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Application of thermoelectric cooling and heating to control the temperature of irrigation fluid in ophthalmic surgery

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The paper considers the possibilities of using thermoelectric cooling and heating irrigation fluid during ophthalmic surgery. A comparative analysis of the use of compression, cryogenic and thermoelectric devices in the required temperature range of irrigation solutions for surgery at an ambient temperature of about 20°C is carried out. The advantages of using devices based on thermoelectric cooling (heating) in medical practice are shown. The results of the design and study of the parameters of a thermoelectric device to ensure the optimal temperature of the irrigation fluid during ophthalmic operations are presented.

Keywords: thermoelectric cooler, irrigation fluid, temperature conditions, ophthalmic surgery.

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Introduction

General characterization of the problem.

Today, surgical treatment methods are widely used in ophthalmology (cataract surgery, vitreoretinal surgery for retinal detachment, penetrating eye injuries, diabetic retinopathy), in which surgical instruments are inserted into the middle of the eye and irrigation fluid circulates intraocularly. Typically, the irrigation fluid used for surgery is at room temperature, i.e., significantly lower than the temperature of the intraocular media [1-3]. Standard vitreoretinal surgery involves artificial uncontrolled (often prolonged) deep hypothermia of the intraocular structures followed by rapid uncontrolled warming after the cooling stage. Rapid uncontrolled changes in intraocular temperatures pose a risk of damage to retinal nerve cells, as well as the occurrence of undesirable vascular reactions during surgery [4].

During cataract surgery, the phacoemulsification technique is used to fragment the lens. In this case, the ultrasound energy generates excessive heat, which can lead to thermal damage to intraocular structures [5]. Thus, elevated temperatures can damage endothelial cells and contribute to the development of corneal edema after surgery [6]. Cataract surgery also uses irrigation solutions that are at the same temperature as the operating room environment. However, neither cataract surgery nor vitreoretinal surgery typically involves monitoring of intraocular temperature and the temperature of the irrigation solutions [1]. The surgeon also has no ability to intraoperatively control the temperature of the irrigation fluid delivered intraocularly and to influence the temperature of the intraocular media.

Thus, surgical interventions in ophthalmology are mainly performed in conditions of uncontrolled hypothermia. Unlike other medical specialties, intraoperative temperature control in ophthalmology is not given enough attention and clear recommendations have not been developed regarding the temperature of the irrigation fluid and the level of hypothermia of intraocular structures that should be used during surgery.

Depending on the depth of cooling in relation to body temperature, hypothermia is divided into mild (32-35°C), moderate (28-32°C), and profound (less than 28 °C) [7].

In modern intensive care, mild hypothermia is considered the only effective method of neuroprotection that affects the survival rate and quality of neurological recovery of patients in the post-resuscitation period [8]. Both moderate and deep hypothermia have been widely used in cardiac surgery. Deep hypothermia provides safe circulatory arrest as a prerequisite for cardiac surgery. Deep hypothermia is also used to correct complex heart and aortic arch defects, in the surgical treatment of pulmonary embolism and aortic dissection [9].

Therefore, the development of effective and safe methods for regulating the temperature of irrigation solutions with the subsequent introduction of a controlled hypothermia system into the practice of ophthalmic surgery is an urgent task given at the general increase in eye diseases and injuries during combat operations.

The purpose of the proposed work is to determine the optimal energy and temperature conditions for using cooling (heating) of irrigation fluid by thermoelectric devices and their comparison with other methods of thermal regulation; development and experimental study of the parameters of a highly efficient thermoelectric device for controlling the temperature of irrigation fluid during ophthalmic operations.

I. Analysis of thermoregulation methods in ophthalmology

The cryogenic temperature range, i.e. temperatures below 120 K (–153 °C), is characterized by its uniqueness for such temperatures are not observed under natural conditions on the planet Earth [10]. The operation of cryogenic devices for ophthalmological manipulations requires complex control and distribution equipment. The technology based on obtaining cold due to the properties of liquefied gases is currently used in ophthalmology primarily for cryodestruction of epibulbar neoplasms and eyelid neoplasms [11].

