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2D/3D Heat Transport Maps of Biological Tissue in Therapeutic Hypothermia

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Abstract. Strokes are an acute neurological disorder resulting from blockage of blood supply to an area of the brain or cerebral hemorrhage. Strokes are a clinical syndrome produced by brain tissue damage following ischemic events. One effective method in combating the consequences of trauma is therapeutic hypothermia. Currently, there is an important direction in modern biotechnology and physiology associated with experimental and theoretical study of heat transfer processes in the body and its individual organs and tissues. In this brief study, we simulate the heat transport processes while performing therapeutic hypothermia by using the Heat Transfer Module of COMSOL MULTYPHYSICS™ software in view of improving the design of the device we built for hypothermia for therapeutic treatment.

Key-words: Hypothermia, Brain cooling, Bio heat transfer, Peltier effect.

1. Introduction

Various hardware and software solutions have been proposed in the last decades for increasing the degree of intelligence of medical equipment and procedures [4], [14], [15], [16], [19]. The evolution of devices for hypothermia for therapeutic treatment follows the same pattern [1], [3], [8]. Hypothermia is used because of its cooling effect on damaged areas of the patient's body, with its main purpose to reduce the risk of ischemic tissue injury. The hypothermic

procedure was studied by empirical ways, but further research and improvement of hypothermia for therapeutic treatment have enabled it to become an effective option in modern treatments and intensive care. Previous research has established four categories of hypothermia: moderate (32–35℃), mild (25–31℃), deep or prolonged (0–24℃) [1], [2], [11]. Mild hypothermia shows various neuro-protective effects and this property can be used to limit the extent of secondary brain damage [2]. Multiple animal studies have shown that the most effective temperature range for neuro-protection is between 32 and 35℃[3], [4]. Medical trials conducted on infants confirmed these results [5]. On the other side, prolonged hypothermia is associated with severe side effects, thus possibly negate potential benefits. Noninvasive methods of localized cooling may open new opportunities of elaborating fast and desired biological effect with minimum side effects. In this paper, we study induced hypothermia on human head, created by thermoelectric effect made by our own experimental setup made of four Peltier elements. Thermoelectric coolers (TECs) based on the Peltier effect are preferred because they have small thickness, low weight, lack of moving mechanisms, high precision, and safe operation [12]. Despite of their advantages, TEC Peltier cooling abilities show some dependence from the ambient temperature. This dependence can be reduced to minimum by applying an exact mathematical model to it [6], [13].

Besides neurological effects of hypothermia, this induced cooling influences also other conditions. For example, as stated in [8], hypothermia of the scalp tissue during chemotherapy treatment (scalp cooling) showed to reduce chemotherapy-induced hair loss.

2. Method

Using the software Comsol Multiphysics™ we simulated the multi-layered human head for bio heat transfer. The brain was assumed to be a hemisphere and was therefore modeled in a two dimensional axisymmetric plane, with symmetry along the y-axis. This allowed for fewer computations with similar results found in a three dimensional model. The model has four layers: the scalp, the bone, the gray matter and the white matter. The properties of these layers that were used as parameters in Comsol Multiphysics™ are presented in the table below.

3. Simulation Part

The last two of the four layers described are used to simulate the heat transfer through the brain. Peltier elements are modeled as constant temperature drop across the scalp region. These particular temperature drops serve to find out the temperature distribution across the human head.

