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R.R. Kobylianskyi[1,2] (https://orcid.org/0000-0002-4664-3162),
V.V. Lysko[1,2] (https://orcid.org/0000-0001-7994-6795),
Yu.M. Kanut[1,2] (https://orcid.org/0009-0003-1964-4324),
O.I. Ivaschuk[3] (https://orcid.org/0000-0003-1747-2648),
V.Yu. Bodiaka[3] (https://orcid.org/0000-0003-1422-6652),
I.O. Malyshevskyi[4] (https://orcid.org/0009-0007-5831-8256),
S.L. Hovornian[3] (https://orcid.org/0000-0003-2766-2218)

[1]Institute of Thermoelectricity of the NAS and MES
of Ukraine, 1 Nauky str., Chernivtsi, 58029, Ukraine;
[2]Yuriy Fedkovych Chernivtsi National University,
2 Kotsiubynsky str., Chernivtsi, 58012, Ukraine;
[3]Bukovinian State Medical University,
2 Theater Square, Chernivtsi, 58002, Ukraine;
[4]Municipal Enterprise "Bukovinian Clinical Oncology Center", Chernivtsi, Ukraine

Corresponding author: R.R. Kobylianskyi, e-mail: *romakobylianskyi@ukr.net*

Computer Simulation of Temperature Effect on Human Biological Tissue in the Treatment of Obesity

This study developed a physical, mathematical, and computational model of temperature effect on human biological tissue in the treatment of obesity. Temperature distributions in different layers of biological tissue during cooling were determined. The obtained results allow us to predict the depth of biological tissue freezing and the maximum cooling effect during cryomassage and cryodestruction.

Keywords: thermoelectric cooling, computer simulation, biological tissue, temperature effect, obesity, cryodestruction.

Introduction

It is known that temperature effect promotes activation of processes in the human body and is an important factor in the treatment of various diseases, namely dermatological, oncological, allergic, gynecological, cardiovascular, respiratory, musculoskeletal, etc. Cold activates

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metabolism, helps slow down the skin aging process, cleanses and facilitates its breathing, accelerates blood circulation, helps remove waste products from the surface layers of the skin, maintains muscle tone, etc. The therapeutic effect of cold locally reduces skin temperature, has anti-inflammatory, antipruritic, analgesic effects, exfoliates the epidermis, and with prolonged exposure makes it possible to remove benign or malignant neoplasms, etc. [1–15].

The above information on the temperature effect on human biological tissue demonstrates the promising application of thermoelectric cooling and heating in dermatology and oncology [11–13]. This is due to its advantages: the ability to accurately set the required temperature of the surface of the working tool, the time of temperature exposure to the corresponding area of the human body, and to provide a cyclic change in cooling and heating modes. However, the use of low and high temperatures in medical practice requires a comprehensive and in-depth study of the features of thermal effects on biological tissue, which is a complex task that requires the creation of accurate physical and mathematical models (with account for blood circulation, metabolic and heat exchange processes, as well as obesity) and the use of computer simulation [14–16].

The study of temperature fields is a fundamental theoretical and practical task for modern industry, microelectronics, medicine and materials science [17, 18]. Precise control of thermal processes allows to ensure the reliability of equipment operation, increase the efficiency of treatment and ensure the appropriate quality of products [19, 20]. However, direct experimental studies in this field often have limited application due to the high complexity of measuring temperature distribution, the duration and cost of direct temperature measurement inside closed objects or in aggressive environments.

To overcome these limitations, mathematical and computer simulation methods are often used [21–23]. There are several main approaches: the use of analytical methods, which allow obtaining accurate functional dependencies for calculating the temperature distribution, but their application is limited to geometries of simple shapes [23]; a combination of analytical and numerical methods, which allows finding a compromise between the accuracy of calculations and the speed of calculations for more complex cases; numerical methods, in particular those implemented using developed software [20, 22–23] or specialized application software packages (such as ANSYS, COMSOL Multiphysics or SOLIDWORKS). They enable highly accurate simulation of complex thermal fields, including dynamics, with regard to material heterogeneity and boundary conditions. Such virtual computer simulation allows for the optimization of designs at the design stage, significantly reducing the need for actual physical testing, and also identifies critical conditions requiring increased attention and potential experimental studies [24–30].