Compression freon coolers are energy efficient (require 0.4÷0.5 kW of electricity for every 1 kW of cold), their mass is from 65 to 150 kg depending on the nominal cooling capacity. However, the energy efficiency of compression units can significantly decrease with a decrease in the temperature difference between the ambient and the ophthalmologist's surgical instrument [12]. The similar situation occurs when the temperature in the room where the treatment or surgery is performed increases. In this case, precise temperature control is difficult to ensure with the heat carrier used in such devices. When hydraulic connections become depressurized, personnel may be poisoned.

In operating rooms, thermoelectric thermostats have an undeniable advantage over other methods of cooling (heating) irrigation fluid.

In terms of energy consumption, thermoelectric air conditioners are less efficient than compression ones: about 1.4 kW of electricity is required for 1 kW of cooling at a temperature difference between the ambient and the operating instrument of about 15 °C [13, 14].

However, unlike compression systems, thermoelectric cooling devices do not deteriorate energy efficiency at the increase of the outside air temperature and significantly improve the coefficient of performance (COP) in case the temperature difference decreases (Fig. 1).

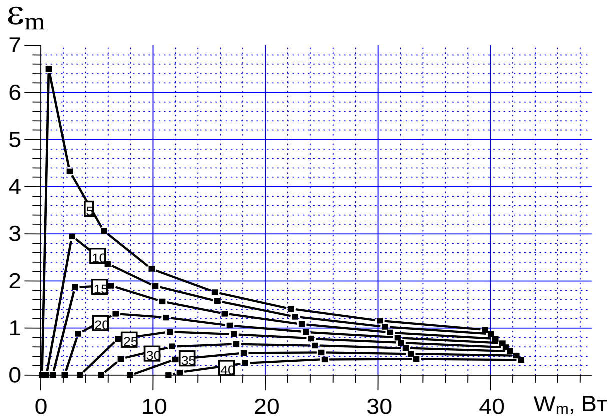

Fig. 1. Dependence of the COP of the thermoelectric cooling module on the power supply and temperature difference at T=27^{0}C.

The use of thermoelectric devices does not require periodic inspection and preventive maintenance. They do not use toxic coolants. The service life of thermoelectric units can last for decades. The adjustment of the cooling depth, unlike a compression air conditioner with strict modes of phase transitions of the coolant, is smooth and soft due to the change in the supply current. By changing the direction of the current, the thermoelectric device is easily switched from the cooling mode to the heating mode of the irrigation solution.

II. Computer analysis of the effectiveness of thermoelectric cooling of irrigation fluid

The experimental study was preceded by a computer analysis of the possibility of cooling the irrigation fluid (BSS+ saline solution) with a thermoelectric device to a certain temperature with the determination of the required cooling capacity.

According to the documentation of the surgical equipment in the irrigation/aspiration mode, the fluid flow rate varies from 0 to 20 cm^3 /min. Previous studies indicate the feasibility of using for surgery an irrigation fluid with a temperature of 32–35 °C, which is higher than the ambient temperature and several degrees lower than the intraocular temperature, to maintain intraoperative conditions of mild or moderate intraoperative hypothermia [4, 15]. Short-term deep cooling of the intraocular media by lowering the temperature of the irrigation fluid to 10–15°C may be useful in some situations during surgery, for example, when stopping intraocular bleeding [16]. The listed parameters were used in computer simulation, which was carried out in the Comsol Multiphysics software environment [17].

The physical model of the thermoelectric cooler is presented in Fig. 2.

