DEVELOPMENT AND VALIDATION OF A MATHEMATICAL MODEL FOR HUMAN BRAIN COOLING IN COLD WATER

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INTRODUCTION

There have been several recent advances in our understanding of cold water near-drowning: a condition where victims survive cold water submersion for as long as *66* min with full or partial neurological recovery (1). The ability to withstand prolonged total submersion, especially in cold water, seems to be more evident in children. Explanation of this phenomenon relates to both of the following: the mechanisms for, and amounts of, body/brain cooling that occurs; and the mechanisms for the protective effects of this cooling.

It is commonly accepted that the cerebral protection is due to the decreased metabolic requirements of the cold brain tissues. However, it seems unlikely that survival from prolonged cold water submersion can be based solely on a decrease in cerebral metabolic requirements for oxygen *(2)*. Several recent studies, directed mainly toward protection of the brain during or following cerebral ischemic events, have demonstrated that even moderate brain cooling to between **35** and **33°C** provides substantial cerebral protection from 10 to 20 min of total cerebral ischemia in rats (3). An additional mechanism for cold protection from anoxia involves decreased glutamate and hydroxyl radical production. **As** irreversible brain damage usually occurs in humans within **4** to *6* min of anoxia, it is likely that the brain would have to cool at least 3°C within a maximum of ***5*** min to explain the intact survival of prolonged cold water submersion.

The rate of brain cooling basically depends on external heat exchange, internal heat exchange and local brain metabolic heat production. The aim of the present work is to develop a model to estimate the contributions of the different avenues of brain cooling during cold water submersion.

METHODS

Geometrical Representation

The head is represented simplistically by a hemisphere consisting of the brain and uniformly thick layers of bone and soft surface tissue. Boundary 1 represents the soft tissues (i.e., fat, muscles and skin) and bone layer of the spherical skull surface where heat transfer to the surrounding cold water occurs. The **soft** tissue and bone layers at the basal lower flat surface of the brain represent Boundary 2.

Mathematical Model

The assumed hemispherical geometry of the head and its uniformly thick outer boundaries allow us to express the energy balance in the two-dimensional **(2-D)** spherical coordinate system as:

$$\frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2\frac{\partial T}{\partial r}\right)+\frac{1}{r^2 \sin\theta}\frac{\partial}{\partial\theta}\left(\sin\theta\frac{\partial T}{\partial\theta}\right)+\frac{1}{\lambda}Q(\rho c)_{blood}(T_b-T)+\frac{1}{\lambda}M=\frac{(\rho c)_{tissue}}{\lambda}\frac{\partial T}{\partial\tau}$$

where T is temperature ("C), l is heat conductivity $(W \cdot m^{-1} \cdot {}^{\circ}C^{-1})$, M is metabolic heat production $(W \cdot m^{-1})$, Q is blood flow to brain $[m^{-1} \cdot s^{-1} \cdot m^{-1}(tissue)]$, pc is heat capacity $(KJ \cdot m^{-1} \cdot {}^{\circ}C^{-1})$, T_b is carotid blood temperature ("C), and **is** time (s). Arterial blood flow and temperature will vary with submersion time (defined further below).

Assumptions for Submersion

Circulation. Blood circulation eventually arrests during submersion. Fainer et al. (4) studied 160 mongrel dogs during fresh water drowning and observed that blood pressure started to fall precipitously after a mean of 130 s and reached zero after an average of 262 s. In the present model, it is assumed that blood flow to the brain is normal within the first 2 min and then decreases linearly to zero in the next minute.

Brain Metabolism. The metabolic heat production is also related to the cerebral blood flow. During circulatory arrest, the metabolic rate decreases proportionally with the decrease in cerebral blood flow. Therefore, it **is** assumed that the metabolic rate changes according to Q10 during the first **2 min** but is then reduced to zero over the next 1 min while the blood flow decreases to zero.

Ventilation **of** Water. Two pathways must be considered to estimate the effects of ventilation of water on brain cooling: direct conductive cooling through the airway at Boundary 2 and indirect circulatory cooling via the lungs.

Conductive Cooling. If water is breathed during submersion, some water will always enter the nasal cavities. This will enhance conductive heat transfer from the brain to this water at Boundary 2.

Circulatory **Cooling.** When water is breathed during submersion, the lungs act as a heat exchanger where the pulmonary blood is cooled by the water entering the distal airways. This will result in a significant decrease of systemic arterial blood temperature, causing core, as well as brain, cooling. **This** effect is taken into account by the changing T_b. **Com** et al. (5) showed that dogs breathed water for several minutes during submersion in 4°C water. Under this condition, carotid artery blood temperature decreased exponentially by **8°C** within **5** min. It was assumed that the results from the canine model were applicable to humans under similar conditions.

Simulation Conditions

The ambient water temperature is assumed to be **2°C** for all cases. Condition 1: Effect of conductive cooling at Boundary 1, Boundary 2 insulated, without circulation or ventilation. Condition 2: Effect of conductive cooling at Boundary 1 and Boundary 2 (without circulation). Condition 3: Effect of conductive cooling at Boundary 1 and circulatory cooling via the lung (Boundary 2 insulated, circulation intact). Condition 4: Effect of conductive cooling of Boundary 1, conductive cooling of Boundary 2 and circulatory cooling via the lung (circulation intact). Condition 5: Effects of the head size.

RESULTS AND DISCUSSION

The data are presented either as an average brain temperature over time or the 2-D temperature distributions within the brain hemisphere at different times.

Average Brain Temperature

The pre-cooling average temperature is 37.0°C and temperatures after 5 min submersion are as follows: 36.7°C for Condition 1, 35.1°C for Condition 2, 33.4°C for Condition 3, 32.0°C for Condition 4, 36.3°C for Condition 5 (Condition 1 with child's head size) and 33.8°C for Condition 5 (Condition 2 with child's head size). The results of Condition 1 indicate that conductive cooling of the brain through Boundary 1 is slow. This can be explained by the low heat conductivity of human tissue. The results of Condition 2 show that added conductive cooling through Boundary 2 enhances brain cooling, but it is still too slow to meet the required brain cooling of 3°C within 5 min. In fact, the conductive cooling through Boundary 2 would be less, because the actual surface of the nasopharynx is much smaller.

Two-Dimension Temperature Distribution

Results were calculated at the pre-cooling baseline condition, after 5 min with conductive cooling only at Boundary 1 (Condition 1), and after conductive cooling at both Boundaries 1 and 2 (Condition 2). After 5 min of cooling, the temperature of the brain surface is reduced by conductive cooling through Boundary 1, but the deep part of the brain is still not cooled. In Condition 2, the temperature at Boundary 2 is also reduced by conductive cooling; however, the deep part of the brain is still not yet influenced.

Condition 4 accurately depicts the situation when water is respired, as the additional affect of conductive heat transfer with the cold water in the upper airways is included. The large and continual decrease in brain temperature is qualitatively comparable to the decrease in carotid artery temperature in the study of Conn et al. *(5)*.

CONCLUSIONS

The simulation indicates that conductive heat loss either through the skull surface or through the upper airways is minimal. However, the ventilation of cold water has the potential to provide substantial brain cooling through circulatory cooling. When brain blood flow ceases, there are big differences in temperature between the brain surface and the deep brains. Head size is an important factor as a small, child-size head will conductively cool faster than a larger adult head. While it seems that water breathing is required for rapid "whole" brain cooling, it is also possible that conductive cooling may provide some advantage by cooling the brain cortex peripherally and the brain stem centrally via the upper airway.

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