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COMPUTER SIMULATION OF THE THERMOELECTRIC HEAT FLOW SENSOR ON THE SURFACE OF THE HUMAN BODY

This paper presents the results of computer simulation of cyclic temperature effect on the human skin in dynamic mode. A three-dimensional computer model of the biological tissue has been built with regard to thermophysical processes, blood circulation, heat exchange, metabolic processes and the phase transition. As an example, the case is considered when on the skin surface there is a working tool the temperature of which changes cyclically according to a predetermined law in the temperature range [– 50 ÷ + 50] °C. Temperature distributions in different human skin layers in heating and cooling modes have been determined. The results obtained make it possible to predict the depth of the biological tissue freezing and heating under a given temperature effect.
Key words: temperature effect, human skin, dynamic mode, computer simulation.

Introduction

It is known that various diseases of the human body are treated with the help of temperature effect [1 – 2]. However, the devices used for this purpose are in most cases bulky, without adequate temperature regulation and thermal regime reproduction capabilities. To obtain lower temperatures, liquid nitrogen systems are generally used [3], which significantly limits the possibilities of their use in medical institutions, where the supply of liquid nitrogen is rather problematic. Moreover, the use of liquid nitrogen or the Joule-Thomson effect during gas expansion does not allow for the implementation of precisely required temperature regimes, which also reduces the overall efficiency of using cold in treatment.

This problem can be solved with the use of thermoelectric cooling (heating) [4 – 13]. The studies of thermal effect on the biological tissue, creation of thermoelectric devices based on them and their use in medicine confirm their efficiency. However, thermoelectric medical devices have certain disadvantages. The main one is the lack of ability to manage cooling and heating processes in time. This significantly narrows the possibilities of heat and cold treatment.

Studies show that cooling rates play an important role in treatment [4 – 13]. Very fast cooling does not lead to the destruction of the biological tissues at all. On the contrary, moderate but cyclic cooling promotes effective destruction of tumours. Therefore, the time functions of cooling and heating are vital in the treatment of various diseases.

Thus, the problem lies in the necessity to create scientific fundamentals for the development and creation of thermoelectric medical devices of a new generation, allowing to reproduce the specified heating and cooling functions in the biological tissue. It should be noted that in most cases it is quite difficult to control the cyclic processes of heating and cooling of the biological tissue, therefore it is necessary to be able to predict the depth of heating and freezing of skin layers under a given temperature effect at different moments in time.

Therefore, *the purpose of the work* is to determine, using computer simulation, the temperature distribution in the layers of the human skin in dynamic mode under a given cyclic effect.

1. Physical model

According to the physical 2D model with axial symmetry (Fig. 1), a section of the biological tissue of the human body is a structure of three layers of skin (epidermis 1, dermis 2, subcutaneous layer 3) and internal biological tissue 4 and is characterized by the following thermophysical properties [14 – 20]: thermal conductivity κ_i, specific heat C_i,, density ρ_i, blood perfusion rate ω_{bi}, blood density ρ_b, blood temperature T_b, blood heat capacity C_b and specific heat release Q_{meti} due to metabolic processes and latent heat of phase transition L. The thermophysical properties of the skin and the biological tissue of the human body in normal [21 – 25] and frozen states [26, 27] are shown in Tables 1, 2. The corresponding layers of the biological tissue 1 – 4 are considered as volume sources of heat q_i, where:

$$q_i = Q_{meti} + \rho_b \cdot C_b \cdot \omega_{bi} \cdot (T_b - T), \quad i = 1..4 . \tag{1}$$

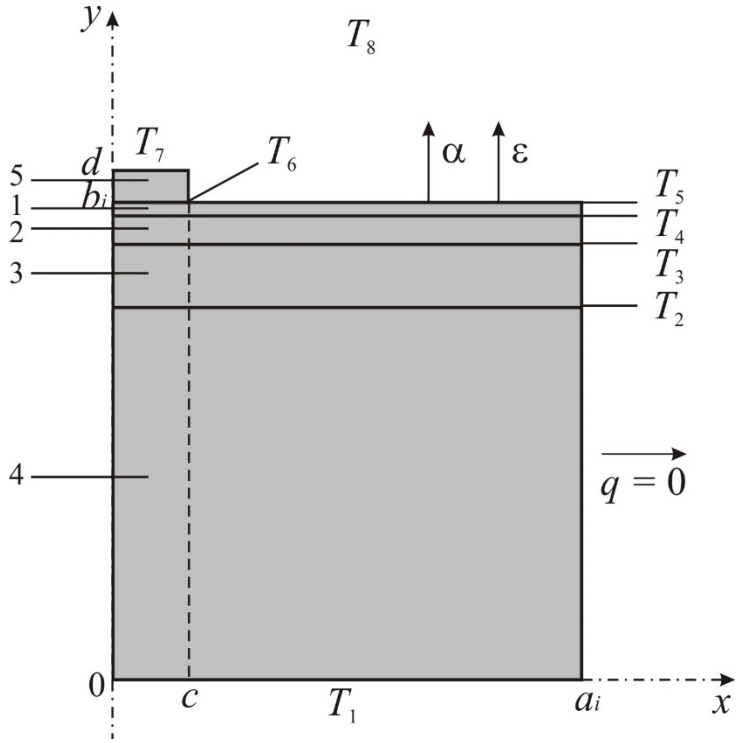

Fig. 1. Physical 2D model of the human skin with axial symmetry: 1 – epidermis, 2 – dermis, 3 – subcutaneous layer, 4 – internal biological tissue, 5 – working tool.

