction with the environment. The thermal disorders carry diagnostic information on the functional status of the organism and may be used for interpretation of thermographic images as indicators (markers) of various pathological conditions. Therefore for perception of the mechanism of the thermal disorders it is important to take into account the processes of self-regulation while analyzing the algorithm of formation of the surface temperature of biological object.

The phenomenon of sweating in athletes is important. This is the subject of a technical solution in a patent [7]. The invention relates to medicine, electrical engineering and can be used for obtaining data on condition of human sweat glands. Method comprises, on portion of human body, applying thermal action from closely fitting to human skin surface of flexible electric heater. Skin surface temperature is measured simultaneously using a sensor installed on inner surface of said elastic electric heater. According to temperature in time, reaction of sweat glands is set as response to thermal action. However, remote thermographic studies of sweating were not performed.

When training astronauts, training simulators of loads are widely used. For example cosmonaut running and walking simulator [8], that has bandage which is put on cosmonaut s waist, not-extensible braces whose ends are secured on bandage and thrown over cosmonaut s shoulders and two loading members secured to bandage at one end and to bandage strip at other end; bandage strip is placed between cosmonaut s feet. Ends of strip are secured at the front and at the rear of bandage. Loading members are located at the right and at the left along cosmonaut s thighs. Simulator has two flexible members connected with bandage strip at one end and with ends of loading members at other end. Flexible members are secured to support on both sides placed under cosmonaut s foot and provided with length control units. Loading members are provided with units for forming power characteristic with force regulator. However, authors are convinced that these complexes gave more information about perspiration and body temperature with prolonged loads.

This method helps establish a relationship between clinical evidence of a disease and a BO surface temperature. In this case IR-output depends on the state of blood circulation in tissues, which is not always followed by patient's complaints, thus enabling the diagnosis of a disease at a preclinical stage [9-15].

A rise in body temperature causes an increase in tissue demand for oxygen whose deficiency may well bring about hypoxia, entailing primarily the disorder of the central nervous and cardiovascular systems [16-19].

A steady temperature of the BO is kept by the processes of thermoregulation, heat production and heat emission. Thermoregulation centers of the body and thermoreceptors are respectively located in the hypothalamus and on the surface of skin. Like any matter whose temperature is above absolute zero, the human body emits the heat band of electromagnetic radiation, namely IR-output, into the environment at the rate proportional to a temperature [1, 20-22].

Remote infrared thermography (RIT) stands out among other diagnostic techniques [22-24] and enables temperature measurement of any point on a BO surface, including the organs whose temperature is impossible to take by means of familiar methods. The accuracy of temperature measurement ranges from 0.03 °C to 0.07 °Cin thermographs with a cooled matrix that enables the high-precision temperature measurement of the all BO surface [5, 10, 19]. Infrared thermography makes possible to take temperature measurement of any point on cutaneous integument, including the mouth (Tm), as well as to determine the average temperature of the body (Tb), without using specialized sensors. To determine these values, the following equations have been formulated [24, 25]:

$$T_b=(0.4T_{skin})+(0.6T_{arm}) \quad (1)$$

In the case of a change in the temperature of the arm (Ta), body (Tb), leg (Tl) and head (Th), skin temperature (Tskin) is established by the following equation:

$$Tskin=(0.1Ta)+(0.6Tb)+(0.2Tl)+(0.1Th) \quad (2)$$

Given body temperature and body mass (Mb) make possible to determine the heat content of the body and survey a change in its amount during physical loading or other effects on the body. The heat content of the body is established by the following equation [24]:

$$HC=0.83(MbxTb) \quad (3)$$

The heat content of the body permits to determine the rate of a heat exchange. The weighted average temperature of skin (WATS) for the integral evaluation of BO thermotopography can be established by the following equation [26, 27]:

$$WATS=0.04T1+0.13T2+0.05T3+0.16T4+0.12T5+0.07T6+0.12T7+0.015T8+ +0.03T9+0.13T10 \quad (4)$$

where T1-T10 is the absolute radiation temperature of the middle of the forehead, right upper chest area, back of the right hand, middle of the lateral surface of the right thigh, middle of the lateral surface of the right shin, back of the right foot, middle of the right scapular area, right hypochondrium, projected lymph nodes, and middle of the lateral surface of a shoulder respectively. As a rule, this indicator is used in practice as a temperature gradient (ΔT), measured as the temperature difference in the area under study (T1) of the surface of the human body and adjacencies (T2) ΔT=T1-T2.

