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Simulation of Human Thermoregulatory Responses to Micro-Cooling in Hot Environments

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ABSTRACT

Situations occur where individual cooling is desirable to reduce heat injury and improve productivity. Simulation of human responses while wearing possible micro-cooling systems can assist planning and shorten their development. A thermo-physiological model modified for micro-cooling was developed to predict body temperatures, other physiological parameters, and discomfort in hot environments. The micro-cooling simulated was: 1) uniform whole body cooling under clothing, 2) cooling of upper torso with a water cooled vest under clothing and 3) cooling of upper torso with an air cooled vest under clothing. The modeling suggests upper torso cooling above 200 watts can cause vasoconstriction reducing the effectiveness of greater cooling.

INTRODUCTION

Many situations inside and outside are just too hot to work in effectively and safely. Often it is impossible, impractical or undesirable to alter the environment of the work area. Further required protective clothing against toxic gases, pathogens, fire, abrasion and such can further exacerbate the situation. Because of the environment, activity and protective clothing not all of the metabolic heat produced can be transferred to the environment causing body temperatures to rise and impairing the person's health, function and concentration. In such situations direct microclimate cooling of the person's skin by some electrical or mechanical means could facilitate the task being done and reduce the risk and complications of hyperthermia.

To assess the potential of micro-cooling for a task and reduce the health risks and time delays of human

experiments, computer simulations of the responses of humans wearing micro-cooling were performed.

MICRO-COOLING

The simulation employed an existing thermo-physiological model (Gagge, 1986) that has proven successful for warm and hot conditions. Micro-cooling capabilities were added to this model. The model characterizes the person as 2 bio-thermal compartments representing the core and skin and is surrounded by a 3rd passive compartment representing the clothing.

In this scheme, all of the metabolic heat is generated in the core compartment. Except for the energy lost by breathing and the work of the muscles all of the remaining heat can flow to the skin. Core temperature is maintained within narrow limits by actively regulating blood flow to the skin and to a lesser extent by shivering. Both controls are modeled as proportional to deviations in body temperatures. All other heat transfer processes of the core are passive. The skin in turn transfers the heat to the environment. The secretion of sweat for evaporation is the skin models' only actively controlled (proportional) heat loss mechanism.

UNIFORM MICRO-COOLING OF WHOLE BODY

Initially, micro-cooling was explored assuming it to be uniformly applied to all the skin without changing the other heat transfer pathways. Figure 1 has results for a person 60 minutes after going outside from a comfortable location into the noon day heat and sun of a summer day in Georgia and working steadily with a metabolism three times that of resting while wearing a long sleeved shirt and trousers. It is seen that body temperatures decrease fairly linearly toward healthier levels with increased cooling. The simulated uniform micro-cooling also reduces the physiological effort of the

task by reducing sweating and blood flow to the skin (not shown).

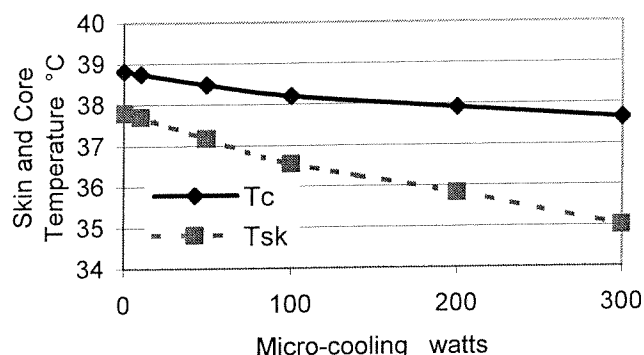


Figure 1. Skin and core temperatures with ideal uniform micro-cooling under long sleeved shirt and trousers after walking one hour in 37°C air with 17°C dew point in direct sun light near solar noon with a 1.8m/s wind.