Therefore, *the purpose of the work* is to develop a computer simulation technique that will allow predicting the results of local temperature effects on human biological tissue, including during cryodestruction in dermatology and oncology.

1. Physical model of biological tissue with a cooling element

The biological tissue of the human body (Fig. 1) is a structure of three layers of skin (epidermis 1, dermis 2, subcutaneous fat 3) and internal tissue (fat) 4. The temperatures at the

boundaries of the corresponding layers of biological tissue with thicknesses h_1, h_2, h_3, h_4 are T_1, T_2, T_3, T_4, and the specific heat fluxes inside are Q_1, Q_2, Q_3, Q_4. The free surface of the skin area (epidermis 1) is in a state of heat exchange with the environment at a temperature of T_7. The specific heat flux from the free surface of the skin is Q_6, and the specific heat flux of the human internal organs is Q_5. Heat exchange of the skin by radiation and sweating is not taken into account.

A cooled element 5 with a height of l is placed on the surface of biological tissue (epidermis 1) with a temperature of T_5, the temperature on the contact surface is T_6.

Since the physical model represents a section of biological tissue consisting of four layers, and the same biochemical processes occur in other neighboring layers, we can assume that heat flow through the side surfaces of biological tissue does not occur ($Q = 0$).

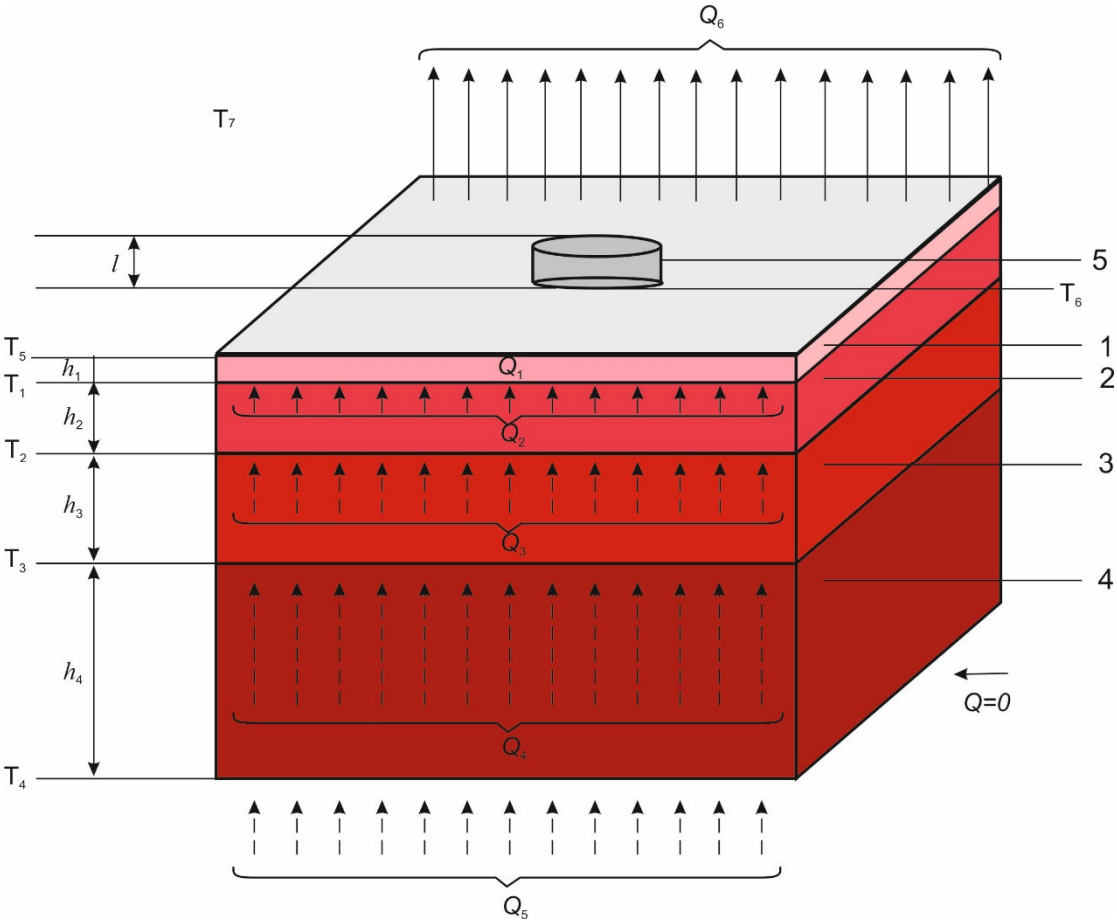

Fig. 1. Physical model of biological tissue with a cooling element: 1 – epidermis, 2 – dermis, 3 – subcutaneous fat, 4 – internal tissue (fat), 5 – cooling element

2. Mathematical description of the model

To describe the process of heat exchange in "living" human biological tissues, the Pennes model is used [31]. The model is based on four assumptions:

1) heat exchange between blood and biological tissue in prearterioles and postarterioles is neglected;

2) blood flow in small capillaries is considered isotropic, the direction of blood flow is neglected;

3) large blood vessels in close proximity to capillary vessels do not contribute to the energy exchange between biological tissue and capillary blood (i.e., the Pennes model does not take into account the local geometry of the vessels);

