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SAFE DURATION OF A PERSON SOAKING INSIDE A HOT TUB: THEORETICAL PREDICTION OF TEMPERATURE ELEVATIONS IN HUMAN BODIES USING A WHOLE BODY HEAT TRANSFER MODEL

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INTRODUCTION

Soaking in hot tubs has become a popular relaxation activity during all seasons. Unfortunately, hot tub related emergency visits increase in recent years. Based on a New York Times article, approximately more than 6000 emergency visits in 2007 are related to hot tube injury. Although most of the injuries were due to slips or falls, still more than 10% of those visits were heat stroke related. People often mistakenly assume a sense of safety since the head is typically not soaking inside the hot water. Understanding how high the body temperature especially the brain temperature will rise is crucial to educate the public to prevent heat stroke from happening when using hot tubs.[1]

In this study, we first develop a whole body model based on measurements of a human body, with realistic boundary conditions incorporated before and after a person jumps into a hot tub. For the transient heat transfer simulation, the initial condition is the established steady state temperature field of the human body with appropriate clothing layer to ensure thermal equilibrium of the body with its surroundings. Once the person is inside a hot tub, the Pennes bioheat equation[2] is used to simulate the transient temperature elevations of the body, and the rising of the arterial blood temperature is solved by an energy balance equation modeling thermal exchange between body tissue and the blood in the body.[3] The safe duration of soaking in hot tubs is then determined as affected by the hot tub water temperatures.

METHODS

A physical whole body model based on realistic measurements of a human body was generated. As shown in Figure 1, the body (81 kg, 1.82 m tall) consists of three components: the hemispherical brain, the rectangular column of the internal organ, and the muscle for the rest of the body. Each component has its own thermal and physiological properties. The Pennes bioheat equation[2] is used to model the transient temperature field of the body as

$$\rho_t c_t \frac{\partial T_t}{\partial t} = k_t \nabla^2 T_t + \omega_t \rho_b c_b (T_b(t) - T_t) + Q'''_{met,t} \qquad (1)$$

where ρ is density, c is specific heat, k is thermal conductivity, ω is local blood perfusion rate, and Q'''_{met} is volumetric heat generations rate. Initially, the body is exposed to an ambient environment, and the thermal resistances due to clothing layers and convection/radiation with the air are lumped as an overall heat transfer coefficient U_{air}. Once the body is soaking inside a hot tub with water, the overall heat transfer coefficient is same for the head surface, however, a new overall heat transfer coefficient U_{water} is calculated based on free convection in water. The boundary condition can be written as

$$-k_t \frac{\partial T_t}{\partial n}\bigg|_{surface} = U_{air,or,water}(T_t - T_{air,or,water}) \qquad (2)$$

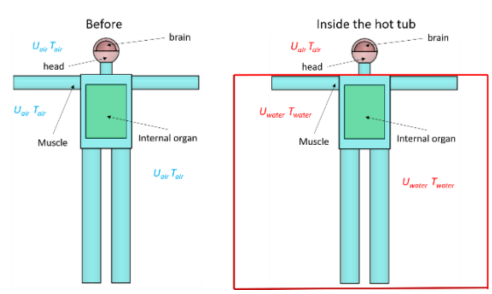

Figure 1: Schematic diagrams of the whole body model and its boundary conditions before and after the body inside a hot tub.

In Eq. 1, the arterial temperature T_a that is initially prescribed as 37°C rises with time. One can model the blood in the body as a lumped system that only varies with time.[3] The increase or decrease in the arterial blood temperature is due to its heat exchange with the surrounding tissue in the body, described by the Pennes perfusion source term in Eq. 1. The following equation is developed for determining the time-dependent arterial temperature $T_a(t)$ as

$$\rho_b c_b V_b \frac{dT_a(t)}{dt} = Q_{tissue-blood}(t) = \rho_b c_b \bar{\omega} V_{body}\left[\bar{T}_t(t) - T_a(t)\right] \qquad (3)$$

where V_b is the blood volume and V_{body} is the body volume, $\bar{\omega}$ is the average blood perfusion rate, and $\bar{T}_t(t)$ is the weighted average tissue temperature of the body, they are defined as

$$\bar{\omega} = \frac{1}{V_{body}} \iiint_{bodyvolume} \omega \, dV_{body}, \quad \bar{T}_t(t) = \iiint_{bodyvolume} \omega T_t(x,y,z,t) dV_{body} \Big/ \iiint_{bodyvolume} \omega dV_{body} \qquad (4)$$

Eq. 1 and Eq. 3 are solved simultaneously to demonstrate thermal exchange between the arterial blood and tissue. Numerical simulations are carried out by ANSYS 19.2 Fluent.

RESULTS

Table 1 gives the physical and physiological parameters used in the heat transfer simulation. Note that the local blood perfusion rate of the internal organ region is adjusted so that the cardiac output of the body is equal to 5.5 liter/min, while the other two blood perfusion rates are obtained from literature.[4] The overall heat transfer coefficient U_{air} = 4.4 W/m^{2}K is determined so that the body establishes a thermal equilibrium with the surrounding air before the person is inside the hot tube. U_{water} is calculated as 61.93 W/m^{2}K, however, its value would be much bigger if the water is actively stirred to move around. Three water temperatures (40°C, 43°C, and 46°C) are prescribed to evaluate the temperature elevations in the body.

