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COMPUTER SIMULATION OF TEMPERATURE DISTRIBUTIONS IN THE HUMAN HEART DURING CRYOABLATION

The work presents a computer simulation of the temperature distribution in human cardiac tissue during the cryoablation procedure, taking into consideration thermophysical processes, in particular, blood circulation, heat exchange, metabolic processes, and phase transition. Using the Comsol Multiphysics computer programme and the finite element method, the dependence of the depth of cardiac tissue freezing on the cooling time was determined. Temperature distributions in different layers of the heart at different cooling temperatures of the working tool were obtained. The simulation results can be used to optimize cryoablation parameters in order to increase its efficiency and safety. Bibl. 35, Figs. 7, Tabl 1.

Key words: cryoablation, computer simulation, heart tissue, thermoelectric cooling.

Introduction

Cardiac arrhythmia belongs to one of the most common pathologies of the cardiovascular system, which can significantly reduce the quality of life and increase the risk of serious complications, including stroke and heart failure [1]. One of the effective methods of treating arrhythmia is cryoablation, a procedure that involves extremely low temperatures to destroy pathological electrical pathways in the myocardium [2].

It is a conventional medical practice to use liquid nitrogen or nitrous oxide for cryoablation, which, when evaporated, cools biological tissues down to temperatures of -80 ... -150°C [3]. It causes the formation of controlled cryonecrotic lesions that isolate pathological foci and restore normal electrical conductivity of the heart. The main advantages of cryoablation are a lower risk of tissue perforation as compared to radiofrequency ablation, together with the preservation of the structural integrity of collagen fibers, thus reducing the likelihood of thrombosis [4].

More and more attention has been recently paid to the use of thermoelectric coolers (Peltier modules) in medical procedures, in particular, in cryoablation [5]. Thermoelectric cooling has a number of advantages, such as precise temperature control, no need for liquid refrigerants, compactness, and the possibility of local cooling without the risk of spillage or leakage of chemicals [6]. The application of thermoelectric systems in cryoablation can provide stable temperature control in the range of -40 ... -80°C, which is sufficient enough for effective destruction of pathological tissues without excessive damage to surrounding structures [7].

To understand the effectiveness of thermoelectric coolers in cryoablation procedures, it is necessary to conduct detailed computer simulation of temperature distributions in heart tissues during cooling [8-22].

Therefore, the purpose of this work is to determine, using computer simulation methods, temperature distributions and heat flows in the human heart at a given cooling temperature of the contacting working tool.

Physical model

According to the physical 2D model with axial symmetry (Fig. 1), the human heart region is a structure of three layers (endocardium 1, myocardium 2, epicardium 3) and a blood-filled cavity 4 and is characterized by the following thermophysical properties [23-25]: thermal conductivity κ_i, specific heat capacity C_i, density ρi, blood perfusion velocity 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 corresponding layers of biological tissue 1-4 are considered as volumetric heat sources q_i, where:

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

The geometric dimensions of each such layer from 1 to 4 are a_i, b_i. On the surface of the skin there is a round cold working tool 5, with a thickness d and a diameter c . The temperatures at the boundaries of the corresponding layers 1to 4 and the working tool 5 are T_1, T_2, T_3, T_4, T_5, T_6. The temperature of the working tool is T_7. The temperature inside the heart is T_1 = +37°C. The ambient temperature is T_8 = +22°C. The surface of the human heart with a temperature of T_6 is in a state of heat exchange with the surrounding environment (heat exchange coefficient α and radiation coefficient ε) at a temperature of T_8. The lateral surface of the heart is adiabatically insulated.

