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COMPUTER SIMULATION OF THERMAL PROCESSES IN HUMAN EYE

The paper presents the results of computer simulation of thermal processes in human eye. The schematic, mathematical and computer models of human eye were built with regard to its thermophysical features, blood circulation, metabolic and heat exchange processes. The patterns of temperature distribution in different segments of human eye at controlled local hypothermia of corneal surface were determined. It was established that the required temperature decrease of eye retina by 2°C is achieved by cooling corneal surface to +18°C. Bibl. 38, Fig. 6, Table 2.
Key words: human eye, computer simulation, diagnosis and treatment of ophthalmologic diseases.

Introduction

General characterization of the problem. Currently, therapeutic hypothermia is widely used to protect biological tissues and organs from ischemia in various fields of medicine, in particular in cardiac surgery, neurosurgery and resuscitation [1 - 3]. Therapeutic hypothermia is considered as the most efficient physical method for the protection of nerve cells (brain, retina, etc), since from the point of view of evidence-based medicine there is no efficient pharmacological neuroprotection method in neuro-reanimation practice. In ophthalmic practice, there is also information that local hypothermia leads to a decrease in intraocular pressure, a reduction in pain syndrome, a decrease in the inflammatory response, stops bleeding, in conditions of acute ischemia reduces damage to retinal nerve cells, reduces edema and traumatization of the cornea at chemical burns of eyes and has other useful properties [4, 5].

In the world literature, there are data on the dynamics of biochemical processes, as well as hemo- and hydrodynamic parameters in the eye of animals and humans under the influence of low temperatures on the eye [6 - 11], as well as on the methods for measuring the intraocular temperature [12 - 20]. However, until now, the question of the distribution of intraocular temperature under the influence of various physical factors remains poorly understood [21 - 25].

Understanding the patterns of intraocular temperature distribution, as well as evaluating the relationship between the temperature parameters of the external and internal segments of the eye under various environmental conditions, in norm and pathology, under the influence of physical factors on the eye, will allow the development of a computer model for intraocular temperature distribution. Thus, in biological systems that are not susceptible to direct investigation, such as human eye, computer simulation can be used as an alternative method for assessing the intraocular temperature and is the best tool for predicting intraocular thermal processes. If such a computer model is available, it will be possible to more accurately imagine the dynamics of thermal processes in the eye under the influence of various external thermal factors (hypothermia and hyperthermia), which are used in clinical ophthalmology. Consequently, there will be an additional opportunity to improve the efficiency and safety of some methods of treatment of ophthalmic diseases.

It should be noted that the study of the dynamics of intraocular temperature under hypothermia will allow the development of a technology for controlled hypothermia of the eye, more efficient use of advantageous low-temperature effects for the treatment of eye diseases and reduce the risk of a number of complications in ophthalmic surgery. Prospects for neuroprotection with the use of moderate local hypothermia in ophthalmosurgery also require the creation of a computer model for the evaluation of thermal processes in the eye under the influence of one or several external factors [26, 27]. To create an adequate computer model of thermal processes, it is not enough to have temperature data recorded on the outer corneal surface [28]. It is necessary to understand the general patterns of temperature distribution in different segments of the eye, as well as the interrelation between the temperature parameters of the external and internal segments of the eye under various environmental conditions and when the physical factors affect the eye.

The development of thermoelectric devices for controlled local hypothermia of the eyes looks promising for the purpose of using such devices in patients with acute (eye injury) and chronic (diabetes) pathology of the eye. It is also advisable to use such devices in patients with traumatic eye injuries, retinal detachment and other acute pathology of the organ of vision at the prehospital stage (including in combat conditions), which will reduce the risk of complications and preserve the viability of eye structures until the patient is delivered to a specialized a medical institution for the provision of highly qualified care. Thus, the development and introduction of such thermoelectric equipment into medical practice is relevant, as it will provide physicians with a simple and effective method of diagnosis and treatment of various ophthalmic diseases. However, to develop the design and select the optimal dynamic modes of operation of thermoelectric devices for controlled local eye hypothermia, it is also necessary to develop computer methods for modeling thermal processes and to determine the patterns of the distribution of temperature and heat fluxes of the human eye.

