Influence of external head cooling on the head, core body and blood temperatures using 3D whole-body model

Surendra Balaji Devarakonda
Department of Mechanical and Materials Engineering, College of Engineering and Applied Science, University of Cincinnati, Cincinnati, Ohio, USA

Pallavi Bulusu
College of Engineering and Applied Science, University of Cincinnati, Cincinnati, Ohio, USA

Marwan Al-rjoub
Department of Mechanical and Materials Engineering, College of Engineering and Applied Science, University of Cincinnati, Cincinnati, Ohio, USA

Amit Bhattacharya
Department of Environmental Health, University of Cincinnati Medical Center, Cincinnati, Ohio, USA, and

Rupak Kumar Banerjee
Department of Mechanical and Materials Engineering, College of Engineering and Applied Science, University of Cincinnati, Cincinnati, Ohio, USA

Received 3 November 2017
Revised 10 February 2018
24 February 2018
Accepted 5 March 2018

Abstract

Purpose – The purpose of this study is to evaluate the impact of external head cooling on alleviating the heat stress in the human body by analyzing the temperatures of the core body (T_c), blood (T_{blood}) and head (T_h) during exercise conditions using 3D whole body model.

Design/methodology/approach – Computational study is conducted to comprehend the influence of external head cooling on T_c, T_{blood} and T_h. The Pennes bioheat and energy balance equations formulated for the whole-body model are solved concurrently to obtain T_c, T_{blood} and T_h for external head cooling values from 33 to 233 W/m^2. Increased external head cooling of 404 W/m^2 is used to compare the numerical and experimental Th data.

Findings – Significant reductions of 0.21°C and 0.38°C are observed in Th with external head cooling of 233 and 404 W/m^2, respectively. However, for external head cooling of 233 W/m^2, lesser reductions of 0.03°C and 0.06°C are found in T_c and T_{blood}, respectively. Computational results for external head cooling of 404 W/m^2 show a difference of 15 per cent in T_h compared to experimental values from literature.

Originality/value – The development of stress because of heat generated within human body is major concern for athletes exercising at high intensities. This study provides an insight into the effectiveness of external head cooling in regulating the head and body temperatures during exercise conditions.

Keywords Blood temperature, Core body temperature, Exercise condition, External head cooling, Head temperature, Whole body model

Paper type Research paper

This research study has been (partially) supported by National Institute for Occupational Safety and Health Pilot Research Project (NIOSH-PRP) Training Programme of the University of Cincinnati Education and Research Center Grant Number #T42/OH008432-09.

International Journal of Numerical Methods for Heat & Fluid Flow
Vol. 28 No. 10, 2018
pp. 2491-2504

0961-5539
DOI 10.1108/HFF-11-2017-0442

Nomenclature

BSA = body surface area (m^2);
c = specific heat capacity (J/kg °C);
E_{sw} = heat loss because of sweating (W/m^2);
f_{cl} = clothing area factor;
h = overall heat transfer coefficient (W/m^2°C);
h_e = evaporative heat transfer rate (W/m^2. kPa);
k = thermal conductivity (W/m °C);
P_{air} = partial pressure of water vapor in ambient air (mmHg);
P_s = vapor pressure of water at skin temperature (mmHg);
q_m = volumetric heat generation rate because of metabolism (W/m^3);
Q_{ext} = external cooling (W/m^2);
T = temperature (°C);
T_{air} = ambient air temperature (°C);
T_{blood} = blood temperature (°C);
T_{blood_b} = blood temperature without external cooling (°C);
T_{blood_ec} = blood temperature with external cooling of 233 W/m^2°C;
T^S_{blood} = blood temperature at near steady state condition at 270 min (°C);
T_c = core body temperature (°C);
T_{c_b} = core body temperature without external cooling (°C);
T_{c_ec} = core body temperature with external cooling of 233 W/m^2°C;
T^S_c = core body temperature at near steady state condition at 270 min (°C);
T_h = head temperature (°C);
T_{h_b} = head temperature without external cooling (°C);
T_{h_ec} = head temperature with external cooling of 233 W/m^2°C;
T_{h_ref} = head temperature with external cooling of 404 W/m^2°C;
T^S_h = head temperature at near steady state condition at 270 min (°C);
T_t = body tissue temperature (°C);
T_{wt} = perfusion-weighted average tissue temperature (°C);
V_{body} = volume of human body (m^3);
V_{blood} = total volume of blood in the human body (m^3);
WBM = whole body model; and
w = skin wettedness.

Greek symbols

ρ = density (kg/m^3);
ω = local volumetric blood perfusion rate (1/s); and
ω_{avg} = volumetric average blood perfusion rate (1/s).

Subscript

air = air;
avg = average;
blood = blood;
b = baseline (without external cooling);
body = body;
c = core;
ec = external cooling of 233 W/m^2;
ext = external;
h = head;

m = metabolism;
ref = external cooling of 404 W/m^2;
s = skin;
sw = sweating;
t = tissue; and
wt = perfusion-weighted average.

Superscript
s = steady state condition.