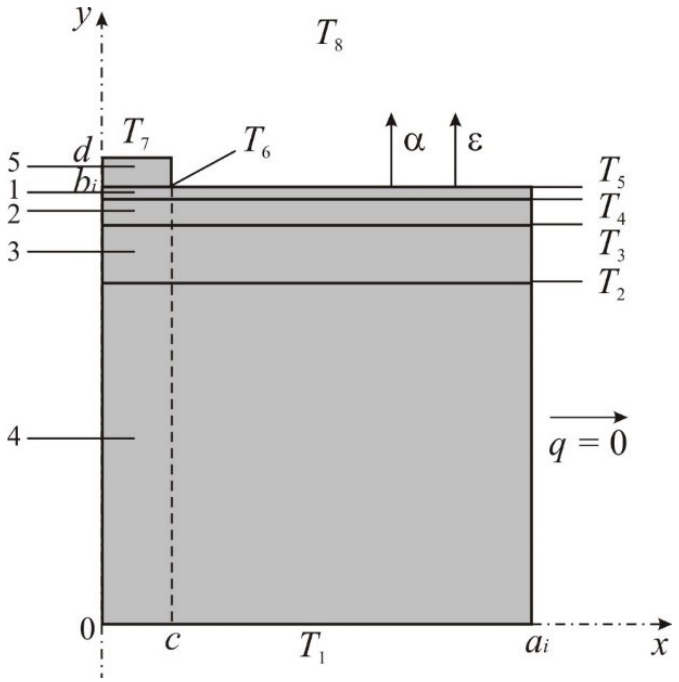

Fig. 1. Physical 2D model of biological tissue of the human heart with axial symmetry:
1 – endocardium, 2 – myocardium, 3 – epicardium, 4 – cavity filled with blood, 5 – working tool.

This model ignores the thermal contact resistance between the working tool and the human heart tissue, since it is estimated to be insignificant and is $R_c = 2 \cdot 10^{-6}$ m^2·K/W.

Mathematical description

In general, the heat transfer equation in biological tissue has the following form [26]:

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

where C_i, κ_i are specific heat capacity and thermal conductivity of the corresponding layers of the heart, ρ_b is blood density, C_b is specific heat capacity of blood, ω_{bi} is blood perfusion of the corresponding layers, T_b is blood temperature, T is biological tissue temperature; Q_{meti} is heat released as a result of 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 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 heat transfer equation in biological tissue (2) is solved with the appropriate boundary conditions. The temperature on the surface of the working tool is T_7 = 60 °C. Inside the biological tissue, the temperature is T_1 = +37 °C. The side surfaces of the biological tissue are adiabatically isolated (q = 0), and the upper surface is in a state of heat exchange (heat transfer coefficient α and radiation coefficient ε) with the surrounding environment at a temperature T_8.

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

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

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

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

As a result of solving the initial boundary value problem (2)-(4), the temperature distributions T_i(x,y,t) and heat fluxes q_i(x,y,t) in the corresponding layers of the heart at an arbitrary time are determined. In this work a case is considered as an example, where the temperature of the working tool changes according to a given law in the temperature range T_7 = -50÷-70 °C. However, it should be noted that the proposed method allows considering cases when the temperature of the working tool T_f(t) changes in any temperature range or according to a predetermined function.

During the freezing process, cells will undergo a phase change at the freezing point, while there will be losses of phase transition heat (L) but the temperature in these cells will not change. The phase transition in biological cells occurs in the temperature range (-1 ÷ -8)°C. The properties of cardiac tissue are given in Table 1 [28-34]. In the temperature range (1 ÷ 8) °C, when cells are frozen, the heat of the phase transition is absorbed, which can be modeled by adding the corresponding value to the heat capacity [33, 34].

Table 1.

Thermophysical properties of biological tissue of the human body [30-33]

Layer/Substance	**Thickness**	Thermal conductivity (W/(m K))	Density (kg/m³)	Specific heat capacity (J/(kg K))
Endocardium	~ 0.5 – 1 mm	~ 0.5	~ 1100	~ 3500
Myocardium	~ 8 – 12 mm	~ 0.6	~ 1050	~ 3600
Epicardium	~ 0.5 – 1 mm	~ 0.4	~ 1040	~ 3400
Blood	–	~ 0.5	~ 1060	~ 4200

When a given area of a human heart is frozen, the blood vessels in the capillaries constrict until all the blood in the capillaries freezes, and the value ω_{bi} approaches zero. Moreover, the cells will not be able to generate metabolic heat when frozen and Q_{meti} will be zero at temperatures below zero.