Therefore, *the purpose of this work* is to develop a computer model and computer simulation methods of human eye processes in order to determine the patterns of temperature distribution in different segments of the eye with controlled local hypothermia of corneal surface.

Schematic model of human eye

A schematic model of human eye was developed with due regard to its anatomic structure, thermophysical features, blood circulation, metabolic and heat exchange processes (Figs.1*a,b*, 2*a,b*).

Human eyeball is composed of three tunics (external (cornea and sclera), middle (vascular tunic), inner (nervous tunic of eyeball)) and internal content (vitreous body, lens, watery moisture of the anterior and posterior chambers of the eye) [29].

The external (fibrous) tunic of the eye is represented by cornea and sclera. Cornea is a transparent nonvascular part of the external tunic of the eye. The cornea performs the function of conducting and refracting rays of light, as well as protecting the content of the eyeball from adverse external influences. The diameter of the cornea is, on the average, 11.0 mm, the thickness in the centre is about 0.5 mm, the refractive power is 43.0 diopters (dpt). Normally, the cornea is smooth, transparent, shiny, spherical. Nutrition of the cornea occurs due to the pericorneal network of vessels, the moisture of the anterior chamber of the eye and tears. Transparency of the cornea is ensured by its homogeneous structure, lack of vessels and strictly defined water content. Sclera is an opaque part of the external fibrous tunic of the eye. Its thickness is 1 mm. The sclera performs protective and shape-forming functions.

The middle (vascular) tunic of the eye, or uveal tract, consists of three parts: iris, ciliary body and choroid. Iris is a diagram of the eye. The thickness of the iris is merely 0.4-0.6 mm. The iris consists of connective-tissue stroma, vessels, epithelium, covering iris at the front and two layers of pigment epithelium at the back, providing its opacity. Pupil is a round hole in the centre of the iris. Due to a change in its diameter, the pupil controls the flow of light incident on the retina. The ciliary body is a part of the choroid of the eye, which in the form of a ring passes between the root of the iris and the choroid. The boundary between the ciliary body and the choroid lies along cogged line. The ciliary body produces intraocular fluid and participates in the act of accommodation (provides a clear vision at various distances due to a change in the lens curvature). The choroid is a part of the uveal tract, separated from the ciliary body by cogged line. The choroid is composed of several layers of vessels. The layer of wide chorio capillaries adjoins the retina and is separated from it by a thin Bruch's membrane. Located externally is a layer of middle vessels (mostly arterioles), behind which there is a layer of larger vessels (venules). Between the sclera and the choroid there is a suprachoroidal space where vessels and nerves transit. The choroid assures nutrition to the external layers of the retina (visual receptor cells).

The inner tunic of the eyeball (nervous tunic) is a highly nervous tissue that provides the perception of light stimuli. From the optic nerve disk to the cogged line there is the optically active part of the retina. In front of the cogged line located 6 – 7 mm from the limb it is reduced to the epithelium that covers the internal parts of ciliary body and iris. This part of the retina does not participate in the act of vision. The nutrition of the retina is due to the choroid and vessels of the central retinal artery system. The most photosensitive part of the yellow spot is the central fossa, or foveola. In the retina there are neurons of visual analyzer: photoreceptors (first neuron) - rods and cones, bipolar cells (second neuron) and ganglion cells (third neuron). Rods and cones are a receptor part of visual analyzer and are in the outer layers of the retina, directly in its pigment epithelium. Rods located on the periphery are responsible for peripheral vision – a field of view and light perception. Cones that are largely concentrated in the field of yellow spot provide central vision (visual acuity) and color perception. Axons of ganglion cells converge, forming the optic nerve. The disk of the optic nerve corresponds to the point of exit of the nerve fibers from the eyeball and does not contain photosensitive elements.