The determination of the BO temperature condition with the help of the temperature gradient permits to promptly obtain information about the state of the area under study and to quantify the extent of pathological changes with a minimum measurement error.

The purpose of this work was to study the process of evaporation of drops of sweat during BO physical loading in imitation of evaporation of drops of water.

2. Object and Methods of Research

A thermograph with a cooled matrix was used in this work. The works [11, 16, 19] provided the detailed description of this thermograph and its characteristics. Standard methods for preparing a patient for a thermo-diagnosis were used [1, 11, 19, 22]. The thermograms, which show the potential wide temperature range of a diagnosis with the help of RIT, have been selected from among their large amount, the temperature gradient varying from - (12,5-2,6) ℃ to + (3,5-4,6) ℃. The results of the correlation between temperature gradients and corresponding pathological changes detected in BO condition are shown on a fig. 1 and in a table..

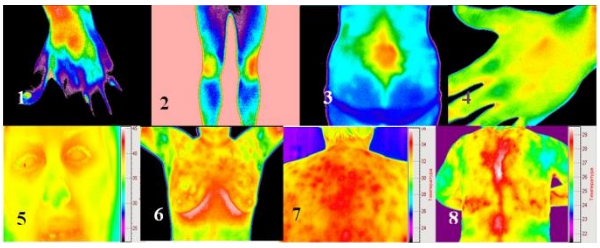


Figure 1. *Temperature changes in the body, depending on the detected pathological changes.*

Table 1. *Correlation between detected pathologies and temperature gradients.*

Figure No.	Detected pathologies	Temperature gradient
1	A decrease in the tone of vessels in the left arm.	-12.5°C
2	Pronounced venous insufficiency of lower limbs, a periarthritis of the knee joint.	-(7-11)°C
3	Osteochondrosis of the limbosacral section of the spine with myofascial lumbago syndrome.	+(2.1-2.5)°C
4	A fracture of the metacarpal of the fourth finger of the left hand.	+1.18°C-(-0.17)°C
5	A burn in the area of the sclera of the right eye.	+3.59°C
6	A benign growth in the right mammary gland.	-1.73°C
7	Hyperthermal neoplasms of unclear genesis on the cutaneous integument.	+ (0.69-3.17)°C
8	Metastases in the spinal column.	+(3.5-4.5)°C

In this work, a temperature was taken at the points shown in fig. 2. T_{skin} (equation 2), WATS (equation 4) and ΔT_{navel} (fig.3) were determined on the basis of the measurement results.

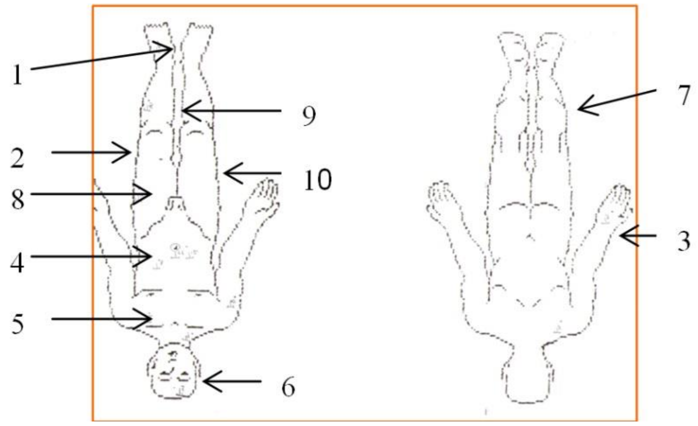


Figure 2. *Diagram of temperature measuring points on the surface of the human body (WATS).*

