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Research Article

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Robust Modeling of Human Thermal Response to Hand and Forearm cooling for Improved Performance and Energy Efficiency

M Rida, W Karaki, N Ghaddar* and K Ghali

Mechanical Engineering Department, American University of Beirut, P.O. Box 11-0236, Beirut 1107-2020, Lebanon

Abstract

A modeling approach is used to study the effectiveness of the Active Cooling (*AC*) method of hand and forearm immersion in cold water to reduce core temperature following heavy physical activity. A transient multi-node segmental bioheat model based on physiology and accurate mathematical modeling of thermoregulatory functions are used to predict human segmental core and skin temperatures, and arterial blood flow for given metabolic rate and environmental conditions. The validity of the model is confirmed by comparison with published experimental data on core temperature during and after immersion of forearms and hands in cold water. The validated model is used in a case study to enhance understanding of associated body thermal changes and arterial blood flow and *AVA* mechanisms during *AC* interventions that alleviate thermal stress in hot environment.

The time needed for the core temperature to drop from 38.0°C to 37.0°C is found to be 33 minutes when subject is at rest and is exposed to air cooling at 21°C compared to 15 minutes when hands and forearms are immersed in water at 10°C. The average sensible heat loss during the cooling period associated with immersion of forearms and hands in water at 10°C was found to be 106.2 W compared to 75.9 W for passive air cooling at 21°C. The active cooling was found to be an effective method for accelerating reduction on core temperature and can be used with efficient, localized, and portable cooling devices.

Keywords: Active cooling of extremities; Bioheat Modeling; Alleviation of Thermal Stress; Arterio; Venous Anastomoses

Nomenclature

AC : Active cooling
AVA : Arterio-venous anastomoses
CIVD : Cold induced vasodilation
M : Metabolic rate (W)
$\dot{m}_a$: Blood flow rate through the artery (kg/s)
$\dot{m}_{AVA}$: Blood flow due to *AVA* (kg/s)
$\dot{m}_{CIVD}$: Blood flow due to *AVA* (kg/s)
$q_{o,finger}$: Initial sensible heat loss upon finger immersion in cold fluid (W)
Q_{res} : Heat dissipated through respiration (W)
$Q_{cr\text{-}sk}$: Heat exchange between the core and skin through contact resistance (W)
t : Time (s)
t_{CIVD} : *CIVD* period (s)
t_0 : Time at which *CIVD* response starts (s)
$T_{CIVD,min}$: *CIVD* threshold temperature to trigger reaction (°C)
T_{cr} : Core temperature (°C)
T_{sk} : Skin temperature (°C)
$T_{sk,f}$: Finger skin temperature (°C)

Greek Symbols

τ : Time constant of the *AVA* response (s)

Introduction

Global warming and its implications on the well-being of outdoor workers and high performing athletes caused more attention to be devoted to heat stress in light of the increase in the prospects of living in a warmer world and the need to avoid the productivity loss of workers. It is well established that high core temperature resulting from physical work, high ambient temperature, and wearing protective clothing is a primary factor for limiting work performance and endurance. The rise of core temperature can cause early fatigue because much of the blood flow pumped by the heart is diverted away from the muscle cells to the skin where heat can escape [1]. To improve human endurance and productivity in conditions that cause rise in body temperature, methods for quickly cooling the body are sought to reduce rest periods.

People feel comfortable when there is a balance between the metabolic heat produced and the body heat loss without the active need of the thermoregulatory system. In the other hand, people's feeling of discomfort increases when their thermoregulatory system needs to work harder to maintain thermal neutral state [1]. In extreme cases, when the thermoregulatory system fails in maintaining the thermal balance, heat stress occurs. Means to reduce or delay the state of heat stress and prolong work or activity period have included the use of active and passive personal cooling systems and clothing for improved ventilation in hot humid climates. One of the reported effective methods for decreasing quickly the core temperature in literature is the immersion of hand and fore arm in cold water [2-5]. Extremities are effective areas for extracting heat and therefore it is a good idea to consider cooling body temperature from these regions. The most inexpensive and the simplest method to use is cold water hand immersion where water is

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***Corresponding author:** Nerren Ghaddar, Mechanical Engineering Department, American University of Beirut, P.O. Box 11-0236, Beirut 1107-2020, Lebanon, Tel: 961-1-350000; E-mail: farah@aub.edu.lb

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known to conduct the heat from the body at about 20 to 26 times faster than air at the same temperature [3,6].

Hands play a thermostat's role and can be considered as temperature sensors with low skeletal muscle and high skin surface area of hands (5% of the body surface area) [7]. Heat loss from the skin surface is increased in limbs when Arterio-Venous Anastomoses (AVA) blood from hand and feet returns through the superficial veins of the forearms and calves since the AVA blood flow rate is greater than capillary blood flow rate [8-11]. In cold environments, vasoconstriction of the arterial system prevails to prevent body heat loss (this is true for both vasoconstriction of arteries and closure of the AVA). In hot environments, the body tries to lose heat by dilating and hence increasing blood flow to the skin. The AVA will divert large amounts of the hot arterial blood from going through the high resistance path of the capillaries to a lower resistance path which connects the arterial and venous blood directly. [10-11].