The internal content of the eyeball includes vitreous body, lens and watery moisture of the anterior and posterior chambers of the eye.

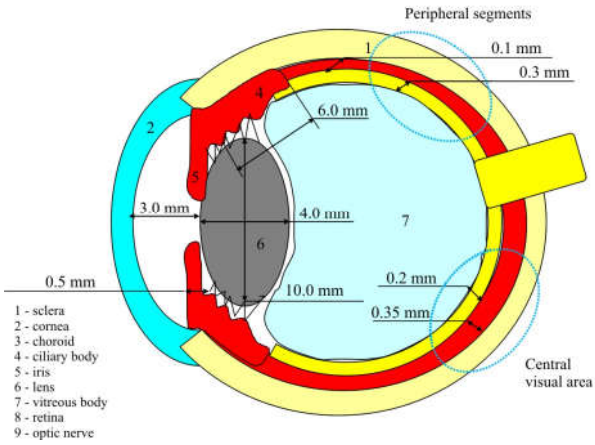
The vitreous body by weight and volume is about 2/3 of the eyeball. This is a transparent non-vascular gelatinous structure that fills the space between the retina, the ciliary body, the fibers of Zinn's zonule and the lens.

The vitreous body is covered with a thin membrane, inside which there is a skeleton of fine fibrils and a gel-like substance. The vitreous humor is more than 99 % water, in which a small amount of protein, hyaluronic acid and electrolytes are dissolved.

The lens is a transparent, non-vascular elastic formation which has the shape of a double-convex lens of 3.5 – 4 mm in thickness and 9 – 10 mm in diameter. The substance of the lens of dense consistency is enclosed in a thin capsule. The lens performs the functions of conduction and refraction of light, as well as participation in accommodation. The refractive power of the lens is about 18-19 dpt. The lens is located directly behind the iris and suspended on the fibers of Zinn's zonule which are woven into a lens capsule at its equator. The equator divides the capsule of the lens into the anterior and posterior. Under the anterior capsule of the lens there is the subcapsular epithelium, which produces fibers throughout life. The lens becomes flatter and denser, losing its elasticity. Gradually, the ability to accommodation is lost, since the condensed matter of the lens cannot change its shape. The lens almost 65 % consists of water, and the protein content reaches 35 % – more than in any other tissue of our body.

Intraocular fluid is produced in the ciliary body, fills the anterior and posterior chambers of the eye. The anterior camera of the eye is the space between the cornea, iris and lens. The posterior chamber of the eye is a narrow gap between the iris and lens with Zinn's zonule. Watery moisture takes part in the nutrition of non-vascular media of the eye, and its exchange largely determines the value of intraocular pressure. The main way of the outflow of intraocular fluid is the angle of the anterior chamber of the eye, formed by the root of the iris and the cornea. Through the system of trabeculae and a layer of cells of the inner epithelium, fluid enters Schlemm's canal (venous sinus), from where it flows into the veins of the sclera.

All arterial blood enters the eyeball by the ophthalmic artery, a branch of internal carotid artery. Ophthalmic artery forms the following branches which run to the eyeball: central retinal artery assuring blood supply to internal retinal layers; posterior short ciliary which dichotomously branch out in the choroid and supply it with blood; posterior long ciliary arteries which pass to suprachoroidal space to ciliary body; anterior ciliary arteries extend away from the muscular branches of the ophthalmic artery. Posterior long and anterior ciliary arteries, anastomosing with each other, form a large arterial circle of iris. Away from it, in the radial direction, extend vessels that form around the pupil a small arterial circuit of iris. Due to posterior long and anterior ciliary arteries, the iris and ciliary body are provided with blood, a pericorneal vessel network is formed, which is involved in the nutrition of the cornea. The outflow of blood from the eyeball is via vorticose veins, anterior ciliary veins and the central retinal vein. Vorticose veins collect blood from the uveal tract and leave the eyeball, obliquely piercing the sclera near the equator of the eye. The anterior ciliary veins and the central vein of the retina divert blood from the territory of homonymous arteries [29].



