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# ON TEMPERATURE DISTRIBUTION IN HUMAN HEAD AT GIVEN THERMAL FLUXES ON ITS SURFACE

*The paper presents a review and analysis of the existing physical and computer models of human head cooling. With the aid of object-oriented computer simulation of currently available physical models the distributions of temperature in human head at given thermal fluxes on its surface are determined. The disadvantages of the existing models of human head are determined and the ways for their improvement are proposed.*

**Key words:** thermoelectric cooling, human head cooling, brain hypoxia, computer simulation.

## Introduction

Brain oxygen starvation (hypoxia) is a relevant problem in medical practice which is due to inadequate oxygen flow to nervous tissues. This happens for two reasons: the lack of oxygen in blood or disturbance of blood delivery to brain. Hypoxia is observed at cerebrovascular accidents, shock states, acute cardiovascular insufficiency, atrioventricular heart block, head injuries and asphyxia of different origin. Brain hypoxia can be a complication of cardiac surgery and vascular procedures, as well as in the early postoperative period – at hypoxic brain edemas, intoxication and central nervous system injuries.

It is known that brain cooling reduces its oxygen requirement, increases resistance to hypoxia, thus increasing permissible duration of oxygen starvation. Thus, for instance, cooling by 5 °C extends brain lifetime several times [1 – 4].

For a correct design of brain hypothermia devices it is necessary to know the distributions of human brain temperature. However, physical models and the results of computer simulation of thermal processes in human head reported in the literature are contradictory.

In [5], a two-dimensional mathematical model was developed to study brain cooling of newborns and adults at cold water diving. The model of head is simplified and has the form of a hemisphere composed of brain, skull and skin. The results of simulation show that for newborns the temperature of blood in carotid artery is reduced by as low as 0.1 °C within 5 min at diving to water with temperature $T = 2$ °C, and no cooling was observed in this case for adults. In [6], a three-dimensional model of human head was built with regard to thermophysical properties of human head constituent layers. Computer simulation of human head cooling with ice was performed. It is established that brain cooling will be observed only in the case when blood perfusion is disregarded. Brain cooling with the aid of cooling helmet of temperature $T = 0$ °C was studied, in which case there is slight cooling of brain cortex, while brain nucleus temperature remains constant ($T = 37$ °C). Besides, this paper studies cooling of blood that circulates through the neck. It is established that cooling of arterial blood will take place only in the case when blood rate will be reduced by an order of magnitude, which is impossible under real conditions. A three-dimensional (3D) simulation of human head was done in [7]. In this case a physical model comprises four layers: the white and grey substance, skin, and skull. It is established that slight temperature reduction of brain surface will take place, but similar to [6] the model does not take into account blood perfusion. In [8], computer simulation of brain cooling of newborns and adults with the aid of cooling helmet is performed using Comsol Multiphysics. The results for newborns show that only 5 – 6 mm of near-surface brain layer are cooled, and the temperature of brain nucleus is not reduced even after six hours of use. The results of simulation of adult head show that at a minimum temperature of cooling helmet $T = 0$ °C the temperature of brain is reduced by 0.4 °C. In [9], an experimental study of human head and neck cooling was performed on 5 volunteers at the ages from 31 to 48. Cooling was performed for 30 min with the aid of cooling helmet and collar made of a double nylon layer, with openings for air blasting in the inner layer, air temperature 14.5 °C, and flow rate 42.5 l/s. Brain temperature control was performed via MRT-scanner. It was established that brain temperature within 30 min was reduced by 0.45 °C, and the esophagus temperature – by 0.16 °C. The results obtained testify that there is a slight cooling of human brain and circulating blood.

Therefore, *the purpose of this paper* is to reveal the incorrectness of the existing models of human head and to determine the distributions of temperature in human head at given thermal fluxes on its surface.