4) the temperature of the blood in the arterioles is equal to the body temperature. Energy exchange occurs instantly: the blood temperature equalizes with the local temperature of the biological tissue.

Based on the above assumptions, Pennes modeled the effect of blood as an isotropic heat source, proportional to the blood flow velocity and the difference between body temperature and local tissue temperature [32–34]:

$$\rho_{skin} Cp_{skin} \frac{\partial T}{\partial t} = \nabla \cdot (\kappa_{skin} \nabla T) + (\rho Cp)_{blood} \omega_b (T_a - T) + q_m , \quad (1)$$

where ρ_{skin} – human skin density;

Cp_{skin} – specific heat capacity of human skin;

k_{skin} – thermal conductivity of human skin;

ρ_{blood} – human blood density;

Cp_{blood} – specific heat capacity of human blood;

ω_b – human blood perfusion;

T_a – arterial blood temperature (T_a=37 °C);

T – biological tissue temperature;

q_m – heat released due to metabolism.

The metabolic heat generation considered in this model is assumed to be uniformly distributed throughout the biological tissue, and blood perfusion is also assumed to be uniform and isotropic. According to the Pennes model, thermal equilibrium occurs directly in the capillary circle of the microcirculatory bed (blood at temperature T enters the capillaries, where heat exchange occurs and the temperature decreases to the temperature of the biological tissue T).

The term on the left side of equation (1) represents the rate of change of thermal energy contained in a unit volume of biological tissue. The three terms on the right side of this equation represent the rate of change of thermal energy due to thermal conductivity, blood perfusion, and metabolic heat, respectively.

For the steady-state case $\frac{\partial T}{\partial t} = 0$, therefore equation (1) is simplified to the form:

$$\nabla \cdot (\kappa_{skin} \nabla T) + (\rho Cp)_{blood} \omega_b (T_a - T) + q_m = 0 . \quad (2)$$

The steady-state heat transfer equation in biological tissue (2) is solved with the following boundary conditions (3), resulting in the distribution *T(x, y, z).*

$$\begin{cases} Q\big|_{x=0} = 0, \\ Q\big|_{x=a} = 0, \end{cases} \quad \begin{cases} Q\big|_{y=0} = 0, \\ Q\big|_{y=a} = 0, \end{cases} \quad \begin{cases} T\big|_{z=0} = 37\ ^\circ C, \\ q\big|_{z=b} = \alpha \cdot (T_0 - T), \end{cases} \tag{3}$$

where Q is heat flux density, T is absolute temperature, T_0 is ambient temperature, α is heat transfer coefficient.

