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Computersimulation of the Dynamic Operating Modes of Thermoelectric Device for Cryodestruction

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This paper presents the results of computer simulation of optimal dynamic modes of thermoelectric device for cryodestruction. The optimal time function for controlling the supply current to thermoelectric micromodule in a device for cryodestruction is determined, which ensures given cyclic temperature effect on the local area of human body.

Keywords:computer simulation, optimal dynamic mode, cryodestruction, thermoelectric cooling.

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Introduction

General characterization of the problem and analysis of the literature. It is well known in medical practice that temperature effect is an important factor in the treatment of many human health problems [1]. One of the promising lines is cryodestruction – a set of surgical treatments based on the local freezing of biological tissues of the human body. To perform cryodestruction, it is necessary to cool a certain area of the human body to a temperature of -50°C. Today, such cooling is realized with the help of special cryoinstruments using nitrogen [1-6]. However, the use of nitrogen has a number of disadvantages, namely nitrogen does not allow cooling with the necessary temperature accuracy, and there are risks of overcooling with negative consequences. Moreover, liquid nitrogen is a very dangerous substance and requires proper caution during use, while delivery of liquid nitrogen is not always available, which limits the possibilities of applying this method. This opens the prospects for using thermoelectric cooling for cryodestruction, with the possibility of cooling to temperature (0 ÷ -80) °C. Medical purpose thermoelectric devices offer the opportunity to accurately set the required temperature of working instrument, the time of temperature effect on the corresponding area of the human body and provide a cyclic change of cooling and heating modes [7, 8]. However, thermoelectric medical devices developed so far have no possibility of computer control of current supply to thermoelectric modules in order to reproduce the necessary preset unsteady temperature modes.

Therefore, the purpose of this paper is to develop computer methods for simulation and optimization of the unsteady operating conditions of thermoelectric device for cryodestruction.

I. Temperature and time modes for cryodestruction

From the literature it is known [9-12] that decrease in temperature of biological tissue to (-5 ÷ -10)°C leads to the onset of crystallization process in the extracellular space, and with decrease in temperature to (-15 ÷ -20)°C and lower, the formation of ice crystals starts inside the cells, leading to the death of biological tissue. It is noteworthy that the mass of ice formed is 10 % larger than the volume of liquid from which ice crystals are formed. The maximum damaging effect is achieved by cooling biological tissue to -50°C, and further temperature drop does not increase the mortality of the cells [4, 5, 10–21].

The intensity of cells destruction in the freezing focus depends not only on the minimum temperature in the focus, but also on the rate of cooling of biological tissue. The relatively fast freezing, i.e. (40–50)°C/min. at the exposure of 30 s, is optimal [9, 22]. The efficiency of cell cryodestruction is high, if it has no time to displace through membranes the intracellular liquid in the process of cooling of tissue prior to freezing [10-15].

Slower freezing (3–5°C/min) is unreasonable, as long as in this case the processes of intracellular ice formation do not take place. It is also not rational to use super-fast freezing (more than 100 °C/min), since this creates amorphous ice that does not damage the structure of biological tissue [10].

The reliability of cryodestruction largely depends not only on the cooling rate, but also on the rate of further warming, since the harmful effects of low temperatures occur both during the process of transformation of cells into ice crystals and during their thawing to normal temperatures. The destruction of cells during thawing occurs no less intensively than during freezing, since in the process of thawing there is a recrystallization of ice increasing the destructive effect on living cells. At slow warming, intracellular ice crystals continue to grow and damage intracellular formations for some time. Thawing at a rate (10-12) C/min ensures the most reliable destruction of cells [10-15].

Multiple cyclic freezing-thawing makes it possible to reduce the lethal temperature of the pathological tissue, find a peculiar compromise between the aspiration to freeze the tumor site as much as possible and the need to preserve healthy surrounding tissues [10-21].

II. Schematic model of a thermoelectric device for cryodestruction

Fig. 1 schematically shows a thermoelectric device for cryodestruction which is connected to PC to set the predefined optimal function of current supply to thermoelectric micromodule in order to ensure the necessary temperature mode of device working instrument 2.

The device consists of two main parts: an electronic control and power supply unit 1 and a working instrument 2. In its turn, the working instrument 2 is made of a thin-walled metal tube 4, a coaxial tube 5, a liquid heat-exchanger 6, a thermoelectric micromodule 7 and a tip 8. Cooling liquid circulates through the pipes 4 and 5 for heat removal through the heat-exchanger 6 from the thermoelectric micromodule 7. In this way the temperature of the tip 8 is reduced. When using a pre-cooled liquid to a temperature of 5÷10ºC, the temperature of the tip is reduced to (-40 ÷ -50)ºC. The working instrument 2 can be used for local cryodestruction, removal of frozen tissue, as well as for removal of foreign inclusions by freezing them to the surface of the working instrument.

