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Analytical heat transfer model for targeted brain hypothermia

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ABSTRACT

This paper reports an analytic solution to the heat transfer in targeted brain hypothermia. This study simplifies brain as a two-layer structure consisting of scalp and brain matter and uses Pennes bioheat equation to describe the thermal process in the brain. We derived an analytical solution for temperature distribution using the method of Laplace transform. The solution is validated by a published rat experiment. Our study reveals that temperature distribution in the brain can be divided into two zones: a superficial zone and a core zone. The outside-scalp temperature significantly affects the temperature distribution in the superficial zone, but the temperature has little influence on the temperature in the core zone. In contrast, arterial blood perfusion can significantly affect the temperature of the core zone. Decreasing arterial blood temperature will cause a drastic decline in the core zone temperature, leading to a large decrease in the temperature gradient between the core zone and the head surface. Our theoretical results support that controlling the blood perfusion and temperature into the brain is the efficient approach to brain hypothermia.

1. Introduction

Mild hypothermia, as a method of cerebral protection, has received considerable scientific and clinical interest. Research has revealed that the main benefits of brain hypothermia are the reduction of tissue–oxygen demands [1] and the slow process of deleterious cellular biochemical mechanisms [2–4], including calcium shift [2], release of free radicals [3], and DNA damage [4]. Brain hypothermia is a condition under which the head is selectively cooled while the rest of the body is kept at a normal temperature. Targeted brain cooling protocols include easily implemented approaches, such as using a cooling helmet [5–7] or packing the head with ice to cool the surface of head, and invasive methods, such as nasopharyngeal cooling, direct catheter cooling, and intra-carotid flushing with a coolant [8,9].

Understanding temperature responses of gray and white matter to various brain cooling techniques is of paramount importance in evaluating cooling methods, standardizing guidelines for treatment and patient care, as well as developing effective and well-controlled approaches for cerebral hypothermia. Therefore, many theoretical [5–12] and animal experimental [13–16] studies have recently investigated the effects of different cooling methods or devices on the temperatures of gray and white matter. These studies demonstrated that surface cooling is a feasible approach to cooling gray matter. However, head-surface cooling provides more preferential cooling of the superficial areas in the brain than the deep regions [5,6,13,14,16]. Large temperature gradients occur in the brain tissue, and temperature variation strongly depends on the local blood perfusion rate and other factors. Invasive approaches can directly cool the deep brain regions [8] or effectively affect the arterial blood temperature and perfusion rate supplied to the brain tissues without changing the surface temperature of the brain [9,12]; however, invasive methods often require several technical skills and specific equipment, which may damage healthy tissues.

Theoretical studies of brain hypothermia have been attracted great attention because experimental methods are relatively difficult to perform. Many previous studies have modeled the heat transfer in the brain by using Pennes bioheat equation because of its simplicity, effectiveness, and ease of application; this equation has successfully predicted the temperature distributions in kidney cortexes [17], knees [18], canine prostates [19], feet [20], and brains [5–12]. Solving the Pennes bioheat equation is difficult because of its complicated form for the differential equation and the tissues. Various numerical methods [5–12,18,21–36], including finite difference method [5,6,8,9,21–24], finite volume method [10,18],

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Nomenclature

k_e	effective heat conductivity of skin layer (W m^{-1} K^{-1})
T_s	temperature outside skin layer (°C)
r	radial coordinate (mm)
c	the specific heat of brain matter (J kg^{-1} K^{-1})
ρ_b	the density of blood (kg m^{-3})
T_a	arterial blood temperature (°C)
Q_m	the rate of metabolic heat (W m^{-3})
R_2	thermal resistance of brain matter (m^2 K W^{-1})
d	thickness of skin layer (mm)
t	time (min)
ρ	the brain density (kg m^{-3})
k	the heat conductivity of brain matter (W m^{-1} K^{-1})
c_b	the specific heat of blood (J kg^{-1} K^{-1})
V_b	the blood perfusion rate of brain matter (s^{-1})
R_1	thermal resistance of skin layer (m^2 K W^{-1})
R	overall thermal resistance of head (m^2 K W^{-1})

finite element method [7,9,11,12,25,26], boundary element method [27–32], meshless method [33], control volume method [34] and numerical Green's approach [35], have been widely used to solve the Pennes bioheat equation. Among them, for solving the Pennes bioheat equation for the brain, finite difference method [5,6,8,9], finite volume method [10], and finite element method [7,9,11,12], have been used.