In the frozen state, the properties of biological heart tissue will have the following values (5) (8):

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

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

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

$$\omega_{b_i} = \begin{cases} 0,0005 & T \geq -1°C \\ 0 & -8°C \leq T \leq -1°C \\ 0 & T \leq -8°C \end{cases} \quad (8)$$

Computer model

A two-dimensional computer model of the heart was developed in a cylindrical coordinate system, on whose surface there is a medical working tool. To build the computer model, the Comsol Multiphysics application programme package [35] was applied, which enables simulating thermophysical processes in biological tissue where blood circulation, heat exchange, metabolic processes and phase transition are considered.

The calculation of temperature distributions and heat flux density in the heart tissue 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 calculated, 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 [35].

Fig. 2 and Fig. 3 show the finite element method grid and the temperature distribution in the human heart, respectively.

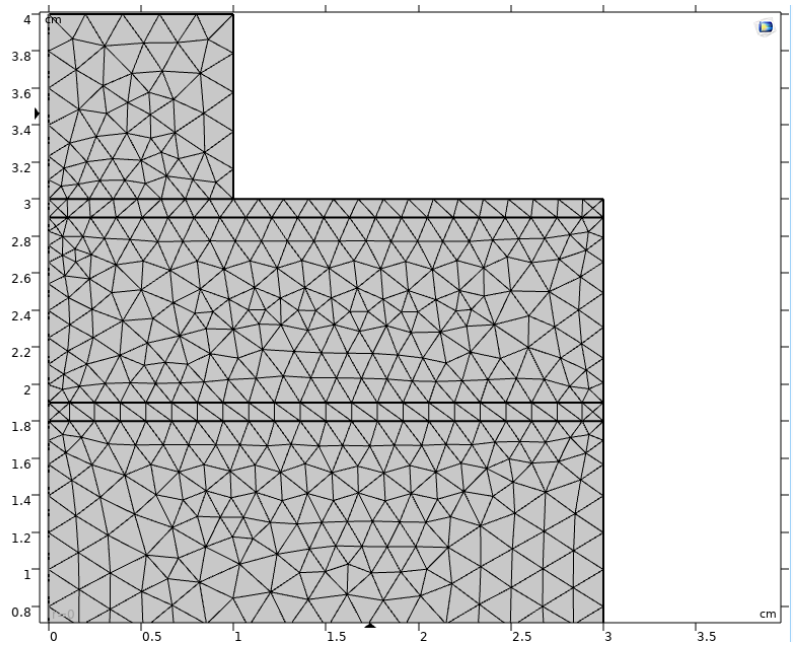

Fig. 2. Finite element method grid for calculation.