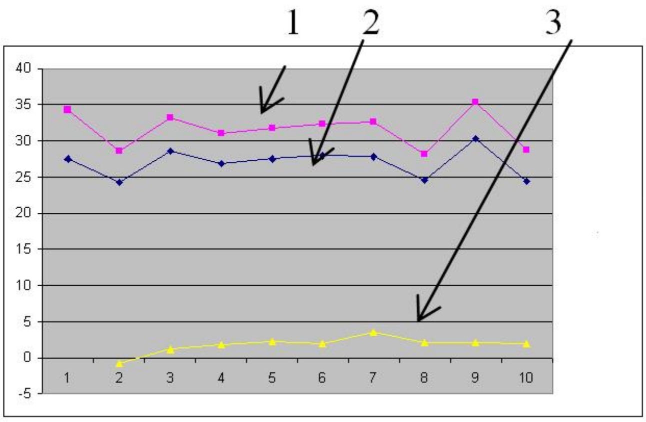


Figure 3. *10 patients' temperature distribution, namely Tskin (curve 1), WATS (curve 2) and ΔTnavel (curve 3).*

BO thermoregulation properties depend heavily on functions of the sweat excretory system that is too evident during physical loading of diverse nature.

The BO body is covered with drops of sweat in the form of a meniscus or hemisphere during physical loading. The process of cooling the human cutaneous integument as a result of the evaporation of hemispherical drops of water or sweat was simulated as follows.

The human body can discharge heat in the environment in the form of infrared rays emitted by the surface of the body (radiation); by heating the air that envelops the surface of the body (convection); by evaporating moisture (sweat) from the surface of the body (skin), the lungs and mucous membranes of the upper respiratory tract. When drops of water or sweat appear on the human skin, they evaporate. The process of evaporation is followed by a heat transfer from the skin to the air while diffusion and convection are the main mechanisms of a mass and heat exchange.

James Clerk Maxwell found a solution for the velocity of the evaporation of a spherical drop in the air on the basis of a diffusive model [23]. The solution found by Maxwell also holds true for hemispherical drops located on the infinite plane, the coefficient of a form being reduced by half. In accordance with the Sreznevskiy theorem [23] we may state the following: if the spherical drop, which lies on a surface, evaporates without changing its form, then the evaporation rate (a decrease in mass) is proportionate to the radius of the drop while a surface area is linearly dependent on the time as is the case with a free drop.

In addition, Maxwell formulated equations for the temperature of a drop in the course of its evaporation [23], considering that the evaporation process is stationary and the amount of the heat flux to the drop equals the amount of heat used for evaporation.

Apart from diffusion, a heat exchange by convection is also taken into consideration in this work [29]. As a result, a generalized equation for the temperature of a drop at the time t+ t has been formulated:

$$T_{d(t+\Delta t)} = T_{d(t)} + \Delta t \cdot f_d[\alpha(T_a - T_d) - Lj]/(m_d \cdot c_{Pd}) \qquad (5)$$

where f_d is the field of a drop; T_a is the temperature of the air (atmosphere); T_d is the temperature of a drop; α is the coefficient of convection; L is latent heat of evaporation; j is mass flow per unit area; m_d is the mass of a drop; t – time; c_{Pd} is the specific heat capacity of water.

We can get the mass influx from the Maxwell's equation, assuming that water vapor obeys ideal gas laws and the temperature of a drop equals the temperature of water vapor T [24]:

$$j = 2\pi DM(\rho_0 - \rho_\infty)/RT \qquad (6)$$

where M – is the molar mass of water vapor; D – is the diffusivity of water vapor; R is the gas constant; ρ0, ρ∞ is the partial pressure of water vapor on the surface of a drop and at a distance from it.

In the equation (6), we have taken account of the hemispherical form of drops and reduced the dimensional coefficient by half, which was initially equal to 4π.

Based on the similarity theorem, Sreznevskiy also deduced the theorem by which the rate of evaporation of similar substances in gaseous media is proportionate to their linear dimensions [23]. The Maxwell's equation for the area of a drop's surface in relation to the time is the special case of the Sreznevskiy's theorem (in this instance we have also reduced the dimensional coefficient by half in consideration of the form of the drop):

$$f_0 - f_d = 4\pi D(c_0 - c_\infty)t/\gamma \qquad (7)$$

where γ is the density of water; c_0, c_∞ - is the concentration of water vapor.