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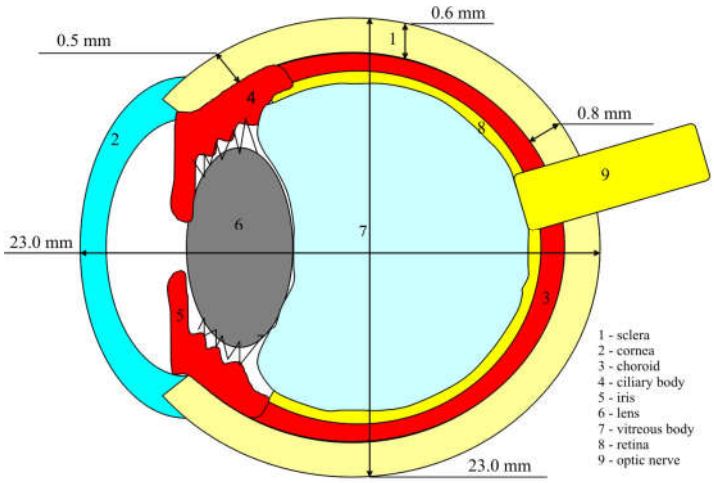
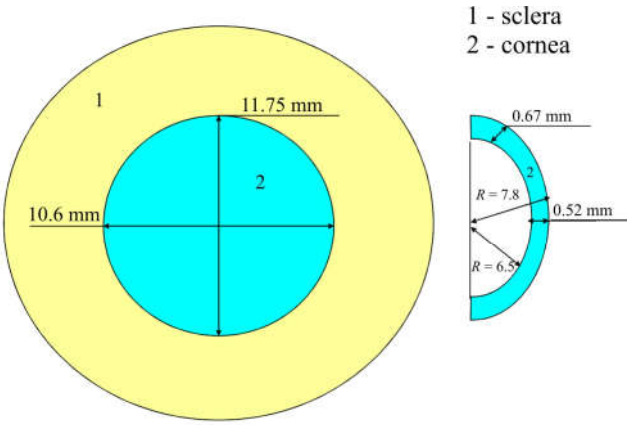


b)

Fig.1 a,b. Schematic model of eye (side view)
1 – sclera; 2 – cornea; 3 – choroid; 4 – ciliary body;
5 – iris; 6 – lens; 7 – vitreous body; 8 – retina; 9 – optic nerve



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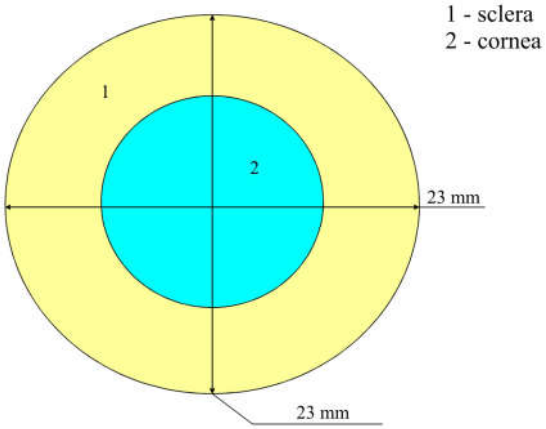


b)

Fig.2 a,b. Schematic model of eye (front view). склера - sclera ; рогівка - cornea

Blood circulation in the choroid is the main source of heat in the eye of animals and humans. Blood coming to the eye at a temperature practically equal to body temperature, forms thermal gradient which induces transfer of heat from the blood to eye tissues. The more intensive blood circulation, the greater amount of heat is passed to eye tissues. Blood circulation in the iris and ciliary body is also the source of heat. However, to a lesser degree, since blood circulation in the iris and ciliary body is relatively small as compared to blood circulation in the choroid. Heat distributed in the eye tissues passes to the environment through corneal surface due to convection and radiation [30].

