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L.I. Anatychuk, *Acad. NAS Ukraine* [1,2]
R.R. Kobylianskyi, *Cand. Sc (Phys &Math)* [1,2]
R.V. Fedoriv [1,2]

[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
e-mail: anatych@gmail.com

COMPUTER SIMULATION OF THE WORKING TOOL OF THERMOELECTRIC DEVICE FOR CRYODESTRUCTION WITHOUT TAKING INTO ACCOUNT PHASE TRANSITION

The paper presents the results of computer simulation of the working tool of thermoelectric device for cryodestruction without taking into account phase transition, as well as cyclic temperature effect on the human skin in dynamic mode. A physical model of the working tool, a three-dimensional computer model of biological tissue taking into account thermophysical processes, blood circulation, heat exchange, metabolic processes and phase transitions, is constructed. As an example, a case is considered when the working tool is on the skin surface, the temperature of which changes cyclically according to a given law in the temperature range [– 50 ÷ + 50] °C. Temperature distributions in different layers of the human skin in cooling and heating modes were determined. The obtained results make it possible to predict the depth of freezing and warming of biological tissue at a given temperature effect.

Key words: cryodestruction, working tool, temperature effect, human skin, dynamic mode, computer simulation.

Introduction

Temperature effect is an important factor in the treatment of many diseases of the human body [1 – 12]. 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 used [13 – 17], which significantly limits the possibilities of their use in medical institutions where the supply of liquid nitrogen is problematic. In addition, 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 reduces the overall efficiency of using cold in treatment.

The use of thermoelectric cooling (heating) can solve this problem [12, 18 – 21]. The studies of thermal effects on biological tissue conducted over many years, the creation of thermoelectric devices based on them and their use in medical practice confirm their efficiency. Thermoelectric devices are promising in such areas of medicine as cryotherapy, cryosurgery, ophthalmology, traumatology, neurosurgery, plastic surgery, urology, dermatology [10 – 12].

However, the experience of using thermoelectric medical devices revealed a number of their shortcomings. Among them, the most important is the lack of ability to manage cooling and heating processes in time. The latter significantly narrows the possibilities of heat and cold treatment.

Studies show that cooling rates (their dynamics) play a decisive role in treatment [16, 22 – 34]. Thus, very fast cooling does not lead to the destruction of biological tissues at all. On the contrary, moderate but cyclical cooling promotes energetic destruction of tumors. The time functions of cooling and heating are also important in the treatment of other diseases.

Therefore, the general problem is to develop a thermoelectric device for the destruction of biological tissue or oncological neoplasms, which will provide the possibility of cyclic temperature effects on the tumor. This determines the relevance of the problem posed in the present work.

The importance of solving this problem is obvious, otherwise thermoelectric devices for medicine of a new generation with the possibility of cyclic temperature effects on the human skin cannot be developed.

Therefore, the purpose of this work is computer simulation of the working tool of thermoelectric device for cryodestruction without taking into account the phase transition.

1. Physical model of the working tool of thermoelectric device for destruction the walls of which are made of steel

Fig.1 shows a physical model consisting of housing 1, inside which substance 2 (25 % alcohol solution) with a phase transition temperature T_1 is placed. Housing 1 with a hemispherical end 3 touches the skin 4 with a plane 5 with a diameter d. Housing 1 is made of medical grade stainless steel. Skin model 4 takes into account its complex structure.

The model takes into account heat inleak Q_1 at the ambient air temperature T_2 = 25 °C, as well as heat inleak Q_2 from the ambient air. The upper part of housing 1 is adiabatically insulated (q = 0). The diameter of the thermal contact 5 is 5 mm.