For this simulation, we chose the cooling elements' temperature to be 0℃ 5℃, 20℃, 30℃ and the time interval to be a total of five hours. The figures

Table 1. Numerical values used in Comsol Multiphysics [9, 10, 11]

Constant Layer	Scalp	Bone	Gray Matter	White Matter
Density [kg/m^3]	1000	1500	1050	1050
Conductivity [W/m K]	0.34	1.16	0.5	0.5
Heat Capacity [J/kg K]	4000	2300	3700	3700
Perfusion Rate [m^3/s]	6.940E-08	8.564E-08	9.188E-06	4.410E-06
Volume [m^3]	2.082E-04	1.903E-04	6.563E-03	1.260E-03
Metabolic Heat Generation [W/m^3]	368.3	368.3	16700	4175
Thickness [m]	0.004	0.004	0.018	0.067

below show the temperature across the brain's surface after cooling elements (Peltier elements) are installed on the human head. Fig. 1 is for 0℃ cooling temperature and Fig. 2 is for 5℃ cooling temperature. The temperatures 0℃ and 5℃were chosen to obtain reference results for comparison with result from 20℃ and 30℃ and to test the simulation for such low temperatures, which in real life will not be used for safety reasons.

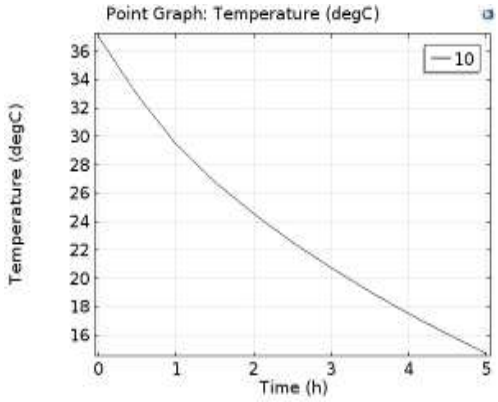

Fig. 1. Head cooling at 0℃ temperature on the cooling elements.

Figures 1 and 2 indicate that there is a drop in temperature across head?s surface, with the minimum at 16℃ for 0℃ Peltier temperature and respectively 18℃ for 5℃ Peltier temperature. The initial head's temperature was set to 37℃.

Next, we increased Peltier elements temperature to 20℃ and 30℃. These chosen temperatures are closer to the real temperature values used in such kind of cooling devices with the intent of not hurting the biological tissues.

After 5 hours of cooling, temperature on brain?s surface will be 27℃ for 20℃ on the cooling elements and 33℃ for 30℃ (Fig. 3 and Fig. 4).

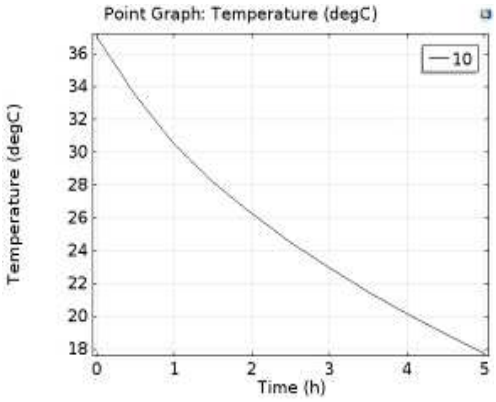

Fig. 2. Head cooling at 5°C temperature on the cooling elements.

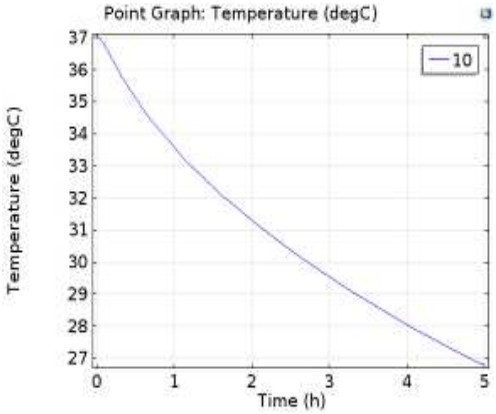

Fig. 3. Head cooling at 20°C temperature on the cooling elements.