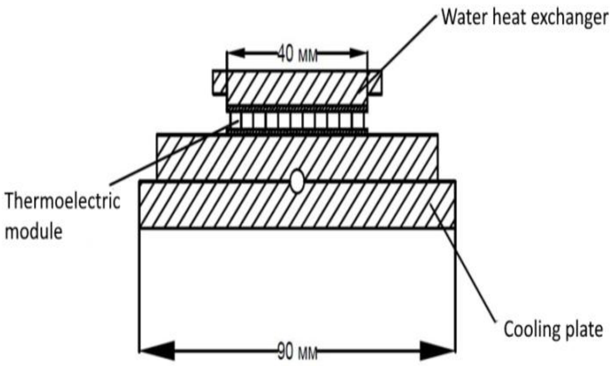

Fig. 2. Physical model of a thermoelectric cooler.

The physical model consists of a heat exchange unit, a medical tube with an inserted metal heat exchange tube, which was placed in the cooling unit. The heat exchange unit was made of duralumin, the polymer tube was made of polyvinyl chloride; the heat exchange tube was made of stainless medical steel. Cooling was performed using a 40×40 mm^2 Peltier thermoelectric module of the Altec-22 type. The effect of thermal resistance of the thermal paste between the thermoelectric module and the cooling unit, as well as heat exchange with the ambient (the air temperature was taken to be 25 °C) were considered.

The calculation was based on the heat balance, the efficiency of the thermoelectric cooler was determined by the COP:

$$\varepsilon_r = \frac{Q_c}{W_{TE}+W_1+W_2} = \frac{\alpha I(T_c+Q_cN_1)-0.5I^2R-\lambda\big(T_h-T_c-(Q_hN_2+Q_cN_1)\big)}{W_{TE}+W_1+W_2},$$

where χ_i are heat exchanger thermal resistances, Q_c is cooling capacity, Q_h is thermal capacity, W_{TE} is electrical power of the thermoelectric converter, α is EMF coefficient, I is electrical current, R is electrical resistance, λ is heat transfer coefficient of heat exchangers, T_h, T_c are temperatures of the hot and cold sides of the thermoelectric converter, W_i is additional power supply capacity of the heat exchange system,

$$N_1 = \frac{(\chi_1+\chi_2)}{\chi_1\chi_2}, \qquad N_2 = \frac{(\chi_3+\chi_4)}{\chi_3\chi_4},$$

Computer modeling showed that it was sufficient to provide about 6.6 W of cooling capacity to achieve a liquid temperature at the outlet of the cooling unit of about 0 °C (Fig. 3). The COP in this case reached 0.6. The length of the polymer tube from the cooling unit to the cannula was 300 mm.

Computer modeling showed that with a tube length from the cooling unit to the surgical cannula of 900 mm, the temperature of the liquid at the cannula level can be 12.6°C whereas with a length of 500 mm it is 8.2°C. This difference is explained by the heat exchange effect of air on the temperature of the irrigation liquid.

The power consumption of the thermoelectric module did not exceed 11 W.

III. Experimental studies of cooling modes of irrigation fluid

The experimental part of the research was aimed at assessing the possibility of optimal cooling of the irrigation fluid down by 2 °C relative to the ambient temperature and achieving a temperature of 15 °C on the surgical cannula.

The efficiency of the thermoelectric cooler significantly depends on the quality of heat removal from the hot surface of the thermoelectric module. Modern design solutions provide air cooling (with and without fan blowing), heat removal by liquid radiators, massive metal assemblies and the use of phase transitions of some substances for this purpose [13]. The scheme of conducting an experimental study with air heat removal is shown in Fig. 4.

A polymer tube, through which a liquid was passed with an average flow rate of 4.5 ml/min, was placed in a corresponding channel between duralumin plates with good thermal conductivity (120 W/m·K). The upper plate was cooled by a thermoelectric Peltier module of the *Altec-CM-1-S-SQ-127-1.0x1.0-2.0 type* (30×30 mm^2).