The geometric dimensions of each such layer 1 – 4 are a, b. On the surface of the skin there is a round working tool 5, the geometric dimensions of which are as follows: thickness d = 1 mm and

diameter c = 10 mm. According to medical recommendations and analysis of known cryoprobes used for cryodestruction, it was determined that the diameter of such probes is from 5 mm to 15 mm [28]. Therefore, in this paper, as an example, the average value of the diameter of the probe, which is c = 10 mm, is taken. The temperatures at the boundaries of the corresponding layers 1 – 4 and the working tool 5 are T_1, T_2, T_3, T_4, T_5, T_6. The temperature inside the biological tissue is T_1 = + 37 °C. The temperature of the working tool varies in the range – T_7 = [- 50 ÷ + 50] °C. The ambient temperature is T_8 = + 22 °C. The surface of the human skin with temperature T_6 is in a state of heat exchange with the environment (heat exchange coefficient α and radiation coefficient ε) at temperature T_8. The side surface of the skin is adiabatically insulated.

Table 1

Thermophysical properties of the biological tissue of the human body [21 – 25]

Biological tissue layers	Epidermis	Dermis	Subcutaneous layers	Internal tissue
Thickness, l (mm)	0.08	2	10	30
Specific heat, C ($J \cdot kg^{-1} \cdot K^{-1}$)	3590	3300	2500	4000
Thermal conductivity, κ ($W \cdot m^{-1} \cdot K^{-1}$)	0.24	0.45	0.19	0.5
Density, ρ ($kg \cdot m^{-3}$)	1200	1200	1000	1000
Metabolism, Q_{met} (W/m^3)	368	368	368	368
Blood perfusion rate, ω_b (ml/s·ml)	0	0.0005	0.0005	0.0005
Blood density, ρ_b ($kg \cdot m^{-3}$)	1060	1060	1060	1060
Blood heat capacity, C_b ($J \cdot kg^{-1} \cdot K^{-1}$)	3770	3770	3770	3770

Table 2

Thermophysical properties of the biological tissue of the human body in the normal and frozen states [26, 27]

Thermophysical properties of the biological tissue	Value	Units of measurement
Heat capacity of normal biological tissue (C_1)	3600	J/m^3 °C
Heat capacity of frozen biological tissue (C_2)	1800	J/m^3 °C
Thermal conductivity of normal biological tissue (κ_1)	0.5	W/m °C
Thermal conductivity of frozen biological tissue (κ_2)	2	W/m °C
Latent heat of phase transition (L)	$250 \cdot 10^3$	J/m^3
Upper temperature of phase transition (T_1)	– 1	°C
Lower temperature of phase transition (T_2)	– 8	°C

In this model, the thermal contact resistance between the working tool and the human skin is not taken into account, since it is estimated to be insignificant and equals $R_c = 2 \cdot 10^{-3}$ m^2·K/W [29].

2. Mathematical model

In its general form, the equation of heat exchange in the biological tissue is given by [30]:

$$C_i \cdot \frac{\partial T}{\partial t} = \nabla \cdot (\kappa_i \cdot \nabla T) + \rho_b \cdot C_b \cdot \omega_{bi} \cdot (T_b - T) + Q_{meti}, \quad i = 1..4, \tag{2}$$

where C_i, κ_i are specific heat and thermal conductivity of corresponding skin layers, ρ_b is blood density, C_b is specific heat of blood, ω_{bi} is blood perfusion of corresponding layers, T_b is blood temperature, T is temperature of the biological tissue; Q_{meti} is heat released due to metabolic processes in each layer.

The term on the left side of equation (2) represents the rate of change of thermal energy contained in a unit volume of the biological tissue. The three terms on the right side of this equation represent, respectively, the rate of change of thermal energy due to thermal conductivity, blood perfusion, and metabolic heat.

The equation of heat exchange in the biological tissue (2) is solved with the appropriate boundary conditions. The temperature on the surface of the working tool changes according to a given law in the temperature range T_7 = [– 50 ÷ + 50] °C. Inside the biological tissue, the temperature T_1 = + 37 °C. The side surfaces of the biological tissue are adiabatically isolated (q = 0), and the upper surface of the skin is in a state of heat exchange (heat exchange coefficient α and radiation coefficient ε) with the environment at temperature T_8.

$$q_i(x,y,t)\Big|_{\substack{c \le x \le a \\ y = b_i}} = \alpha \cdot (T_8 - T_5) + \varepsilon \cdot \sigma \cdot (T_8^4 - T_5^4), \tag{3}$$

where $q_i(x,y,t)$ is the heat flux density of the i-th layer of the human skin, α is the convective heat exchange coefficient of the skin surface with the environment, ε is the radiation coefficient,
σ is the Boltzmann constant, T_5 is the surface temperature of the human skin, T_8 is the ambient temperature (T_8 = + 22 °C).

At the initial time moment t = 0 s it is assumed that the temperature in the entire skin volume is T = + 37 °C, i.e. the initial conditions for solving equation (2) are as follows:

$$T_i(x, y, 0) = T_b, \qquad i = 1,...,4. \tag{4}$$

As a result of solving the initial-boundary problem (2)–(4), the distributions of temperature $T_i(x,y,t)$ and heat fluxes $q_i(x,y,t)$ in the corresponding layers of the skin at an arbitrary moment in time are determined. As an example, this paper considers the case in which the temperature of the working tool changes according to a given law in the temperature range T_7 = [– 50 ÷ + 50] °C. However, it should be noted that the proposed technique allows considering cases when the temperature of the working tool $T_f(t)$ changes in any temperature range or according to a predetermined function.