The above Figs. 1a, b – 2a, b show the schematic layout of human eye structures and their dimensions.

The thermophysical properties of human eye structures (cornea, anterior chamber humidity, lens, vitreous body and retina), namely the values of thermal conductivity, density and specific heat that are taken as control values, are listed in Table 1. The values of thermal conductivity, density and specific heat of iris and ciliary body were considered to be equal to indicators of anterior chamber humidity. For the cornea and vitreous body the physical constants are close to the values of water, but the values of thermal conductivity and specific heat for the lens are considerably lower [31].

Table 1.

Thermophysical properties of human eye [31]

Eye structures	Thermal conductivity W/(m·K)	Density kg/m^3	Specific heat J/(kg·K)
Cornea (external surface temperature 32.0 – 34.0 ºC)	0.580	1050	4178
Humidity of anterior eye (volume 0.25 – 0.3 ml)	0.580	1000	3997
Lens	0.400	1050	3000
Vitreous body (volume 3.5 – 4 ml, temperature 34.0 – 36.0 ºC)	0.603	1000	4178
Retina	0.628	1000	4190
Blood Plasma (36.85 ºC)	0.53 – 0.55 0.599	1050 1025	4050 3820
Water (20 ºC)	0.6	993.4	4184
Retinal blood perfusion 0.012 s^{-1}.			

Mathematical description

To describe the process of heat exchange in "living" biological tissues, use is made of the Pennes equation (1) [32]. The generation of metabolic heat is considered to be uniformly distributed along the entire biological tissue, blood perfusion is also considered to be uniform and isotropic. According to the Pennes model, thermal equilibrium is created directly in the capillary circle of the microcirculatory bed (blood at temperature T_b comes to capillaries where heat exchange takes place, and blood temperature drops to temperature of biological tissue T).

Pennes simulated the effect of blood as isotropic heat source proportional to blood flow velocity and the difference between body temperature and local temperature of tissue in the form of the following equation [33 – 37]:

$$k\nabla^2 T + \rho_b c_b \omega_b (T_b - T) + Q_m + Q_i = \rho c \frac{\partial T}{\partial t}, \quad (1)$$

where k is thermal conductivity of biological tissue;
T is temperature of biological tissue;
ρ_b is blood density;
c_b is blood specific heat;
ω_b is blood perfusion;
T_b is arterial blood temperature (T_b = 37 °C);
Q_m is heat released due to metabolism;
Q_i is internal source of heat;
ρ is biological tissue density;
c is biological tissue specific heat;
t is time variable.

In Eq.(1), ∇^2 is a Laplacian operator which for the three-dimensional model is as follows:

$$\nabla^2 = \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2}. \quad (2)$$

The summand in the left side of Eq.(1) is the rate of change in thermal energy located in the unit volume of biological tissue. Three summands in the right side of this equation are, accordingly, the rate of change in thermal energy due to thermal conductivity under temperature gradient, blood perfusion and metabolic heat.

For the steady-state case $\partial T/\partial t = 0$, so Eq.(1) is simplified to:

$$k\nabla^2 T + \rho_b c_b \omega_b (T_b - T) + Q_m + Q_i = 0. \quad (3)$$

Eq.(3) should be solved with the following boundary conditions:

1. Blood temperature is approximately equal to biological tissue temperature $T_b = T$ =37°C.

2. Heat flux density (convection) from the surface of biological tissue q_0 is determined by means of the Newton-Richman equation (4):

$$q_0 = \alpha(T_{ext} - T), \quad (4)$$

where α = 12 is heat exchange coefficient; T_{ext} = 20°C is ambient temperature.