## Physical model of human head

Physical model was created on the basis of the existing models of human head and is a hemisphere of radius $R$ equal to the average radius of an adult human head (Fig. 1). This hemisphere has near-surface layers 1 – 3 whose thicknesses are equal to the average thicknesses of scalp $h_1$, subcutis layer $h_2$ and cranial bones $h_3$, respectively. Inside the hemisphere there is brain 4 of radius $R_4$. The corresponding layers 1 – 4 are considered as volumetric sources of heat. In each of them uniformly in the volume of the layer a metabolic heat $q_{METi}$ ($i$ = 1..4) is generated, and heat exchange with the circulating blood takes place which is assigned by blood perfusion coefficient $\omega_{bi}$. In so doing, brain is a biological tissue with high perfusion of blood, and blood temperature is constant ($T_b = 37$ °C). The temperatures at the boundaries of corresponding layers are $T_1$, $T_2$, $T_3$, $T_4$. The thermophysical properties of these biological layers are given in Table [10].

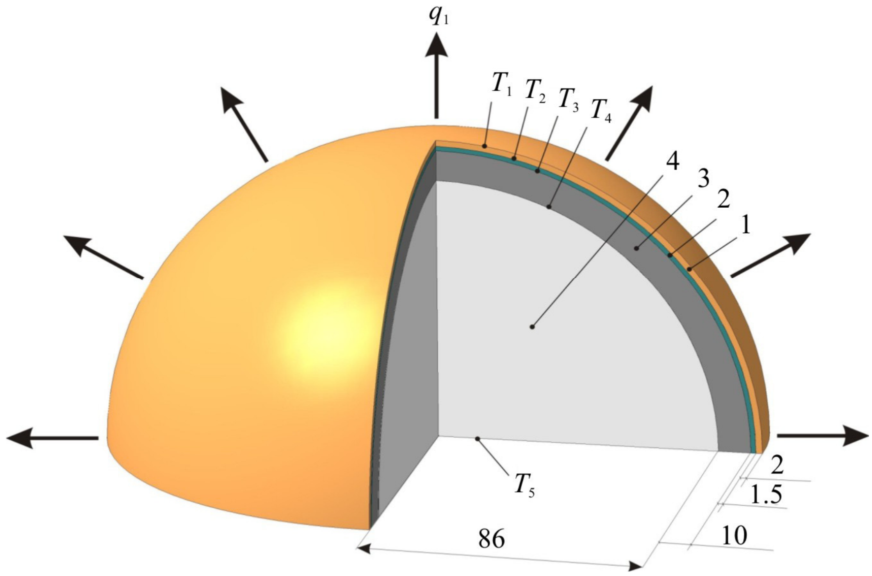


*Fig. 1. Physical model of human head.*

*Table*

*Thermophysical properties of human head biological layers [10]*

| Anatomical organization of human head | Thermal conductivity (k) (W/m·K) | Density (ρ) (kg/m$^3$) | Specific heat ($C_p$) (J/kg·K) | Perfusion ($W_b$) (l·s$^{-1}$ m$^{-3}$) | Metabolism ($q_{met}$) (W/m$^3$) |
|---|---|---|---|---|---|
| Scalp | 0.47 | 1000 | 3680 | 1.5 | 363 |
| Subcutis | 0.16 | 850 | 2300 | 0.2 | 130 |
| Scull | 1.16 | 1500 | 1591 | 0.15 | 130 |
| Brain | 0.49 | 1080 | 3850 | 8.5 | 10437 |
| Blood | 0.5 | 1069 | 3650 | – | – |

The upper surface of hemisphere is in the state of heat exchange with the environment (due to radiation and convection) or with the cooling helmet (with the assigned integral heat transfer coefficient). In so doing, $q_1$ is the density of thermal flux dissipated from human head to the environment. The temperature of the lower hemisphere surface is $T_5$ = 37 °C.