1. Introduction

The human body produces nearly 1,000 kilocalories of heat per hour because of metabolic activities during strenuous exercise (Hyde, 2015). Thermoregulation is achieved when there is a balance between the amount of metabolic heat generation in the body and the amount that is lost through conduction, convection, radiation and sweat evaporation. During exercise conditions, evaporation of sweat is the most efficient method for dissipating heat to the surroundings (Hyde, 2015). If there is more heat generated in the body than what is dissipated, energy is retained in the body leading to higher blood temperature (T_{blood}), core body temperature (T_c) and head temperature (T_h). Therefore, it is essential to regulate the temperature of the brain and the core body during exercise to evade severe physiological consequences such as heat rashes, heat stroke and hyperthermia induced brain edema/inflammation. An experimental study suggests that the head cooling compared to forearm immersion in chilled water, ice water perfusion-cooling vests, ice towels and liquid cooled garments is more effective at removing heat from the body (Hyde, 2015) .

Łaszczyk *et al.* (2014) have evaluated the heat transfer during hypothermia therapy of a neonate's body suffering with hypoxic-ischemic encephalopathy. They modeled the neonate's body, legs and arms as cylinders and the head as an ellipsoid. They calculated the cooling process by considering an ambient temperature of 10.8°C near the head and convective coefficient of 19.5 W/m^2K. This study determined that the neonate's brain was cooled to 28°C. In a later study (Laszczyk and Nowak, 2016), the physiological neonate's geometry was evaluated using magnetic resonance imaging (MRI) and computed tomography (CT) scans. The neonate's body was modeled using MRI and CT images in Mimics software. This study also showed a similar outcome of neonate's brain cooling as reported in their previous study (Łaszczyk *et al.*, 2014). Pichurov *et al.* (2014) have developed a numerical model to predict the skin temperature distribution because of the airflow inside a room. They studied the effect of 22°C (cool) and 28°C (non-cool) air on the skin temperature. They determined that when using 22°C air, skin temperature decreased by 2-5°C when compared to 28°C air. Angelova *et al.* (2015) extended this model and studied the effect of clothing insulation on the skin temperature. They determined that the skin temperature increased to 41°C by using a clothing insulation of 1.54 clo. However, none of these researchers have studied the effect of external cooling on the human head during exercise conditions.

The effects of head cooling on the brain temperature of the human body has been conducted by Harris *et al.* (2008). A forced convective cooling device has been used for delivering cold air to the head. This study reported that with a head cooling of 404 W/m^2, a relatively significant reduction of 0.45°C has been obtained in the brain temperature. The main limitation of this study is that the flow rate of the air delivered by the cooling device is high (2,550 l/min) and its temperature is low (14.5°C), which may not have physiological relevance. Despite the limitation, Harris *et al.* (2008) have experimentally concluded that head cooling leads to a relatively significant reduction of the brain temperature.

Paul *et al.* (2015) developed a whole body model for obtaining the transient response of the human body during cold water immersion and exercise conditions using the Pennes bioheat and energy balance equations. A computational model that resembles the human body is generally referred to as the “Whole Body Model (WBM)”. Although this study focused on obtaining the thermal response of the human body during exercise scenarios, the effect of external head cooling during exercise scenarios is not reported. Similarly, Kalathil *et al.* (2017) assessed the effect of uncertainty of the tissue parameters on the thermal response of a firefighter during firefighting scenarios using the WBM. A maximum overall uncertainty of ±0.23°C in the core body temperature (T_c) is reported because of combined uncertainty in tissue parameters such as metabolic rate, specific heat, density and thermal conductivity. While Kalathil *et al.* (2017) have highlighted the application of the WBM in firefighting scenarios, the importance of head cooling in reducing the heat stress during firefighting conditions is not evaluated.

The present study modifies the WBM developed by Paul *et al.* (2015) to further investigate the impact of external head cooling on T_h, T_c and T_{blood} during exercise conditions. Here, T_c is defined as the average temperature of the internal organs in the human body (Paul *et al.*, 2015). The WBM, representing the limbs, the torso and the head, is shown in Figure 1a. In this study, a physiological scenario of a human exercising on a treadmill for 90 min with a walking speed of 1.8 m/s is simulated using the WBM. The muscles, internal organs and head are categorized as major subdomains constituting the WBM. The physical properties of the blood and tissue are assumed to be equivalent (Paul *et al.*, 2015). The physical and physiological properties of each subdomain are summarized in Table I. The current study analyzes the WBM for a set of external head cooling values ranging from 33 W/m^2 to 233 W/m^2 (Froese and Burton, 1957) to determine the effect of external head cooling in regulating T_h, T_c and T_{blood} during high-intensity exercise conditions. Additionally, a comparison between numerical and reported experimental T_h data for an increased external head cooling of 404 W/m^2 (Harris *et al.*, 2008) is also performed.

2. Methods

The temperature variation within the human body is determined by evaluating the a) Pennes bioheat equation and b) energy balance equation (Kalathil *et al.*, 2017). The Pennes bioheat equation is defined as:

$$\rho_t c_t \frac{dT_t}{dt} = k_t \nabla^2 T_t + q_m + \rho_{blood} c_{blood} \omega (T_{blood} - T_t) \tag{1}$$

where T_t (°C) is the body tissue temperature, ω (1/s) is the blood perfusion rate, ρ (kg/m^3) is the density (subscript t refers to the tissue properties), c (J/kg °C) is the specific heat, k (W/m °C) is the thermal conductivity and q_m (W/m^3) is the volumetric heat generation rate because of metabolism. T_{blood} is computed by solving an energy balance equation using perfusion-weighted average tissue temperature (T_{wt}) and volumetric average blood perfusion rate per unit volume of tissue (ω_{avg}). ω_{avg} and T_{wt} are calculated using user defined subroutines. The energy balance equation is expressed as:

$$\rho_{blood} c_{blood} V_{blood} \frac{dT_{blood}}{dt} = -\rho_t c_t \omega_{avg} V_{body} (T_{blood} - T_{wt}) \tag{2}$$

where ω_{avg} and T_{wt} are defined as:

