HEAT TRANSFER IN THE HUMAN HEAD: RESULTS OF MODELING

I. Yermakova and N. Maslovskaya

Institute of Cybernetics, Academy of Sciences, University of Civil Aviation
Kiev, Ukraine

INTRODUCTION

One of the important problems related to thermal processes in the human head is clarification of the process of brain temperature regulation. The question concerns how human brain temperature is held practically constant in hot environments and during intensive physical exercises when hyperthermia is a real danger. Cabanac supports the existence of selective brain cooling (SBC) in humans (1,2). Brengelman reports that the exceptional capability of humans to dissipate heat from the entire **skin** surface is the result of brain cooling **(3).** We propose that one possible way to research this is to compute the effect of different body heat transfer mechanisms on human brain temperature.

The objective of this study was to perform a quantitative assessment of the dependence of brain temperature on heat transfer via blood flow and respiratory evaporation in neutral and hot environments.

MATERIALS AND METHODS

Quantitative analyses were performed by computer modeling. The model is comprised of a system of differential equations related to whole body heat processes of passive and active systems. Using a traditional structure, the human body in this model is represented as layered cylinders corresponding to human organs or body parts **(4).** The model describes heat processes in the human head, including brain metabolic heat production, heat transfer by blood, heat conduction to head skin, respiratory evaporation, evaporation from head skin and heat exchange with the environment by convection and radiation. Equations 1 and 2 describe the thermal processes in the head: brain and skin.

$$c \times m_{br} \times \partial T_{br} / \partial t = M_{br} - K \times (T_{br} - T_s) - W_{br} \times kb \times p_b \times c_b \times (T_{br} - T_b) - E_{res} \qquad (1)$$

$$c \times m_s \times \partial T_s / \partial t = M_s + K \times (T_{br} - T_s) - w_s \times kb \times p_b \times c_b \times (T_s - T_b) + h_c \times A_s (T_s - T_e) - h_r \times A_s (T_s - T_e) - E_{res} \qquad (2)$$

where T = temperature, M = metabolic rate, E = respiratory evaporation, K = conduction to head skin, w =blood flow, kb = coefficient of convective heat exchange between blood flow and tissue, r = density, m = mass, c = heat capacity; subscripts: br = brain, b = blood, s = head skin.

Table 1. Initial data of model. Air temperature 29°C, velocity 6 $\text{cm}\cdot\text{min}^{-1}$, relative humidity 20%, clothing 0.3 clo.

Head	M (kg)	A (m^2)	M ($\text{kcal}\cdot\text{h}^{-1}$)	W ($\text{L}\cdot\text{h}^{-1}$)	K ($\text{kcal}\cdot\text{h}^{-1}\cdot{}^\circ\text{C}^{-1}$)	K_b	E_{res} ($\text{kcal}\cdot\text{h}^{-1}$)
Brain	4.74	-	12.42	48	2.63	1	4.5
Skin	0.82	0.15	0.12	1.6		1	4.5

Initial data of equation 1 are given in Table 1.

RESULTS AND DISCUSSION

1. Modeling of passive system. The significance of heat transfer via blood flow and evaporation from the upper respiratory tract on brain temperature can be evaluated with an open-loop thermal system. This permits studying the effects of step-changes of heat flow via blood and respiratory evaporation on brain temperature. Modeling was performed for neutral and hot air environments. The results of modeling a twofold increase in respiratory evaporation or in heat transfer by blood flow are given in Table 2. It can be seen that brain temperature depends on both heat transfer by brain blood flow as well as on evaporation from the upper respiratory airways; however, their influences on brain temperature are different in neutral and hot environments. In a neutral environment their effects are practically equal. Brain temperature cooled by -0.26°C from increased evaporation and by -0.32°C from increased heat flow via blood. Blood temperature was decreased by -0.16°C and -0.05°C, respectively. In a hot environment it is evident that changes in respiratory evaporation cannot compensate the initial rise of brain temperature in a passive system from 36.74°C to 38.94°C. The effect of an increase in respiratory evaporation on brain temperature was -0.29°C but only -0.10°C due to increased heat transfer via blood flow.