The thermophysical properties of the layers of human biological tissue are given in Table 1.

Table 1

Thermophysical properties of human skin layers [35–43]

Layers of human biological tissue	*Property*	*Value*	*Measurement units*
Epidermis	Thermal conductivity, k_{skin}	0.24	W/m°K
	Density, ρ_{skin}	1200	kg/m^3
	Specific heat, Cp_{skin}	3590	J/kg°K
	Thickness, h	8×10^{-5}	m
	Perfusion, ω_b	0	s^{-1}
Dermis	Thermal conductivity, k_{skin}	0.45	W/m°K
	Density, ρ_{skin}	1200	kg/m^3
	Specific heat, Cp_{skin}	3300	J/kg°K
	Thickness, h	2×10^{-3}	m
	Perfusion, ω_b	0.00125	s^{-1}
Subcutaneous fat	Thermal conductivity, k_{skin}	0.19	W/m°K
	Density, ρ_{skin}	1000	kg/m^3
	Specific heat, Cp_{skin}	2500	J/kg°K
	Thickness, h	1×10^{-2}	m
	Perfusion, ω_b	0.00125	s^{-1}
Internal tissue (fat)	Thermal conductivity, k_{skin}	0.5	W/m°K
	Density, ρ_{skin}	1000	kg/m^3
	Specific heat, Cp_{skin}	3800	J/kg°K
	Thickness, h	3×10^{-2}	m
	Perfusion, ω_b	0.00125	s^{-1}

3. Computer simulation results

A three-dimensional computer model of human biological tissue with a cooling element on its surface was created in a cylindrical coordinate system. The Comsol Multiphysics software package [44] was used to construct the computer model, allowing for the simulation of thermophysical processes in biological tissue, taking into account blood circulation and metabolism.

The calculation of temperature distributions and heat flux densities in human 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 given second-order differential equation with the corresponding boundary conditions. The accuracy of the solution of the problem depends on the level of division and is ensured by the use of a large number of finite elements [44].

Fig. 2 shows the temperature distribution in the volume of biological tissue of the human body, on the surface of which a cooling element is placed at a temperature of $T = 25$ °C.