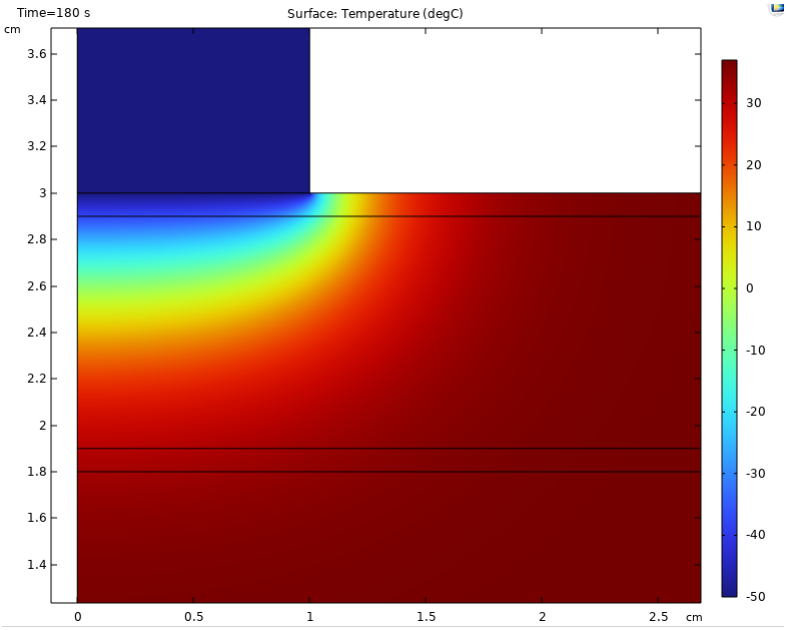

Fig. 3. Temperature distribution in the human heart when a working tool is in contact with a temperature of T = – 50 °C at time t = 180 s.

Results of computer simulation

According to known methods of cryoablation of cardiac tissue, the depth of freezing should be from 2.5 to 5 mm, and the minimum temperature required for the onset of cell necrosis during cryoablation is in the range of – 20 °C ÷ – 30 °C [7, 28, 33 – 35]. Therefore, in this work, as an example, specific cases are considered in which the temperature of the working tool is – 50 °C, – 60 °C, – 70 °C at the cooling time points t = 60 s, t = 120 s, t = 180 s.

Fig. 4-6 shows the distributions of isothermal surfaces in the depth of the biological tissue of the human heart at working tool temperatures T = – 50 °C, T = – 60 °C, T = – 70 °C at the cooling time points t = 60 s, t = 120 s, t = 180 s.