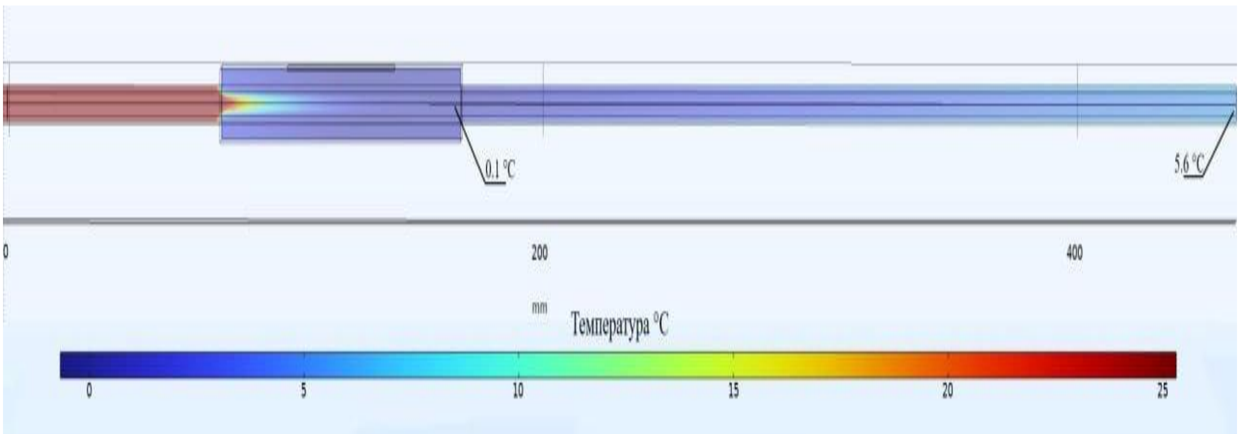

Fig. 3. Change in coolant temperature during thermoelectric cooling.

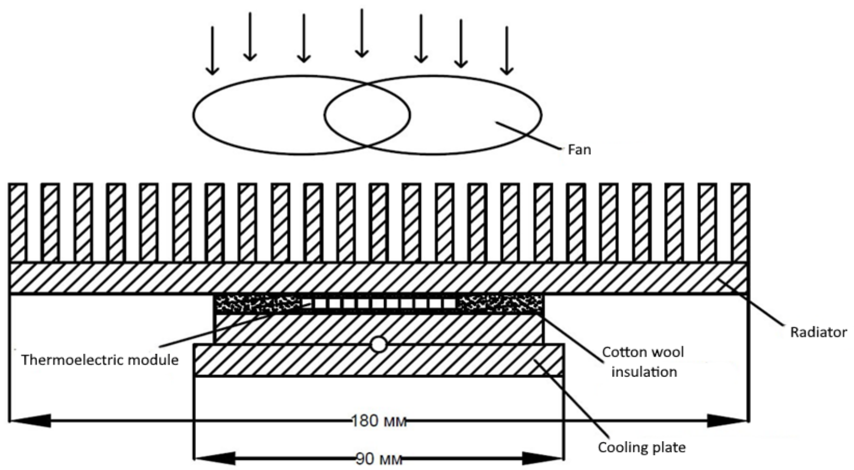

Fig. 4. Layout diagram of the experimental unit with air heat removal.

Heat from the hot side of the thermoelectric module was removed by a needle air radiator with overall dimensions of 140×140×50 mm^3, the number of needle rods was 380 pieces, diameter was 2.5 mm and the height equaled 40 mm. Initially, heat transfer was convective, without forced blowing by a fan; a fan was then connected to blow the hot radiator. Using differential chromel-copel thermocouples, the temperature of the irrigation fluid "before" and "after" the cooling unit, the temperature of the radiator and the cooling plate were monitored. The measurement frequency was 5 minutes. The results of the cooler operation with air heat removal are presented in Table 1.

Forced convection significantly improves the cooling dynamics. However, the placement of the polymer tube in the thermoelectric device does not allow achieving the desired temperature at the cannula. At a liquid temperature at the outlet of the device of 14.4°C, the cannula temperature was about 20°C due to heat exchange with the air.