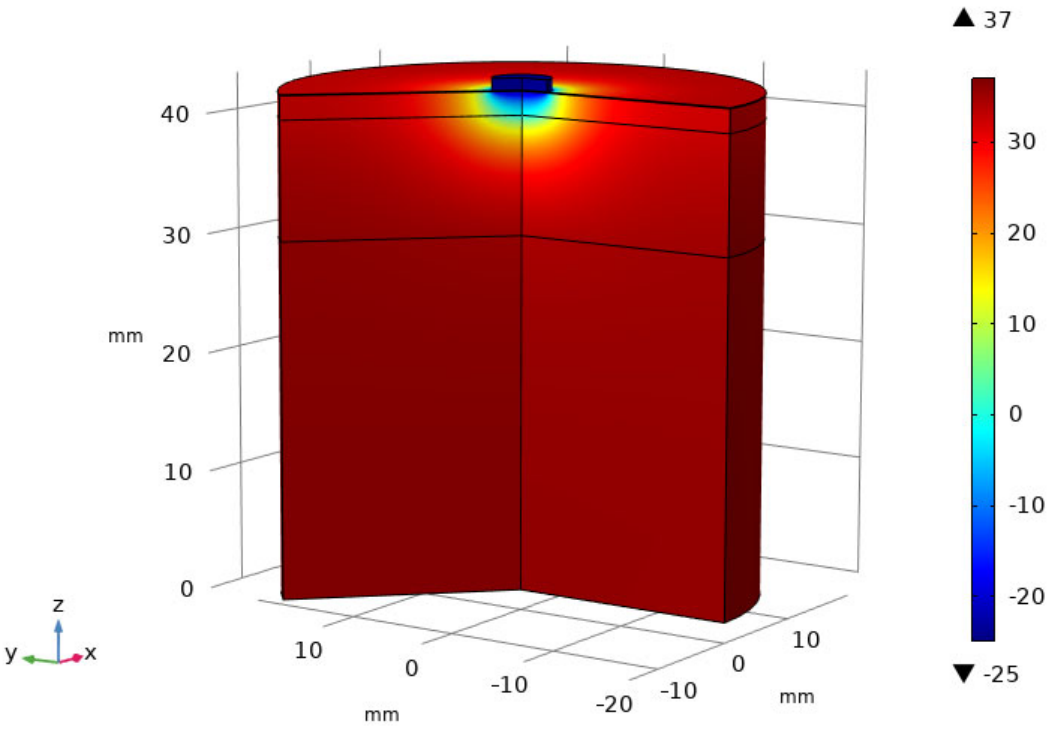

Fig. 2. Temperature distribution in the bulk of human biological tissue with a cooling element located on its surface at a temperature of –25 °C.

Computer simulation was also used to obtain the distribution of isothermal surfaces in human biological tissue (Fig. 3), taking into account edge effects in an improved three-dimensional computer model.

Using computer simulation, the temperature distribution in human biological tissue was obtained. As an example, Fig. 4 shows the specified temperature distribution in biological tissue at cooling element temperatures in the range $T = +20 \div -25$ °C.

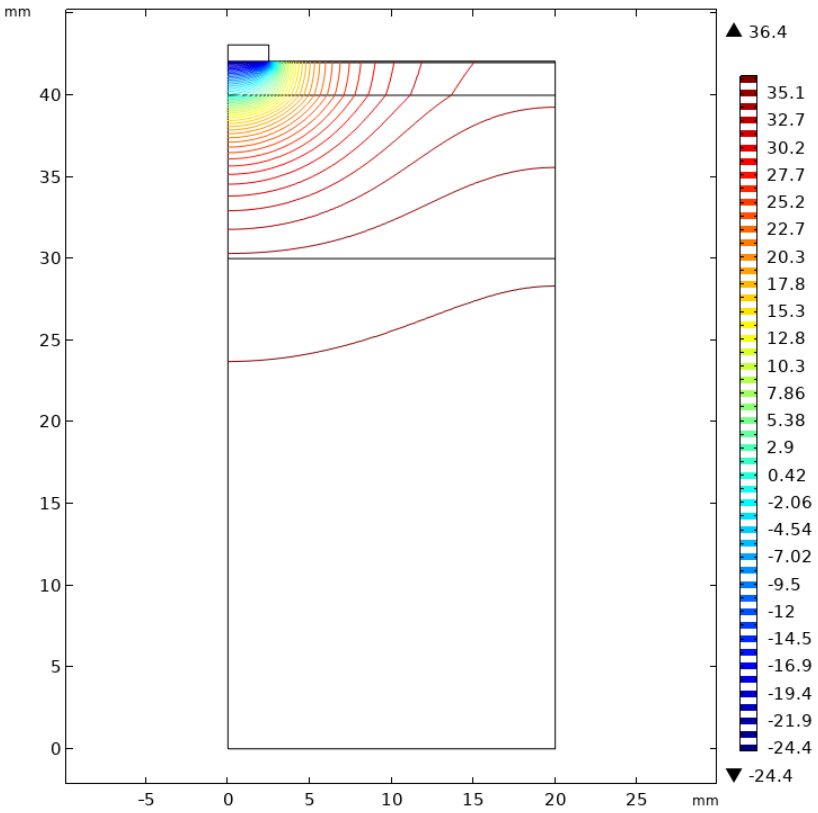

Fig. 3. Distribution of isothermal surfaces in human biological tissue, with a cooling element located on its surface at a temperature of T = –25 °C

