SBC2013-14398

THEORETICAL PREDICTIONS OF BODY TISSUE AND BLOOD TEMPERATURE DURING COLD WATER IMMERSION USING A WHOLE BODY MODEL

Anup K Paul[1], Swarup A Zachariah[1], Liang Zhu[2], Rupak K Banerjee[1]

[1]School of Dynamic Systems,
Mechanical Engineering Program,
University of Cincinnati,
Cincinnati, Ohio 45221
United States

[2]Department of Mechanical Engineering,
University of Maryland Baltimore County,
Baltimore, Maryland 21250
United States

ABSTRACT

Understanding the thermal response of the human body under various environmental and thermal stress conditions is of growing importance. Calculation of the core body temperature and the survivability of the body during immersion in cold water require detailed modeling of both the body tissue and the time-dependent blood temperature. Predicting body temperature changes under cold stress conditions is considered challenging since factors like thickness of the skin and blood perfusion within the skin layer become influential. Hence, the aim of this research was to demonstrate the capability of a recently developed whole body heat transfer model that simulates the tissue-blood interaction to predict the cooling of the body during immersion in cold water. It was shown that computed drop in core temperature agrees within 0.57 °C of the results calculated using a detailed network model. The predicted survival time in 0 °C water was less than an hour whereas in 18.5 °C water, the body attained a relatively stable core temperature of 34 °C in 2.5 hours.

INTRODUCTION OF THE WHOLE BODY MODEL

In this study, the previously developed whole body model that simulates tissue-blood thermal interaction [1] was used to compute the thermal response of the body under cold temperature stress. The whole body model consists of two components: the Pennes bioheat equation to simulate the temperature distribution in the body (T_t), and an energy balance equation to calculate the change in blood temperature (T_{blood}) during a process. The Pennes equation is defined as

$$\rho c \frac{dT_t}{dt} = k_t \nabla^2 T_t + q_m + (\rho c)_{blood} \omega (T_{blood} - T_t) \qquad (1)$$

where ω is the blood perfusion. Note that in Pennes equation T_{blood} is a known input parameter. During cold water immersion, it is expected that T_{blood} will continuously decrease. In this study, an energy balance equation was derived to compute the change in blood temperature, where the body blood is considered as a lumped system [1]. The governing equation for T_{blood} was written as

$$(\rho c V)_{blood} \frac{dT_{blood}}{dt} = -(\rho c \omega_{avg})_{tissue} V_{body}(T_{blood} - T_{wt}) \quad (2)$$

where ω_{avg} is average blood perfusion and T_{wt} is the weighted average tissue temperature. As shown in equation 2, T_{blood} will decrease when T_{wt} is less than T_{blood}. During cold water immersion, the decrease in T_{wt} leads to loss of heat from the blood during its circulation. Since both equations are coupled, they are solved simultaneously.
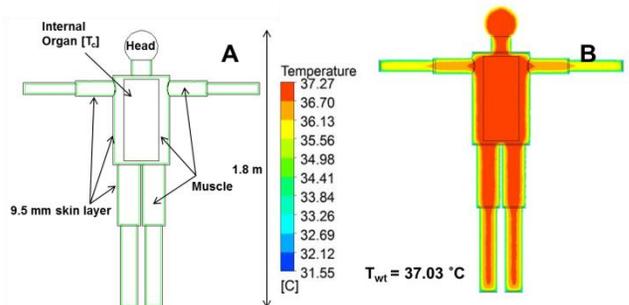

Figure 1: Geometry of realistic human model (A) and initial temperature field in 25 °C air (B).

METHODS

Geometry. A realistic human body geometry (Fig 1A) was developed and it consisted of limbs, torso, neck, head, and skin. The human model was 1.8 m tall, weighing 80 kg and had a calculated

body surface area (BSA) of 2 m^2 [1]. The skin layer was 9.5 mm thick [3].

Physical and Physiological Parameters. The physical and physiological parameters (Table 1) of the muscle, internal organs and head were unchanged during cold water immersion. There was no blood perfusion and heat generation in the skin layer during immersion thereby simulating vasoconstriction. The average blood perfusion was calculated from a cardiac output of 5.4 liter/min and the average metabolic rate was based on a food consumption of 2000 kcal/day.