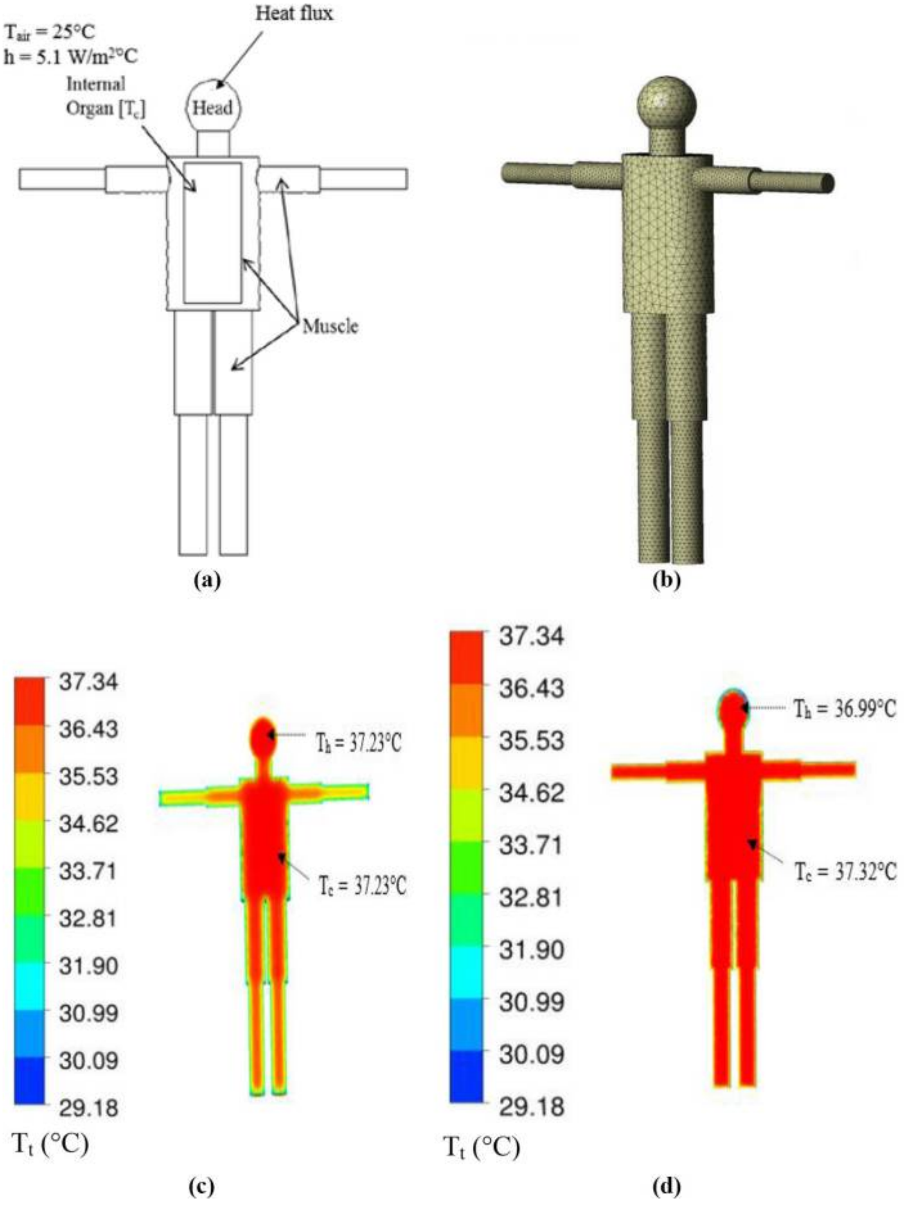

Figure 1.
(a) Schematic of the 3D whole body model. (b) Mesh used in the study. (c) Contour plot of steady state temperature of the whole body model under ambient conditions (T_{air} = 25°C). (d) Contour plot of the temperature of the human body model after 90 min of exercise with an external head cooling of 233 W/m^2

$$\omega_{avg} = \frac{1}{V_{body}} \iiint_{V_{body}} \omega dV_{body} \tag{3}$$

$$T_{wt} = \frac{1}{\omega_{avg} V_{body}} \iiint_{V_{body}} \omega T_t dV_{body} \tag{4}$$

where V_{blood} (m^3) is the total volume of blood in the human body and V_{body} (m^3) is the combined volume of all the domains of the human body. As the governing equations (1) and (2) are coupled, they are solved simultaneously to calculate the temperature variation in the human body. An overall heat transfer coefficient (h) of 5.1 W/m$^{2\circ}$C is obtained by iterating the value of "h" until T_{wt} becomes equal to the initial T_{blood} value of 37°C (Paul *et al.*, 2015). Therefore, the obtained "h" value of 5.1 W/m$^{2\circ}$C with an ambient temperature of 25°C are used as boundary conditions (Paul *et al.*, 2015) to evaluate the steady state temperature profile of the human body. This steady state temperature profile is later used as an initial condition for solving the transient heat transfer problem.