In the process of freezing, the cells will undergo a phase change at the freezing point, while the heat loss of the phase transition (L) will occur and the temperature in these cells will not change. The

phase transition in the biological cells occurs in the temperature range (– 1 ÷ – 8) °C. The properties of the skin and the biological tissue in normal and frozen states are shown in Tables 1, 2 [21 – 27]. In the temperature range (– 1 ÷ – 8) °C, when the cells are frozen, the heat of the phase transition is absorbed, which can be simulated by adding the appropriate value to the heat capacity [26, 27].

When human skin freezes, the capillary vessels constrict until all the blood in the capillaries freezes, and the value tends to zero. In addition, cells will not be able to generate metabolic heat when frozen, and $Q_{met\,i}$ will be zero at sub-zero temperatures.

In the frozen state the properties of the skin and the biological tissue will have the following values (5) – (8):

$$C_i = \begin{cases} C_1 & T \geq -1°C \\ \dfrac{L}{-1-(-8)} + \dfrac{C_1 + C_2}{2} & -8°C \leq T \leq -1°C \\ C_2 & T \leq -8°C \end{cases} \tag{5}$$

$$\kappa_i = \begin{cases} \kappa_1 & T \geq -1°C \\ \dfrac{\kappa_1 + \kappa_2}{2} & -8°C \leq T \leq -1°C \\ \kappa_2 & T \leq -8°C \end{cases} \tag{6}$$

$$Q_{met_i} = \begin{cases} 368 & T \geq -1°C \\ 0 & -8°C \leq T \leq -1°C \\ 0 & T \leq -8°C \end{cases} \tag{7}$$

$$\omega_{b_i} = \begin{cases} 0.0005 & T \geq -1°C \\ 0 & -8°C \leq T \leq -1°C \\ 0 & T \leq -8°C \end{cases} \tag{8}$$

3. Computer model

A three-dimensional computer model of the biological tissue was created in a cylindrical coordinate system, on the surface of which a medical working tool is located. The Comsol Multiphysics package of application programs [31], was used to build a computer model, which makes it possible to simulate thermophysical processes in the biological tissue, taking into account blood circulation, heat exchange, metabolic processes, and the phase transition.

The calculation of temperature distributions and heat flux density in the biological tissue was carried out using the finite element method, the essence of which is that the object under study is divided into a large number of finite elements and in each of them the value of the function is sought that satisfies the specified second-order differential equations with the corresponding boundary conditions. The accuracy of the solution to the problem depends on the level of division and is ensured by using a large number of finite elements [31].

As an example, Figs. 3 – 10 show the distribution of temperature and isothermal surfaces in the volume of the human skin, on the surface of which the working tool is placed, the temperature of which

changes cyclically according to a predetermined law in the temperature range [-50 ÷ +50] °C at different moments of time.

4. Results of computer simulation of cyclic temperature effects on the human skin in dynamic mode

According to known methods of cryodestruction and coagulation of the biological tissue [10, 11] the cooling rate should be at least (40 – 50) °C/min, and the heating rate should be (20 – 25) °C/min. Therefore, in this paper, as an example, we consider a case in which the temperature of the working tool $T_f(t)$ changes in the range of operating temperatures [– 50 ÷ + 50]°C as follows: first, cryodestruction of the skin is carried out with a cooled working tool at a temperature of T = – 50 °C for t = 120 s, then the temperature of the working tool changes from *-50°C* to *+50°C* for the next 240 s, after that, skin coagulation is performed with a heated working tool at temperature T = + 50 °C for t = 120 s, the next temperature decrease to T = – 50 °C occurs for 120 s, then this temperature effect is repeated cyclically to achieve better destruction of the human skin. The specified cyclic temperature effect on the human skin is presented in Fig. 2.

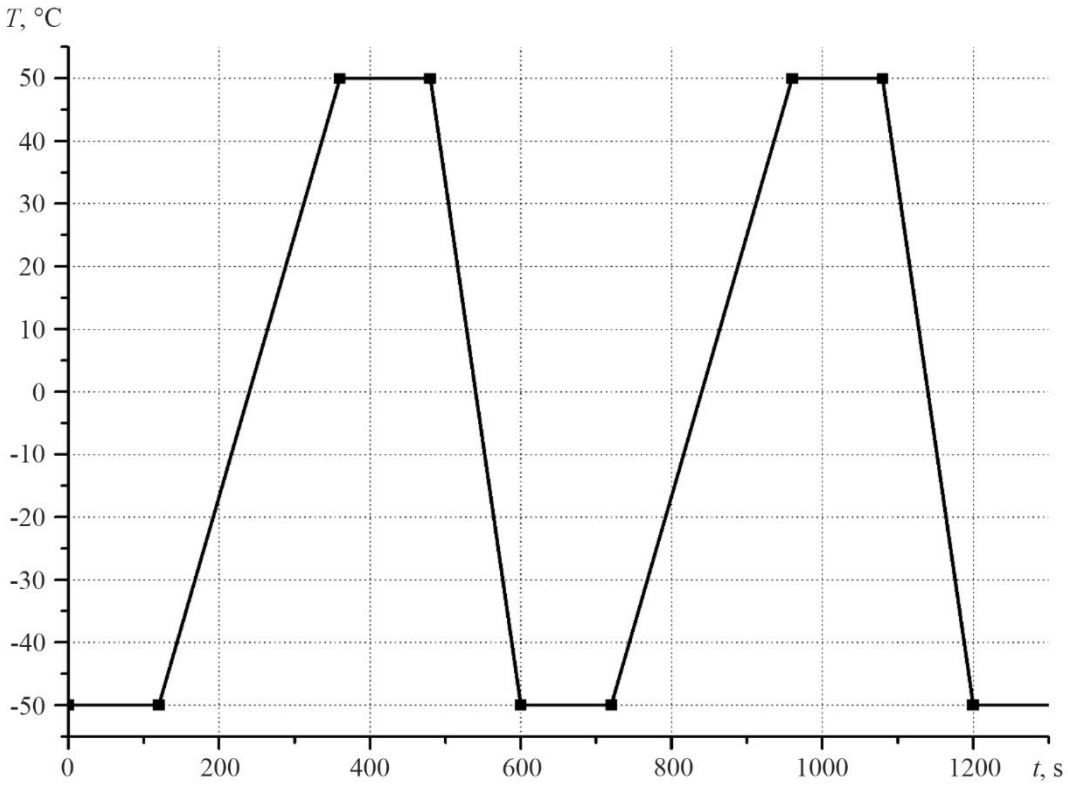

Fig. 2. Dependence of the working tool temperature on time.