Within each layer, the 2D-axisymmetric heat transfer equation was solved under transient conditions (equation (1)). This equation assumed no convection and a heat generation term, Q, to account for metabolic heat generation [17]. Equation (2) is the heat flux condition describing heat transfer from the scalp to the head [18].

$$\rho C_p \frac{\delta T}{\delta t} = k \frac{1}{r^2} \frac{\delta}{\delta r} \left(r^2 \frac{\delta T}{\delta r} \right) + \frac{\rho c \gamma (T_a - T)}{Vol} + Q. \tag{1}$$

$$\bar{n}(-k \nabla T) = h(T_{env} - T). \tag{2}$$

In equation (1), notations and their meaning follow those in the COMSOL module, namely ρ is the density of each layer, C_p is the heat capacity of each layer, k is the heat transfer of each layer, 8.37 W/(m^{2}C) for dry skin [4], and Q

is the metabolic heat generation in each layer (constant). Within the perfusion term, ρ is the blood density, c is the blood heat capacity, γ is the perfusion rate, T_a is the arterial blood temperature (constant 37℃), and Vol is the volume of each layer. The independent variables are time (t) and radius (r), and the dependent variable is temperature (T). T_{env} in equation (2) is the ambient temperature.

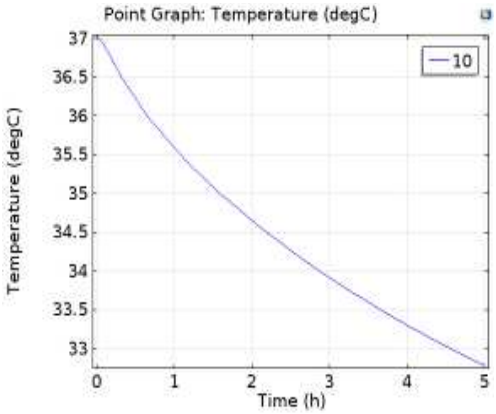

Fig. 4. Head cooling at 30℃ temperature on the cooling elements.

The boundary conditions implemented are listed below:

- axisymmetric about the vertical axis;
- constant temperature along the head surface ;
- continuity between each layer.

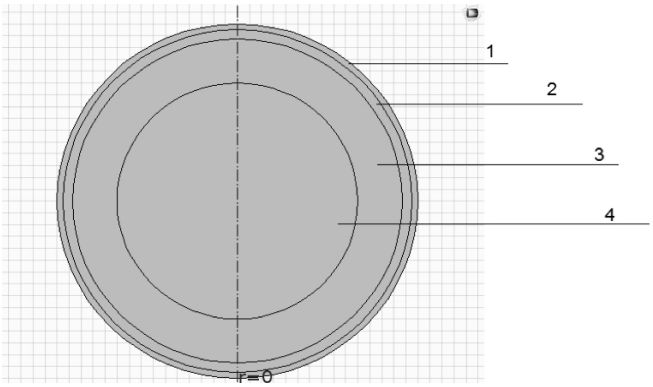

Fig. 5. Simplified model of the human head
with four layers (scalp, bone, grey and white matter).

Figure 5 shows the simplified multi layered model of the human brain and its temperature profile. Layer 1 is the scalp tissue, layer 2 is the bone structure and layer 3 and 4 are the brain itself made of the grey matter and white matter.

The models presented above are used in optimizing the control of the equipment shown in Fig. 6, which consists in several Peltier elements, their cooling system (with circulated water), a microcontroller-based system for the control of the Peltier temperature.

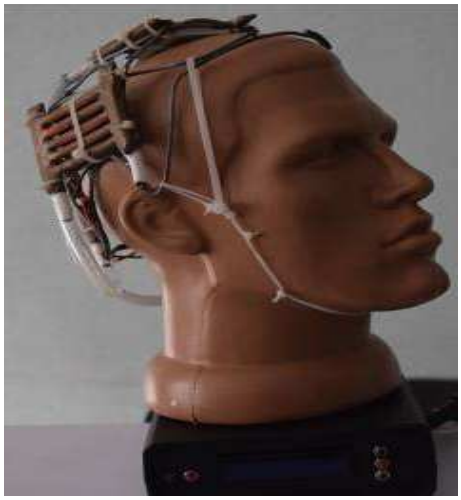

Fig. 6. Setup of the cooling device.

