The Effects of Evaporation and Convection on Skin Tissue Temperature Distribution

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SUMMARY
The aim of this study is to solve one dimensional Pennes’ bioheat equation by means of backward finite difference formulation. The implicit variant of finite difference method is applied to the heat equation and the results of numerical computations are presented. Physical and physiological factors taken into account are: sweat secretion, capillary blood circulation (perfusion), metabolic heat, heat and water exchange with the environment through convection and evaporation. The model studies the effect of ambient temperature variation of 40 to 70°C on skin tissue temperature. The results show that thermal disease such as hyperthermia can be expected if uncovered skin is held for a specific time at hot environment. It is observed that increasing ambient temperature causes a shift in the location of the maximum temperature toward the surface of the skin, i.e., the maximum temperature occurs at the depth of about 8 and 6 mm of skin surface for ambient temperature of 60 and 70°C, respectively.

INTRODUCTION
The clinical treatments and therapies such as thermal disease diagnostics, cancer hyperthermia, cryosurgery and cryopreservation require the understanding of bioheat transfer characteristics and temperature behavior in living tissues. Furthermore, skin burns caused by exposing human body to heat in a fire or hot environment are some of the most commonly encountered hazards in daily life and in industry [1]. In addition, hot environment can produce a strain on a human body leading to discomfort, heat stress and even death. It should be also noted that any physical discomfort due to heat could be a potential for accidents and loss of production, particularly in a mechanized operation where a simple error can have serious consequences. Therefore, the subject of studying thermal energy transport in living tissues is useful for assessing skin burns accurately, for planning clinical thermal treatments, and for developing thermal protections for different purposes.

Besides, the important role of sweat in maintaining body temperature in a hot environment has been mostly neglected in the proposed models. The thermoregulating role of sweat is to remove heat from the body and prevent heat stress, during different daily activities such as sport and work. Therefore, to overcome the shortcoming of previous investigations, the proposed model considers the effect of main contributing factors as, sweat secretion and evaporation, blood perfusion, metabolic heat, and convection on the heat transfer of skin structure.

METHODS
The one-dimensional Pennes’ bioheat transfer equation for the transient problem is given as:
\[ \rho_c c_b \frac{\partial T}{\partial t} = k(x) \frac{\partial^2 T}{\partial x^2} + k(x) \frac{\partial T}{\partial x} + \omega_b c_b T + Q_m \]
where \( \rho_c, c_b, k, \omega_b, c_b \) and \( Q_m \) are, respectively, the density, specific heat, thermal conductivity of tissue, blood perfusion rate, specific heat of blood, and the volumetric heat due to metabolic heating rate. \( T = T - T_b \) is the elevated temperature, where \( T \) represents the skin temperature and \( T_b \) represents the blood temperature. A one dimensional multi-layer skin tissue (Fig. 1) consisting of epidermis, dermis, and subcutaneous, with a thickness of 12.08 mm, is used. Table 1 gives the physical and thermal properties of the skin constituents. The metabolic heat rate of tissue is assumed to be 4200 J/m³. Two sources of heat loss are the convection and latent heat of vaporization. Evaporative heat loss comprises a significant means of cooling the body and is of particular importance in hot environments. The maximum sweat rate for a standard subject is 650gr/h for men with body surface of 1.8m² [3]. Therefore, 1w.m⁻² heat dissipation would correspond to a flow of 2.67gr/h sweat rate for a standard subject. Also, the model considers an air velocity of 0.5m/s and a relative humidity of 20%. The skin initial temperature is 34 °C.

To validate the present study, first, the proposed model is compared to the work of Zhao et al. [4] in which all main parameters in heat equation are included except the evaporation term. Then, the model is modified to take into account the sweat secretion or evaporation term. Hot climate causes to act sweat secretion from sweat duct into the surface skin. The rate of sweat is considered to be equal to the rate of evaporation.
RESULTS AND DISCUSSION

Figure 2(A, B, C, D) presents the skin temperature along the skin thickness at 250, 500, 750, and 1000s after being exposed to ambient temperature of 40, 50, 60, and 70 °C, respectively. Figure 2A shows that for ambient temperature of 40°C, the skin temperature and core temperature stays below 37°C. As time increases, the temperature reduces and one could expect a steady state temperature profile assuming a constant continuation of sweat secretion. Figures 2B and 2C also present a similar pattern for skin temperature at different time intervals. However, the pattern changes for ambient temperature (Fig. 2D) of 70°C. That is, at ambient temperature up to 60°C, evaporation term has more significant impact on skin temperature than that of convection while at ambient temperature of 70°C, the temperature –time pattern reverses, i.e., higher temperature is predicted as time increases.

Figure 2 shows that as ambient temperature rises, the skin surface temperature increases from initial 34°C to above 37°C. Moreover, it can be seen that the temperature of the dermis tissue changes significantly, while the deeper tissue temperature shift is smaller. The other interesting point in the results, is the change in the location of the maximum temperature, e.g., the maximum temperature is located at the depth of 8 and 6 mm for ambient temperature of 60 and 70°C, respectively. It means that symptoms of thermal disease such as hyperthermia may be occurred at these locations.

CONCLUSIONS

We developed a new finite difference scheme for solving the one dimensional multi-layer Pennes’ bioheat equation. First, we validated our model using work of Zhao et al. [4]. Then, the model was revised to include the sweat secretion and evaporation. The simulation was carried out to analyze the effects of variations in ambient temperature on the skin transient temperature and to possibly predict the thermal diseases in living tissues. Analysis of results showed that heat stress and symptoms of hyperthermia could occur if uncovered skin is held at high ambient temperatures. The significant impact of sweat evaporation in lowering body temperature was also presented. It should be noted that the model accuracy was restricted by the accuracy of the thermal properties of the tissues. It should be noted that thermal conductivity is an effective factor for heating of skin tissue and that is related to genetic factors and age among others.

Table 1: Thermal properties of different skin layers.

<table>
<thead>
<tr>
<th>Layer</th>
<th>Specific heat, C (J/kg °C)</th>
<th>Density $\rho$(kg/m³)</th>
<th>Thickness (mm)</th>
<th>Thermal conductivity $k$ (W/m°C)</th>
<th>Blood perfusion rate $\phi_b$ (kg/m².s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Epidermis</td>
<td>3590</td>
<td>1200</td>
<td>$80 \times 10^{-3}$</td>
<td>0.24</td>
<td>0</td>
</tr>
<tr>
<td>Dermis</td>
<td>3300</td>
<td>1200</td>
<td>2</td>
<td>0.45</td>
<td>0.5</td>
</tr>
<tr>
<td>Sub-cutaneous</td>
<td>2500</td>
<td>1000</td>
<td>10</td>
<td>0.19</td>
<td>0.5</td>
</tr>
</tbody>
</table>