## Mathematical description of physical model

A general equation of heat exchange in biological tissue is as follows [1 – 10]:

$$\rho_i \cdot C_i \cdot \frac{\partial T}{\partial t} = \nabla(\kappa_i \cdot \nabla T) + \rho_b \cdot C_b \cdot \omega_{b_i} \cdot (T_b - T) + q_{met_i}, \quad (1)$$

where $i$=1..4 are corresponding layers of human head physical model,

$\rho_i$ is the density of corresponding biological tissue layer (kg/m$^3$),
$C_i$ is specific heat of corresponding biological tissue layer (J/kg·K),
$\rho_b$ is blood density (kg/m$^3$),
$C_b$ is specific heat of blood (J/kg·K),
$\omega_{bi}$ is blood perfusion rate in corresponding biological tissue layer (m$^3$·s$^{-1}$·m$^{-3}$),
$T_b$ is human blood temperature (K),
$q_{meti}$ is the amount of metabolic heat of corresponding layer (W/m$^3$),
$T$ is absolute temperature (K),
$\kappa_i$ is thermal conductivity of biological tissue (W/m·K),
$t$ is time (s).

The summand on the left-hand side of equation (1) is the rate of change in thermal energy comprised in the unit volume of biological tissue. Three summands on the right-hand side of this equation are the rate of change in thermal energy due to thermal conductivity, blood perfusion and metabolic heat, respectively.

The equation of heat exchange in biological tissue (1) should be solved with the following boundary conditions (2) – (3):

$$\begin{cases} q_1 = q_{rad} + q_{conv} = \varepsilon \cdot \sigma \cdot (T^4 - T_0^4) + h_{conv} \cdot (T - T_0) \\ або \\ q_1 = h_{fluid} \cdot (T - T_{fluid}) \end{cases}, \tag{2}$$

$$T_5 = 310\ \text{K}, \tag{3}$$

where $q_1$ is the density of heat flux dissipated from human head to the environment, $q_{rad}$ is the density of heat flux due to radiation, $q_{conv}$ is the density of heat flux due to convection, $\varepsilon$ is emissivity factor, $\sigma$ is the Boltzmann constant, $T$ is absolute temperature, $T_0$ is ambient temperature, $h_{conv}$ is coefficient of convective heat exchange, $h_{fluid}$ is coefficient of convective heat exchange with fluid, $T_{fluid}$ is fluid temperature.

## Computer simulation results

In order to determine thermal influence on human head, a 3D computer model of a head whose surface is in contact with cooling helmet was created. To construct the model, Comsol Multiphysics software package was employed [11], allowing simulation of thermophysical processes in human body biological tissue with account of blood circulation and metabolism. Calculation of temperature and heat flux density distributions inside human head was done by finite element method (Fig. 2). [12].

Object-oriented computer simulation was employed to determine temperature distribution inside human head. As an example, Fig. 3 shows temperature distribution in the axial section of human head with the total thermal flux from its surface $Q$ = 10 W.