In order to determine time-optimal control functions of current supply to thermoelectric module, which ensure given dependences of change in cooling temperature with time, computer simulation methods should be employed. The results of computer simulation are presented below.

III. Computer simulation of optimal control function of current supply to thermoelectric device

The problem of computer simulation of the unsteady operating mode of device for cryodestruction lies in the determination of control time function of current supply to thermoelements $I(t)$, which ensures given time dependence of the working instrument surface temperature $T_c(t)$.

The problem was solved with the use of the following approximations in the device model. It is assumed that all thermoelements of the module which is used in the device are identical and stay in the same conditions. Thermoelement legs of height l and cross-section s are made of materials of n- and p-type conduction. Characteristics of leg materials, namely the Seebeck coefficient $\alpha_{n,p}(T)$ and resistivity $\rho_{n,p}(T)$ are temperature-dependent, and coefficients of thermal

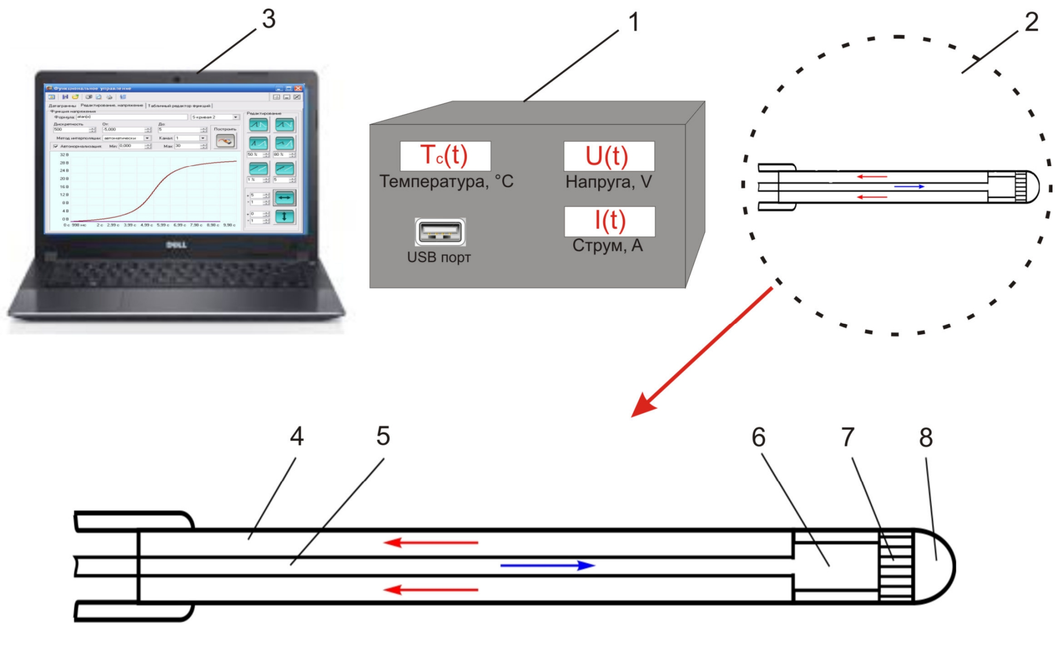

Fig. 1. Schematic of thermoelectric device for cryodestruction:
1 – electronic control and power supply unit, 2 – working instrument, 3 – personal computer (PC), 4 – thin-walled metal tube, 5 –coaxial tube, 6 – liquid heat-exchanger, 7 – thermoelectric micromodule, 8 – tip.

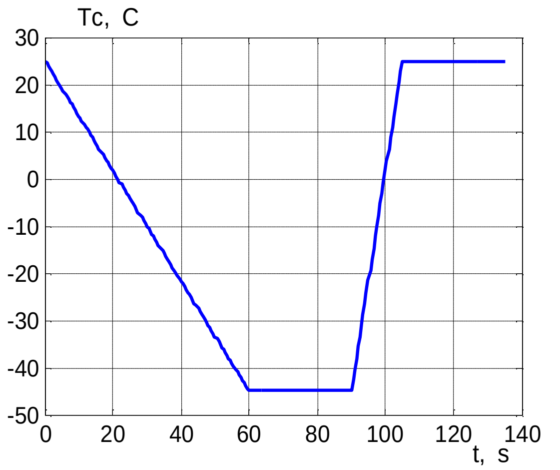

Fig. 2. Given time dependence of operating temperature $T_c(t)$ of device for cryodestruction