There is wealth of empirical literature reporting human thermal response to extremity cooling methods to reduce core body temperature. DeGroot et al. [12] reported that arm immersion up to the elbow results in greater heat lost compared to hand only immersion and may reduce cardiovascular strain by lowering heart rate by 10-25 beats/min and increase work tolerance time by up to 60%. McTiffin and Pethybridge [13] reported that the cold water immersion of the hands and feet is very effective in reducing core temperature after exercise. They tested 12 subjects conducting continuous work of 310 W in ambient condition of 40°C. When their aural temperature reached 38.5°C, subjects sat and immersed their hands in cold water. They reported 272 W of dissipated heat from the hands immersion cold water [13]. House [14] reported aural and skin temperature of six subject wearing firefighting clothes after exercising in 40°C environment and resting in 30°C environment with their hand immersed in 20°C water. Results show that there was a difference in the reduction in aural temperature during rest period with hand immersion by 1.22 ± 0.39°C compared to a reduction 0.68 ± 0.3°C without hand immersion.

Giesbrecht et al. [2] conducted experiments on 6 subjects wearing firefighter clothing and going through three consecutive bouts of 20 min of stepping exercise in 40°C and 40% RH environmental conditions followed by 20 min of rest/cooling after each bout. Five different experiments were done to each subject: a control one without any immersion in water, and four for immersing hands only or hands and forearms in water at 10°C or 20°C.

Giesbrecht et al. [2] found that the core temperature after the second exercise period was highest in the control experiment. Hand and forearm immersion at 10°C resulted in the lowest core temperature.

Hsu et al. [15] used a new cooling device, purported to extract heat from the body core through the palm of the hand to attenuate core temperature rise during sub maximal exercise in hot environmental conditions and to facilitate a higher sustained workload. They suggested a device that can be used in increasing the hand heat exchange by applying a negative pressure and a heat sink to the palm of the hand. Hsu et al. [15] tested the device on eight male triathletes who cycled for one hour in a heated room at 31.9°C and 24% humidity with hand cooling and without. Cooling attenuated the rise in tympanic temperature by 1.2°C vs. 1.8°C without hand cooling.

Previous work on assessing performance of hand cooling methods has focused on empirical methods and few modeling studies of hand cooling were found. Two modeling approaches were used to predict the thermal response of the fingers and hand. One approach was to model the hand as independent segments from the body such as the models of Shitzer et al. [16] and Shitzer et al. [17]. This modeling approach is not relevant to hand cooling applications in which the core temperature cannot be predicted. In addition, the model does not incorporate the thermoregulatory mechanism that connects with the central response of the human body. The second modeling approach relied on segmental bioheat modeling to predict skin and core segmental temperatures based on physiology and thermoregulatory functions. Karaki et al. [11] extended the multi-branched arterial tree of Avolio [18] to include the hand artery branching into the five fingers while adjusting terminal impedances of the smaller fingers' arteries. They introduced a new *AVA* model for the fingers and incorporated their modified circulatory system model to the multi-node multi-segment bio heat model of Salloum et al. [19]. They predicted the segmental core and skin temperatures in the extremities during exposure to cold and hot environments. According to Karaki et al. [11], the maximum vasodilatation happens when body temperature is 37.2°C (although it starts at core temperature above 36.7°C) and the maximum vasoconstriction happens when the skin temperature reaches 27.8°C although it starts when core temperature is below 33.7°C. Recently, Rida et al. [20] introduced modification to Karaki et al. [11] model to accurately predict the transient Cold Induced Vasodilation (*CIVD*) response in fingers after local exposure to cold conditions. Their *CIVD* model introduced the local thermal conditions of finger skin temperature and body core average temperature that trigger *CIVD* reaction and determines when AVA mechanism is off and on. Their model compared very well with experimentally published data in Shitzer et al. [17] during one immersion cycle of the hand for one hour in cold environment, and with experimental data of Sawada et al. [21] during repeated finger immersions.

It is important to predict the physiological responses of the human body from a detailed model including hands and fingers. Such models will be a good predictor of the body physiological responses in hot environment and the body core and skin temperature. The empirical approach will not be useful when considering active intervention methods that can improve work endurance through prolonging work or active periods using personal cooling systems. A robust model for predicting effect of cooling extremities on the core temperature would be a useful tool for improving human performance and to appropriately suggest hand and fore arm cooling temperatures for different metabolic rates and environmental conditions.