3. Heat flux density (radiation) from the surface of biological tissue q is determined by means of the Stephan-Boltzmann equation (5):

$$q = \sigma \cdot S \cdot \varepsilon_{1,2} \cdot (T_{ext}^4 - T^4), \quad (5)$$

where σ is the Stephan-Boltzmann constant, S is the area of the surface from which radiation occurs, ε_{12} is emissivity.

4. Total heat flux Q from the surface of biological tissue is determined by the expression:

$$Q = q_0 + q. \quad (6)$$

The analytical solution of Eq.(3) with the boundary conditions (4 – 6) is rather complex, so COMSOL Multiphysics applied software package was used [38], which allows simulation of thermophysical processes in biological tissue.

Computer model of human eye and simulation results

In order to determine temperature distribution in human eye, a three-dimensional computer model of human eye was created with regard to its thermophysical features, blood circulation,

metabolic and heat exchange processes. For this purpose, Comsol Multiphysics applied software package was used [38], allowing simulation of thermophysical processes in biological tissue with consideration of blood circulation and metabolism.

The distribution of temperature and heat flux density in human eye was calculated by the finite element method. According to this method, an object under study is split into a large number of finite elements, and in each of them the value of function is sought which satisfies given differential equations of second kind with the respective boundary conditions. The accuracy of solving the formulated problem depends on the level of splitting and is ensured by using a large number of finite elements [38].

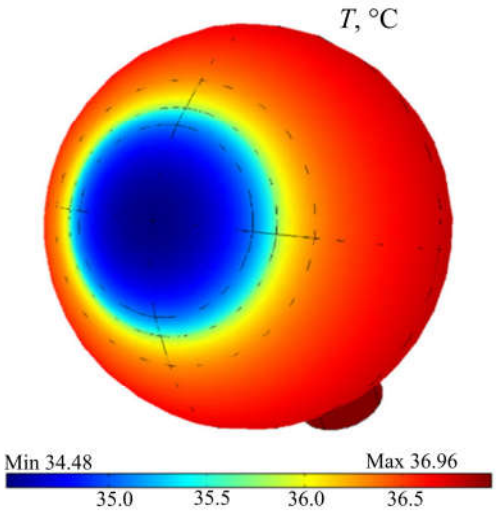
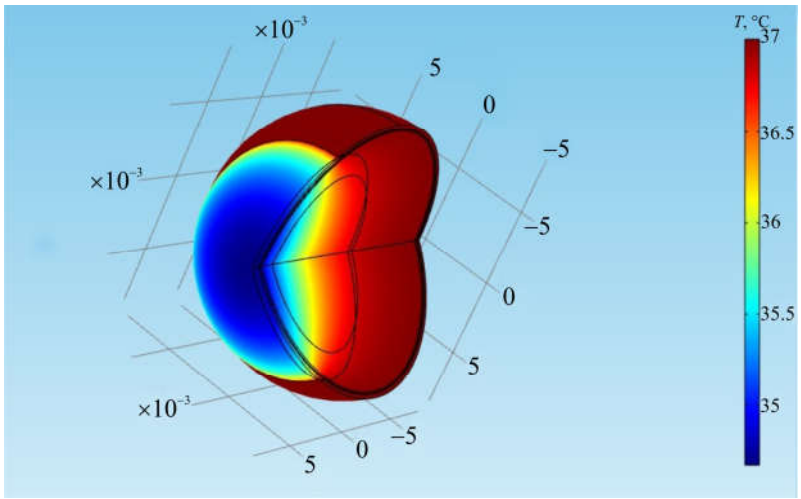


Fig.3. Computer model of human eye in Comsol Multiphysics program

With the aid of object-oriented computer simulation, the distributions of temperature and thermal flows in different structures of human eye were obtained that are shown in in Figs.3 - 4 *a, b*.