However, few studies have applied an analytical approach to brain hypothermia. Compared with analytical methods, numerical approaches present several inherent shortcomings despite their extensive applicability. For example, the temperatures at all mesh points must be simultaneously computed when only the temperatures at a single point are needed, which accurately increases the calculated quantity of computers and decreases the computational efficiency. Otherwise, analytical solutions provide a benchmark for numerical simulation. Therefore, deriving the temperature distribution in the brain matter when the head is cooling with a given device by using analytical method contributes to the development of brain hypothermia.

In the current study, we first propose a heat transfer analytical model for brain hypothermia based on brain structure and heat transfer mechanisms. We also derive an analytical solution to Pennes bioheat equation in one-dimensional spherical coordinate system (radial) by using the Laplace transform method. The accuracy of the present analytical model is assessed using the data of Wang's numerical model and corresponding rat experiment. All the thermal properties obtained from the literature are incorporated into the theoretical model to simulate the temperature distribution of the brain, including the duration time of brain hypothermia, blood flow rate of the brain matter, and head dimensions. Subsequently, we present a relevant graph to elucidate the temperature and heat flux distribution of the brain against time and radial distance, as well as discuss the characteristics of the temperature distribution. Then, since it is very important to analyze the parameters in bioheat studies [32,37–42], we evaluate the sensitivity of several important parameters, including arterial blood perfusion rate (V_b), temperature (T_a), and outside-skin temperature (T_s), which provides guidance for treatment protocols. Finally, several formulas are provided to calculate the temperature of the core zone, the interface between gray matter and scalp, and the thermal resistance of gray and white matter under the progress of hypothermia.

2. Mathematical modeling of brain-tissue heat transfer

A head can be approximately described as a spherical structure with scalp, bone, muscle, as well as brain gray and white matter (Fig. 1). Compared with gray and white matter, scalp, bone and muscle exhibit small dimensions and thermal capacities. As a first approximation, we neglected the heat capacities of scalp, bone, and muscle and treat them as a whole skin layer. Additionally, the rate of the heat flow through this layer per unit area is

$$\frac{k_e}{d}(T - T_s) \tag{1}$$

where k_e and d are the effective heat conductivity and thickness of this layer. T and T_s are the temperatures inside and outside this skin layer, respectively.

Besides the outside-skin temperature, T_s can also be designated with a cooling helmet temperature, a temperature for ice packing the head, and other surface-cooling medium temperatures. In these cases, an effective thermal resistance of heat conduction or convection will be added.

Cerebral tissues are treated as a continuum medium, and the effects of metabolism and blood perfusion are considered source terms that occur during the heat conduction equation. During cerebral hypothermia, heat is mainly transferred from the brain matter to the surface along the radial direction. Therefore, heat transfer in a brain can be approximated as the radial flow that the Pennes bioheat equation governs as follows:

$$\rho c\frac{\partial T}{\partial t} = \frac{k}{r^2}\frac{\partial}{\partial r}\left(r^2\frac{\partial T}{\partial r}\right) + \rho_b c_b V_b(T_a - T) + Q_m \tag{2}$$

where t and r denote time and radial coordinate; ρ, c, and k are density, specific heat, and heat conductivity of the brain, respectively; ρ_b and c_b are the density and specific heat of blood; T_a is the arterial blood temperature; and V_b is the blood perfusion rate of brain matter. We assume that V_b did not significantly change during the cooling periods; Q_m is the rate of metabolic heat generation per unit volume of tissue. Pennes bioheat equation is derived on the following assumptions: 1) The heat exchange between blood and tissue takes place in the capillary beds, the arterioles, and the venules draining it; 2) The flow of blood in the small capillaries is assumed to be isotropic; 3) Larger blood vessels play no role in the energy exchange between tissue and capillary blood; 4) Blood is

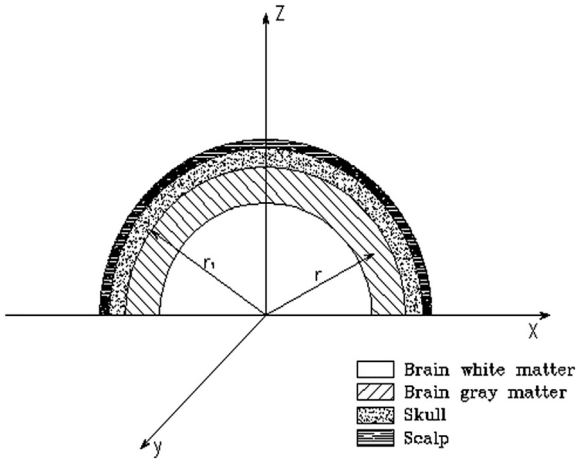

Fig. 1. Schematic of head regions.