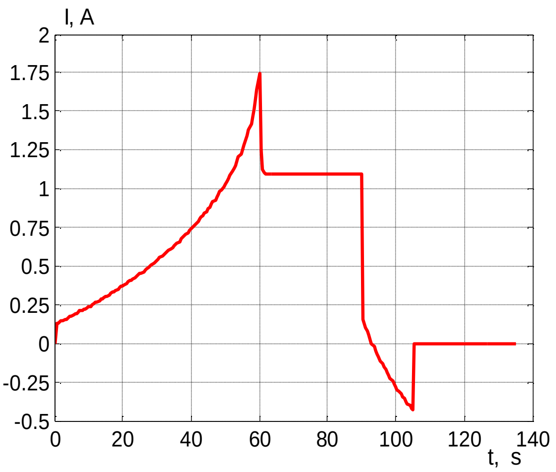

Fig. 3. Calculated control function of current supply I(t) to thermoelectric micromodule.

conductivity $\kappa_{n,p}$ and heat capacity $c_{n,p}$ are assumed to be constants due to their inessential temperature dependence in thermoelectric materials for coolers. It is assumed that the heat-releasing surface of thermoelements is maintained at a fixed temperature T_h, the lateral surfaces of legs are adiabatically insulated. On the hot junctions of thermoelements we take into account the absorption or release (depending on the direction of current) of the Peltier heat and the release of the Joule heat on the contacts of junction with contact resistance r_c. Account is taken of the total volumetric heat capacity g of interconnect and insulating plates of the module and copper working surface of the device per one thermoelement. Thermal load of power q_0 which is created in working mode on thermoelement cold junctions due to heat release from the human body is taken into consideration.

For such a model the temperature distribution in thermoelement legs is given by a system of one-dimensional equations of the unsteady heat conduction in the form:

$$\begin{cases} c_n \dfrac{\partial T_n}{\partial t} = \kappa_n \dfrac{\partial^2 T_n}{\partial x^2} + r_n(T)\dfrac{I^2(t)}{s^2} - T_n \dfrac{\partial \alpha_n(T)}{\partial T_n}\dfrac{I(t)}{s}\dfrac{\partial T_n}{\partial x} \\ c_p \dfrac{\partial T_p}{\partial t} = \kappa_p \dfrac{\partial^2 T_p}{\partial x^2} + r_p(T)\dfrac{I^2(t)}{s^2} - T_p \dfrac{\partial \alpha_p(T)}{\partial T_p}\dfrac{I(t)}{s}\dfrac{\partial T_p}{\partial x} \end{cases}, \quad (1)$$

where $x \in [0,l]$, $t \in [0,t_{\max}]$. $I(t)$ is the current in thermoelement legs which is a function of time. Eqs.(1) take into account the influence of the Thomson effect that arises in the bulk of thermoelement legs due to the temperature dependence of the Seebeck coefficients $\alpha_{n,p}(T)$.

The boundary conditions for these equations are given by:

$$\left[\kappa_n s \frac{\partial T_n}{\partial x} + \kappa_p s \frac{\partial T_p}{\partial x}\right]_{x=0} - \left[\alpha_p(T_c(t)) + \left|\alpha_n(T_c(t))\right|\right] I(t) T_c(t) - g\frac{\partial T_c(t)}{\partial t} + 2\frac{r_c}{s} I^2(t) + q_0 = 0, \quad (2)$$

$$T_n(l,t) = T_p(l,t) \equiv T_h,$$

where $T_c(t)$, the temperature of thermoelement working surface, is the assigned function of time.

Under conditions when the initial current value I_0=0A, and $T_h=T_a$, the initial conditions of the boundary problem (1)-(2) have a simple form:

$$T_n(x,0) = T_p(x,0) \equiv T_a. \quad (3)$$

As mentioned before, the problem is to find control function of current $I(t)$ that ensures given time dependence of cold temperature $T_c(t)$.