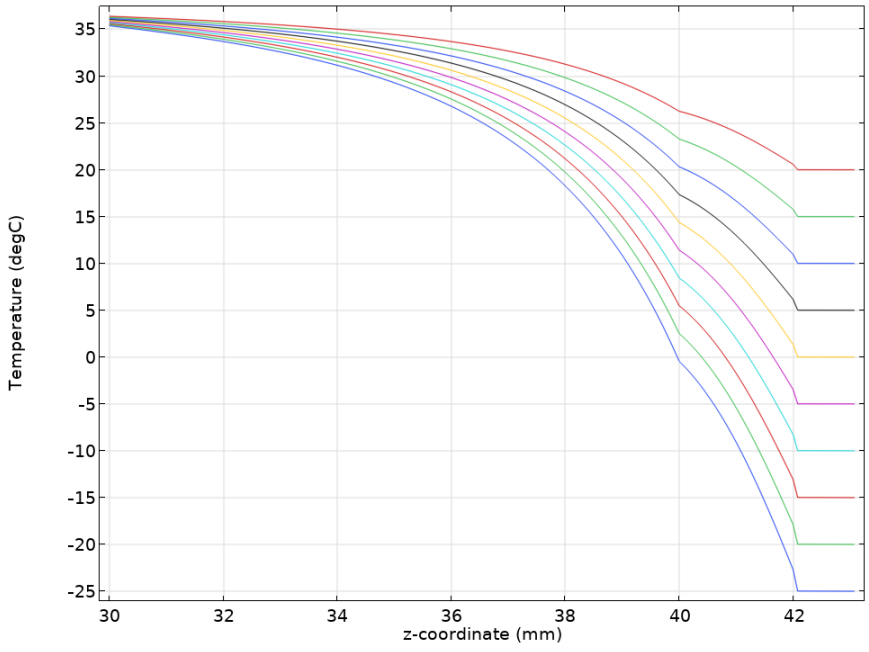

Fig. 4. Temperature distribution in biological tissue at cooling element temperatures in the range T = +20 ÷ –25 °C

The relationship between the temperature of the cooling element on the skin surface and the freezing depth of biological tissue was also determined (Fig. 5). It was found that to achieve

freezing of biological tissue to a depth of 2.5 mm, a skin surface temperature of –25 °C was required.