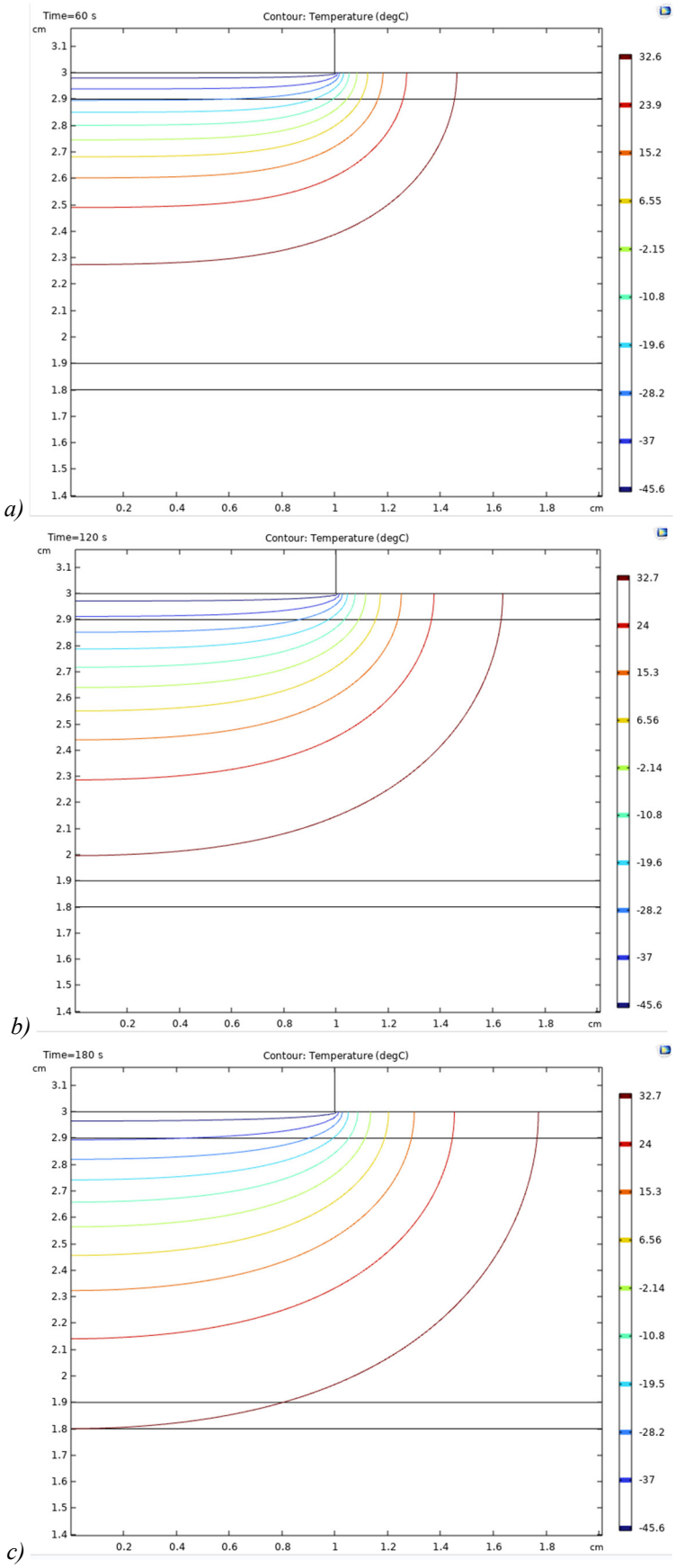

Fig. 4. Distribution of isothermal surfaces in the depth of the biological tissue of the human heart at the temperature of the working tool T = – 50 °C and different cooling times: a) t = 60 s, b) t = 120 s, c) t = 180 s.