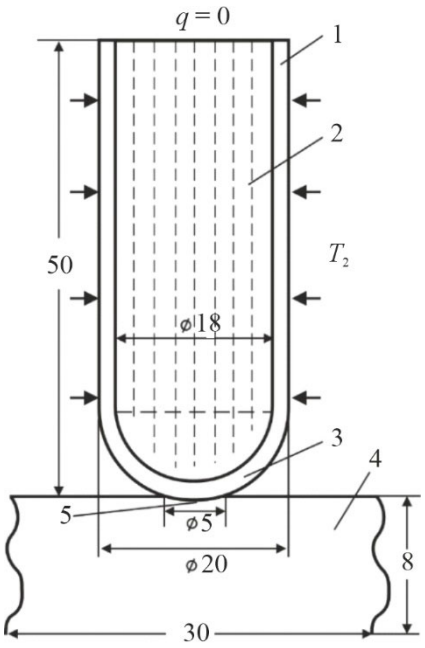


Fig. 1. Physical model of the working tool of thermoelectric device for cryodestruction, the walls of which are made of steel.

2. Computer model

A three-dimensional computer model of biological tissue was created in a cylindrical coordinate system, on the surface of which there is a thermoelectric medical device for local cooling. The Comsol

Multiphysics package of application programs [45] was used to build computer models, which makes it possible to simulate thermophysical processes in biological tissue, taking into account blood circulation, heat exchange, metabolic processes, and phase transition.

The calculation of temperature distributions and the density of heat flows in biological tissue and cold accumulator was carried out by 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, which satisfies the given second order differential equation with the corresponding boundary conditions. The accuracy of solving the given problem depends on the level of division and is ensured by the use of a large number of finite elements [45].

Thermophysical properties of the skin and the biological tissue of human body [35 – 38] in normal and frozen states are shown in Tables 1, 2.

Table 1

Thermophysical properties of the biological tissue of human body [35 – 38]

Biological tissue layers	Epidermis	Dermis	Subcutaneous layer	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
Heat capacity of blood, C_b ($J \cdot kg^{-1} \cdot K^{-1}$)	3770	3770	3770	3770

Table 2

Thermophysical properties of the biological tissue of human body in normal and frozen states [35 – 38]

Thermophysical properties of 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

3. Computer simulation results

Fig. 2 shows temperature distributions in human skin, directly under the center of action of the working tool