With $\Delta t \rightarrow 0$ we also have $T_{d(t+\Delta t)} - T_{d(t)} \rightarrow 0$ and then, deducing $T_d = T$ from (5) – (7), we get the following:

$$dT_d/dt = [f_0 - 4\pi D(c_0 - c_\infty)t/\gamma] \{ \alpha(T_a - T_d) - 2\pi LDM(\rho_0 - \rho_\infty)/RT_d]/(m_d \cdot c_{Pd}) \qquad (8)$$

The mass of a hemispheric drop in the radius r:

$$m_d = (2/3)\pi\gamma r^3 \qquad (9)$$

or, given the area of drop's surface evaporation fd = 2πr2, we get the following:

$$m_d = \gamma f_d^{3/2}/(3 \cdot 2^{1/2}\pi^{1/2}) \qquad (10)$$

Using the equation (7) for (10), we get the following:

$$m_d = \gamma[f_0 - 4\pi D(c_0 - c_\infty)t/\gamma]^{3/2}/(3 \cdot 2^{1/2}\pi^{1/2}) \qquad (11)$$

Representing the rate of a decrease in field of a drop as $4\pi D(c_0 - c_\infty)/\gamma = A$, as well as introducing the constant $B = 2\pi LDM(\rho_0 - \rho_\infty)/R$, and then putting (11) in (8), we get the following:

$$dT_d/dt = 3\cdot(2\pi)^{1/2}[\alpha(T_a - T_d) - B/T_d]/c_{Pd}\gamma(f_0 - At)^{1/2} \quad (12).$$

Dividing variables, we get the following:

$$dT_d/\{3\ (2\pi)^{1/2}\ [\alpha(T_a - T_d) - B/T_d]\} = dt/c_{Pd}\gamma(f_0 - At)^{1/2} \quad (13)$$

or:

$$dT_d/(C_1 + T_d + C_2T_d^{-1}) = - dt/C_3(t_0 - t)^{1/2} \quad (14)$$

where $C_1 = - T_a$; $C_2 = B/\alpha$; $C_3 = 3\ (2\pi)^{1/2}\ \alpha\ c_{Pd}\gamma \cdot A^{1/2}$; $t_0 = f_0/A$ is the time interval during which a drop will wholly evaporate.

Now we do calculation of coefficients for T_a = 293 C at 50% relative humidity. $C_2 = 2\pi LDM(\rho_0 - \rho_\infty)/R\alpha$.

C_2=6.28 ⋅2,453 ⋅10^3J/kg ⋅21.9 ⋅$10^{-6}$$m^2$/c⋅0.018kg/mole(2.2 1.1)kPa/(8,31J/moleK)⋅(5W/m^2K)=160K^2.

A = (12.56 ⋅21.9 ⋅$10^{-6}$$m^2$/s ⋅0,008kg/$m^3$)/1,000 kg/$m^3$ =2.2 ⋅10^{-9} m^2/s.

C_3 = 3 ⋅2.505 ⋅5W/m^2K ⋅4.2 ⋅10^3J/kgK ⋅1,000kg/m^3(2.2 ⋅10^{-9} m^2/s$)^{1/2}$ = 7,402$K^{-2}s^{-1/2}$.

Now we represent $(C_1^2 - 4C_2)^{1/2} = \Delta$ as $T = T_d$. for our calculation Δ = 292 K.