Figs.3-10 show the distribution of temperature and isothermal surfaces in a cross-section of the biological tissue, on the surface of which the working tool is placed, the temperature of which changes according to the above law in the range of working temperatures [– 50 ÷ + 50]°C at the initial and final moments of the cooling-heating cycle.

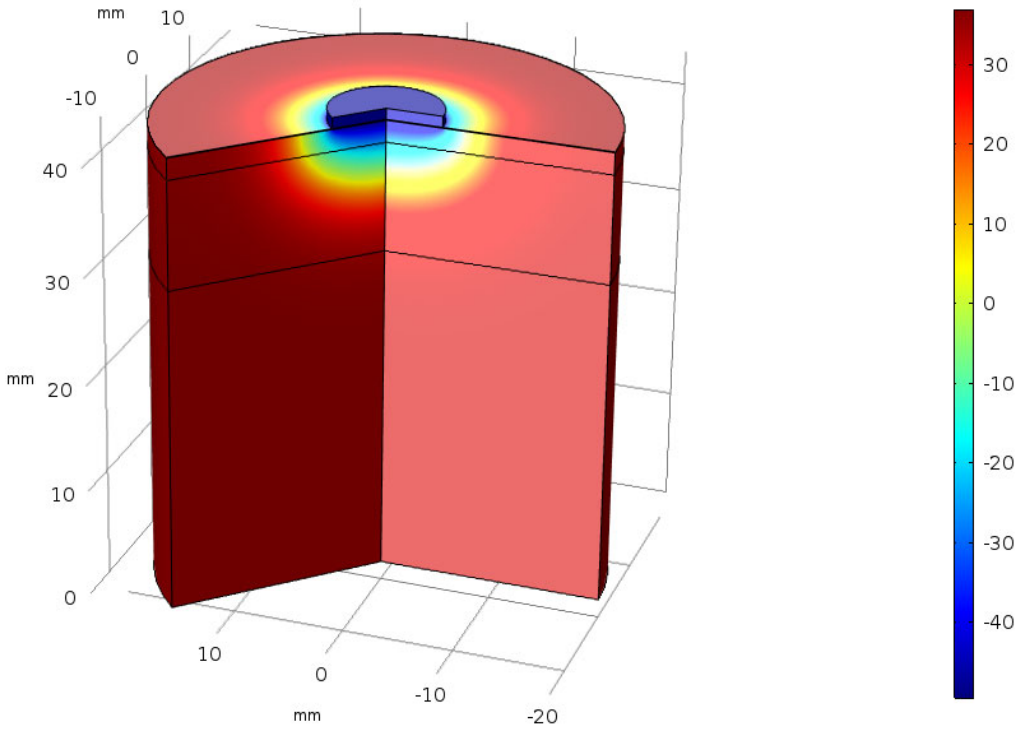

Fig. 3. Temperature distribution in the volume of the skin on the surface of which the working tool is placed at a temperature of T=-50°C at the moment of time t=120 s