In this work, we aim to confirm validity of utilizing the bioheat model of Karaki et al. [11] and Rida et al. [20] in accurately predicting thermal response of active human subject (body core temperature, and segmental skin and core temperature) when subject to Active Cooling (*AC*) of extremities by immersion in cold fluid. The validated model will be used in a case study to enhance understanding of associated body thermal changes and arterial blood flow and *AVA* mechanisms during *AC* interventions that improve productivity in hot environment and correlate it to worker physiological thermal state.

Methodology

A simulation tool is developed to investigate the effectiveness of active cooling method that relies on immersing the hands and forearms in cold water as a strategy for reducing body core temperature and hence alleviate physiological strain following high physical activity. A human subject is assumed to exert physical work for a period of time for a given metabolic rate M, high insulative/protective clothing resistance, and environmental condition at T_{amb}. The activity continues until a critical body core temperature is reached normally at values exceeding 38°C. Once the critical core temperature is reached, the human reduces activity level to sitting state and immerses the hands and forearms in

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cold water bath at temperature T_w (which can be any value between 10°C and 20°C) while exposed to similar or lower environmental conditions with same or different clothing resistance. The simulation tool is based on: 1) multi-node segmental bioheat model, 2) blood circulation model based on actual arterial tree blood flow, and 3) robust thermoregulatory model of *AVA* and *CIVD* mechanisms associated with exposure of hands to cold environment. The models used in the simulation tool are described in this section as well as the adopted numerical methodology.

Bioheat Model

The bioheat model of Karaki et al. [11] and the model of thermoregulatory *AVA* and *CIVD* reaction to local cooling of Rida et al. [20] are used in this work to predict local and overall thermal and blood flow responses to changes in environmental conditions, clothing, and activity level. The model divides the human body into 25 segments as shown in Figure 1 which include head, upper trunk, lower trunk, upper arms, lower arms, palms and fingers, thighs, calves, and feet. Each segment is composed of a core node, skin node, artery node, vein node, and when applicable a superficial vein node. The modelling of blood flow was based on a modified multi-branched arterial tree model of Avolio [18] to include the five fingers for each hand. Based on metabolic rate and body core temperature, the blood flow into each individual body segment including fingers is determined. The bioheat model solves transient energy balance equations of the nodes of each body segment constrained by thermoregulatory controls to predict segmental core and skin temperatures, and arterial blood flow for given metabolic rate and environmental conditions [11,19]. The details of the bioheat mathematical formulation can be found in Karaki et al. [11] and will not be repeated here. Figure 2 shows a flow chart of the input and output parameters of the bioheat simulation model.

Blood flow in fingers and *AVA* and *CIVD* mechanism

Blood flow to the extremities is controlled by finger skin temperature and initial heat loss from the finger when subjected to cold environment. For that reason is it important to describe the thermal control mechanism used in the adopted model for simulation of hand cooling. The total skin blood flow in the fingers was divided into two distinct parts: skin blood perfusionand *AVA* blood flow to the skin $\dot{m}_{AVA}$. The *AVA* flow, $\dot{m}_{AVA}$, is function of local skin temperature. The blood flow flowing into the hand, obtained from the bioheat model simulation, was equally divided between the fingers and the palm and dorsal hand, and the flow into the fingers was divided equally amongst the five fingers. The exact temperature at which the AVA turns on and off under total body heating or cooling was reported at finger $T_{skin,f}$=32°C which is the temperature at which a sharp decline of finger skin temperature begins as reported by several researchers [11,17,22-23]. The AVA blood flow model during ON-mode (T_{skin} of finger >32°C and $T_{co\text{-}av}$>36.7°C) and during OFF-mode were based on the model Rida et al. [20]. When the *AVA* turns ON, it increases the *AVA* flow, $\dot{m}_{AVA}$, exponentially to a maximum value equal to the total amount of blood flow in the finger ($\dot{m}_{finger}$) minus the skin perfusion which passes from the arterial node through the core and to the skin, and minus the initial AVA flow present when the *AVA* turned on at time t_0. If the *AVA* turns OFF, the *AVA* blood flow decreases exponentially from the initial *AVA* flow present when the *AVA* was turned off to a minimum value of zero with a time constant of 500 s. This effectively makes the *AVA* flow range from a minimum of zero to a maximum possible value equal to 70% of the total skin blood flow at maximum dilation.

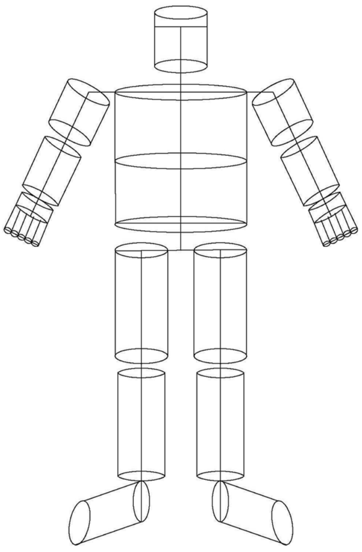

Figure 1: Different parts of the human body used in the bio-heat model.