In the future, the simulation results will be compared with the measurements results during the equipment operation and the temperature control loop will be optimized. We also plan to introduce a simple predictive control, possibly as in [19]; the predictive control of the cooling may use an improved version of linear predictor as in [20].

4. Conclusions

In this paper, we simulated temperature distribution in a 'standard' human head after being exposed to cooling via Peltier elements. We studied heat transfer specifically in the brain because our experimental setup is designed in such a way that allows induced hypothermic cooling for patient's head only. By doing these simulations, we intended to find the temperature range of cooling which is safe from the medical point of view. As shown in Fig. 1 and Fig. 2, there is an effective drop in temperature from 37℃ to 18℃ in the core (the brain itself) and Fig. 3 and Fig. 4 are results for real life biomedical application, because temperatures of the cooling devices are more probably used for real treatment with induced hypothermia. Figures 7 and 8 show the 3D model of the human

head under cooling for 10 seconds and 60 seconds. The lower temperature region is where the Peltier elements are located on the patient's head.

This is a simplified model with idealistic boundary condition like constant cooling temperature and blood perfusion is neglected, yet this model can be used in medical application as a way to physically visualize the effects of induced hypothermia on an adult human being. This paper is a direct continuation of a previous paper published in [11], with the same topic, but includes a better simulation model; as a consequence, more exact results in terms of temperature cooling rate and heat distribution are given in this study.

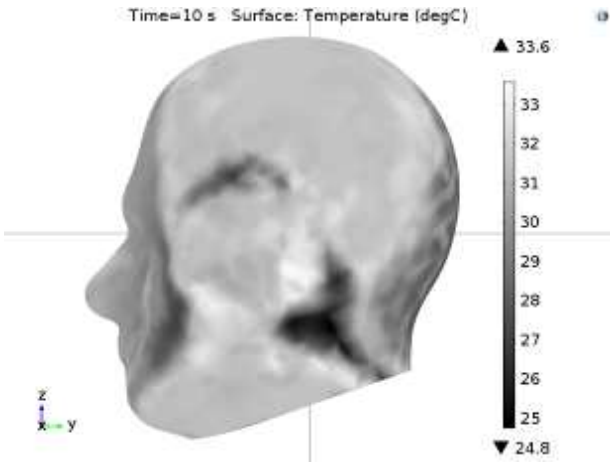

Fig. 7. Temperature distribution for 10 seconds of cooling.

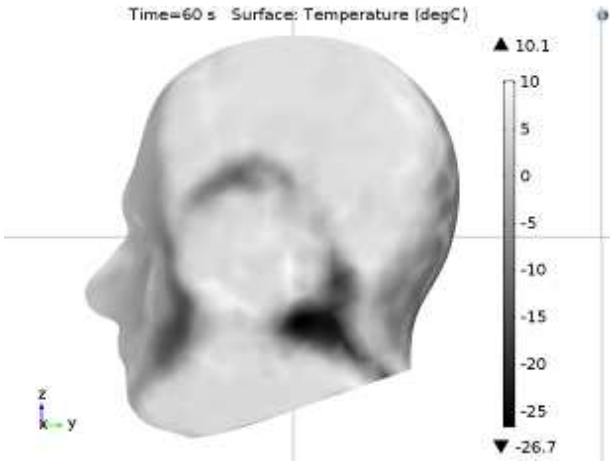

Fig. 8. Temperature distribution for 60 seconds of cooling.

All authors have read the submitted version of the paper. The authors' contributions: Cojocaru Victor and Sidorenko Anatol designed the experiment and the methodology; Vrabii Daniel conducted simulations in Comsol Multiphysics; Sidorenko Anatol analyzed data; Cojocaru Victor and Vrabii Daniel wrote the paper.

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