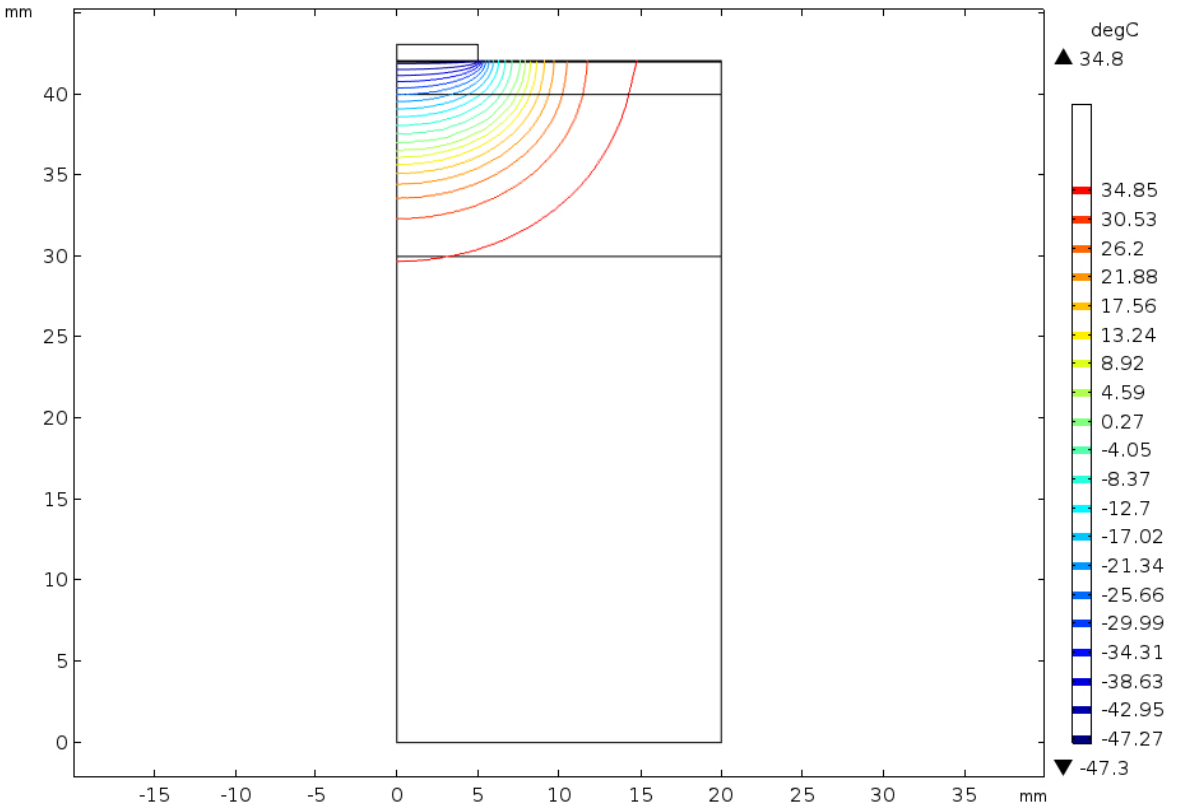

Fig.4. Distribution of isothermal surfaces in the volume of the skin on the surface of which the working tool is placed at a temperature of T = – 50 °C at the moment of time t = 120 s.

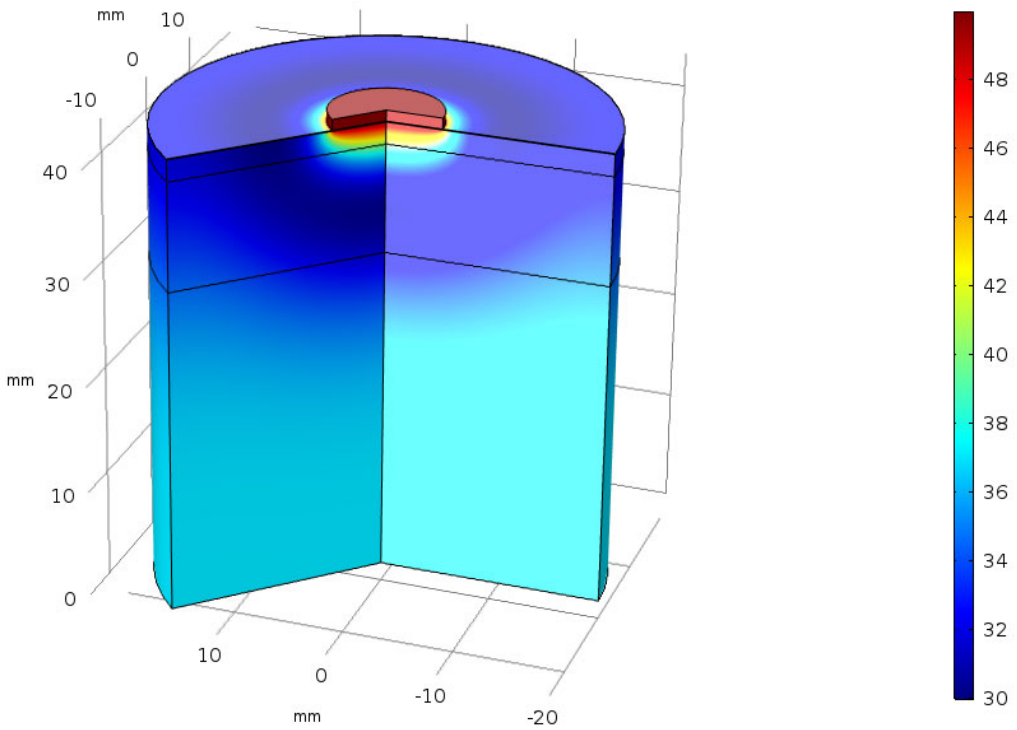

Fig. 5. Temperature distribution in the volume of the skin on the surface of which the working tool is placed at a temperature of T = + 50 °C at the moment of time t = 480 s.