It is known that the basis for the neuroprotective effect of hypothermia is a reduction in the induction of apoptosis of neurons by decreasing the rate of metabolic processes therein. Thus, a reduction of brain temperature by 1°C assures a reduction of oxygen consumption by neurons and glucose metabolism by 5% [39]. Thus, according to medical requirements for the development of technology of controlled local hypothermia of the eye, it is necessary to predict what temperature of corneal surface should be reached in order to lower the temperature of the retina by 2 – 5°C.



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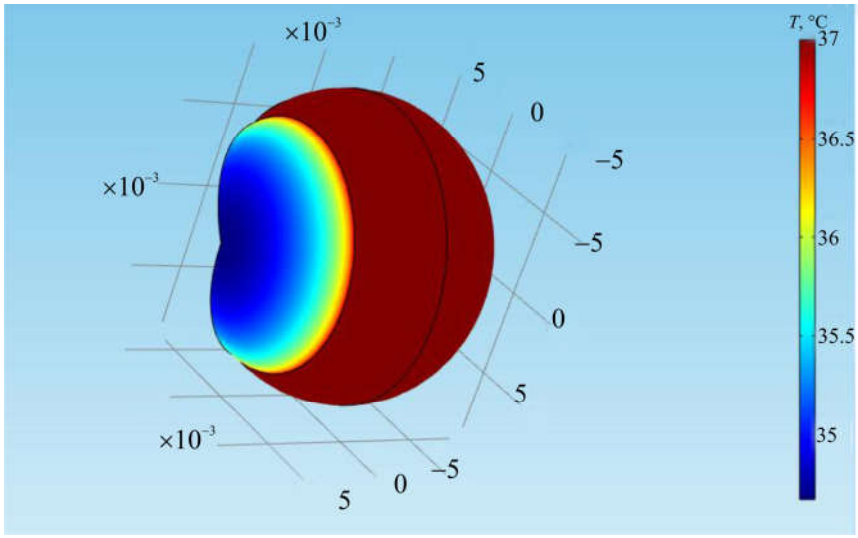

b)

Fig.4 a, b. Temperature distribution in human eye at ambient temperature T = 22°C

Also, computer simulation was made of temperature distributions in different structures of human eye at cooling of cornea to the required temperatures. As an example, Figs. 5 - 6 show temperature distributions in human eye at corneal surface temperatures T = 18°C and T = -5°C.

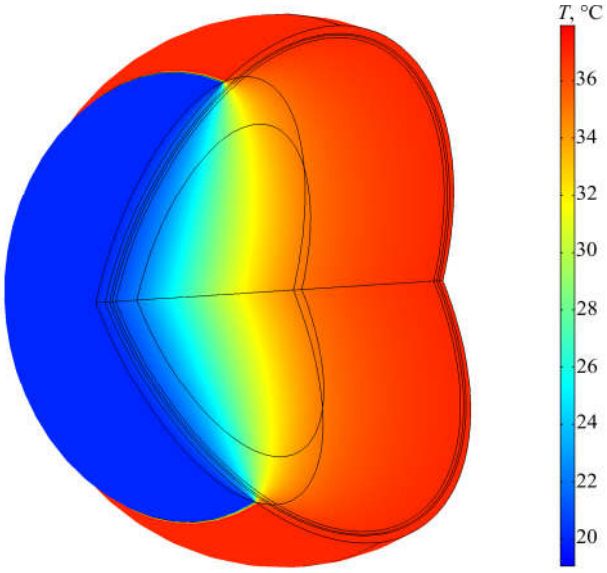

Fig. 5. Temperature distribution in human eye at corneal surface temperature T = 18°C

By means of computer simulation it was established that the required decrease of temperature of vitreous body and, accordingly, eye retina by 2 °C is achieved by cooling corneal surface to +18 °C, and to decrease eye retina temperature by 5 °C, corneal surface should be cooled to -5 °C. The results obtained enable one to develop the technology of controlled local therapeutic hypothermia in ophthalmology.