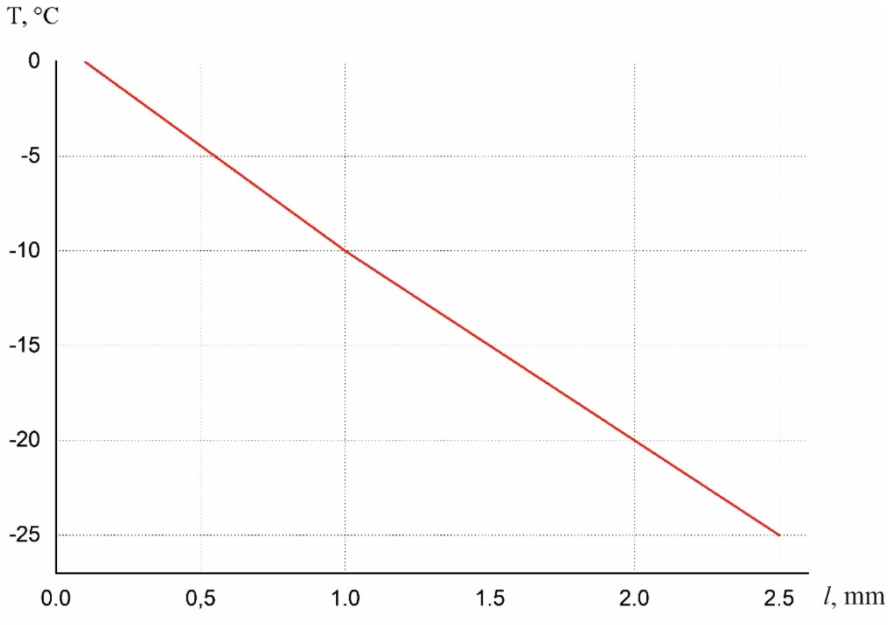

Fig. 5. Dependence of the temperature of the cooling element on the surface of biological tissue on the depth of freezing

The results obtained make it possible to determine the required depth of freezing of human biological tissue and achieve the maximum cooling effect when performing cryodestruction in dermatology and oncology.

Conclusions

1. A physical, mathematical and computer model of the temperature effect on human biological tissue has been developed, with regard to obesity. Temperature distributions and isothermal surfaces in different layers of biological tissue in the cooling mode have been determined. It has been established that to achieve freezing of biological tissue to a depth of 2.5 mm, it is necessary to ensure a temperature on the surface of biological tissue of $T = –25$ °C.
2. A computer simulation technique has been developed that makes it possible to predict the results of local temperature effects on human biological tissue, including during cryodestruction in dermatology and oncology.

Authors' information

R.R. Kobylianskyi – Candidate of Physical and Mathematical Sciences, Head of the Department of Thermoelectricity and Medical Physics.
V.V. Lysko – Candidate of Physical and Mathematical Sciences, Acting Director of the Institute of Thermoelectricity.
Yu.M. Kanut – Laboratory assistant of the Institute of Thermoelectricity.

O.I. Ivaschuk – Doctor of Medical Sciences, Professor.
V.Yu. Bodiaka – Doctor of Medical Sciences, Professor.
I.O. Malyshevskyi – CEO, Bukovinian Clinical Oncology Center.
S.L. Hovornian – Graduate Teaching Assistant of Department of Oncology and Radiology, BSMU, PhD (Doctor of Philosophy).

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Кобилянський Р.Р.[1,2] (https://orcid.org/0000-0002-4664-3162),
Лисько В.В.[1,2] (https://orcid.org/0000-0001-7994-6795),
Канут Ю.М.[1,2] (https://orcid.org/0009-0003-1964-4324),
Іващук О.І.[3] (https://orcid.org/0000-0003-1747-2648),
Бодяка В.Ю.[3] (https://orcid.org/0000-0003-1422-6652),
Малишевський І.О.[4] (https://orcid.org/0009-0007-5831-8256),
Говорнян С.Л.[3] (https://orcid.org/0000-0003-2766-2218)

[1]Інститут термоелектрики НАН та МОН України,
вул. Науки, 1, Чернівці, 58029, Україна;
[2]Чернівецький національний університет імені Юрія Федьковича,
вул. Коцюбинського 2, Чернівці, 58012, Україна;
[3]Буковинський державний медичний університет,
Театральна площа, 2, Чернівці, 58002, Україна;
[4]ОКНП «Буковинський клінічний онкологічний центр», Чернівці, Україна

Комп'ютерне моделювання температурного впливу на біологічну тканину людини при лікуванні ожиріння

У роботі побудовано фізичну, математичну та комп'ютерну моделі температурного впливу на біологічну тканину людини при лікуванні ожиріння. Визначено розподіли температури у різних шарах біологічної тканини в режимі охолодження. Отримані результати дають можливість прогнозувати глибину промерзання біологічної тканини та максимальний ефект охолодження при проведенні кріомасажу та кріодеструкції.

Ключові слова: термоелектричне охолодження, комп'ютерне моделювання, біологічна тканина, температурний вплив, ожиріння, кріодеструкція.