Table 1 Physical and physiological properties[4]

	Brain	Internal organ	Muscle	Blood
k, W/mK	0.52	0.52	0.52	0.50
ρ, kg/m^3	1050	1050	1050	1050
c, J/kg K	3800	3800	3800	3800
ω, 1/s	0.0087	0.0021	0.00052	-----
Q'''_{met} W/m^3	9225	2198	554	-----

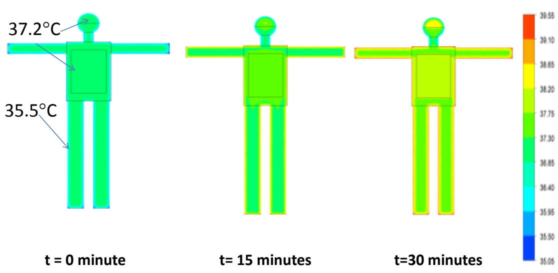

Figure 2: Contours of the temperature field of the body in a hot tub for 30 minutes, T_{water} = 40°C.

Figure 2 shows the temperature contours of the body for the beginning, 15 min, and 30 min inside the hot tub. The initial temperature field is reasonable.[5] Once the person is soaking inside a hot tub at 40°C, one can see the skin surface temperature rises from 35.5°C initially to that of the water, and the brain has the highest temperature in the body during the soaking from 37.2°C initially to 38.2°C after 30 min.

The weighted average tissue temperature (Eq. 4) and the arterial temperature T_a during the soaking are plotted in Figure 3. Initially they are the same as 37°C, due to the prescribed thermal equilibrium before the hot tub soaking. Once the body is immersed in hot water, heat conduction from the skin to the body tissue elevates the body temperature, making the right side of Eq. 3 positive, thus, resulting in an increase in the arterial blood temperature. The warmer arterial blood then further elevates the tissue temperature, shown in the perfusion source term in Eq. 1, continuing positive feedbacks between T_a and the weighted average tissue temperature. The shoulder by shoulder temperature rises in Figure 3 are consistent with our previous studies of a human body subject to harsh environment or during heavy exercise.[5] If one follows the recommendation of hot tub manufactures to soak in water at 40°C for up to 30 min, the maximal body temperature is less than 38.1°C. However, the threshold of body temperature at 38.5°C is reached after soaking for 25 or 18 min when T_{water} is 43°C or 46°C, respectively. Body temperature can rise to 39.4°C when staying in a 46°C hot tub for 30 min.

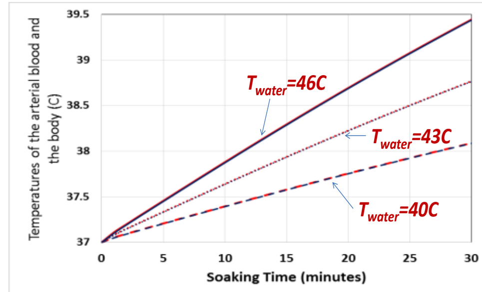

Figure 3: Temperature increases during soaking (red: weighted average tissue temperature, blue: T_a).

Table 1 lists temperatures of individual components in the body with time. Initially, the brain and internal organ have almost the same temperatures, which are higher than the muscle temperature. The brain maintains the highest temperature during most of the soaking time even if it is exposed to ambient air. However, the muscle temperature surpasses the temperature of the internal organ first, then the brain temperature once the soaking time is long. An increase in muscle temperature would divert more blood flow to the muscle region. If the cardiac output can't catch up, it may lead to reductions of the blood flow to vital organs, particular to the brain, and may also cause a decrease in systemic pressure to a dangerous level.

Table 1: Temperatures of individual components, °C

T_{water}		0 min	10 min	20 min	30 min
40°C	Brain	37.234	37.518	37.8704	38.204
	Internal organ	37.228	37.404	37.7297	38.071
	Muscle	36.684	37.357	37.7597	38.082
43°C	Brain	37.234	37.694	38.2664	38.809
	Internal Organ	37.228	37.511	38.0423	38.598
	Muscle	36.684	37.78	38.4348	38.951
46°C	Brain	37.234	37.862	38.6567	39.410
	Internal organ	37.228	37.611	38.3485	39.119
	Muscle	37.484	38.198	39.1055	39.832

SUMMARY

In this study, a whole body heat transfer model is developed to simulate temperature rises in individual body components when the body is soaking in hot water. The Pennes equation is coupled with an energy balance equation to determine both the temperature field of the body and the arterial temperature rises during the soaking. The recommended hot tub water of 40°C by manufactures is safe when the soaking time is less than 30 minutes. However, the soaking time should be limited to 25 minutes or 15 minutes when the hot water is 43°C or 46°C, respectively. Actively stirring the water in hot tubs would lead to shortening of the predicted soaking time, especially in adults with cardiac conditions.

ACKNOWLEDGEMENTS

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