2.1 External head cooling

When an external cooling Q_{ext} (W/m^2) is applied to the head subdomain during exercise, the body loses additional heat along with the heat lost by sweating. A physiological heat flux (233 W/m^2) has been considered from Froese and Burton (1957) to evaluate the effect of external head cooling on T_h, T_c and T_{blood}. Additionally, increased external head cooling of 404 W/m^2 based on reported experimental data (Harris *et al.*, 2008) is also assessed to determine its impact on T_h. For comparison, external head cooling (Q_{ext}) values of 33, 83, 133 and 183 W/m^2 are also evaluated. These external cooling (Q_{ext}) values are incorporated as boundary conditions at the surface of the head, as described below:

$$-k_t \frac{\partial T_t}{\partial n}\Big|_{at\ \ the\ \ surface} = Q_{ext} + E_{sw} \tag{5}$$

where n is the normal direction to the skin surface and E_{sw} (W/m^2) represents the heat loss because of sweating. E_{sw} is determined using the evaporative heat transfer rate (h_e, W/m^2. kPa), vapor pressure of water at the skin temperature (P_s, mmHg) and the partial pressure of water vapor in the ambient air (P_{air}, mmHg) (Brake and Bates, 2002). The equation for E_{sw} is as follows:

Table I. Physical and physiological properties of each subdomain used in the whole body model

Subdomain	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	0.000500	553.5
Head/brain	0.5	1060	3800	0.008330	9225
Internal organs	0.5	1060	3800	0.001266	1401.5

Notes: The physical and physiological properties of the muscle, head and internal organs are obtained from Paul *et al.* (2015) and Zhu *et al.* (2009). Thermal conductivity and specific heat of the muscle are obtained from Skalak and Chien (1987)

$$E_{sw} = h_e(P_s - P_{air}) \tag{6}$$

These parameters (h_e, P_s and P_{air}) are chosen to incorporate the maximum possible evaporative loss in the absence of clothing by neglecting the f_{cl} (clothing area factor), $R_{e,cl}$ (clothing resistance) and w (skin wittedness), respectively (Paul *et al.*, 2015; Pichurov *et al.*, 2014). It is noted that external cooling is applied only for the head subdomain. Therefore, the boundary condition defined for the rest of the body surface is:

$$-k_t \frac{\partial T_t}{\partial n}|_{at\ \ the\ \ surface} = h(T_t - T_{air})|_{at\ \ the\ \ surface} + E_{sw} \tag{7}$$

The WBM is solved using the finite volume solver Fluent (ANSYS, Inc., Canonsburg, PA). A mesh independence study (Figure 1b) is conducted on the WBM to obtain a refined mesh of 60,000 tetrahedral elements. A second-order spatial discretization, first-order implicit transient formulation and an implicit scheme are used to solve the Pennes bioheat equation and the energy balance equation, respectively. For an implicit scheme, the value of a dependent variable at a node at the current time is calculated using the combination of values at the neighboring nodes at the current or the previous time, if the current data are not available. Values at all nodes are calculated by solving multiple equations simultaneously at the current time step. The advantage of implicit scheme is that it is unconditionally stable with respect to selected mesh size and time step (1 min for the 90 min duration of exercise) in this study. A time increment of one min and a convergence criterion of 1E-10 are used for obtaining the transient response of the WBM. The convergence criterion refers to all degrees of freedom (T_c, T_{blood} and T_h). Compared to a recommended value of 1E-6, a lower residual value of 1E-10 was selected to achieve an improved numerically accurate solution. Further details regarding the numerical scheme are given in Kalathil *et al.* (2017) and Paul *et al.* (2015).

3. Results and discussion

3.1 Temperature profile of the whole-body model at steady and transient conditions

Figure 1c shows the steady state temperature profile obtained using the WBM under ambient conditions (T_{air} = 25°C). T_t varies from 30.24°C at the finger tip area to 37.3°C in the head, while T_c and T_h have a uniform temperature of 37.23°C (Figure 1c). Due to an efficient heat removal mechanism observed in the head, T_h is very close to T_c despite having a metabolic rate 6.5 times greater than that of the internal organs. A maximum T_t of 37.3°C is observed in the head because of the large metabolic heat generation rate of 9225 W/m^3 (Zhu *et al.*, 2009). There is an increased ratio of surface area to volume, 103.9 m^{-1} and 67.59 m^{-1} (Tikuisis *et al.*, 2001), for hands and feet of a human body, respectively, for a body surface area (BSA) of 2 m^2. Therefore, a lower T_t, varying from 32.81°C to 36.43°C, are observed in the skin regions of the hands and feet. Figure 1d shows the temperature profile obtained after 90 min of exercise when an external head cooling of 233 W/m^2 is provided. T_t varies between 29.18°C and 37.34°C, while T_c and T_h are computed to be 37.32°C and 36.99°C, respectively.