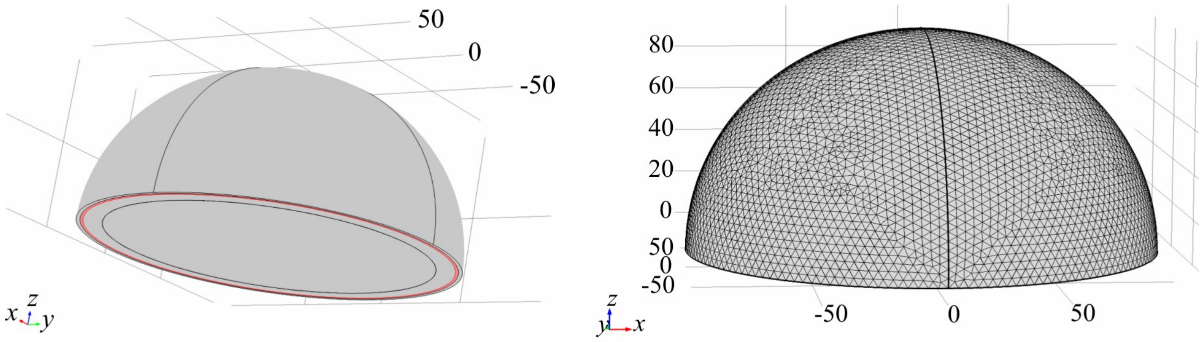


*Fig. 2. Finite element method mesh in COMSOL MULTIPHYSICS computer program.*

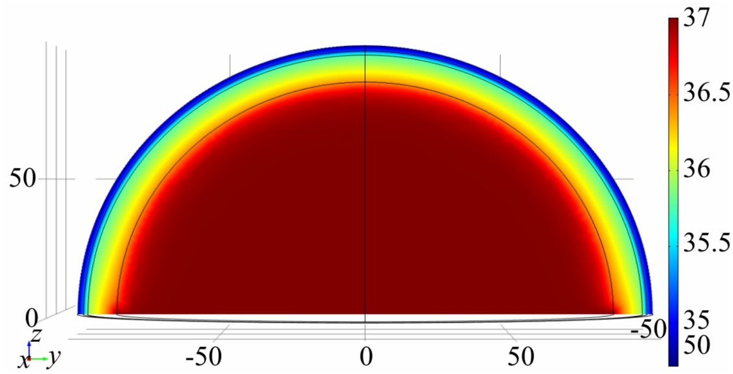


*Fig. 3. Temperature distribution in the axial cut of human head with the total thermal flux from its surface $Q$ = 10 W.*

The range of values of thermal fluxes from the surface of human head is $Q$ = 10 ÷ 100 W, which is limited by minimum allowable head surface temperature + 2 °C. For convenience of comparison of said thermal modes, Fig. 4 shows temperature distributions along the radius of head hemisphere with the respective values of thermal fluxes from human head surface.

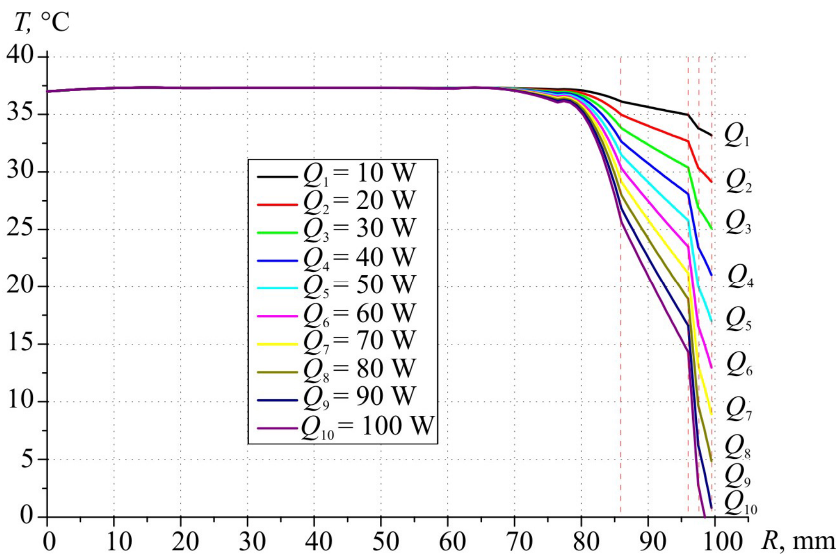


*Fig. 4. Effect of cooling power $Q$ on temperature $T$ distribution along radius $R$ of human head hemisphere.*

From Fig. 4 it can be seen that on condition of maintenance of a minimum allowable temperature of head skin (+ 2 °C), only 3 mm of human brain surface layer can be cooled to the required temperature + 32 °C. In so doing, the temperature of brain nucleus remains constant (+ 37 °C). In this case, 90 W of heat is removed from the head, which according to the literature data [13] is 90 % of total heat production of human organism. However, in actual practice, brain must be cooled, since heat removal on the level of 90 W exceeds 6-fold the total heat production of human head. As a result, blood that passed through the head must be cooled, and passing through human body it must cool the entire human organism, and, on coming back to the head, the temperature of blood must be somewhat lower than + 37 °C which in the existing models is given by a constant. It is apparent that exactly this fact is the main disadvantage of the existing physical and computer models of human head.