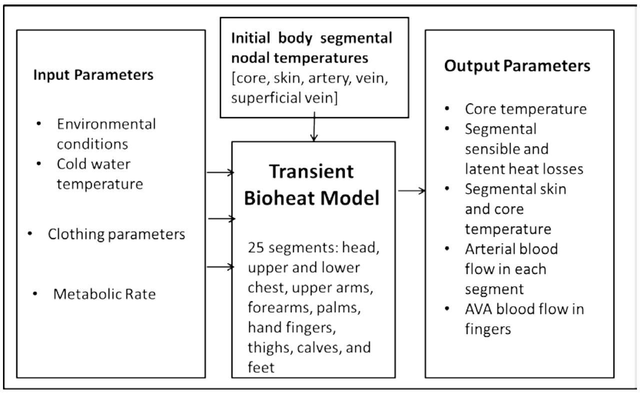

Figure 2: Flow chart of bioheat model inputs and outputs.

When the local finger skin temperature drops below 32°C, constriction of *AVA* flow to the fingers occur [17,22,23]. If the body is subject to warm conditions (T_{core}>36.7°C) and the fingers are exposed to cold conditions where the local skin temperature crosses the $T_{CIVD,min}$ limit, *CIVD* response is triggered and a second *CIVD-AVA* mechanism is activated. The response path of the *CIVD-AVA* flow is described by the *AVA* flow being dilated below a finger skin temperature $T_{CIVD,min}$ where it remains dilated until it reaches a skin temperature $T_{CIVD,max}$. Then the *AVA* is constricted again once above a temperature $T_{CIVD,max}$ and remains constricted while the skin temperature is dropping till $T_{CIVD,min}$. The periodic constriction and dilation of the *AVA* in the fingers results in the periodic *CIVD* finger skin temperature response observed in experimental literature [10]. The *AVA* and *CIVD* triggering conditions for ON and OFF state are summarized in Table 1. The *CIVD* response is central in the sense that it depends on the average core temperature of the body and this has been determined by the threshold set at 36.7°C as reported by many researchers [11,22,23]. However, the local heat loss rate from the finger will control the openness of the AVA and the onset temperature of the *CIVD* activation. Rida et al. [20] reported a correlation, which is used in this work, for determining $T_{CIVD,min}$ as a function of the initial heat loss in the finger immediately after immersion as follows:

Average Body Core Temperature	**Finger skin temperature**	**Rate of change of skin temperature**	***AVA* state**	***CIVD* mechanism**
T_{cr_av}<36.7°C			OFF	OFF
T_{cr_av}>36.7°C	$T_{skin} \geq 32°C$		ON	OFF
	$T_{CIVD,max} \leq T_{skin} < 32°C$		OFF	OFF
	$T_{CIVD,min} \leq T_{skin} < T_{CIVD,max}$	$\frac{dT_{skin}}{dt} < 0$	OFF	OFF
	$T_{CIVD,min} \leq T_{skin} < T_{CIVD,max}$	$\frac{dT_{skin}}{dt} > 0$	OFF	ON
	$T_{skin} < T_{CIVD,min}$		OFF	ON

Table 1: The *AVA* and *CIVD* triggering conditions for ON or OFF state in fingers.

$$T_{CIVD,\min} = 0.4429 \times q_{o,finger} + 9.2916 \text{ Valid for } 1.59\text{ W} < q_{o,finger} < 10.48\text{ W}$$

where $T_{CIVD,min}$ is in degree Celsius and finger initial sensible heat loss, $q_{o,finger}$ is in watts. When the initial finger heat loss is high, it triggers earlier *CIVD* reaction at higher $T_{CIVD,min}$. The heat loss through the fingers depends on the difference between the finger skin and local environment temperatures and on the associated heat transfer coefficient. The magnitude of *CIVD* defined as $\Delta T_{CIVD} = (T_{CIVD,\max} - T_{CIVD,\min})$ is taken as 4°C which occurred for the majority of subjects from the published experimental data [17,21].