3.2 Temporal variation of T_h, T_c and T_{blood}

Figures 2a, b and c represent the temporal variation of T_h, T_c and T_{blood} without external cooling (T_{h_b}, T_{c_b} and T_{blood_b}; subscript "*b*" is baseline) and with external head cooling of 233 W/m^2 (T_{h_ec}, T_{c_ec} and T_{blood_ec}; subscript "*ec*" is external head cooling). Maximum reductions of 0.21°C (= 37.30°C – 37.09°C) or 0.57 per cent, 0.03°C (= 37.30°C – 37.27°C) or

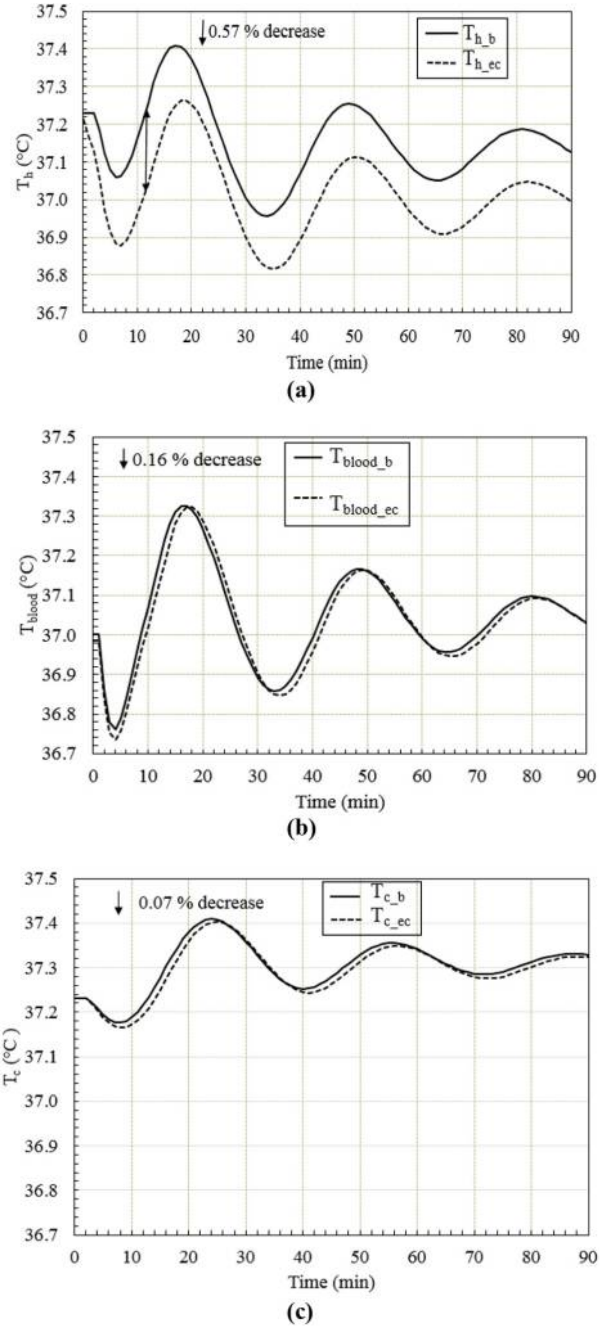

Figure 2.
Computation of (a) head temperature (T_h), (b) core body temperature (T_c) and (c) blood temperature (T_{blood}) for the human body model during exercise for: i) without external cooling, i.e. baseline (T_{h_b}, T_{c_b} and T_{blood_b}) and ii) with external head cooling of 233 W/m^2 (T_{h_ec}, T_{c_ec} and T_{blood_ec})

0.07 per cent and 0.06°C (= 37.24°C−37.18°C) or 0.16 per cent are observed in T_h, T_c and T_{blood}, respectively, because of external head cooling. T_h is lowered because of external cooling provided directly to the head. This localized head cooling affects primarily T_h without significantly influencing T_c and $T_{blood.}$

3.3 Validation of numerical results and comparison of a steady state T_c and T_{blood} with T_h

Figure 3a shows the temporal variation of T_h for:

- without external cooling i.e. baseline (T_{h_b});
- with external head cooling of 233 W/m^2 (T_{h_ec}); and
- with external head cooling of 404 W/m^2 (T_{h_ref}).

The validation of the computational WBM is achieved by comparing the numerical results to the clinical results of Harris *et al.* (2008). Harris *et al.* (2008) have used an external head cooling of 404 W/m^2 to obtain a difference of 0.45°C between T_{h_b} and T_{h_ref}. In the current study, with the same external head cooling (404 W/m^2), a maximum difference of 0.38°C or 1.02 per cent [{(37.31−36.93)/37.31} ×100 per cent] is obtained between T_{h_b} (37.31°C) and T_{h_ref} (36.93°C) in the presence of sweating. Hence, the 15 per cent difference in T_h between the current study and the clinical data by Harris *et al.* (2008) show that the WBM, which has been developed for assessing the impact of head cooling on T_h, is reasonable. One of the possible reasons for the 15 per cent difference could be because Harris *et al.* (2008) used a forced convective cooling device to the head, while the current study implemented heat transfer cooling using a heat flux boundary condition. The absence of external cooling and increases in metabolic and perfusion rate (Paul *et al.*, 2015) allow T_{h_b} to remain steady for the initial 2 min (Figure 3a). T_{h_b}, $T_{h_ec}$and T_{h_ref} reach their peak temperatures at t = 17, 19 and 20 min, respectively. Due to the absence of cooling, T_{h_b} reaches its peak temperature at an earlier time point of t = 17 min. However, when external head cooling of 233 W/m^2 is provided to the head, T_{h_ec} reaches the peak temperature after 2 min when compared to T_{h_b}. Further, with external head cooling of 404 W/m^2, T_{h_ref} takes a longer time (20 min) than T_{h_b} and T_{h_ec} to reach its peak temperature (Figure 3a).