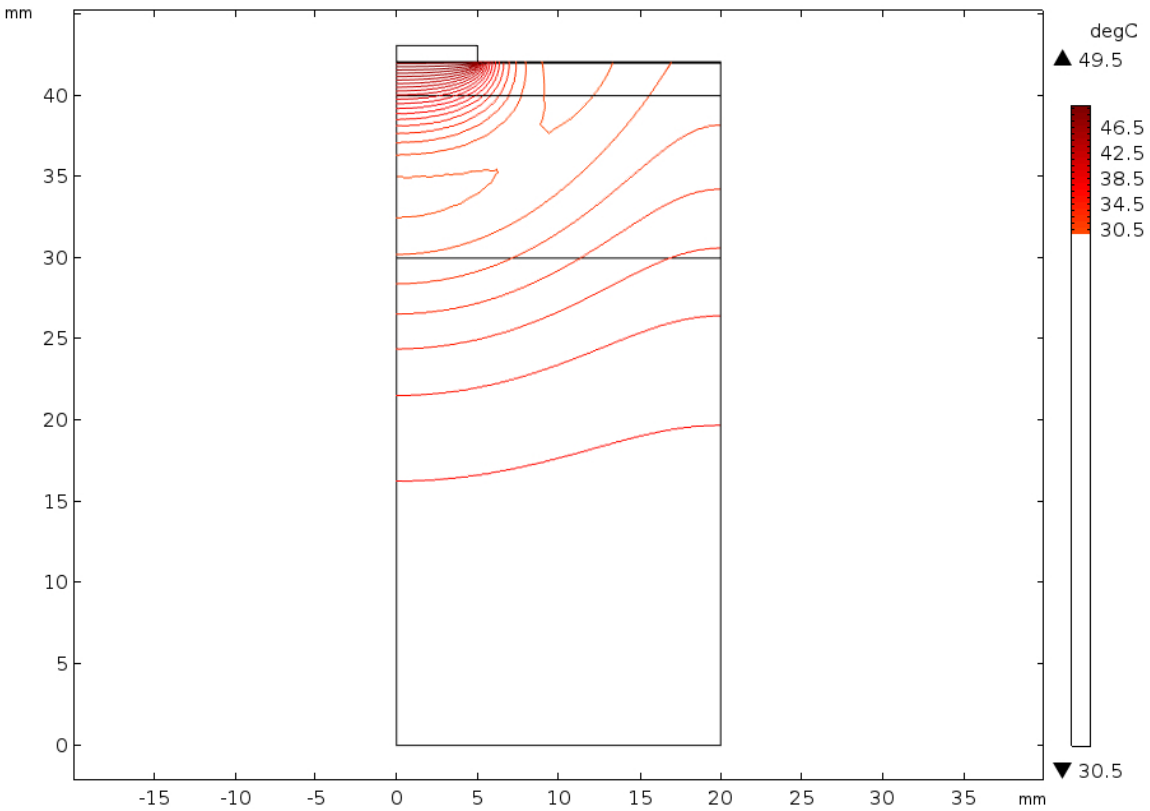

Fig. 6. Distribution of isothermal surfaces in the volume of the skin on the surface of which the working tool is placed at a temperature of T = + 50 °C at the moment of time t = 480 s.

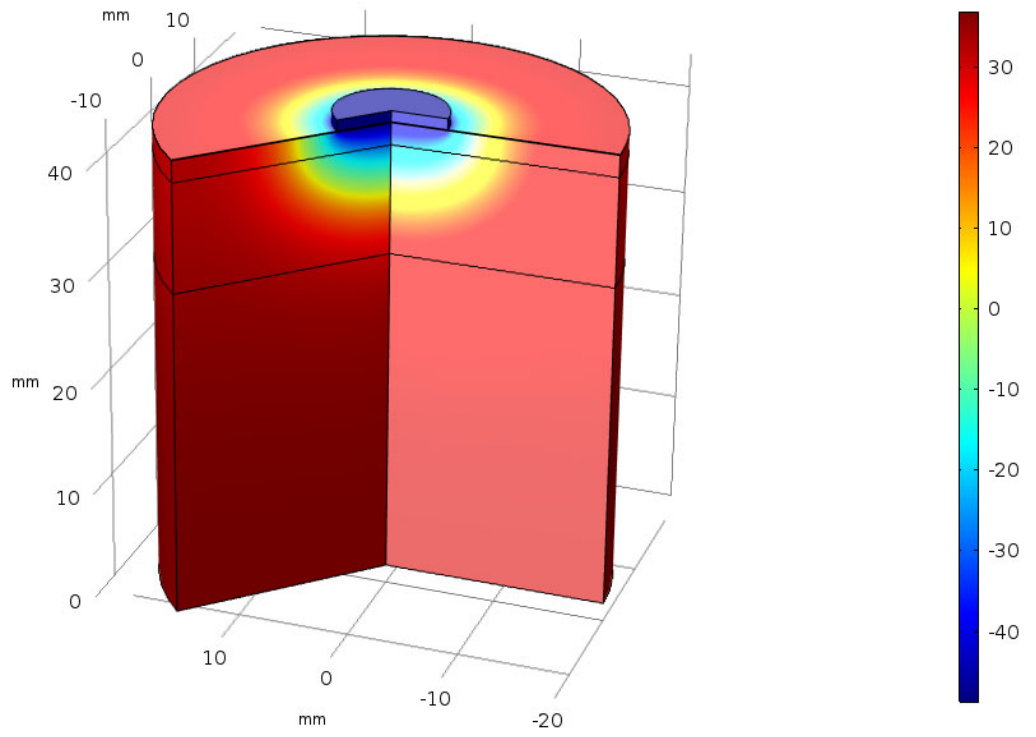

Fig. 7. Temperature distribution in the volume of the skin on the surface of which the working tool is paced at a temperature of T = – 50 °C at the moment of time t = 720 s.