Thus, currently available approaches to creation of physical models and computer simulation of human head assuming arterial blood temperature to be constant ($T_{blood}$ = + 37 °C), should be improved by taking into account gradual cooling of circulating blood and heat capacity of the entire human organism.

## Conclusions

1. With the aid of object-oriented computer simulation on the basis of the existing physical models the distributions of temperature in human head were determined under given thermal fluxes on its surface. It was established that on condition of maintenance of a minimum allowable temperature of head skin (+ 2 °C), only 3 mm of human brain surface layer can be cooled to the required temperature + 32 °C, while the temperature of brain nucleus remains constant (+ 37 °C).
2. It was established that currently available approaches to creation of physical models and computer simulation of human head assuming arterial blood temperature to be constant ($T_{blood}$ = + 37 °C), should be improved by taking into account gradual cooling of circulating blood and heat capacity of the entire human organism.

## References

1. Liu Jing, Cooling Strategies and Transport Theories for Brain Hypothermia Resuscitation, *Frontiers of Energy and Power Engineering in China* **1**(1), 32 – 57 (2007).
2. A.M.Belous, V.I.Grischenko, *Cryobiology* (Kyiv: Naukova Dumka, 1994), 431 p.
3. T.M.Darbinyan, A.N.Zirakadze, S.M.Zolnikov, P.Ya.Kintraya, B.A.Komarov, S.N.Kopshev, N.P.Kupin, and K.D.Chachava, *Artificial Hypothermia* (Moscow: Soviet Encyclopedia, 1989).
4. R.R.Kobylianskyi, I.A.Moskalyk, The Prospects of Using Thermoelectricity for Human Head Cryotherapy, *J.Thermoelectricity* 4, p. 85 – 94 (2015).
5. Xiaojiang Xu, Peter Tikuisis, and Gordon Giesbrecht, A Mathematical Model for Human

Brain Cooling during Cold-Water Near-Drowning, *J. Appl Physiol.* **86**, 265 – 272 (1999).
6. Brian H. Dennis, Robert C. Eberhart, George S. Dulikravich, and Steve W. Radons, Finite Element Simulation of Cooling of Realistic 3-d Human Head and Neck, *J. Biomechanical Engineering*, January (2004).
7. Matthew A. Neimark, Angelos-Aristeidis Konstas, Jae H. Choi, Andrew F. Laine, and John Pile-Spellman, Brain Cooling Maintenance with Cooling Cap Following Induction with Intracarotid Cold Saline Infusion: A Quantitative Model, *J.Theoretical Biology* **253**(2), 333 – 44 (2008).
8. Michael Christiansen, Nikolai Rakhilin, Anna Tarakanova, and Kevin Wong, *Modeling Brain Cooling Treatment Approved for Hypoxic-Ischemic Encephalopathy in Infants to Treat Stroke and Cardiac Arrest in Adult Patients*, Cornell University. Fall 2010.
9. B.A.Harris, P.J.D.Andrews, I.Marshal, T.M.Robinson, and G.D.Murray, Forced Convective Head Cooling Device Reduces Human Cross-Sctional Brain Temperature Measured by Magnetic Resonance: a Non-Randomized Healthy Volunteer Pilot Study, *British J.Anaesthesia* **100** (3), 365 – 72 (2008).
10. D.Fiala, K.J.Lomas, and M.A.Stohrer, Computer Model of Human Thermoregulation for a Wide Range of Environmental Conditions: the Passive System, *J. Appl. Physiol*. **87**(5): 1957 – 1972 (1985).
11. *COMSOL Multiphysics User's Guide*, COMSOLAB, 2010, 804 p.
12. A.D.Legostayev, *Finite Element Method, Synopsis* (Kyiv: KNUBA, 2004), 112 p.
13. S.C.Jiang, N.Ma, H.J.Li, and X.X.Zhang, Effects of Thermal Properties and Geometrical Dimensions on Skin Burn Injuries, *Burns* **28**, 713 – 117 (2002).

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