The oscillatory nature of temperatures (Figure 3a) is because of the balance of the physiological mechanism of sweating and metabolic heat generation. As exercise begins, an initial small decrease (<0.3°C) is observed in T_{blood}, T_c and T_h because of the initiation of cooling effect of blood perfusion that acts as a heat sink. However, as the exercise period increases, blood perfusion is unable to remove the excess heat generated by metabolism and therefore, the temperature increases (Paul *et al.*, 2015). As temperatures become greater than 37.23°C, sweating initiates thermoregulation, leading to decrease in temperatures. As the body cools down, sweating decreases which again causes the temperatures to rise. This results in the temperature profile being oscillatory in nature. The influence of external head cooling on T_{blood} and T_c is insignificant because the amount of heat transfer from the head surface area is relatively smaller in relation to the other parts of the body. Therefore, the head cooling does reduce T_h but does not significantly influence T_{blood} and T_c. T_h is affected because the proximity of the head is close to the external cooling.

Figure 3b shows the comparison of T_{blood} and T_c with T_h at a near steady state condition at 270 min (T^S_{blood}, T^S_c and T^S_h) for external head cooling rates ranging from 0 to 404 W/m^2. The temporal variation of T_h, T_c and T_{blood} for the time period of 270 min without and with external head cooling (233 W/m^2) have been provided in the appendix (Figure A1). As the external head cooling rate increases from 0 to 404 W/m^2, a reduction of 0.16°C (0.43 per cent) is observed in the T^S_h, while a negligible difference of 0.009°C (0.02 per cent) is observed in

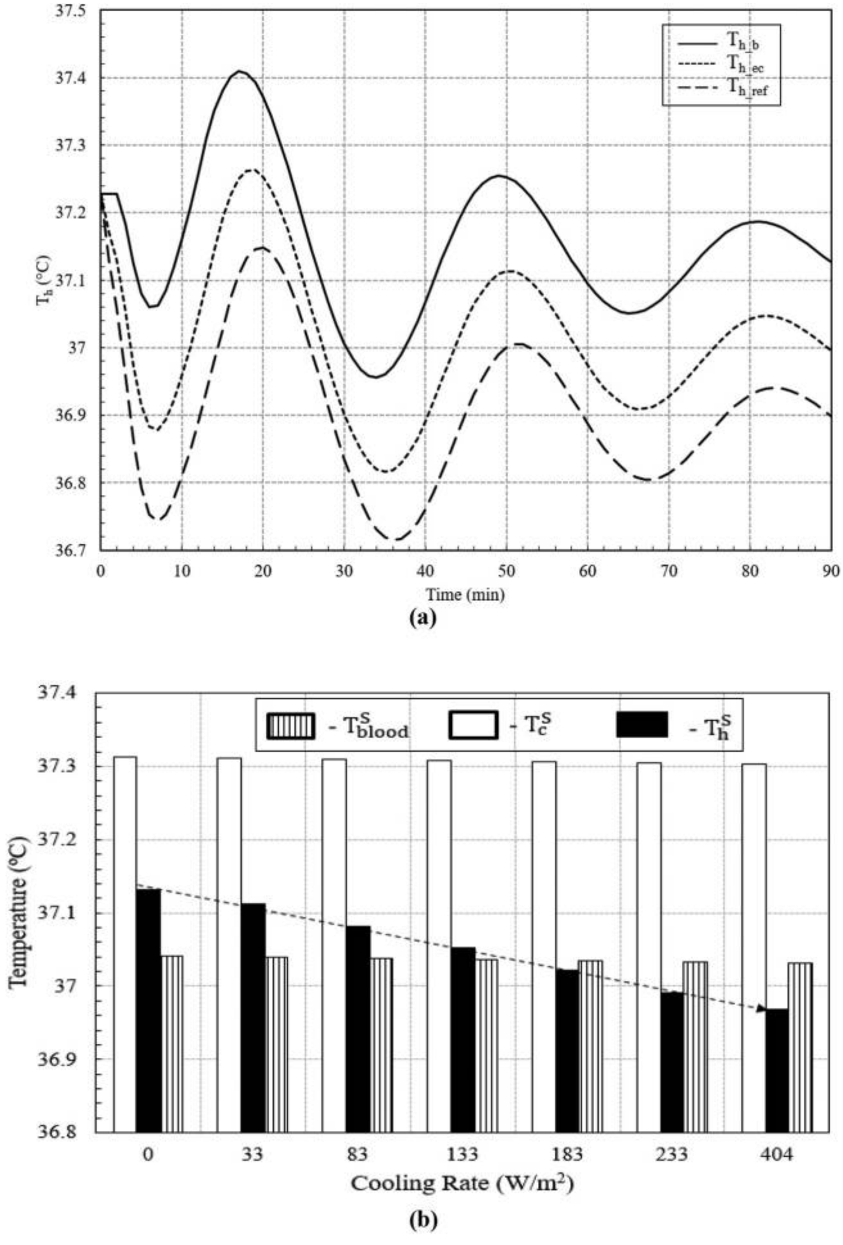

Figure 3.
(a) Variation of T_h with time when i) no external cooling (T_{h_b}), ii) external head cooling of 233 W/m^2 (T_{h_ec}) and iii) external head cooling of 404 W/m^2 (T_{h_ref}) is applied. (b) Comparison of T_c and T_{blood} with T_h at an attained steady state condition (T^S_{blood}, T^S_c and T^S_h) for external head cooling rates ranging from 0 to 404 W/m^2

T_c^S and T_{blood}^S, respectively. This shows that external head cooling is beneficial for regulating T_h in exercise scenarios but not T_c and T_{blood}. Hence, a different cooling modality, instead of head cooling, must be implemented to reduce T_c and T_{blood} appreciably.

