Simulation of temperature distribution in a brain using 3D graphic model

Satoru Honma, Hidetoshi Wakamatsu, Yutaka Takagi
Tokyo Medical and Dental University, Graduate School of Health Care Sciences,

Abstract: Hypothermia treatment needs to control brain temperature within an appropriate range of accuracy, considering the temperature change of the human body with the long time constant. Mathematical models have been used for the study of control capability of brain temperature or cooling capacity of the hypothermia units. In the past models, a hemisphere in a lumped parameter of a uniform temperature has been assumed as a simplified brain without considering the temperature distribution. In this study, a new model, which has the approximate shape and thermodynamic property of each organ of a head of human based on the MRI data, is proposed. The proposed model enables to simulate the temperature distribution in a brain with some biological parameters.
Keywords: Hypothermia , Temperature Distribution , Virtual Reality , 3D graphic , Mathematical Model

1. Introduction

It is important to keep accurate brain temperature for the better hypothermia treatment. Mathematical models are sometimes useful to inspect the temperature regulation of the hypothermia system, its control algorithm and so on(1). However, the conventional models had a simple representation without any consideration of precise distribution of brain temperature. That is, a hemisphere with a uniform temperature has been assumed as a simplified brain model using lumped parameters. Therefore, the difference of the temperature in the brain sites caused by changes of metabolism due to cellar damage does not reflect simulation result. Thus, it is hard to calculate the condition of the particular brain area from such a roughly described model, although medical staff is required to estimate the clinical condition. To solve the problems, authors have ever developed a new model, which represents the heat transfer among the region in the brain visualized by the different colors.(2) In this study, we introduced some biological parameters(3) to the new model to simulate the temperature distribution in a brain.

2. Classification of Brain tissue model

In our proposed model, the cephalic part of human is constructed by the groups of small nodes which present temperature distribution in a brain. The organs are fully filled with the same size nodes. Every node is placed on the apex of the tetrahedrons and interconnected continuously as shown by Fig.1. Hence, nodes mutually exchange heat with adjoining 12 nodes. From MRI data, cephalic part is assumed to consist of four parts such as skull, brain, eye balls and blood vessels. The gap of the organs is regarded to fill with the cerebrospinal fluid(CSF), and the space around the head is assumed to be filled with air. A blood vessel is introduced as a conceptual model, which is synthesized as the main vessels in the brain based on the anatomical knowledge. Hence, the present model consists of six parts. The temperature distribution of each part is simulated using the biological parameters given in Table 1. Here the cephalic part has 64,000 nodes, and each temperature distribution is displayed by 2D & 3D colored images.

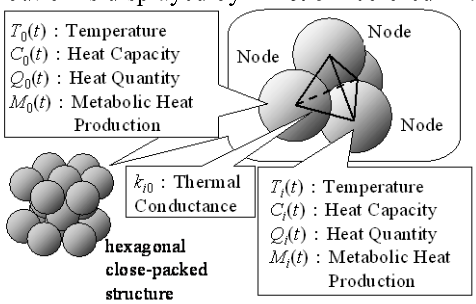

Fig.1 Outline of heat transfer model

Table 1 Number of nodes and parameters of each organ in a head

Property \ Organ	Brain	Skull	Eye ball	Blood vessel	CSF	Air
Number of Nodes	13093	24207	172	497	1805	24226
Temp. [deg C]	37.10	35.47	36.57	36.41	35.21	25.00
Metabolic Heat Production [W]	1.54×10^{-3}	0	2.86×10^{-5}	0	0	0
Thermal Conduc-tance [W/K]	3.17×10^{-3}	6.96×10^{-3}	4.83×10^{-3}	3.29×10^{-3}	3.54×10^{-3}	5.55×10^{-5}
Heat Capacity [J/K]	4.42×10^{-1}	2.74×10^{-1}	4.51×10^{-1}	4.38×10^{-1}	4.64×10^{-1}	1.36×10^{-4}

3. Outline of Heat transfer model

The heat exchange among nodes is calculated by the Fourier's law of heat conduction. In our model, convection heat is ignored. Metabolic heat production of a brain is described as the following:

$Q_0(t)$ is heat quantity of Node 0 at the time t which is described by Eq.(1) using heat capacity $C_0(t)$ and temperature $T_0(t)$.

$$Q_0(t) = C_0(t)T_0(t) \quad (1)$$

$\triangle T_{i0}(t)$ is difference of temperature between node 0 and adjoining node i (i=1-12), described by Eq.(2). Temperature $T_0(t+1)$ is described by Eq.(3) using the metabolic heat production $M_0(t)$, the thermal conductance k_{i0} between node 0 and node i.