Numerical simulation

For given initial thermal state of the human body, metabolic rate, ambient conditions, physiological and physical parameters inherent in the bioheat model of the human body, the simulation program will update at every time step the core and regional blood flow rates, thermoregulatory responses, skin vapor pressure, and temperatures of the core, skin, artery, vein, and superficial vein nodes. The numerical model of Karaki et al. [11] is implemented to calculate the *AVA* blood flow at any time step *i*. At the start of simulation, the *AVA* is initialized to zero and the associated bioheat model of Karaki e al. [11] is allowed to reach steady state at the initial conditions of the simulated experiment (metabolic rate, environment conditions of the room, and clothing parameters for each segment as applicable) before beginning the transient analysis associated with hand and forearm cold immersion. In other words, suitable initial conditions were determined starting from the neutral conditions of T_{cr}=36.7°C, and T_{sk}=33.7°C to simulate a relatively long exposure to any pre-conditioning environment. The obtained steady state values were then used as initial conditions for the unsteady calculations. In the simulations, the convective heat transfer coefficient was set to be 5.1 W/m^{2}•°C for air velocity is lower than 0.2 (m/s) for a reclining person according to ASHRAE [24]. The convective heat transfer coefficient in air is set at 7.6 W/m^{2}•°C for fingers, 5.4 W/m^{2}•°C for the palm and arms, and 3.1 W/m^{2}•°C for the rest of the body [25]. During hands and forearm immersion in water the convective heat transfer coefficient is much higher and a value of 50 W/m^{2}•°C between the immersed skin and water bath.

A time step Δt of 0.02s is used over the desired simulation period given that a complete cycle of the heart beat approximately takes 0.8s at the neutral body state. The cycle can vary with metabolic rate and core temperature [19] and therefore, at high metabolic rate, a smaller time step of 0.005 s is adopted.

Results and Discussion

In this section, the hand cooling human thermal tool based on thermal modeling and physiology is validated by comparing simulated body core temperature variation and associated sensible heat loss through hands and forearm with published experimental data. This will be followed by simulations at different environmental conditions to compare effectiveness of the passive cooling method in reducing core temperature recovery time to reach its neutral temperature value of 37.0°C.

Validation with Published Experiments

Giesbrecht et al. [2] reported experimental data on body core temperature change of firefighters who immersed hands and forearms in 10°C and 20°C water after three 20-min exercise wearing 'turn-out gear' (heavy clothing) each followed by a 20-min rest/cooling (21°C air at relative humidity of 40%) without turn-out gear. The metabolic rate during exercise and rest were taken 6 MET and 1 MET respectively. The experimental conditions that are simulated for validation purposes are presented in Table 2.

Figures 3a,3b presents a plot of the Giesbrecht et al. [2] reported measured core temperature changes data and the model predicted values for hand and forearm cold water immersion at (a) 10°C and (b) 20°C and for control case of air cooling at 21°C. The predicted decrease and increase in core temperature is within acceptable accuracy with max difference less than ± 0.2°C. The change in core temperature for hand immersion at 20°C is not significant. In addition, hand immersion alone without the forearm does lead to significant reduction in core temperature compared to the control case of air immersion. Whereas, the water immersion of forearm and hands resulted in the best response and fastest reduction in core temperature.

Figures 4a-4c shows the variation in time of the predicted (a) finger skin temperature, (b) finger *AVA* blood flow, and (c) the sensible heat loss from the forearm and hands during *AC* for the conditions of the experiments of Giesbrecht et al. [2] for immersion of both hand and forearm. The *AVA* blood flow $\dot{m}_{AVA}$ into the finger synchronizes with local cooling/heating modes during the one hour simulation period where the open *AVA* warm blood heats the finger and when *AVA* closes, the finger skin temperature goes down. The minimum finger skin temperature to trigger *CIVD* was 12.8°C caused by the high heat loss experienced immediately after the immersion of finger in cold fluid 10°C water. However, during the immersion in 20°C the minimum finger skin temperature to trigger *CIVD* reaction was also 12.8°C but this temperature was not reached due to the relative high water temperature. The *AVA* was closed during cooling until finger skin temperature reached its minimum threshold temperature at which *AVA* opened and stayed open during heating. The sensible heat loss from the hands and forearms shows the effect of the fast cooling during water immersion compared to air exposure where the sensible

Cooling method description	**Ambient conditions during exercise**	**Ambient conditions during rest**	**State during exercise and rest**
Air cooled (control case)	40°C 40% RH	21°C 40% RH	Initial state: M=6 MET Clothing during activity Clothing resistance=0.7 clo (0.08 m^{2}•°C/W) Rest state: M=1 MET Clothing during rest Clothing resistance=0.7 clo (0.08 m^{2}•°C/W)
Hands and forearms immersed at 10°C water			
Hands immersed at 10°C water			
Hands and forearms immersed at 20°C water			
Hands immersed at 20°C water			

Table 2: Summary of simulated experimental conditions of Giesbrecht et al. [2].