The initial simulation implies micro-cooling may be desirable and beneficial. However, the uniform micro-cooling simulated above is ideal and hypothetical and may not be do-able. How can a real underclothing micro-cooling system be configured? Could water be circulated through tubes next to the skin in a cooling vest and give similar results, or could air be forced to flow over the skin of the chest and back for cooling. For an idea of the feasibility, advantages and disadvantages of more practical micro-cooling systems, the simulation model was modified to represent the effects of local water and air-cooling systems worn under clothing.

REGIONAL MICRO-COOLING

The above model was extended to include the effects of non-uniform micro-cooling as would occur with a cooling vest worn under clothing. For this, the skin and clothing compartments were divided into mechanically cooled and normal parts. The sizes of the skin compartments are flexible and for the presented results the vest covers the chest and back or about 30% of the total skin area.

A model schematic (Figure 2) shows the core compartment transferring heat to separate skin compartments under normal clothing and under the cooling vest. The cooling is supplied by cooled air or re-circulated water from an external cooling unit.

The code writing for these models was done with the aid of a drawing technique (Dabney and Harman, 2001) that permits model construction by connecting components (heat sources and sinks, multipliers, functions, adders, gains, output display etc) similar to the drawing of an electrical circuit diagram. An example from the model is shown in Figure 3. This model's various subsections and details for heat and mass transfer (Holman, 1997) and physiological function are detailed on 44 separate sheets. Overall, this technique greatly reduces code

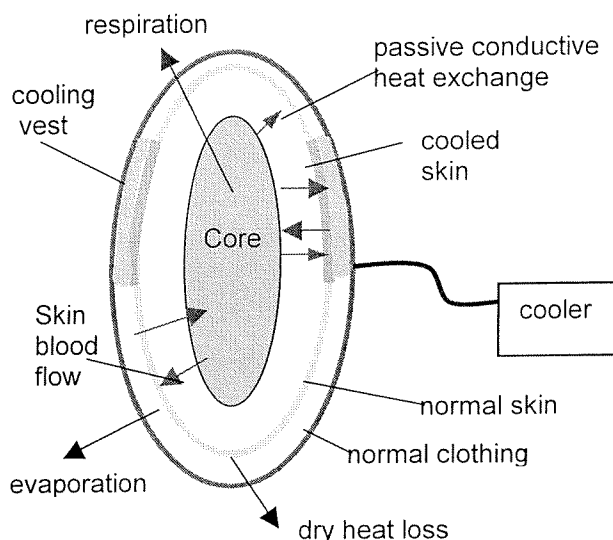


Figure 2. Schematic of model with regional micro-cooling.

writing time and errors and the detailed programming expertise needed to develop working computer models.

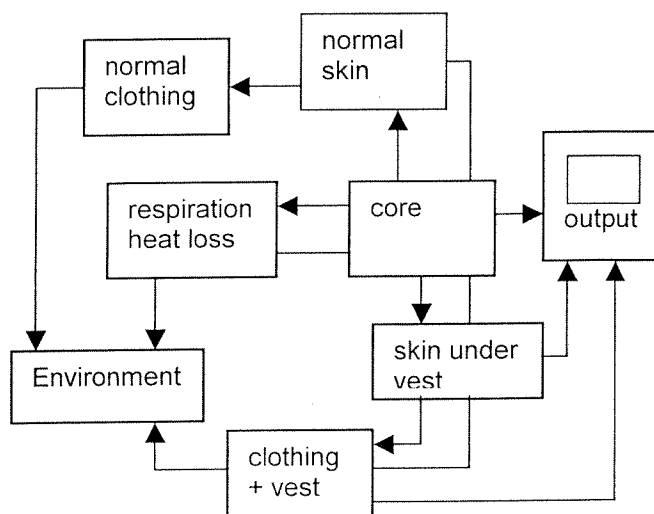


Figure 3. Example of model's representation.