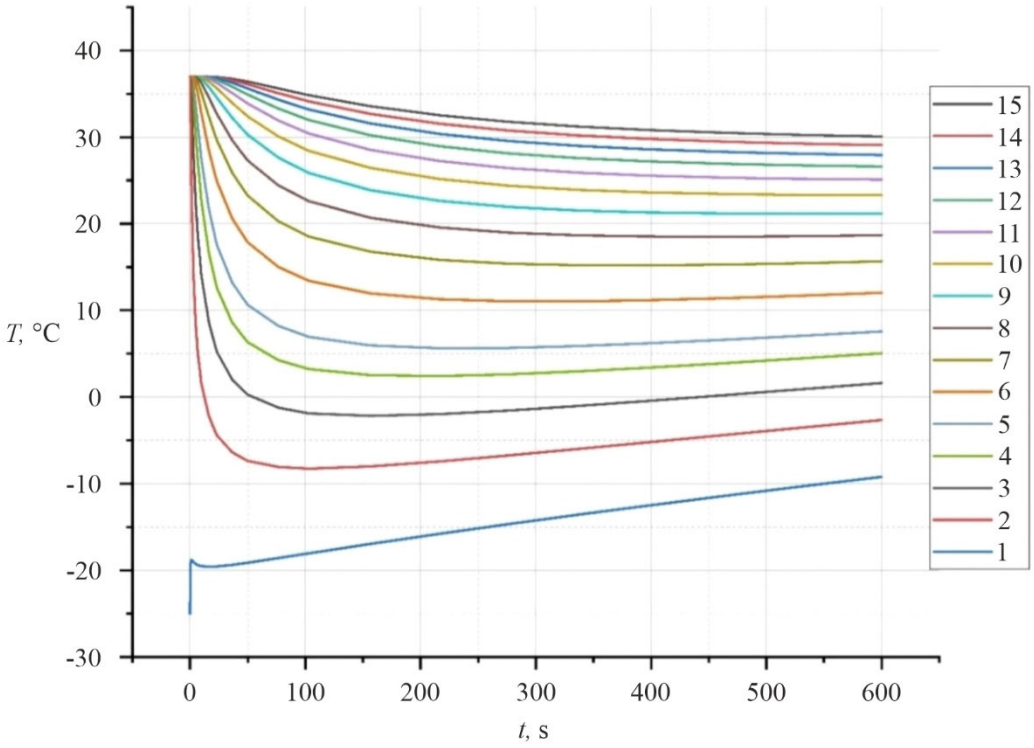


Fig. 2. Dependences of temperature on time in the human skin at different depths: 1 – point of contact between working tool and skin; 2 – 0.5 mm; 3 – 1 mm; 4 – 1.5 mm; 5 – 2 mm; 6 – 2.5 mm; 7 – 3 mm; 8 – 3.5 mm; 9 – 4 mm; 10 – 4.5 mm; 11 – 5 mm; 12 – 5.5 mm; 13 – 6 mm; 14 – 6.5 mm; 15 – 7 mm.

Fig. 3 shows temperature distributions in the skin directly under the centre of action of the working tool at time moments: 10 s, 60 s, 140 s, 200 s, 600 s.

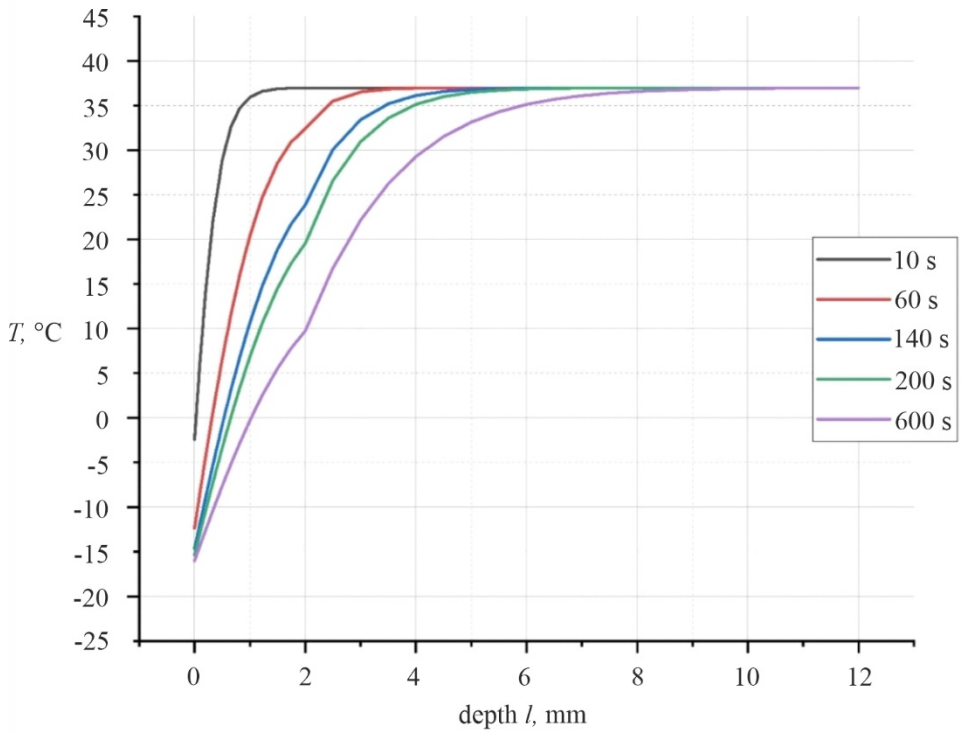


Fig. 3. Dependences of temperature on skin depth at time moments: 10 s, 60 s, 140 s, 200 s, 600 s.

Fig. 4 represents temperature distributions in the cold accumulator at different depths.