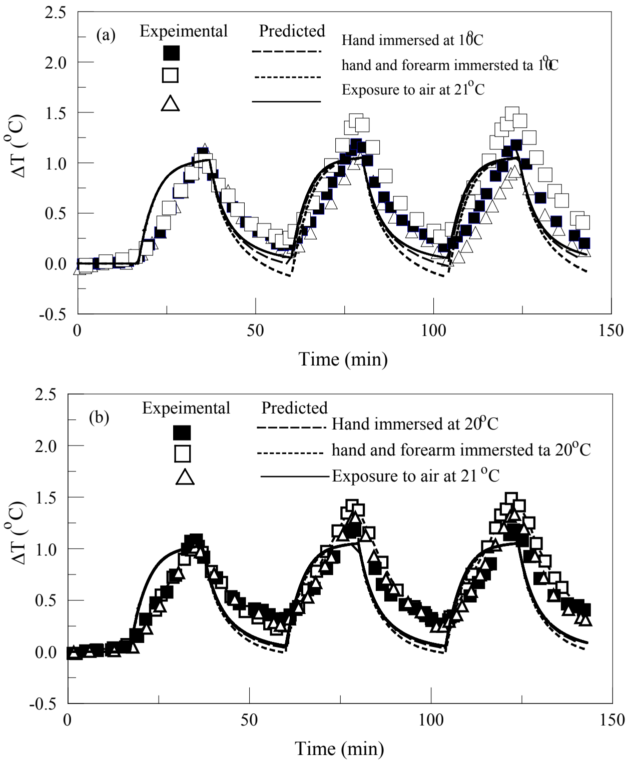

Figure 3: A plot of the Giesbrecht et al. [2] reported measured changes in core temperature and predicted values by our model for immersion of hands and of hands and forearms in cold water at (a) 10°C and (b) 20°C and for control case of air at 21°C.

heat loss during the cooling period is 648.05 kJ, 386.82 kJ for water at immersion temperatures of 10°C and 20°C, respectively compared to 217.8 kJ for air immersion at 21°C. The bioheat and *AVA/CIVD* model captures both physiology and physics predicting well the observed core temperature change and finger skin temperature during exercise and hand-forearm cooling in rest periods.

Case Studies

The effectiveness of the active cooling method depends on activity level, associated clothing and ambient conditions, and immersion water temperature for the hands and fore arms. In this section we will demonstrate the use of the simulation tool in assessing the performance of hand and forearm immersion in cold water in the rate at which core temperature is decreased to reach its neutral value of 37°C. Three water immersion temperatures of 10°C, 15°C, and 20°C were selected at two ambient temperatures of 28°C and 35°C with assumption that the clothing resistance is for athletics ensemble composed of pants and T-shirt. The water immersion of hands and forearms takes place for a period of 40 minutes when core temperature reaches a critical value of 38°C. The selected cases for the simulations are summarized in Table 3 and the control case will be resting in cool environmental condition at 21°C and 40% relative humidity with no hand and forearm cold immersion.

Figure 5a-5b shows the variation in time of the predicted body core temperature for active cooling at different water temperatures for (a) ambient air of 28°C and (b) ambient air at 35°C. The time needed for the core temperature to cool down from 38°C to 37°C is calculated and is presented in Table 4. It takes the active person 33 minutes when subject to air cooling at 21°C to reach core temperature of 37.0°C while only 15 minutes are needed when hands and forearms are immersed in water at 10°C. The ambient condition of 35°C results in faster rise in core temperature, but the following cooling rate is slightly delayed to achieve the 37°C core temperature [26]. Figure 6 shows the variation in time of the predicted (a) total body sensible heat loss during the cooling period when immersion hands and forearms at 10°C for the two different ambient temperatures, (b) the sensible heat loss from the forearm and hands during AC for the cases of ambient air at 28°C, (c) total body sensible heat loss during the cooling periods for the cases of ambient air at 35°C, and (d) *AVA* perfusion through the finger during immersion hands and forearms at 10°C water. Cold Induced Vasodilatation *CIVD* took place during hands and forearm immersion at 10°C and $T_{minCIVD}$

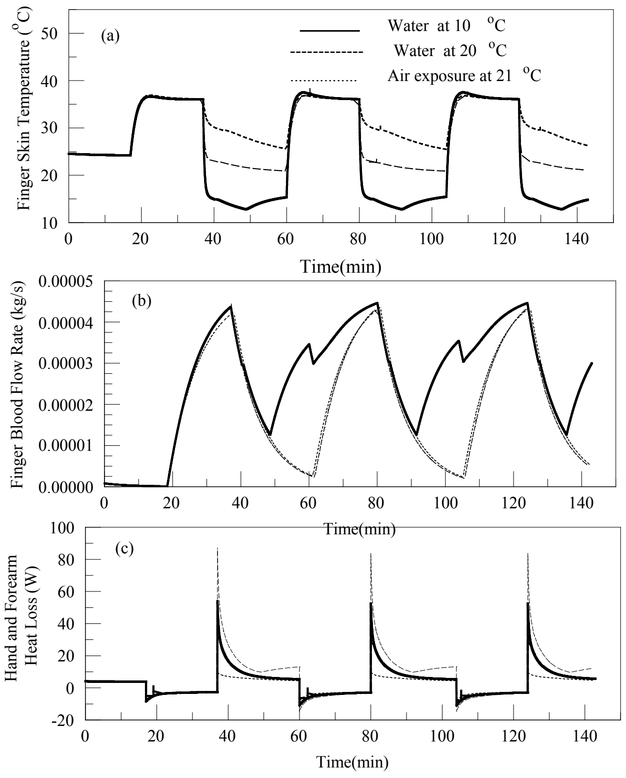

Figure 4: The variation in time of the predicted (a) finger skin temperature, (b) finger *AVA* blood flow, and (c) the sensible heat loss from the forearm and hands during *AC* for the conditions of the experiments of Giesbrecht et al. [2] for immersion of both hand and forearm.