Table 1: Physical and Physiological Parameters

	Thermal conductivity (W/m°C)	Density (kg/m^3)	Specific heat (J/kg°C)	Blood Perfusion (1/s)	Metabolic Heat Generation (W/m^3)
Muscle	0.5	1060	3800	0.005	535.5
Skin	0.3	1060	2802	0.005^a	535.5^a
Head	0.5	1060	3800	0.00833	9225
Internal Organs	0.5	1060	3800	0.001266	1401.5

^{a} for steady state solution in 25°C air

The total blood volume in the body was 5 liters and the physical properties of blood were assumed to be the same as muscle. During cold water immersion, the additional metabolic heat generation due to shivering was modeled in the muscle and organ regions using the Tikuisis-Giesbrecht model [2]. This model relates the shivering metabolism per unit BSA (M_s) to the change in average skin temperature (T_s) and core temperature (T_c).

$$M_s = 32.5(36 - T_c) + 6.6(33 - T_s) - 0.132(33 - T_s)^2$$

where T_c was defined as the average temperature of the internal organs (Fig 1A) in this study.

Boundary and Initial Conditions. The heat transfer from the body to the environment by evaporation, convection and radiation was represented by an overall heat transfer coefficient (h). In ambient conditions (25 °C air), h was determined to be 10 W/m^2-°C. This value of h was chosen such that T_{wt} is equal to the initial blood temperature of 37 °C. For water immersion, h was calculated to be 139 W/m^2-°C from energy balance. Immersion of the human body model up to the neck in 18.5°C, 10°C, and 0°C water was analyzed.

Numerical Method. The whole body model was solved using a combination of subroutines and the finite volume solver Ansys Fluent (v 13.0). An implicit scheme was followed in solving the governing equation for the blood temperature [1]. A steady state temperature field of the human body in 25 °C air was obtained as the initial condition (Fig 1B). Immersion in cold water was simulated by changing h and the external temperature to the representative values. The transient response of the body and blood temperature was solved for each case.

RESULTS

The initial temperature distribution in the body (Fig 1B) ranges from 31.55°C at the extremities to 37.27 °C in the brain. The reduction of skin blood flow in cold environments results in high thermal gradients near the skin. Hence, it was necessary to explicitly model the skin layer for an accurate simulation of human thermoregulation during cold water immersion. Figure 2 shows the change in core temperature (T_c) for the three water temperatures analyzed. The computed drop in T_c for immersion in 18.5 °C water agrees relatively well with that by Wissler's whole body network model. [3]. The heat loss was more rapid at lower water temperatures.

In 18.5 °C water, the body is able to establish a relatively stable T_c of 34 °C in 2.5 hours. Although the human body is able to slow the

cooling rate by shivering, it can be limited by the possibility of shivering fatigue when exposed to very cold environments for extended periods [2, 3]. The body enters mild hypothermia at 35 °C T_c and the critical core temperature for survival typically ranges from 28 °C to 34 °C [2].
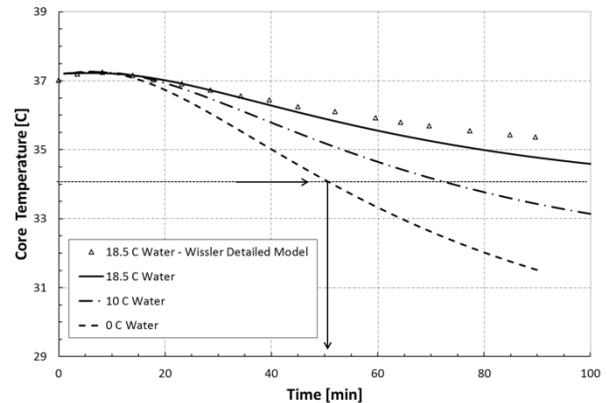

Figure 2. Computed core temperatures for a realistic human body model during immersion in cold water.

Figure 3 shows survival times predicted by the theoretical model used in this study. The survival times were calculated for a 2 °C and a 3 °C drop in T_c. For immersion in 0 °C water, the survival time computed was 50 minutes based on a critical temperature of 34 °C. Similarly for immersion in 18.5 °C water, the survival time varied between 1 to 2 hours based on a critical temperature of 35 °C or 34 °C.
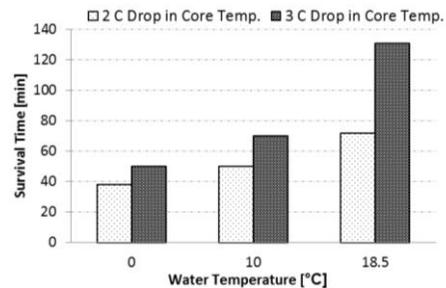

Figure 3. Cold water survival times predicted by theoretical tissue-blood interaction model with shivering.

CONCLUSION

The capability of the relatively simple whole body model to predict survival times during cold water immersion was demonstrated in this study. The model predicted a survival time of 50 minutes in 0 °C water and a survival time of 1 to 2 hours in 18.5°C water. It was necessary to include the skin layer detail to the body geometry due to its importance in thermoregulation under cold stress conditions.

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