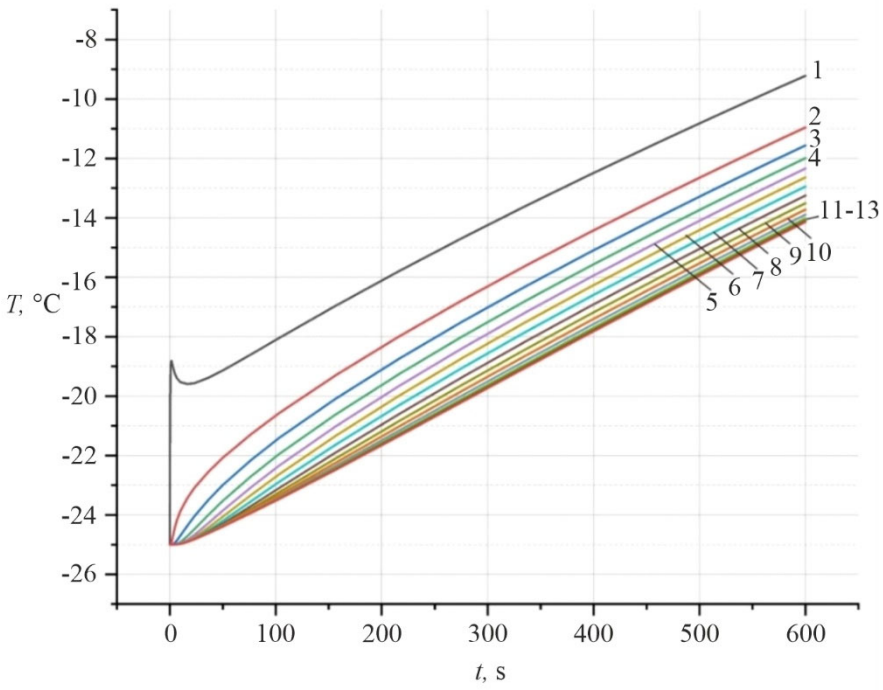


Fig. 4. Dependences of temperature on time in the cold accumulator at different depths: 1 – point of contact between working tool and skin: 2 – 4 mm; 3 – 8 mm; 4 – 12 mm; 5 – 16 mm; 6 – 20 mm; 7 – 24 mm; 8 – 28 mm; 9 – 32 mm; 10 – 36 mm; 11 – 40 mm; 12 – 44 mm; 13 – 48 mm.

Fig. 5 shows the distribution of temperatures in the cold accumulator at the following moments: 10 s, 60 s, 140 s, 200 s, 600 s.

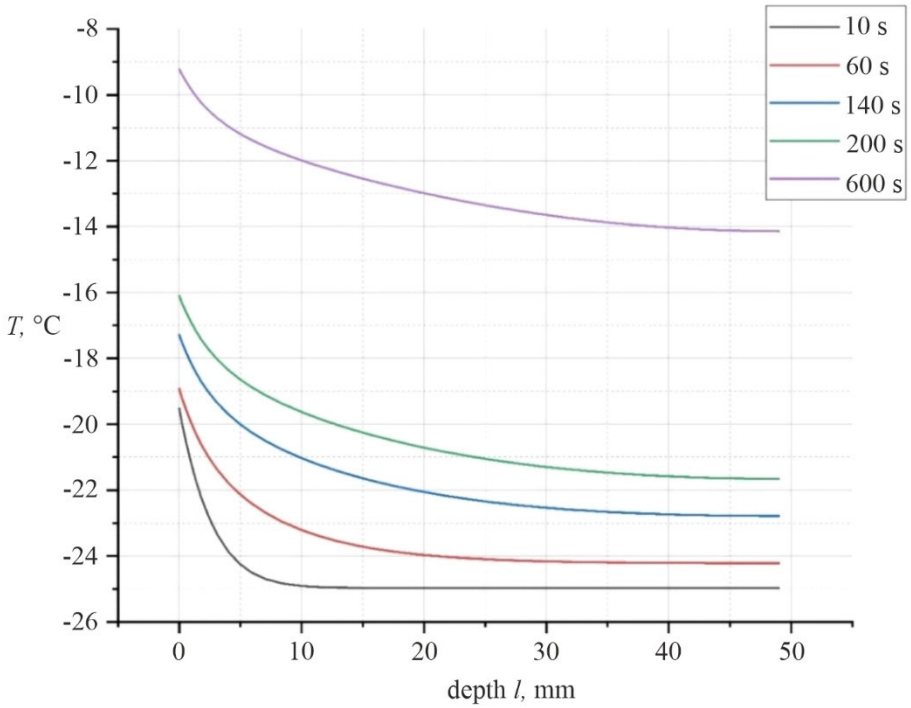


Fig. 5. Dependences of temperature on time in the cold accumulator at time moments:10 s, 60 s, 140 s, 200 s, 600 s.