Case No.	Water temperature (°C)	T_{amb} (°C), Relative Humidity (%)	State
1	10°C	28°C, 40%	Initial state: M=6 MET Clothing during activity Clothing resistance=5.0 clo (0.57 m²•°C/W) Rest state: M=1 MET Clothing during rest Clothing resistance=0.7 clo (0.08 m²•°C/W)
2	15°C	28°C, 40%	
3	20°C	28°C, 40%	
4	No water immersion (control case)	21°C, 40%	
5	10°C	40°C, 40%	
6	15°C	40°C, 40%	

Table 3: Simulated conditions using the validated modeling tool at various ambient conditions and water immersion temperatures.

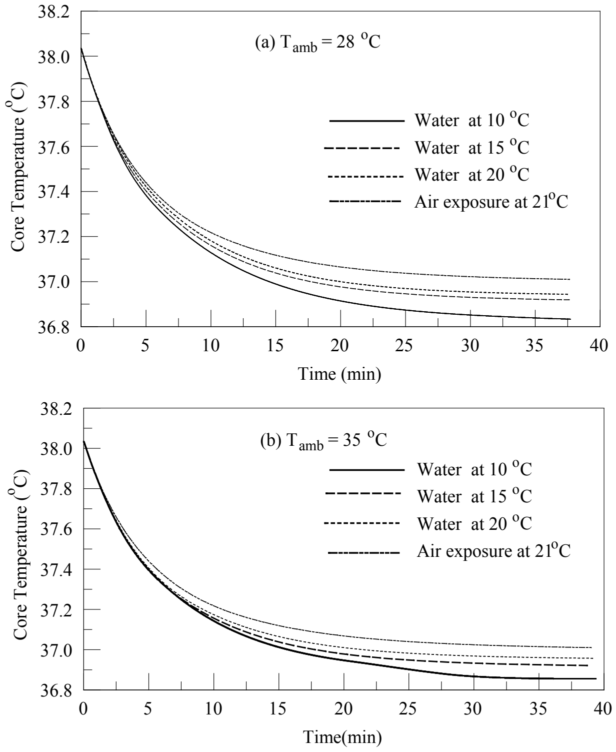

Figure 5: The variation in time of the predicted body core temperature for active cooling at different water temperatures for (a) ambient air of 28°C and (b) ambient air at 35°C.

Case No.	Ambient Air Temperature (°C)	Cooling period to reach 37.0°C
Case 1	28	920 sec [15min]
Case 2	28	1029 sec [17min]
Case 3	28	1200 sec [20min]
Case 4 (control case)	21	2200 sec [36.6 min]
Case 5	35	943 sec [15.7min]
Case 5	35	1066 sec [17.7min]
Case 7	35	1290 sec [21.5min]
Case 8 (control case)	21	2300 sec [38 min]

Table 4: Time needed for body core temperature to cool down from 38°C to 37°C for the different cases at ambient temperatures of 28°C and 35°C.

was at 11.5°C when ambient was at 28°C while $T_{minCIVD}$ was11.72°C when ambient air was at 35°C.

It is clear that significant heat loss takes place in the first few minutes of the immersion in water. The total dissipated sensible and latent heat in energy in kJ for two periods was calculated: 1) during the 40-minute rest and cooling period and 2) for the period required for the core temperature to drop to 37°C. The values of dissipated energy are provided in Table 5. The first observation is that over the 40 minute period, the total dissipated energy is almost the same in all the cases. Note that latent heat loss in air is higher than the cases of water immersion. This is an important feature of the cooling method since evaporation can cause discomfort if clothing does not permeate water vapor. The average sensible heat loss through the whole body during the period needed for the core temperature to reach 37°C was calculated for the various cases. It is found that immersion of forearms and hands in water at 10°C results in an average heat loss of 106.2 W over 15 minutes compared to 75.9 W over 33 minutes for air cooling at 21°C while the average losses at 15°C and 20°C water immersion were 88.56 W over 17 minutes and 72.09 W over 20 minutes, respectively. The total dissipated sensible energy loss from one hand and forearm was also calculated over cooling periods. Results summarized in Table 5 show that the highest heat loss occurred when immersing the hand and forearm in 10°C water at 93 kJ during the 40 minute period and the lowest heat loss was 30 kJ when only exposure to cool air of 21°C took place.