Table 2. Brain and blood temperatures' in neutral and hot environments after a twofold increase in respiratory evaporation and heat flow via blood

	Initial Temperature	With E= 10 ($\text{kcal}\cdot\text{h}^{-1}$)	With $K_b = 2$
		T_A = 29°C	
Brain	36.74	36.48	36.42
Blood	36.65	36.49	36.60
		T_A = 40°C	
Brain	38.94	38.65	38.84
Blood	38.87	38.68	38.80

'Temperatures in °C.

Blood temperature was decreased by -0.19°C with the rise of evaporation and by -0.07°C with the increased blood flow heat transfer. Thus it appears that brain temperature cannot be maintained stable by high respiratory evaporation in a hot environment.

2. Modeling of brain temperature regulation in hot environments in a closed-loop system. To research a more realistic situation regarding brain temperature, we simulated the dynamics of a closed-loop system in a hot environment, The dynamics of thermoregulation after a step-change of air temperature from 29°C to 40°C are shown in Figure 1. In these conditions, skin vasodilatation and sweating take place. It can be seen that at steady-state the final brain temperature was 36.83°C; i.e., it increased by only 0.09°C from its initial 36.74°C. It is important to notice that cooling of the brain was begun only after switching on skin evaporation (see Figure 1). Blood temperature was regulated to 36.79°C from an initial 36.65°C; i.e., it increased only by 0.14°C. Thermoregulatory responses were an increase in skin blood flow and evaporation from the body surface. In steady-state their values of 43 L·h and 120 kcal·h, respectively, provided temperature homeostasis.

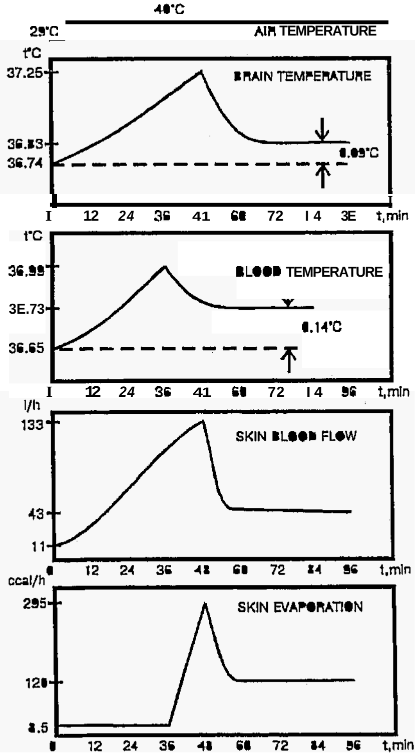

Figure 1. Dynamics of thermoregulation in hot environment.

Further analyses involving blood temperature should be done, as it is the key parameter in brain temperature regulation. Namely, this parameter exerts a cooling effect on brain temperature through an increase in heat removal by blood flow. At first, blood temperature is reduced through the increased blood flow to the skin surface, where sweat evaporation follows (Figure 1). Then, heat removal by blood flow is further increased and brain temperature is controlled. Heat transfer by blood flow, in distinction from that due to respiratory evaporation, is constantly changed following a change in blood temperature. It was shown in the open-loop system that if there is no blood cooling, there is no cooling of the brain; in a regulatory system, there is **a** condition of blood cooling that provides brain cooling.

CONCLUSIONS

The predominant regulatory mechanism of brain cooling is heat removal by blood flow. In a hot environment the thermoregulatory system increases the delivery of blood to the skin where intensive evaporation **of** sweat occurs, resulting in blood cooling. This facilitates the transfer of heat by blood flow in the brain. Respiratory evaporation is a factor in thermoregulation and its value does affect brain temperature. However, its influence is felt only if arterial blood temperature is maintained through skin vasodilatation and sweating.

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