It is observed that an increase of 6.5 per cent [(37.41–37.23)/(40–37.23) × 100], 1.1 per cent [(37.26–37.23)/(40–37.23) × 100] and −3.2 per cent [(37.14–37.23)/(40–37.23) × 100] have been obtained in the head temperature (T_h) using external cooling values of 0, 233 and 404 W/m^2, respectively, when compared to the maximum allowable temperature difference of 2.77°C (40°C – 37.23°C). This maximum allowable temperature difference is the difference in the brain baseline temperature (37.23°C) to the maximum allowable temperature of 40°C (Nybo and Secher, 2004), at which the brain capacity to maintain the physiological motor activity during exercise ceases (Table II). It can be observed that using an external cooling of 404 W/m^2, head can be cooled to a temperature less than the baseline temperature (37.23°C). Further, the model predicted a decrease in relative temperature difference of 83.3 per cent [(6.5–1.1)/6.5 × 100] and 150 per cent [(6.5–(−3.2))/6.5 × 100] using the external cooling values of 233 and 404 W/m^2.

4. Limitations and future work

The WBM used in this study did not consider the brain, bone (skull) and fat regions present inside the head independently. Instead, they are represented as a single subdomain. The rationale behind this assumption is to keep the model as simple as possible, rather than generating a complicated geometry consisting of layers representing different regions. Second, the model assumes a uniform sweating rate to occur all over the body even though certain regions such as the forehead and chest are known to have relatively higher sweating rate (de Dear *et al.*, 1997; Paul *et al.*, 2015). Further, sweating is assumed to begin when $T_c \geq$ 37.23°C the linear variation of the sweating rate with T_c (Brake and Bates, 2002; Paul *et al.*, 2015). Finally, the spatial variations of T_{blood} and the countercurrent heat exchange between arteries and veins are not accounted for in this study (Paul *et al.*, 2015).

A combined uncertainty of 0.23°C has been reported by Kalathil *et al.* (2017) for the case of a firefighting scenario which incorporates the human gut section and the firefighting suit, with boundary conditions applicable to firefighting conditions. However, the current study uses fixed values for blood and tissue properties while incorporating reported ranges of head cooling. The variation in T_h obtained because of the cooling is expected to follow similar trend and magnitude for other fixed values of properties. With the head cooling gear, a future uncertainty analysis can be performed.

The outcome of this study can be used to evaluate the effect of head cooling on T_c and T_h of firefighters during firefighting scenarios by incorporating parameters such as f_{cl} (clothing area factor) and w (skin wettedness). Varying h values and different ambient conditions can be used to check the capability of the WBM. Furthermore, the addition of geometric details

Table II. Comparison of the effect of using external cooling on the relative allowable maximum temperature difference during exercise conditions

External cooling (W/m^2)	Peak temperature (°C)	Temperature rise compared to the maximum allowable temperature rise (%)	Decrease in relative temperature difference (%)
0	37.41	6.5	–
233	37.26	1.1	83.3
404	37.14	−3.2	150.0

including a fat layer and skin layer in each subdomain will contribute to a more realistic WBM. Finally, this study is useful as it can limit the requirement for large-scale experiments and restrict the exposure of subjects to heat stress in clinical trials. This study can also be used as a preliminary study before conducting experiments or clinical trials. In conclusion, this research shows that the use of external head cooling during intense exercise produces a favorable cooling in the head domain and a lesser cooling effect in the core body domains.

References

Angelova, R.A., Pichurov, G., Simova, I., Stankov, P. and Rodrigo, I. (2015), "CFD based study of thermal sensation of occupants using thermophysiological model. Part II: effect of metabolic rate and clothing insulation on human-environmental interaction", *International Journal of Clothing Science and Technology*, Vol. 27 No. 1, pp. 60-74.

Brake, D.J. and Bates, G.P. (2002), "Limiting metabolic rate (thermal work limit) as an index of thermal stress", *Applied Occupational and Environmental Hygiene*, Vol. 17 No. 3, pp. 176-186.

de Dear, R.J., Arens, E., Hui, Z. and Oguro, M. (1997), "Convective and radiative heat transfer coefficients for individual human body segments", *International Journal of Biometeorology*, Vol. 40 No. 3, pp. 141-156.

Froese, G. and Burton, A.C. (1957), "Heat losses from the human head", *Journal of Applied Physiology*, Vol. 10 No. 2, pp. 235-241.

Harris, B., Andrews, P., Marshall, I., Robinson, T. and Murray, G. (2008), "Forced convective head cooling device reduces human cross-sectional brain temperature measured by magnetic resonance: a non-randomized healthy volunteer pilot study", *British Journal of Anaesthesia*, Vol. 100 No. 3, pp. 365-372.

Hyde, J.L. (2015), "The influence of head cooling combined with various cooling modalities on cooling rate after exercise in the heat",

Kalathil, R.T., D'Souza, G.A., Bhattacharya, A. and Banerjee, R.K. (2017), "Uncertainty analysis of the core body temperature under thermal and physical stress using a three-dimensional whole body model", *Journal of Heat Transfer*, Vol. 139 No. 3, p. 031102.