To improve the cooling intensity of the therapeutic fluid, a tube made of stainless medical steel was used instead of a fragment of a polymer tube in the thermoelectric device, and a more powerful Peltier module of the Altec-22 type (40×40×4 mm^3) was also used. The heat from the hot side of the thermoelectric module was removed by a liquid heat exchanger, hdraulically connected to the laboratory water supply network. The results of this study are presented in Table 2.

The length of the polymer tube from the cooling device to the cannula was 0.5 m, the flow rate of the therapeutic irrigation fluid was 4.6 ml/min. As can be seen from the table, liquid heat exchange contributes to more effective cooling of the irrigation fluid. The temperature on the cannula is less than 15 °C and is reached at the 5th minute of the device's operation, while the power consumption of the thermoelectric cooling module does not exceed 9 W.

IV. Discussion

In ophthalmology, various authors support the idea of conducting ophthalmic surgical operations under hypothermia. At the same time, there is currently no consensus on the optimal temperature of the irrigation fluid and the level of hypothermia of intraocular structures during surgery.

Thus, Mauro and co-authors proposed a device capable of heating the infusion fluid and air during vitreoretinal surgery, maintaining their temperature in the range of mild or moderate hypothermia (32–35 °C) [18]. The device developed by the authors allows for vitreoretinal surgical interventions under temperature control. It was tested in an experimental study, which confirmed that vitreoretinal surgery with controlled temperature under mild or moderate hypothermia leads to more favorable functional and structural results as compared to standard vitrectomy [15].

Other authors prefer to perform surgery under conditions of deep hypothermia, citing the beneficial effects obtained. For example, Rinkoff et al. demonstrated experimentally the possibility of using irrigation fluid with a temperature below body temperature (22 °C) for retinal surgery to reduce phototoxic damage to the retina [19]. Tamai et al. experimentally noted the least structural and electrophysiological changes in the retina after surgery under ischemia using low-temperature irrigation solutions (8 °C) [20]. Jabbour et al. experimentally noted a decrease in intraoperative hemorrhagic complications and intraoperative fibrin formation with a decrease in the temperature of the irrigation solution to 7 °C [21].

We also share the opinion on the advisability of using irrigation fluid with a temperature lower than body temperature during retinal surgeries, which is confirmed by our preliminary studies [2, 4]. It is advisable to use a mild level of hypothermia during surgical interventions, since such conditions are safer for intraocular structures, especially during long-term interventions. A mild level of hypothermia can be achieved by heating the irrigation fluid at room temperature before it enters the eye [15].

On the other hand, short-term cooling of irrigation solutions will allow using the beneficial effects of deep hypothermia during certain types of surgeries [16, 19-21]. To solve this problem, it is necessary to resolve the issue of effective intraoperative cooling of the fluid. The use of thermoelectric devices in both heating and cooling modes of the irrigation fluid during surgery by changing the direction of the electric current seems to be the most

Table 1.

Results of operation of the air-cooled heat sink

No.	I mod. A	U mod.,B	T1, ^{0}C	T2, ^{0}C	T3, ^{0}C	ΔT, K	t, хв.	Note
1	0	0	21	21	21/21*	0	0	Fan off
2	2.0	13.5	21.0	20.6	28.6/20.3	0.4	5	
3	«	«	21.1	20.0	29.2/18.1	1.1	10	
4	«	«	21.1	19.8	31.5/17.2	1.3	15	
1	0	0	20	19.8	20.1/20	0.2	0	Fan on 2.3 W/12 V
2	2.0	13.5	20.2	19.9	23.9/14.0	0.3	5	
3	«	«	20.2	19.1	23.3/15.2	1.1	10	
4	«	«	19.5	16.9	23.0/12.6	2.6	15	
5	«	«	19.2	15.8	22.2/11.2	3.4	20	
6	«	«	18.1	14.4	21.8/10.0	3.7	25	

* - corrlation between the temperature of the hot radiator and the cooled plate, T1 is liquid temperature at the inlet to the thermal unit, T2 is liquid at the outlet.