Although the total heat dissipation over the 40 minutes period is the same, the water cooling method can be considered as a more effective method for cooling due to two reasons. The first reason is

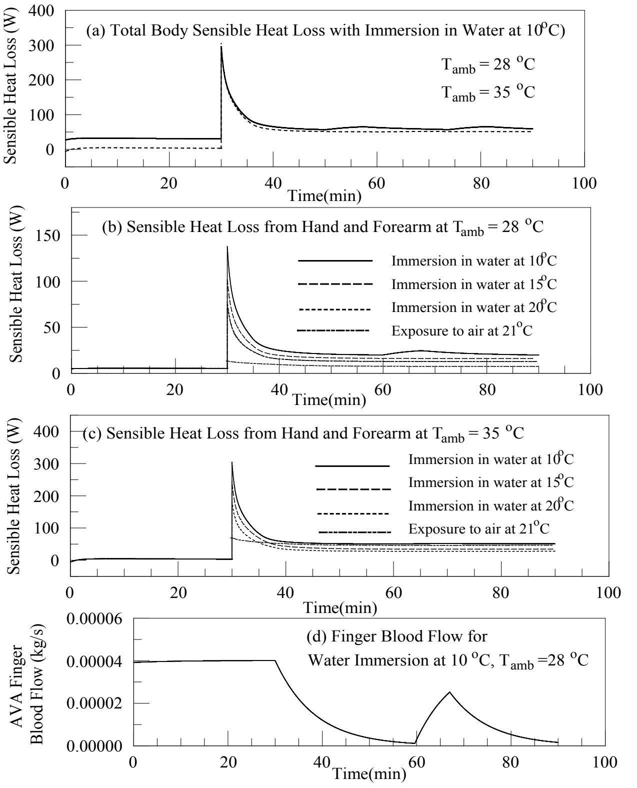

Figure 6: The variation in time of the predicted (a) total body sensible heat loss during the cooling period when immersion hands and forearms at 10°C for the two different ambient temperature, (b) the sensible heat loss from the forearm and hands during AC for the cases of ambient air at 28°C, (c) total body sensible heat loss during the cooling periods for the cases of ambient air at 35°C, and (d) AVA perfusion through the finger during immersion hands and forearms at 10°C water.

Case No.	Total dissipated sensible heat energy [kJ]	Total dissipated latent heat energy [kJ]	Total dissipated sensible energy [kJ]	Total dissipated latent energy [kJ]
	Cooling period of 40 minutes		Period of cooling until core temperature reached 37°C	
Case 1	202.76	57.01	97.77	34.8
Case 2	179.84	58.28	91.13	37.76
Case 3	155.51	59.9	86.51	42.14
Case 4	179.38	71.52	150	65.86
Case 5	93.1	2.6	35.7	1.47
Case 6	71.4	3.3	29.6	1.7
Case 7	56.3	3.8	25.4	2
Case 8	30.1	4.8	19.5	3.55

Table 5: Sensible and latent heat loss through one hand and forearm in kW for two periods: 1) the 40-minute rest and cooling period and 2) the period required for the core temperature to drop to 37°C.

that water immersion reduces the heat stress period by lowering at a faster rate the body core temperature. The core temperature needed 13 to 18 minutes to drop to its neutral value when using the water cooling method compared to about 40 minutes with air cooling. In addition localized water cooling devices are more efficient than space cooling through air distribution systems [27,28]. The surface area for a water cooler is much smaller in size and surface area which reduces surrounding possible environmental heat gain to the water cooler and therefore improving it efficiency. Space cooling heat losses are high due to envelop large surface area and space volume in which the occupants sit. The second feature that makes active cooling more attractive is the portability aspect where these coolers of low power needs can be used in hot outdoor conditions for various human activities.

Conclusions

The active cooling method for fast reduction of body core temperature of 38°C due to physical exertion to acceptable value of 37°C is investigated by numerical simulations using a robust segmental bioheat model. The model is shown to replicate experimental results on fighter fighters reducing their core temperature over rest period by 1°C in less than 20 minutes when hands and forearms are immersed in water at 15°C. The ability to predict human thermal response (core temperature) during localized cooling by modeling offers a valuable tool for use in medical applications to help thermally stressed patients and for optimization of rest periods of workers and athletes to improve performance. An important feature of the model is its ability to capture cold-induced vasodilatation (CIVD) response in the fingers.

The study showed that the implemented modeling approach is successful in predicting human thermal response to active cooling by immersion of hands and forearms in cold water to help in achieving the alleviation of thermal stress of workers through AC mechanism. The developed modeling tool can be used in designing optimal intervention AC methods for use as an emergency treatment for patients with hyperthermia.

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