4. Physical model of the working tool of thermoelectric device for destruction the walls of which are made of copper

Fig. 6 shows a physical model consisting of a housing 1, inside which a substance 2 (25 % alcohol solution) with a phase transition temperature T1 is placed. Housing 1 with its hemispherical end 3 touches skin 4 with a plane 5 of diameter d. Housing 1 is made of copper. The complex structure of skin 4 is taken into account in the model.

The model takes into account the heat inleak Q_1 at the ambient air temperature $T_2 = 25$ °C, as well as the heat inleak Q_2 from the ambient air. The upper part of the housing 1 is adiabatically insulated ($q = 0$). The diameter of the thermal contact is 5 mm.

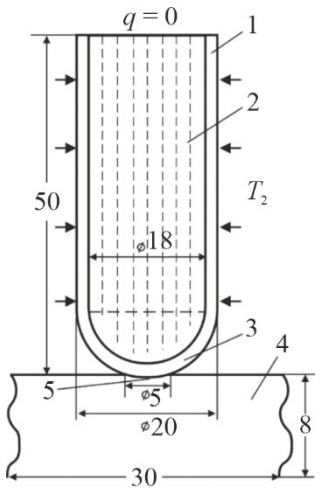


Fig. 6. Physical model of the working tool of thermoelectric device for cryodestruction the walls of which are made of copper.

5. Results of computer simulation

Fig. 7 shows temperature distributions in the human skin, directly under the center of action of the working tool.