Table 2.

Results of operation of the cooler with a liquid heat exchanger

No.	I mod. A	U mod.,B	T1, ^{0}C	T2, ^{0}C	T3, ^{0}C	ΔT, K	t, хв.	Note
1	0	0	16.3	16.2	16.4	0.1	0	Water flow in radiator ~10 ml/s
2	1.5	7.6	17.2	8.8	14.8	8.4	5	
3	«	«	17.3	4.0	13.3	13.3	10	
4	«	«	17.6	1.6	9.2	16	15	
5	«	«	17.6	0.6	8.9	17	20	
6	1.7	5.0	17.5	0.7	8.6	16.8	25	*
7	«	«	17.5	0.7	8.4	16.8	30	

* – power was reduced to prevent freezing of the liquid, T1 is the temperature of the hot side of the thermoelectric module, T2 is the temperature of the cold side of the module, T3 is the temperature of the cannula.

justified.

The study demonstrated the possibility of not only thermoelectric heating, but also thermoelectric cooling of irrigation fluid for use in ophthalmic surgical interventions. This creates new therapeutic opportunities for surgical interventions under conditions of hypothermia by controlling the temperature of solutions entering the eye during surgery.

Therefore, the creation of a thermoelectric device for intraoperative control of the temperature of irrigation fluid will provide ophthalmologists with the opportunity to maximize the beneficial effects of hypothermia (from mild to deep levels). To implement an effective temperature control system in the process of ophthalmic operations, it is advisable to have the ability to change the temperature of the irrigation fluid by its intraoperative heating and cooling to ensure the required depth of hypothermia of intraocular structures. An important issue that also needs to be addressed in further studies remains the ability to control the rate of temperature recovery in the eye after the cooling stage in order to avoid dangerous vascular reactions during surgery.

Conclusions

The development of a thermoelectric device for controlling the temperature of the irrigation fluid provides for the possibility of intraoperative regulation of its temperature by both heating and cooling, which will ensure the achievement of the required depth of hypothermia of intraocular structures during ophthalmological operations.

The possibility of fulfilling both medical and technical requirements for achieving the required temperature of the therapeutic irrigation fluid using thermoelectric equipment has been theoretically and experimentally confirmed.

The use of a powerful thermoelectric cooling module significantly reduces the time to reach the required liquid temperature.

Liquid cooling of the hot side of the thermoelectric module helps to reduce the required level of cooling capacity to achieve a liquid temperature of about 9°C.

The temperature of the liquid at the outlet of the thermoelectric unit is easily regulated by the supply current of the thermoelectric cooling module.

To quickly reach the required temperature of the therapeutic irrigation fluid (less than 5 minutes), it is advisable to use a higher power supply of the thermoelectric module at the beginning of the procedure with its subsequent reduction.

The use of a liquid temperature controller and autonomous liquid heat removal simplifies the operation technology of the thermoelectric cooling unit.

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Застосування термоелектричного охолодження та нагрівання для керування температурою іригаційної рідини при проведенні офтальмологічних операцій

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У роботі розглянуто можливості використання термоелектричного охолодження та нагрівання іригаційної рідини при проведенні офтальмологічних операцій. Проведено порівняльний аналіз використання компресійних, кріогенних і термоелектричних пристроїв у необхідному інтервалі температур розчинів для хірургії при температурі оточуючого середовища біля 20 °С. Показано переваги використання в лікувальній практиці приладів на основі термоелектричного охолодження (нагріву). Представлено результати проектування та дослідження параметрів термоелектричного приладу для забезпечення оптимальної температури іригаційної рідини при проведенні офтальмологічних операцій.

Ключові слова: термоелектричний охолоджувач, іригаційна рідина, температурні умови, офтальмологічні операції.