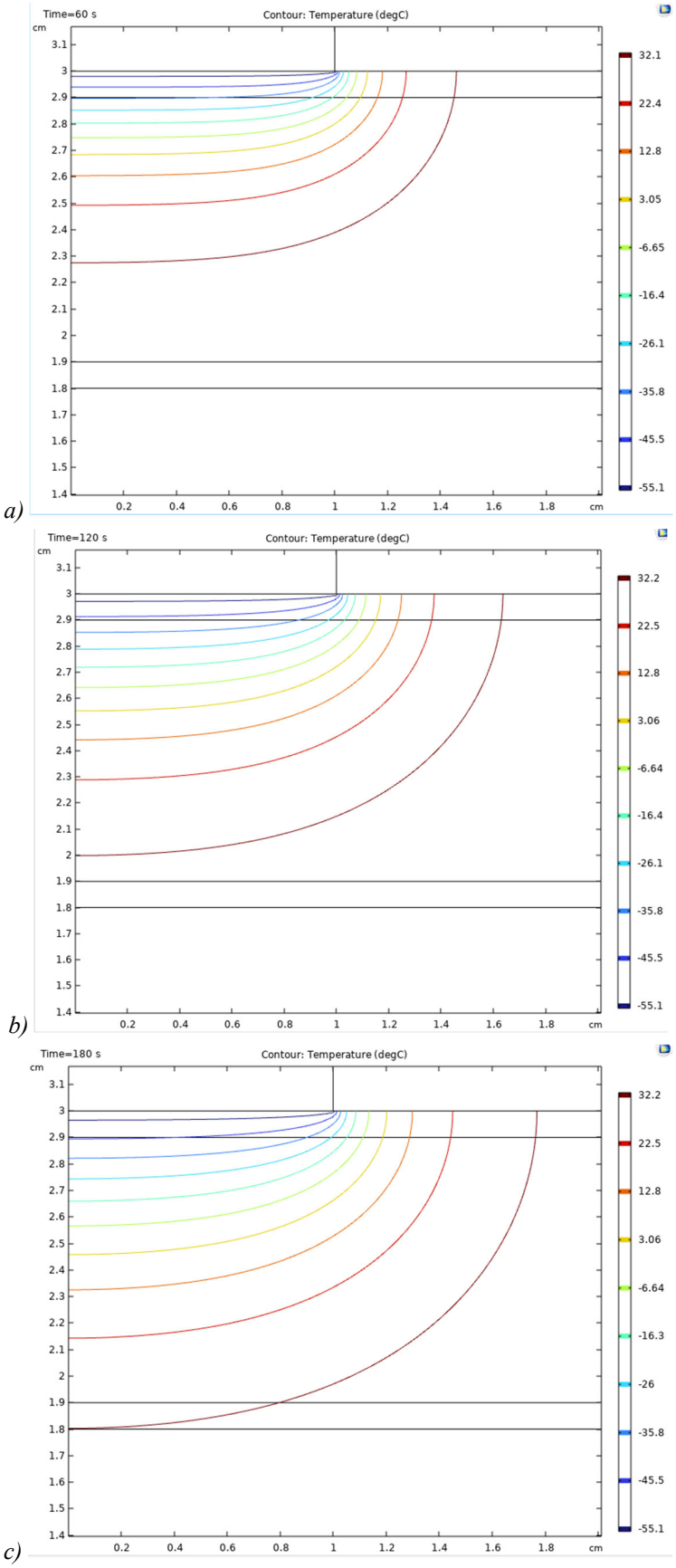

Fig. 5. Distribution of isothermal surfaces in the depth of the biological tissue of the human heart at the temperature of the working tool T = – 60 °C and different cooling times: a) t = 60 s, b) t = 120 s, c) t = 180 s.