Integrating (14), we get the following:

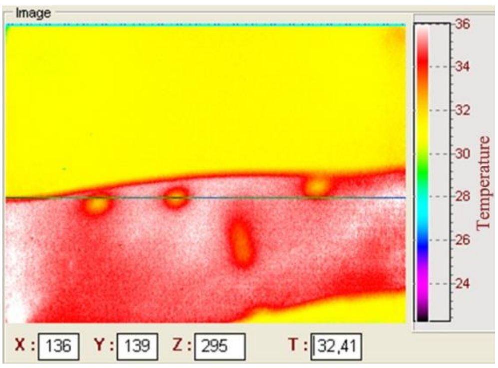
$$\ln(T/T_a) - 0.5\ln(T^2/(T^2 + C_1T + C_2)) - 0.5\ln((2T + C_1 - \Delta)/(2T + C_1 + \Delta)) + C_4 = = -2(t_0 - t)^{1/2}/(T_a^2C_3) \quad (15)$$

where C_4 is the constant of integration that is found from initial condition, for instance, if drops of sweat have initially the temperature of the human body, then it should be taken T_0 = 310 °K at t = 0. In consideration of our case it is T_0 = 293 °K.

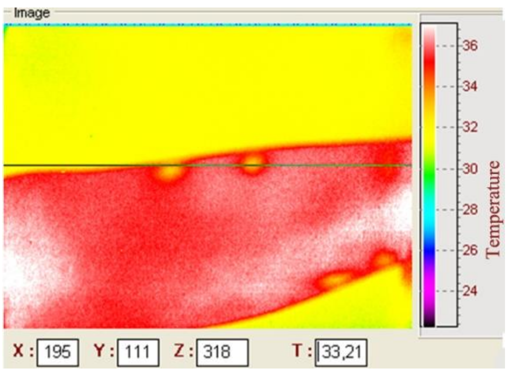
The equation (15) sets implicitly dependence of the temperature of hemispherical drops, therefore the temperature of the human skin, on the time of their drying.

3. Results and Discussion

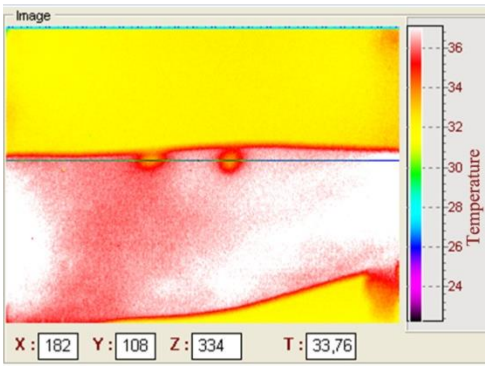
Dependence set for a drop would be true for its spread on the entire surface if we assume that drop are spread evenly on it and have the same dimensions. To provide experimental evidence of the results obtained, drops of moisture were applied to the surface of the forearm (Fig.4). The measurement of a drop temperature has been progressively taken over the course of five minutes. These measurements resulted in experimental dependence of the drop temperature on the time (Fig.5).



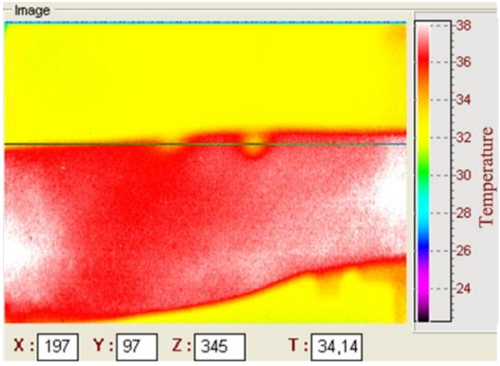
(a)



(b)



(c)



(d)

Figure 4. *Results of the measurement of the temperature of a drop of water evaporating from the skin of the arm: a) temperature t = 32.41ºC; b) t = 33.21ºC; c) t = 33.76ºC; d) t = 34.14ºC; (we measured the temperature of the central part of the second drop to the left at intervals of 120 seconds; the measurement error was Δt = 0.07 ̊C).*