Here, it is noted that the metabolic heat production of the skull, blood vessels, CSF and air is 0.

$$\Delta T_{i0}(t) = T_i(t) - T_0(t) \quad (2)$$

$$T(t+1) = T_0(t) + \left\{ \sum_{i=1}^{12} k_{i0}\Delta T_{i0}(t) + M_0(t) \right\} \Big/ C_0(t) \quad (3)$$

4. Outline of Blood vessel model

The left and right carotid arteries and the vertebral arteries are climbing up from the body, and merge into the circle of blood vessel at the base of the brain which is called the circulus arteriosus cerebri. The anterior cerebral artery arises from the point of the connection. The middle cerebral arteries arise from the connection of the carotid arteries, and go through around the middle of brain from left and right. The arteries in a brain branch off to many capillary blood vessels. The capillary blood vessels go through the brain, and are merged little by little into main veins. However, for the sake of making a simplified model, the arteries are assumed to be merged into the main veins directly. The anterior cerebral artery are connected to the superior sagittal sinus and the straight sinus, and the superior anastomotic veins arise from the superior sagittal sinus. The superior anastomotic veins and the middle cerebral arteries are connected to the jugular veins at the region of the hindbrain. The posterior cerebral arteries come from the circulus arteriosus cerebri and are connected to the jugular veins at the region of the hindbrain, too. A reticulation capillary blood vessels going through the whole in a brain arise from these major blood vessels. Blood go through these vessels. However it is impossible to model all the blood vessels in a brain because of its complexity. In this study, these major blood vessels are modeled with an average pattern. A node belonging to the blood vessel model sends the temperature data to the next node to represent the pseudo-blood-flow. Figure 2 shows the outline of our conceptual model.

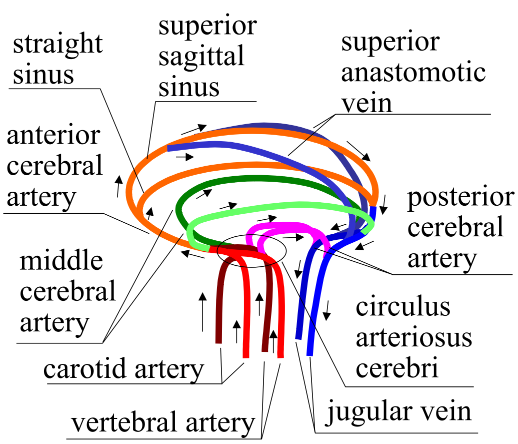

Fig.2 Outline of blood vessel model in a brain

5. Visualizing of the Temperature distribution in a brain

Figure 3 shows the images of the simulation based on the parameters of Table 1. The temperature of the nodes is represented by the different color, which corresponds to the range from 0 and 42 C. For example, the colors around 0 C is blue-tinged, and the colors around 42 C is red-tinged. However, the color out of the range from 0 to 42 degree is black. The result are visualized as 3D-objects and selected parts of a cephalic area or the sagittal section are displayed. It is also possible to regulate the angle of the model around x,y,z-axis. Thus, this model shows the temperature of a particular part of brain at any view angles intuitively to the medical staff. The simulation result with the biological parameters shows appropriate brain temperature. Hence, the proposed system enables to simulate the temperature distribution in a brain.

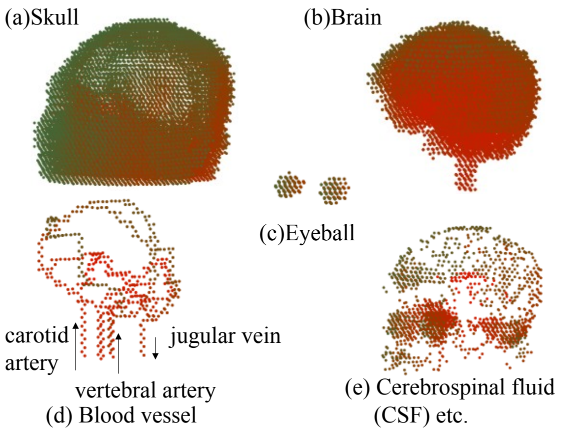

Fig.3 Classification of brain tissue model

Reference

(1) H.Wakamatsu, L.Gaohua:Adaptive control of brain temperature for brain hypothermia treatment using Stolwijk-Hardy model, Artif Life Robotics,8,pp.214-221(2004)

(2) S.Honma, , H.Wakamatsu : 3D visualization model of temperature distribution in a brain based on its structure , The 2011 Annual Meeting Record I.E.E. Japan (in press) (2011)(in Japanese)

(3) Irving P. Herman : Physics of the Human Body: Biological and Medical Physics, Biomedical Engineering, ,Springer-Verlag GmbH & CO.KG(2007)