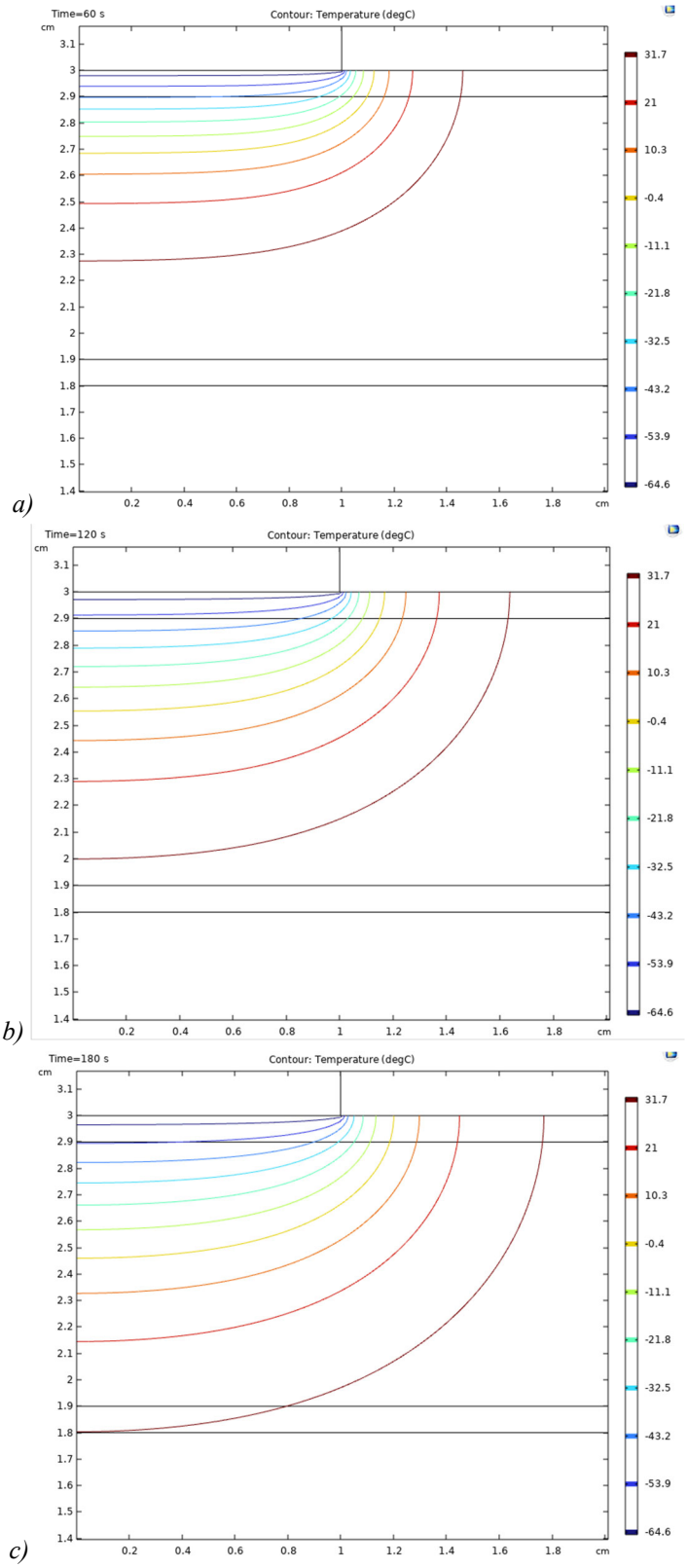

Fig. 6. Distribution of isothermal surfaces in the depth of the biological tissue of the human heart at the temperature of the working tool T = – 70 °C and different cooling times: a) t = 60 s, b) t = 120 s, c) t = 180 s.

Using computer simulation, the temperature dependences in the depth of the human heart (1 – 2.5 mm, 2 – 5 mm) on time at different temperatures of the contacting working tool were also determined: $T = -50$ °C, $T = -60$ °C, $T = -70$ °C (Fig. 7).

