MANAGING COOLING PENETRATION AND MINIMIZING SYSTEMIC HYPOTHERMIA AFTER SURGERY USING A COOLING PAD – WHOLE BODY HEAT TRANSFER SIMULATION

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INTRODUCTION

Managing pain after a surgery is a challenge faced by patients after their discharge from hospital. Placing a cooling device on the skin of the surgical site is one of the recommendations for patients to reduce inflammation and to alleviate pain.[1-2] Cooling can also temporarily reduce nerve activity via disrupting the transmission of pain signals.[1-2] Unfortunately, difficulty to implementing a cooling device, uneven cooling on the surgical site, and collateral systemic cooling, are all contributed to the discontinuous use of the cooling device by patients. Those patients thus turn to take pain-killer medications to relieve pain, and it often leads to the opioid epidemic in the country.

In this study, we develop a comprehensive whole body heat transfer model to simulate the temperature field in the body tissue, especially in the targeted cooling region using a surface cooling device. An energy balance equation for heat exchange between the blood and surrounding tissue is used to predict possible systemic hypothermia during the cooling. The effects of the cooling intensity of the device on the cooling penetration in the tissue, as well as collateral temperature reduction in the body core will be evaluated.

METHODS

A physical whole body model based on realistic measurements of a human body is generated. As shown in Figure 1, the body (79 kg in weight, 1.75 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[3] is used to model the transient temperature field of the body as

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

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 h. The boundary condition can be written as

$$-k_t \frac{\partial T_t}{\partial n} = h(T_t - T_{air}) \qquad (2)$$

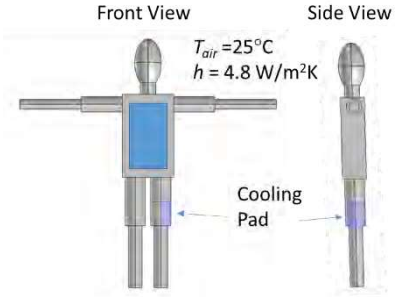

Figure 1: Schematic diagrams of the whole body model and its boundary conditions before and after the surface cooling.

In Eq. 1, the arterial temperature T_a that is initially prescribed as 37°C may decrease with time due to heat transfer to cooled tissue region. In our previous study, we modeled the blood in the body as a lumped system that only varies with time.[4] 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 was developed for determining the time-dependent arterial temperature $T_a(t)$ as[4]

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

where V_b is the blood volume in the body (5 liters) and V_{body} is the body volume (0.079 m³), $\overline{\omega}$ is the average blood perfusion rate, and $\overline{T}_t(t)$ is the weighted average tissue temperature of the body, defined as[4]

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

The obtained steady state temperature of the body before the cooling is used as the initial condition of the transient cooling process. The cooling device is 12 cm in length to cover half of the thigh circumference region, shown in Figure 1. During cooling, the boundary condition at the skin surface in contact with the cooling device, T_{pad}, is a prescribed temperature of either 5, 10 or 20°C representing different cooling intensities, while the boundary condition of the rest of the body surfaces is the same as Eq.2. Eq. 1 and Eq. 3 are solved simultaneously to demonstrate thermal exchange between the arterial blood and tissue.[4] Simulations are carried out to evaluate cooling penetration in the targeted tissue region, as well as temperature drops in the arterial blood. Numerical simulations are carried out by COMSOL.

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.[5] The overall heat transfer coefficient h= 4.8 W/m^{2}K is determined so that the body establishes a thermal equilibrium with the surrounding air before the cooling device is placed.

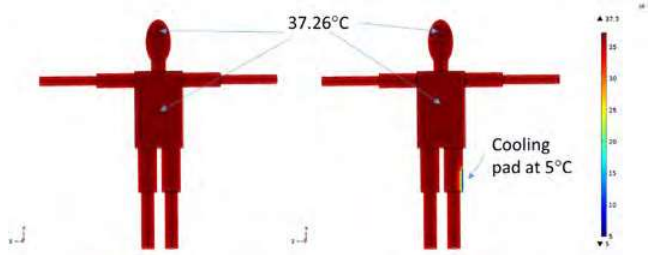

Figure 2: Contours of the temperature field of the body before and after surface cooling, $T_{cooling}$ = 5°C.