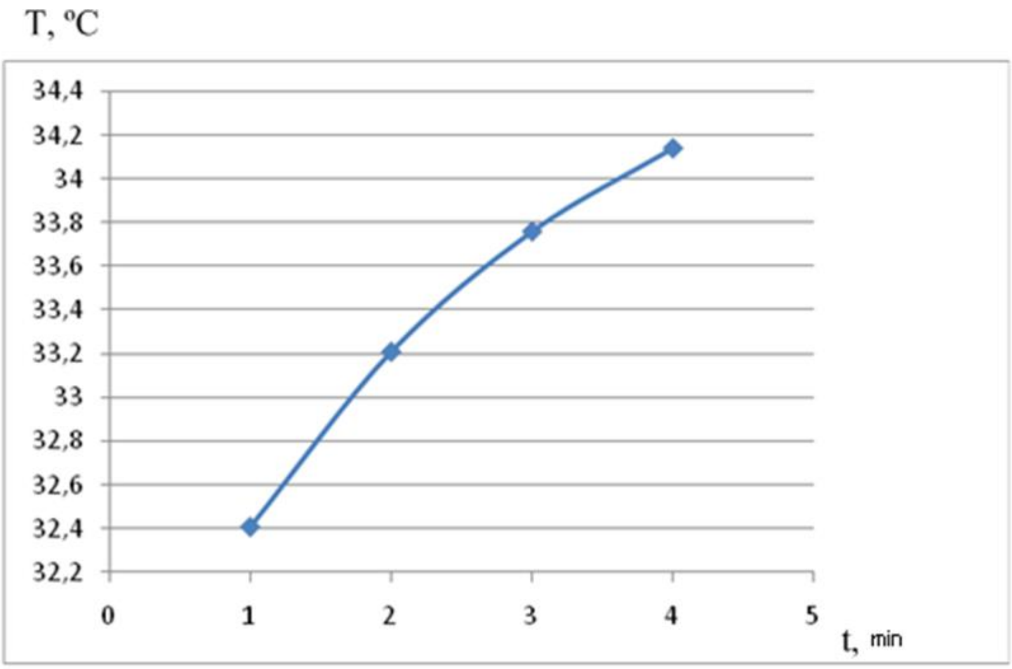


Figure 5. *Experimental dependence of the drop temperature on the time.*

As is seen in Figure 5, the temperature of a drop of water evaporating from the skin is proportionate to the square root of time that conforms to the mathematical model, which has been created earlier on.

Thus time dependence of the temperature of drops of water (sweat), given the convective and diffuse mechanisms of a heat and mass exchange with the ambient air, has been established for the first time. The results obtained can be used for selecting athletes to develop their maximum capacities for international tournaments and Olympic Games. Great achievements in sports can be expected from athletes with the good thermoregulation of the body, which may be basically evaluated by means of remote thermography. So the work [24] shows dynamics of the evaporation of sweat from the surface of the body when the front part of a person's body is exposed to solar shortwave radiation in the amount of 60W/m2. The intensive heat emission of the body in the amount of 260Kcal/h through the evaporation of sweat from its surface is observed. Thus it is clear that heating comfort has been broken in these conditions in virtue of pronounced hypothermia. This entails the reduction in physical activity, which adversely affects athletic performance. Regarding athletes with the perfectly balanced thermoregulatory system, their body is not cooled by intense sweating but the well-functioning thermoregulatory system that can be practically evaluated with the help of thermography.

4. Conclusions

Thermometry of the BO surface permits to detect promptly the areas of hypo- and hyperthermia. The high-precision temperature measurement makes possible to find out changes in BO condition at early preclinical stages before an X-ray or ultrasound examination and, in some cases, long before patient's complaints. Not only does remote infrared thermometry enable the qualitative analysis, but it also permits to quantify the extent of an early change in BO condition.

The work involved modeling, and kinetic dependence of a change in the temperature of drops of water (sweat), given the convective and diffuse mechanisms of a heat and mass exchange with the ambient air, has been determined. It has been experimentally shown that the temperature of a drop of water evaporating from the skin is proportionate to the square root of time, which conforms to the created mathematical model.

The results of the conducted studies have shown the possibility of thermographic studies of the process of cooling the body during the evaporation of water droplets. These results give an opportunity to explore individually for athletes the relationship of dynamic loads and sweating. Further studies in this direction give hope to evaluate the individual characteristics of training athletes for the upcoming competition. It is possible to use this approach in the preparation and selection of astronauts.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this article.

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