Water cooled vest

For upper torso micro-cooling model, cooled water is circulated through a vest worn under the clothing. In the vest, water flows through 6.4mm tubes in contact with the skin. The tubes in a vertical parallel pattern on 13mm centers are attached to the inner surface of a thin T-shirt. The vest adds thermal and vapor resistance. Thus when cooling water is not flowing, the vest increases the difficulty of losing body heat from the skin of chest and back.

An external device cools the water and returns it to the individual. The machine and vest were modeled to provide up to 300 watts of vest cooling. Water temperatures and flow rates were not considered, as it

was assumed that they could be determined later for the modest heat removal rates required.

The results of simulations for a typical person wearing trousers and a water cooled vest under a long sleeved shirt and walking in direct sun light for one hour at solar noon with 37°C air, 17°C dew point and 1.8 m/s wind are presented in Figure 4.

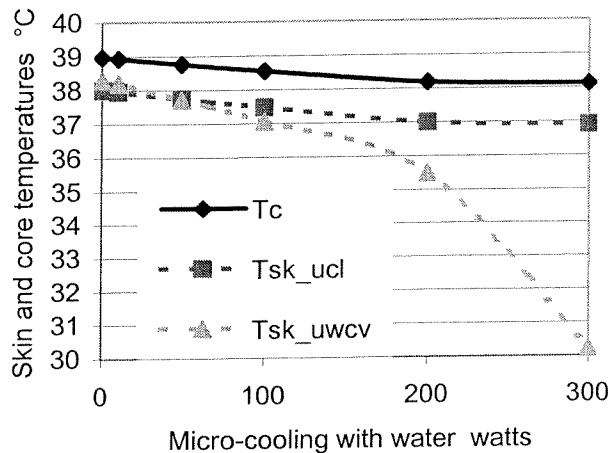


Figure 4. Core (Tc) and skin (Tsk) temperatures with Tsk_ucl under normal clothing and Tsk_uwcv under water-cooled vest. All points are after an hour of walking in direct sun light near solar noon with 37°C air, 17°C dew point and 1.8m/s wind speed.

With this simulation (Figure 4), more cooling is required to achieve the same core temperature (Tc) as with the ideal uniform micro-cooling system simulated for the same conditions in Figure 1.

Air-cooled vest

The air-cooling system used a vest under the clothing of the same size as the water-cooled vest. Air injected at four locations around the torso from vertical manifolds between waist and armpit directed the air horizontally over skin of chest and back. It was assumed that the air would leave the garment thru vents to the ambient. The air conditioning took place in a black box where a constant flow of ambient air was cooled by the specified watt level. When cooling wattage was high and or the ambient humidity was high, condensation occurred in the black box and the air was assumed to then leave with 100% RH.

Skin and core temperature results with the air-cooled vest for the same Georgia summer conditions as in Figures 1 and 4 are displayed in Figure 5. Results were obtained for external cooling rates of 0 to 300 watts with a constant airflow of 10 L/s. Also shown are responses with no airflow (0 L/s), revealing that airflow even with out cooling has a substantial beneficial thermal effect.

Overall, the results show that internal body temperatures are less and less elevated with increased cooling. However beyond about 200 watts, the regional upper torso air and water systems can overcool the skin causing local vasoconstriction that reduces micro-cooling effectiveness. (Compare Tc of Figures 1,4, 5)