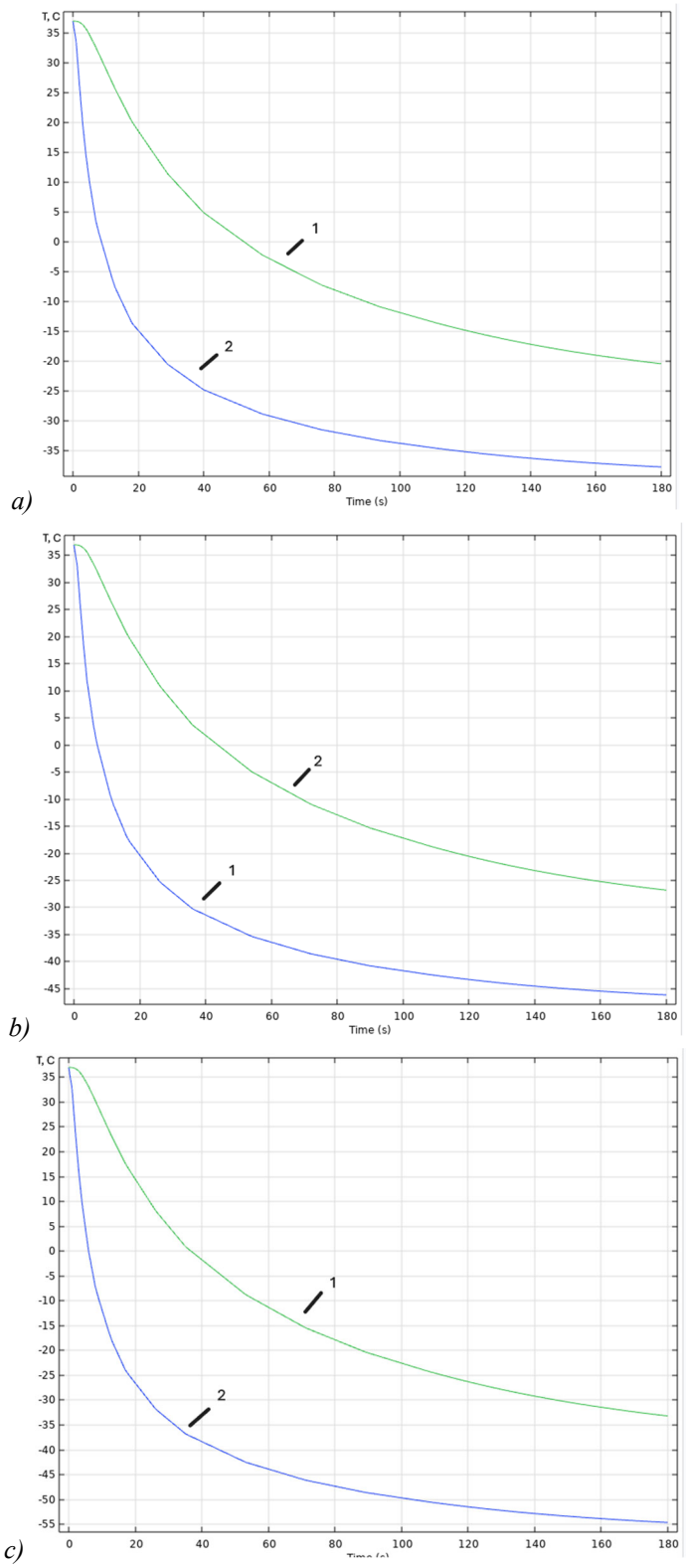

Fig. 7. Dependence of temperature in the human heart on time at different depths of biological tissue (1 – 5 mm, 2 – 2.5 mm) at different temperatures of the contacting working tool: a) T = – 50 °C, b) T = – 60 °C, c) T = – 70 °C.

From Fig. 7 it is clear that at the temperature of the cooling working tool $T = -60$ °C at the time $t = 120$ s the heart tissue is cooled to a temperature of – 44 °C at a depth of 2.5 mm and 20 °C at a depth of 5 mm. With increasing exposure to temperature, deeper cooling of the heart layers is achieved. That

is, with prolonged temperature exposure to – 60 °C, destruction of the corresponding areas of the heart tissue can be achieved.

The results obtained ensure predictions as for the depth of freezing of the layers of the human heart under temperature exposure to achieve maximum effect under cryoablation. The developed method of computer simulation in dynamic mode allows determining the temperature distributions in different layers of the human heart at a predetermined arbitrary temperature of the working tool.

Conclusions

1. Analysis of scientific literature established that the depth of freezing of cardiac tissue during cryoablation should be from 2.5 to 5 mm, and the minimum temperature required for the onset of necrosis of biological tissue is in the range of – 20 °C ÷ – 30 °C.

2. A physical, mathematical and computer model of the human heart during cryoablation was created. Temperature distributions in the heart were determined taking into account phase transitions in the dynamic mode at any given temperature of the working tool.

3. Using computer simulation it was established that at the temperature of the cooling working tool T = – 60 °C at the time t = 120 s the cardiac tissue is cooled down to a temperature of – 44 °C at a depth of 2.5 mm and – 20 °C at a depth of 5 mm. With increasing exposure to temperature, a correspondingly deeper cooling of the heart layers is achieved

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КОМП'ЮТЕРНЕ МОДЕЛЮВАННЯ РОЗПОДІЛІВ ТЕМПЕРАТУРИ В СЕРЦІ ЛЮДИНИ ПРИ КРІОАБЛЯЦІЇ

У роботі виконано комп'ютерне моделювання розподілу температури в серцевій тканині людини під час процедури кріоабляції з врахуванням теплофізичних процесів, зокрема кровообігу, теплообміну, процесів метаболізму і фазового переходу. За допомогою комп'ютерної програми Comsol Multiphysics, використовуючи метод скінченних елементів, визначено залежність глибини промерзання серцевої тканини від часу охолодження. Отримано розподіли температур у різних шарах серця при різних температурах охолодження робочого інструменту. Результати моделювання можуть бути використані для оптимізації параметрів кріоабляції з метою підвищення її ефективності та безпечності. Бібл. 35, рис. 7, табл. 1.

Ключові слова: кріоабляція, комп'ютерне моделювання, серцева тканина, термоелектричне охолодження.

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