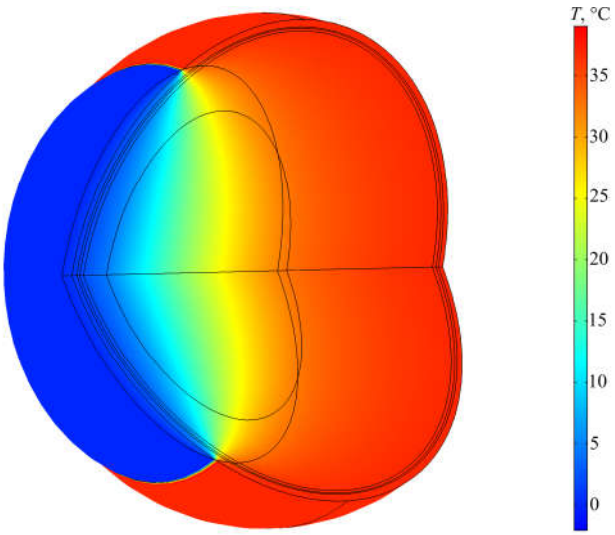

Fig.6. Temperature distribution in human eye at corneal surface temperature T = -5°C

Computer simulation results are listed in Table 2.

Table 2

Computer simulation results

Eye structures	Ambient temperature T = +22°C	Temperature at cooling of corneal surface to T = +18°C	Temperature at cooling of corneal surface to T = -5°C
Cornea	+34	+18	-5
Vitreous body (and, accordingly, eye retina)	+37	+35	+32

Conclusion

1. Schematic, mathematical and computer models of human eye were built with regard to its thermophysical features, blood circulation, metabolic and heat exchange processes.
2. Computer methods for simulation of thermal processes in human eye were developed. The distributions of temperature and thermal flows in human eye were determined. It was established that the required decrease of temperature of eye retina by 2 °C is achieved by cooling corneal surface to +18 °C.
3. The results obtained will be used for creation of up-to-date thermoelectric medical apparatus for the diagnosis and treatment of ophthalmologic diseases, which will improve the efficiency of diagnosis of pathology of visual organs, make it possible to observe in dynamics the development of pathological process in eye structures, improve the efficiency of treatment of acute and chronic eye diseases, develop and introduce the technology of controlled local therapeutic hypothermia in ophthalmology.

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КОМП'ЮТЕРНЕ МОДЕЛЮВАННЯ ТЕПЛОВИХ ПРОЦЕСІВ ОКА ЛЮДИНИ

У роботі наведено результати комп'ютерного моделювання теплових процесів ока людини. Побудовано схематичну, математичну та комп'ютерну моделі ока людини з врахуванням його теплофізичних особливостей, кровообігу, процесів метаболізму і теплообміну. Визначено закономірності розподілів температури в різних відділах ока людини при контрольованій локальній гіпотермії поверхні рогівки. Встановлено, що необхідне зниження температури сітківки ока на 2°С досягається шляхом охолодження поверхні рогівки до температури +20°С. Бібл. 38, рис. 6, табл. 2.

Ключові слова: око людини, комп'ютерне моделювання, діагностика та лікування офтальмологічних захворювань.

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КОМПЬЮТЕРНОЕ МОДЕЛИРОВАНИЕ ТЕПЛОВЫХ ПРОЦЕССОВ ГЛАЗА ЧЕЛОВЕКА

В работе приведены результаты компьютерного моделирования тепловых процессов глаза

человека. Построены схематическая, математическая и компьютерная модели глаза человека с учетом его теплофизических особенностей, кровообращения, процессов метаболизма и теплообмена. Определены закономерности распределения температуры в разных отделах глаза человека при контролируемой локальной гипотермии поверхности роговицы. Установлено, что необходимое снижение температуры сетчатки глаза на 2°С достигается путем охлаждения поверхности роговицы до температуры +20°С. Библ. 38, рис. 6, табл. 2.

Ключевые слова: глаз человека, компьютерное моделирование, диагностика и лечение офтальмологических заболеваний.

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