Laszczyk, J.E. and Nowak, A.J. (2016), "Computational modelling of neonate's brain cooling", *International Journal of Numerical Methods for Heat and Fluid Flow*, Vol. 26 No. 2, pp. 571-590.

Łaszczyk, J., Maczko, A., Walas, W. and Nowak, A.J. (2014), "Inverse thermal analysis of the neonatal brain cooling process", *International Journal of Numerical Methods for Heat and Fluid Flow*, Vol. 24 No. 4, pp. 949-968.

Nybo, L. and Secher, N.H. (2004), "Cerebral perturbations provoked by prolonged exercise", *Progress in Neurobiology*, Vol. 72 No. 4, pp. 223-261.

Paul, A.K., Zachariah, S., Zhu, L. and Banerjee, R.K. (2015), "Predicting temperature changes during cold water immersion and exercise scenarios: application of a tissue–blood interactive whole-body model", *Numerical Heat Transfer, Part A: Applications*, Vol. 68 No. 6, pp. 598-618.

Pichurov, G., Angelova, R., Simova, I., Rodrigo, I. and Stankov, P. (2014), "CFD based study of thermal sensation of occupants using thermophysiological model. Part I: mathematical model, implementation and simulation of the room air flow effect", *International Journal of Clothing Science and Technology*, Vol. 26 No. 6, pp. 442-455.

Skalak, R. and Chien, S. (1987), *Handbook of Bioengineering*, McGraw-Hill Companies, New York, NY.

Tikuisis, P., Meunier, P. and Jubenville, C. (2001), "Human body surface area: measurement and prediction using three dimensional body scans", *European Journal of Applied Physiology*, Vol. 85 Nos 3/4, pp. 264-271.

Zhu, L., Schappeler, T., Cordero-Tumangday, C. and Rosengart, A. (2009), "Thermal interactions between blood and tissue", *Advances in Numerical Heat Transfer*, Vol. 3.

Appendix

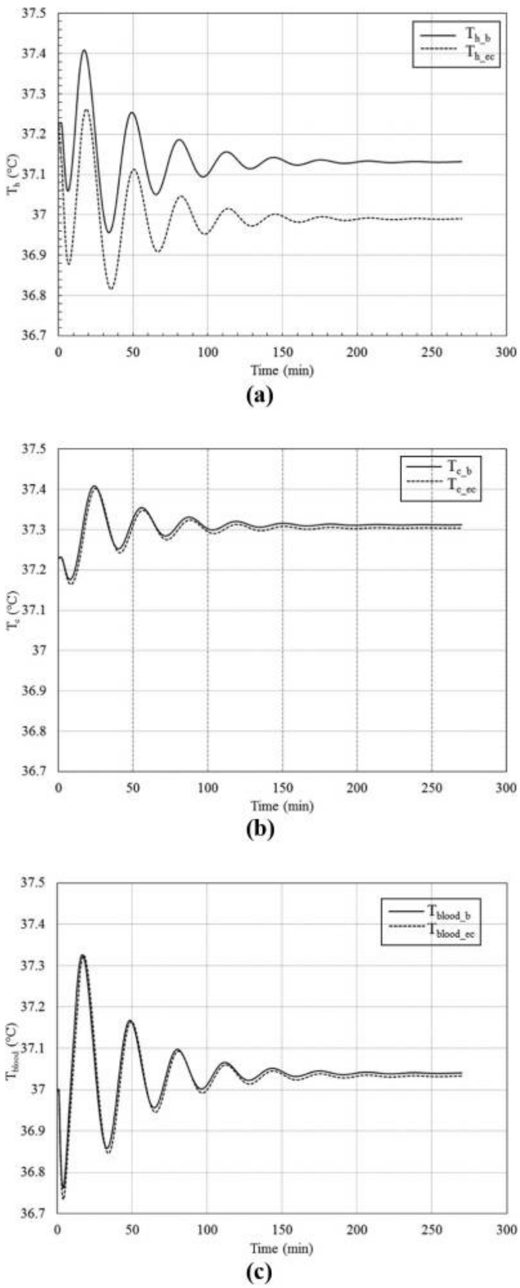

Figure A1. Computation of (a) head temperature (T_h), (b) core body temperature (T_c) and (c) blood temperature (T_{blood}) for the human body model during exercise for: i) without external cooling, i.e. baseline (T_{h_b}, T_{c_b} and T_{blood_b}) and ii) with external head cooling of 233 W/m^2 (T_{h_ec}, T_{c_ec} and T_{blood_ec}) for a time period of 270 min

It can be observed that the temperatures (T_h, T_c and T_{blood}) reach a near steady state after 200 min of exercise without the oscillatory nature. T_h has a reduction of 0.14°C Figure A1(a) using external cooling (233 W/m^2) when compared to no cooling after reaching a near steady state. Using external cooling (233 W/m^2), T_c and T_{blood} have a reduction of 0.01°C [Figure A1(b and c)] each as compared to the baseline case (no external cooling). The external cooling helps in reduction of the head temperature even at a near steady state condition which is critical for hyperthermia scenarios.

Corresponding author
Rupak Kumar Banerjee can be contacted at: rupak.banerjee@uc.edu

International Journal of Numerical Methods for Heat & Fluid Flow

Influence of external head cooling on the head, core body and blood temperatures using 3D whole-body model

Surendra Balaji Devarakonda, Pallavi Bulusu, Marwan Al-rjoub, Amit Bhattacharya, Rupak Kumar Banerjee,