The method of solving this problem is described in [23]. For the formulated problem the solution is obtained in the form of the following integral equation:

$$I(t) = \frac{1}{\alpha(t) T_c(t)}\left[\frac{r_c}{s} I^2(t) + \frac{k}{c}\frac{r(t)}{sl}\int_0^{at} K(t-t) I^2(t)\,dt + \Phi(t, T_c(t))\right], \quad (4)$$

where

$$\Phi(t, T_c(t)) = -g\frac{dT_c(t)}{dt} + q_0 - \frac{k s}{l}\int_0^{at} J_1(t-t)\frac{dT_c(t)}{dt}\,dt$$

$$a = \frac{k}{cl^2}, \qquad K(t) = J_1(t) - J_0(t),$$

$$J_1(t) = 1 + 2\sum_{k=1}^{\infty} \exp(-p^2 k^2 at),$$

$$J_0(t) = 1 + 2\sum_{k=1}^{\infty}(-1)^k \exp(-p^2 k^2 a t),$$

$$a(t) = (\overline{a}_p(t) + |\overline{a}_n(t)|)/2; \quad r(t) = (\overline{r}_p(t) + \overline{r}_n(t))/2; \quad k = (k_p + k_n)/2; \quad c = (c_p + c_n)/2$$

,
$$\overline{a}_{n,p}(t) = (a_{n,p}(T_h) + a_{n,p}(T_c(t)))/2,$$

$$\overline{r}_{n,p}(t) = \frac{1}{(T_h - T_c(t))}\int_{T_c(t)}^{T_h} r_{n,p}(T)dT.$$

The nonlinear Eq.(4) is solved by numerical successive approximation method. The algorithm for solving such an equation is implemented using computer simulation software developed in the MathLab environment.

IV. Computer simulation results

Simulation of current control function which would ensure given time dependence of operating temperature was performed for thermoelectric micromodule Altec-98A used in device for cryodestruction, which comprises 62 legs of height l=0.093 cm, cross-section area s=0.058×0.058 cm^2, and contact resistance value r_c=5·10^{-6} Ohm·cm^2. The legs are made of ***Bi-Te*** based materials of *n-* and *p*-type conductivity with standard thermoelectric characteristics $\alpha_{n,p}$, $\rho_{n,p}$, $\kappa_{n,p}$, $c_{n,p}$ [24]. In the steady-state mode the module has the following characteristics: maximum cooling capacity 3.6 W and maximum temperature difference 70 K are achieved at maximum values of voltage and current 3.9 V and 1.8 A, respectively, provided the temperature of the heat-releasing surface of module is 27°C.

The total volumetric heat capacity of interconnect and insulating plates of the micromodule and the copper tip of the working tool per one leg was g=0.0064J/K. The heat release of the human body was assumed to be equal to 5 mW/cm^2, which creates thermal load on the device thermoelectric leg q_0=0.017 mW.

In conformity with medical requirements [19-15], for the working mode of the cryodestruction instrument, the time dependence of temperature on the surface of human body $T_c(t)$ shown in Fig.2 was selected.

In the operating mode (Fig.2) it is necessary to achieve cooling of working instrument to -45°C within 60 s, maintain this temperature for 30 s with subsequent heating to initial temperature 25°C within 15 s. If necessary, this cycle can be repeated several times.

Fig.3 shows the calculated control function of current supply *I(t)* to thermoelectric micromodule which ensures given time dependence of the operating temperature of the device (Fig.1). The direction of current which ensures cooling of the working surface is considered to be positive, and heating – negative. To attain given level of cooling for 60 s, the value of current should be gradually increased to 1.75A, following which it is sufficient to reduce its value to 1.15A, in order to maintain cooling at the level of -50°C for 30 s. Then, for heating, the direction of current is reversed, for 15s its value is increased to 0.4A and power is turned off when the temperature reaches 25°C. Such current control function *I(t)* is practically implemented with the help of a special electronic regulator.

Conclusions

1. Computer simulation method has been used to determine time-optimal control function of current supply to thermoelectric micromodule in device for cryodestruction which ensures the necessary time dependence of the temperature of working instrument which is in contact with the human body.
2. The determined optimal time function is used for the design and autocalibration of special electronic regulator of control unit which ensures the operation of system for automatic control of operating temperature of device for cryodestruction.

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Комп'ютерне моделювання динамічних режимів роботи термоелектричного приладу для кріодеструкції

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У роботі наведено результати комп'ютерного моделювання оптимальних динамічних режимів роботи термоелектричного приладу для кріодеструкції. Визначено оптимальну часову функцію керування струмом живлення термоелектричного мікромодуля у приладі для кріодеструкції, якою забезпечується заданий циклічний температурний вплив на локальну ділянку тіла людини.

Ключові слова: комп'ютерне моделювання, оптимальний динамічний режим, кріодеструкція, термоелектричне охолодження.