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HUMAN HEAD COOLING: MECHANISMS AND MODELING

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INTRODUCTION

The human head is an important site for heat exchange in both hot and cold environments. Under hyperthermic conditions, a liquid-cooled cap *can* slow the rise of core temperature and improve subjective comfort (1). Many authors interpret head cooling as a component of overall body heat balance with strong sensory effects (1,2), but others invoke "selective brain cooling" (SBC) (3,4). Resolution of this disagreement has implications for the design of environmental control systems, cooling garments, and head enclosures for persons working under hostile conditions. In addition, SBC could provide a useful tool for clinical medicine and has recently been proposed as a key to evolution of the large human cerebral cortex *(5).*

Mammals with SBC generally have one or more of the following characteristics: Panting respirations in heat: elaborate nasal structures or large ears to increase heat loss from the head; specialized vascular sites for heat exchange between the arterial supply to the brain and cooled venous blood (6). Humans have none of these characteristics, but it has been asserted that SBC is nevertheless provided by blood from the face and *scalp* which is said to drain inward through the skull, removing heat from the brain surface and/or cooling the blood supply to the brain (4). Since brain temperature (Tbr) cannot be directly measured in humans, SBC has been inferred from behavioral measurements or from decreases in the temperature of the tympanic membrane (Tty) (3,4). However, there are compelling reasons for doubting that Tty represents Tbr during thermal stress (2).

METHODS

Review of the literature supporting SBC in humans demonstrates a lack of quantitative analysis. We approached this problem by modeling steady-state heat exchange as it affects the human head, using techniques developed by Wissler in modeling whole-body thermoregulation (7). The head was modeled in as a hemisphere containing four layers which represent the **skin, skull,** superficial cortex and white matter. Established values from the literature were used to define for each layer its thickness, thermal conductivity, metabolic heat production, and perfusion rate. Input variables include central arterial temperature (Tar), *dry* bulb temperature (Tdb), *air* movement and evaporative cooling; the base of the hemisphere was assumed to be *at* Tar. The model assumes that blood and tissue come to thermal equilibrium in the capillary bed and that there is little heat exchange with larger vessels. The finite-difference method was used to calculate tissue temperatures.

As a preliminary project, we modeled heat exchange at the two sites which are said to allow arteriovenous heat exchange for SBC in humans: 1) The cavernous sinus, where a 2-cm section of the common carotid artery passes through a pool of venous blood; 2) The juxtaposition of the carotid *artery* and jugular vein for about 20 cm in the neck. Heat exchange in these areas was modeled using standard mathematical techniques (NTU-effectiveness method) (8) and assumptions favoring heat transfer.

RESULTS

Modeling shows that only negligible amounts of heat can be removed from the carotid artery in the cavernous sinus due to its short length, while countercurrent exchange in the neck is limited by the small area available for heat transfer between parallel vessels of large size. Considered together, the two arteriovenous mechanisms could provide no meaningful cooling of the arterial supply to the brain. Specifically, given an initial arteriovenous temperature difference of 3.0 °C, blood in the carotid artery would be cooled by 0.03 "C. The head model therefore was based on the assumption that the temperature of the blood supply to the brain is at Tar.

The head model was run for the following range of conditions: Tar = 37 and 40 °C, Tdb = 10-40 °C, *air* movement = 0-30 $m \cdot s^{-1}$, and sweat evaporation rates = 0-500 $g \cdot m^{-2} \cdot h^{-1}$. For an arterial temperature of 37 °C, brain temperatures remained at or below 37.4 °C with even the hottest environmental conditions (Tdb = 40 °C, high wind, noevaporation). Introduction of evaporative cooling slightly reduced the temperature of the superficial cortex, but failed to affect deep brain temperature. When Tar was elevated to 40 °C to represent systemic hyperthermia, brain temperatures again approximated arterial temperature even in the hottest environment. On the other hand, cold conditions (Tar = 37 °C, Tdb = 10 °C, wind = 3 $m \cdot s^{-1}$), reduced superficial cortical temperame to 36.3 °C while deep Tbr remained slightly above Tar at 37.1 °C.

CONCLUSIONS

Modeling confirms that the brain thermoregulates much as do other metabolically active organs which are subject to circulatory cooling: The blood supply which supports a given level of oxygen uptake is also adequate to remove the major metabolic byproducts, CO_2 and heat. The model indicates that in humans (and other primates) Tbr is largely determined by Tar and only slightly exceeds the latter; brain temperature is not much affected by environmental heat load. This fits with the classical concept that systemic thermoregulation is governed in part by hypothalamic temperature, which closely follows Tar.

We conclude that no special mechanism is needed to protect the brain from overheating under physiological conditions. The possibility of meaningful SBC in humans is minimized due to the limited surface area available for evaporative cooling and the absence of specialized structures for arteriovenous thermal exchange. Furthermore, if SBC were vital to human thermoregulation, then workers should not be able to tolerate conditions which prevent head cooling and/or impose radiant heating to the face as is common in certain industrial settings. We believe that the findings reported in the literature as evidence for SBC can be explained in terms of local cooling effects, systemic heat exchange, and sensory inputs (9); to invoke SBC thus violates Occam's razor by introducing unnecessary complications.

Although the head represents less than 10% of body surface area, a variety of studies indicate the importance of face and scalp temperature for human comfort. This may have important implications for performance of complex tasks, especially in multistress industrial and military environments. In addition, heat loss from the head under cold conditions represents a significant thermoregulatory challenge which we shall address with further modeling of superficial tissues and their circulation.

REFERENCES

1. Nunneley SA, Reader DC, Maldonado RJ. 1983. Head temperature effects on physiology, comfort and performance. Aviat. Space Environ. Med. 53:623-628.

2. Brengelmann GL. 1987. Dilemma of body temperature measurement.. In: Shiraki K, Yousef MK, ed. Man in Stressful Environments: Thermal and Work Physiology. Springfield, IL; Thomas: 5-22.

3. Brinnel H. Nagasaki T, Cabanac M. 1987. Enhanced brain protection during passive hyperthermia in humans. Eur. J. Appl. Physiol. 56540-545.

4. Cabanac M, Caputa M. 1979. Natural selective cooling of the human brain: Evidence of its Occurrence and magnitude. J. Physiol. (London). 286:255-264.

5. Falk D. 1990. Brain evolution in ***Homo*** : The "radiator" theory. Beh. Brain Sci. 13:333-344.

6. Baker MA. 1982. Brain cooling in endotherms in heat and exercise. Annu. Rev. Physiol. 44: 85-96.

7. Wissler EH. 1985. Mathematical simulation of human thermal behavior using whole-body models. In: Shiner A, Eberhart RC, ed. Heat Transfer in Biology and Medicine. New York Plenum Press, 325-373.

8. Incropera FP, DeWitt DP. 1990. Fundamentals of Heat and Mass Tranasfer (Third Edition). New York Wiley & Sons.

9. Deklunder G, Dauzat M, Lecroart J-L, Hauser J-J, Houdas Y. 1991. Influence of ventilation of the face on thermoregulation in man during hyper- and hypothermia. Eur. J. Appl. Physiol. 62342-348.