Table 1 Physical and physiological properties[5]

	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	0.0088	0.0021	0.00055	-----
Q'''_{met} W/m^3	9225	2198	554	-----

Figure 2 shows the temperature contours of the body at the beginning (left) and 30 min after the cooling device is placed (right). The initial temperature field is reasonable.[4] Significant cooling penetration can be seen in the targeted region. Figure 3 illustrates transient temperature drop at several tissue locations with different depths from the skin surface. If one defines effective cooling penetration as a temperature drop of more than 2°C, the cooling penetrates to up to 45 mm when the cooling device temperature is set as 5°C. However, cooling penetration is very shallow as approximately 30 mm when the cooling device temperature is set as 20°C.

Figure 4 illustrates the weighted average tissue temperature of the body and the arterial temperature during the cooling and they are very close in values. Cooling at the skin surface of the targeted site results in systemic hypothermia. The body core temperature defined as the average temperature in the internal organ region of the torso, typically follow the temperature of the arterial blood. As shown in Figure 4, when the cooling is mild as 20°C at the skin surface, the body core temperature only drop by 0.17°C. However, during intense cooling as T_{pad}= 5°C, the body core temperature is 0.35°C lower than the normal value after cooling of 30 minutes, thus, it may lead to patient discomfort. It is expected that the arterial temperature will continue to drop if the cooling time is longer than 30 minutes.

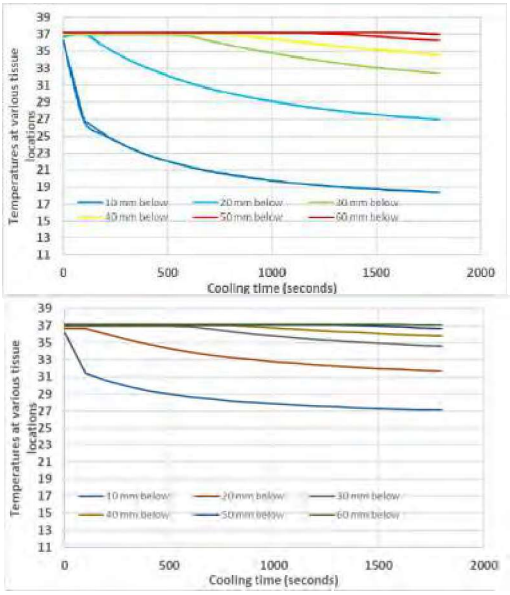

Figure 3: Temperature decreases during cooling at various locations, top: T_{pad}=5°C, bottom: T_{pad}=20°C.

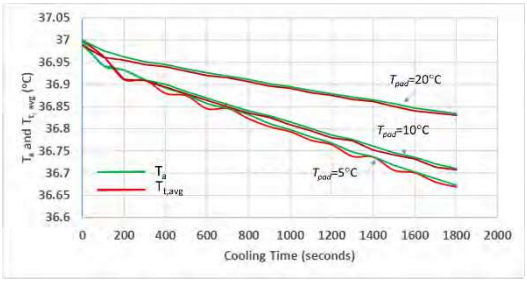

Figure 4: Reductions in the arterial temperature and the weighted average tissue temperature of the body during cooling.

DISCUSSION

In this study, a whole body heat transfer model is developed to simulate temperature reduction in targeted tissue region using a surface cooling device. The Pennes equation is coupled with an energy balance equation to determine both the cooling penetration in tissue and systemic hypothermia. Depending on targeted tissue locations for pain relief, effective cooling penetration defined as more than 2°C temperature drop can be as deep as 45 mm with intense cooling. However, intense cooling may cause systemic hypothermia especially when the cooling time is longer than 30 minutes. The current study could provide guidance to patient to discuss with their physician to identify the cooling intensity needed for pain relief as well as minimizing systemic hypothermia.

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