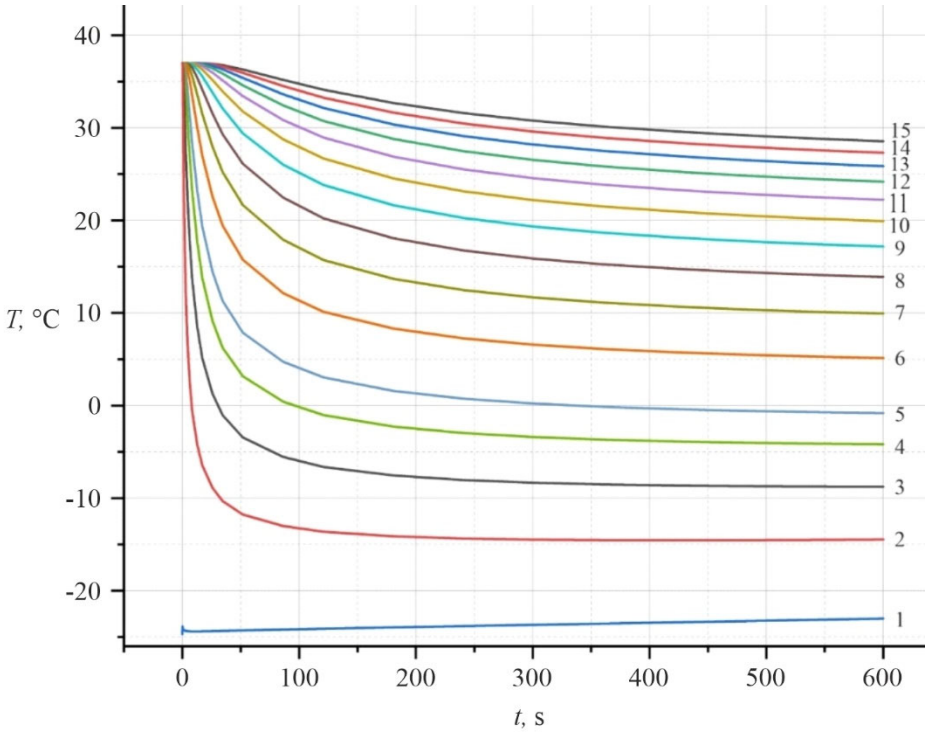


Fig. 7. Dependences of temperature on time in the human skin at different depths: 1 – point of contact between the working tool and skin; 2 – 0.5 mm; 3 – 1 mm; 4 – 1.5 mm; 5 – 2 mm; 6 – 2.5 mm; 7 – 3 mm; 8 – 3.5 mm; 9 – 4 mm; 10 – 4.5 mm; 11 – 5 mm; 12 – 5.5 mm; 13 – 6 mm; 14 – 6.5 mm; 15 – 7 mm.

Fig. 8 shows temperature distributions in the cold accumulator at different depths.

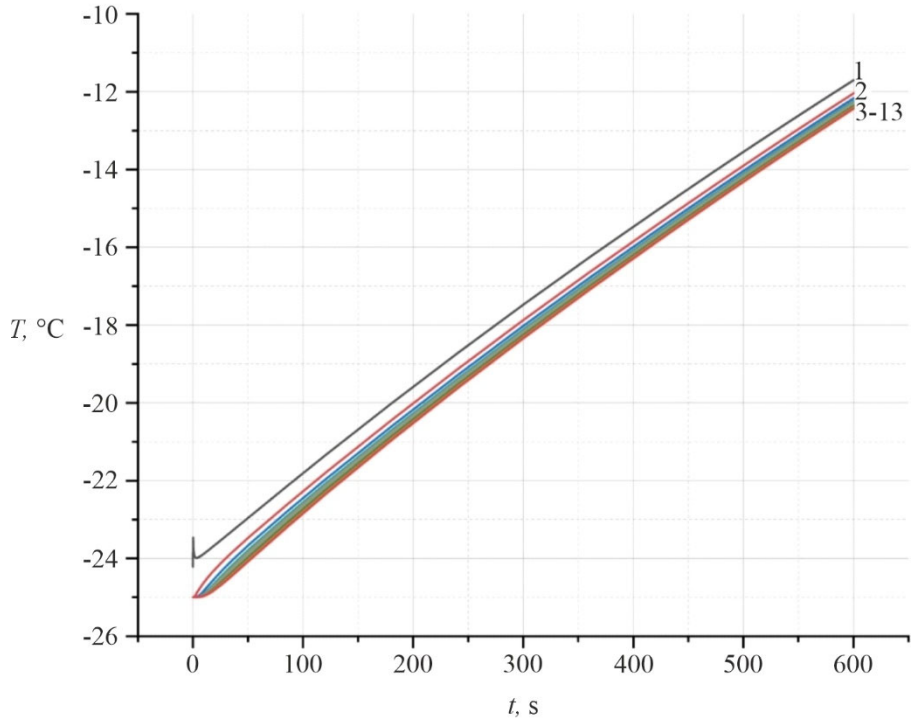


Fig. 8. Dependences of temperature on time in the cold accumulator at different depths: 1 – point of contact between the working tool and skin; 2 – 4 mm; 3 – 8 mm; 4 – 12 mm; 5 – 16 mm; 6 – 20 mm; 7 – 24 mm; 8 – 28 mm; 9 – 32 mm; 10 – 36 mm; 11 – 40 mm; 12 – 44 mm; 13 – 48 mm.

Fig. 9 shows the dependence of temperature on depth at time moments 60, 120, 240, 600 s and depending on the location under the working tool.