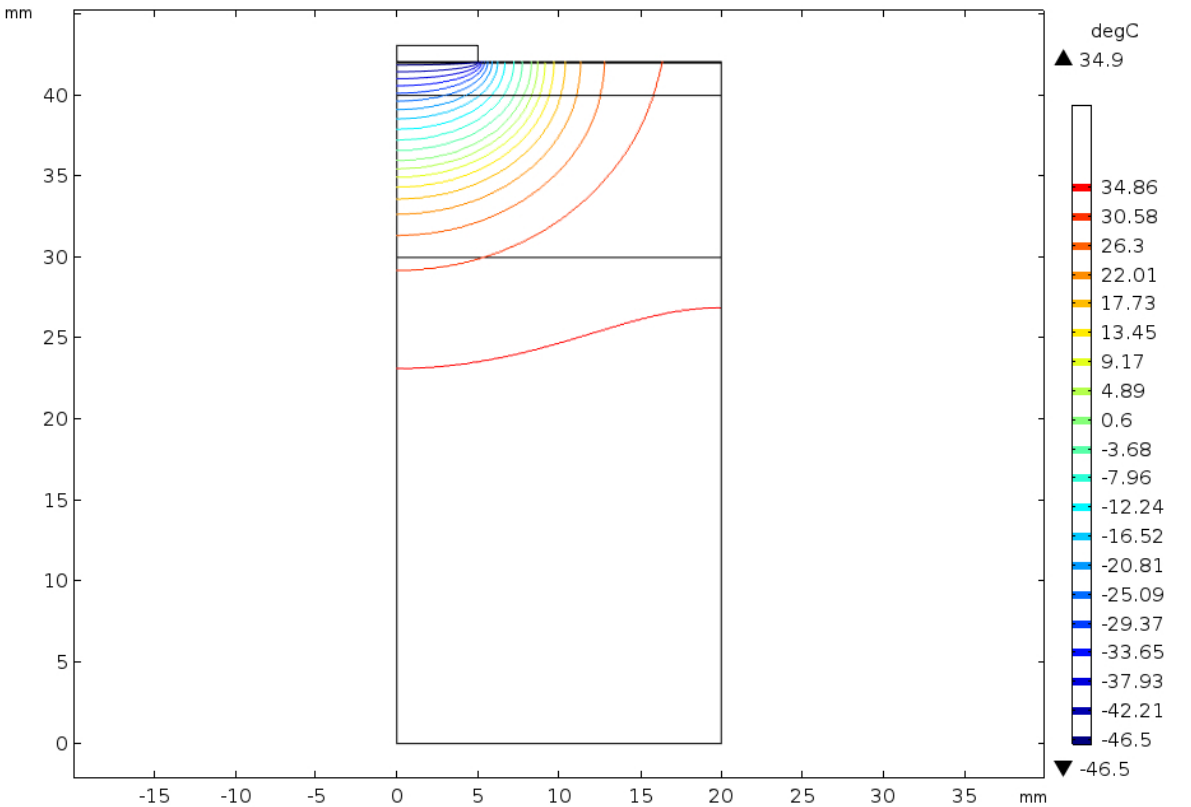

Fig. 8. Distribution of isothermal surfaces in the volume of skin on the surface of which a working tool is placed at a temperature of T = – 50°C at the moment of time t = 720 s.

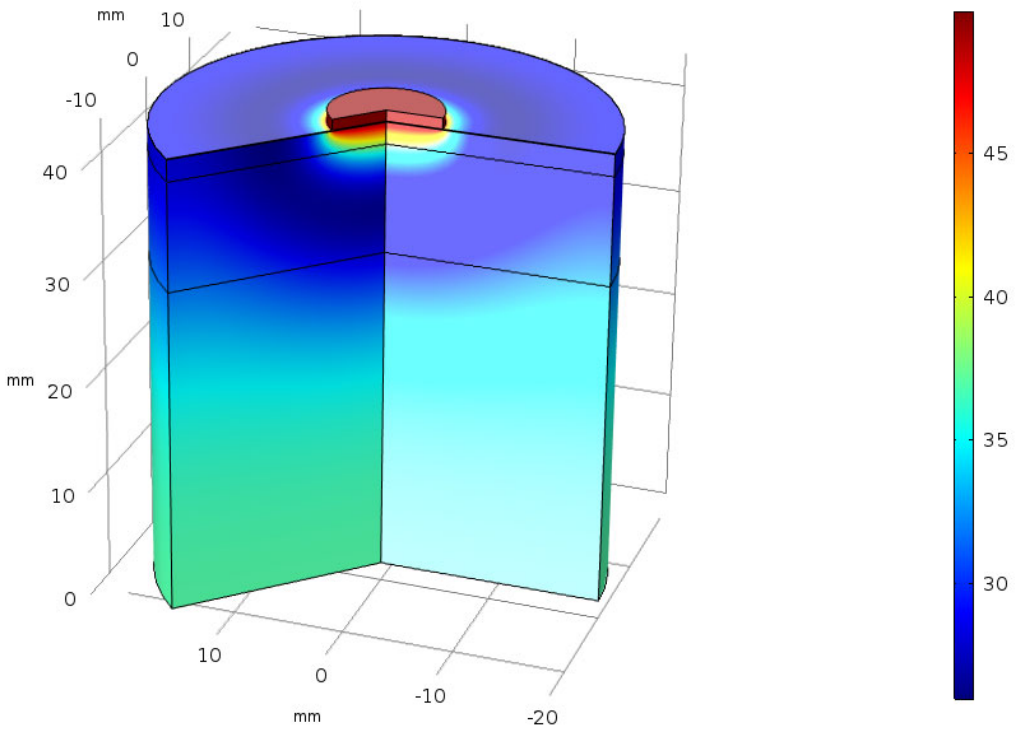

Fig. 9. Temperature distribution in the volume of the skin on the surface of which the working tool is placed at a temperature of T = + 50°C at the moment of time t = 1080 s.