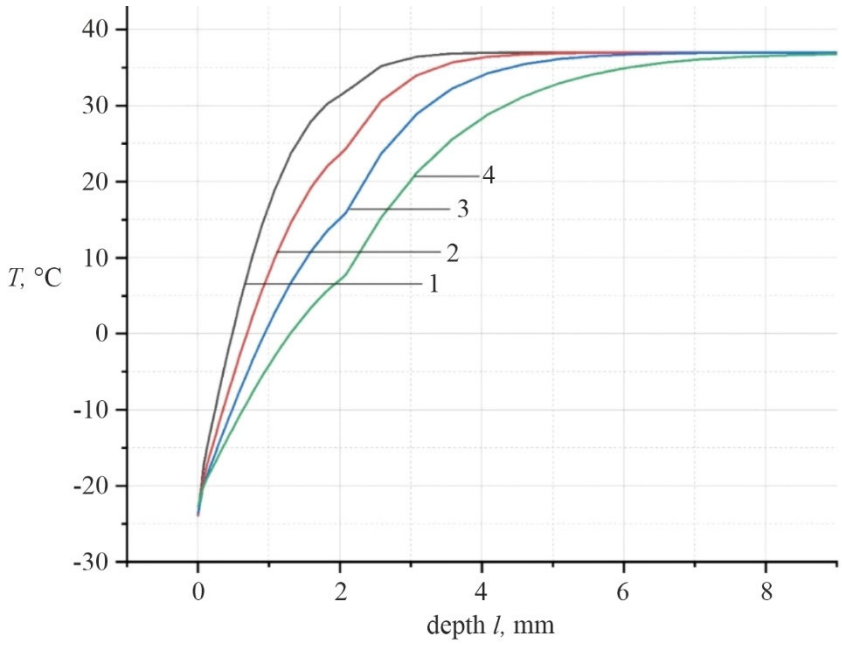


Fig. 9. Dependence of the temperature on the depth directly under the center of the working tool at time moments: 1 – 60 s, 2 – 120 s, 3 – 240 s, 4 – 600 s.

Conclusions

1. The mechanism of cryodestruction was determined from the analysis of the literature and data was obtained that the use of excessive cooling is not necessary. It has been established that for cryodestruction it is sufficient to cool biological tissue to a temperature of – 20 ÷ – 50 °C, and the optimal cooling rate should be 40 – 50 °C/min. To increase the efficiency of cryodestruction, it is reasonable to use cyclic cooling and heating up to (+ 39 ÷ + 45) ºC, which indicates good prospects for using thermoelectric cooling in medical practice, since such conditions can be achieved by using the thermoelectric method of cooling and heating.
2. A method for computer simulation of temperature distribution in the human skin in dynamic mode has been developed, which makes it possible to predict the results of local temperature effects on the skin and determine at any moment in time the temperature distribution in different layers of the skin for a given arbitrary time function of change in the temperature of the working tool $T_f(t)$.
3. A computer model was developed and a computer simulation of the working tool of the thermoelectric device for destruction was performed for two design options in order to determine the temperature in the skin and the cold accumulator without taking into consideration the phase transition:
    a) the working tool made of medical steel without an internal cylinder;
    b) the working tool made of copper without an internal cylinder.
4. With the help of computer simulation, the temperature distributions in different layers of the skin and in the cold accumulator of the working tool of thermoelectric device for destruction at the initial temperature of – 25 ºC were determined. The obtained results make it possible to predict the depth of freezing of biological tissue.

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Анатичук Л.І., *акад. НАН України* [1,2]
Кобилянський Р.Р., *канд. фіз.-мат. наук* [1,2]
Федорів Р.В. [1,2]

[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
e-mail: anatych@gmail.com

КОМП'ЮТЕРНЕ МОДЕЛЮВАННЯ РОБОЧОГО ІНСТРУМЕНТУ ТЕРМОЕЛЕКТРИЧНОГО ПРИЛАДУ ДЛЯ КРІОДЕСТРУКЦІЇ БЕЗ ВРАХУВАННЯ ФАЗОВОГО ПЕРЕХОДУ

У роботі наведено результати комп'ютерного моделювання робочого інструменту термоелектричного приладу для кріодеструкції без врахування фазового переходу, а також циклічного температурного впливу на шкіру людини у динамічному режимі. Побудовано фізичну модель робочого інструменту, 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: кріодеструкція, робочий інструмент, температурний вплив, шкіра людини, динамічний режим, комп'ютерне моделювання.

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