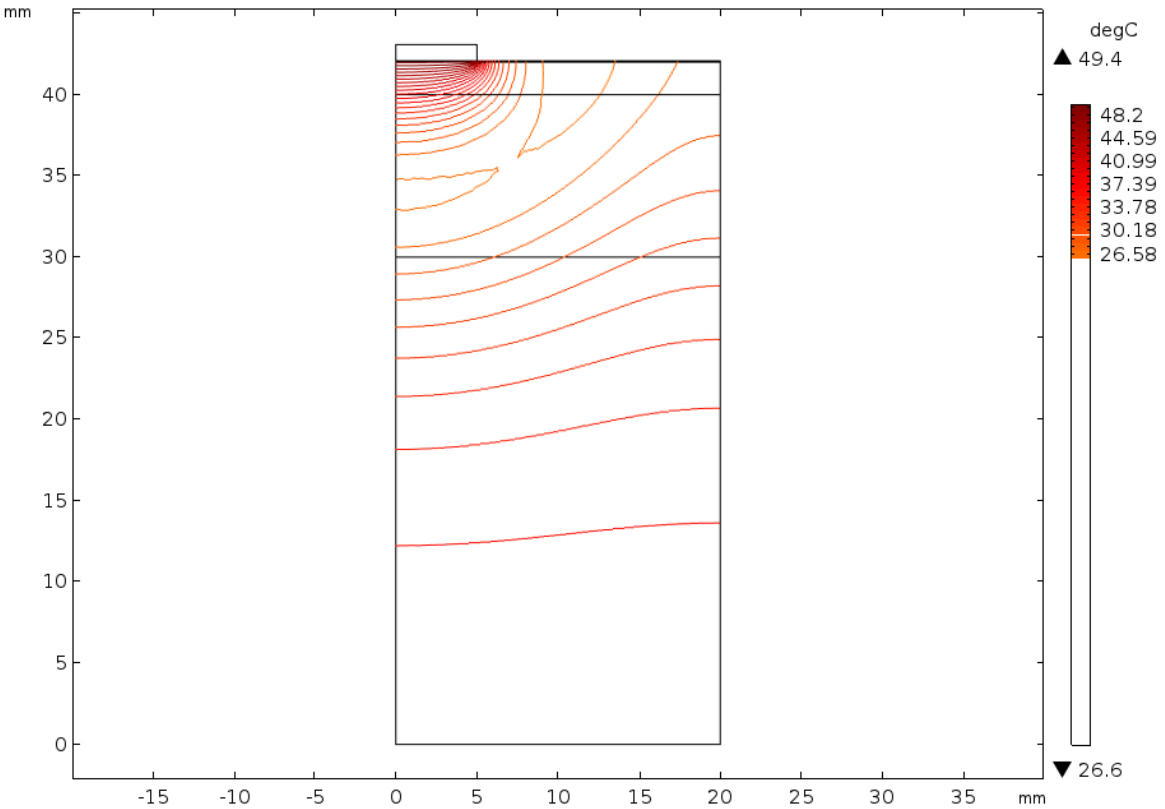

Fig. 10. Distribution of isothermal surfaces in the volume of the skin on the surface of which the working tool is paced at a temperature of T = + 50 °C at the moment of time t = 1080 s.

From Figs. 3 – 6 it can be seen that at $t = 120$ s the epidermis cools to a temperature of – 48.9 °C, at the epidermis-dermis boundary the temperature is – 48.3 °C, at the dermis-subcutaneous-fat tissue boundary the temperature is – 25.5 °C. And at $t = 480$ s, the temperature in the epidermis rises to + 49.8 °C, at the epidermis-dermis boundary the temperature is + 49.5 °C, at the dermis-subcutaneous-fat tissue boundary the temperature is + 40.3 °C. Since the upper layer of the skin (epidermis) has the smallest thickness and blood perfusion in it $\omega_b = 0$, the temperature inside this layer is close to the temperature of the working tool. Subsequently, with repeated cyclic temperature exposure (Figs. 7 – 10), it is observed that at $t = 720$ s after cooling, the temperature inside the skin, for example, at the dermis-subcutaneous-fat tissue boundary reaches – 28 °C, and at $t = 1080$ s after reheating, the temperature at the dermis-subcutaneous-fat tissue boundary is + 38 °C.

Computer simulation has shown that with an increase in the exposure (number of cycles) of temperature effect, deeper cooling of the skin layers and approximately equal heating of the skin are achieved. That is, with prolonged temperature effect in the range of [– 50 ÷ + 50] °C, it is possible to achieve destruction and coagulation of superficial skin neoplasms.

Thus, the obtained results allow predicting the depth of freezing and warming of the layers of the human skin with a given cyclic temperature exposure in order to achieve the maximum effect when performing cryodestruction or coagulation. The developed technique of computer simulation in dynamic mode makes it possible to determine temperature distributions in different layers of the human skin with a predetermined arbitrary function of temperature change of the working tool with time $T_f(t)$.

Conclusions

1. A method for computer simulation of temperature distribution in the human skin in dynamic mode has been developed, allowing to predict the results of local temperature effect on the skin and determine at any moment in time the temperature distribution in the skin layers for a given time function of change in the temperature of the working tool $T_f(t)$.
2. Using computer simulation, temperature distributions in the skin layers were determined in heating and cooling modes with changes in the working tool temperature in the temperature range [– 50 ÷ + 50]°C according to a predetermined law. The results obtained make it possible to predict the depth of heating and freezing of biological tissue under a given cyclic temperature effect.

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КОМП'ЮТЕРНЕ МОДЕЛЮВАННЯ ТЕРМОЕЛЕКТРИЧНОГО СЕНСОРА ТЕПЛОВОГО ПОТОКУ НА ПОВЕРХНІ ТІЛА ЛЮДИНИ

У роботі представлено результати комп'ютерного моделювання циклічного температурного впливу на шкіру людини у динамічному режимі. Побудовано тривимірну комп'ютерну модель біологічної тканини з врахуванням теплофізичних процесів, кровообігу, теплообміну, процесів метаболізму та фазового переходу. Як приклад, розглянуто випадок, коли на поверхні шкіри знаходиться робочий інструмент, температура якого змінюється циклічно за наперед заданим законом у діапазоні температур [-50 ÷ +50] °C. Визначено розподіли температури у різних шарах шкіри людини в режимах охолодження та нагріву. Отримані результати дають можливість прогнозувати глибину промерзання і прогрівання біологічної тканини при заданому температурному впливі.

Ключові слова: температурний вплив, шкіра людини, динамічний режим, комп'ютерне моделювання.

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