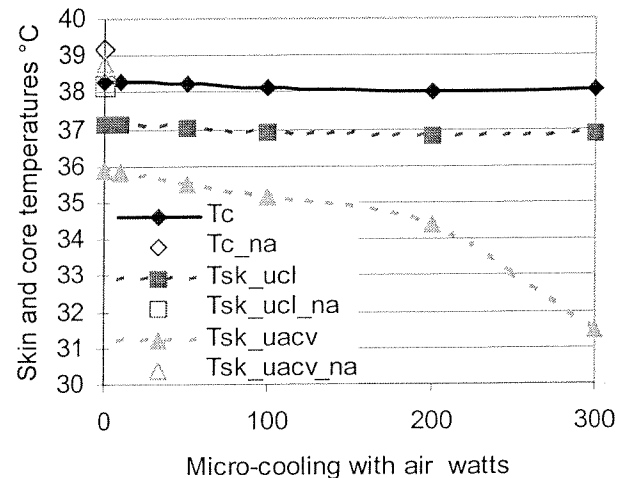


Figure 5. Core and skin temperatures with Tsk_ucl under normal clothing and Tsk_uwcv under air-cooled vest. All points are after an hour of walking in direct sun light near solar noon with 37°C air, 17°C dew point and 1.8m/s wind speed. Tc_na, Tsk_ucl_na, and Tsk_uacv_na are core and skin temperatures with no airflow through vest.

Performance in sun and shade

The following section gives simulated human responses in more detail with and without the solar load. In the shade the average temperature of surrounding surfaces was assumed to equal air temperature. Figures 6-8 give the simulated responses for the water-cooled system and Figures 9-11 give those for the air-cooled system. In both sets of figures the beneficial effect of solar shading on body temperatures, skin blood flow and skin moisture is clear.

The regional coolers are seen to decrease skin temperature under them to below 34°C (Figures 6 and 9) reducing local blood flow to the skin (Figures 7 and 10). This reduces heat transport by the blood from core to skin often causing the core temperature to rise. With full sun, the skin directly under both of the local micro-cooling systems is seen to reach 34°C with 200 watts of cooling in the sun and with 100 watts in full shade. The consequences of vasoconstriction are most evident in the shaded environments suggesting the desirability of automatic or manually adjustable cooling to prevent excessive skin cooling.

Skin moisture (Figures 8 and 11) is characterized by skin wettedness or the fraction of the skin covered with water

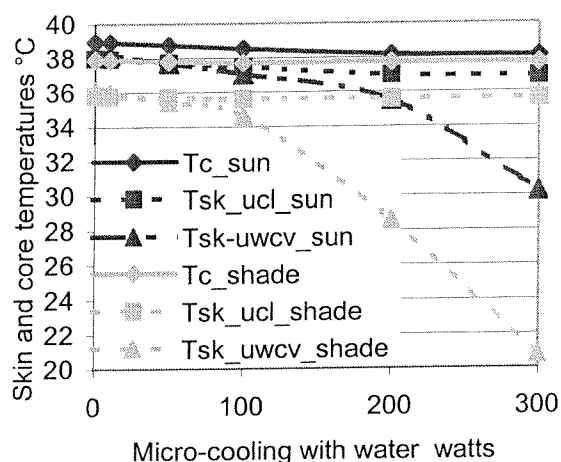


Figure 6. Effect of sun and shade on skin and core temperatures with water-cooled vest, where _ucl and _uwcv is Tsk under normal clothing and under water-cooled vest. _sun and _shade designate full sun and full shade.

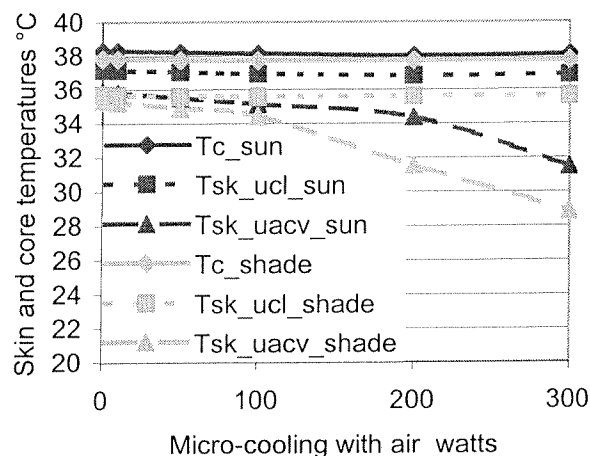


Figure 9. Effect of sun and shade on skin and core temperatures with air-cooled vest, where _ucl and _uacv indicates Tsk under normal clothing and air-cooled vest. _sun and _shade designate full sun and full shade.

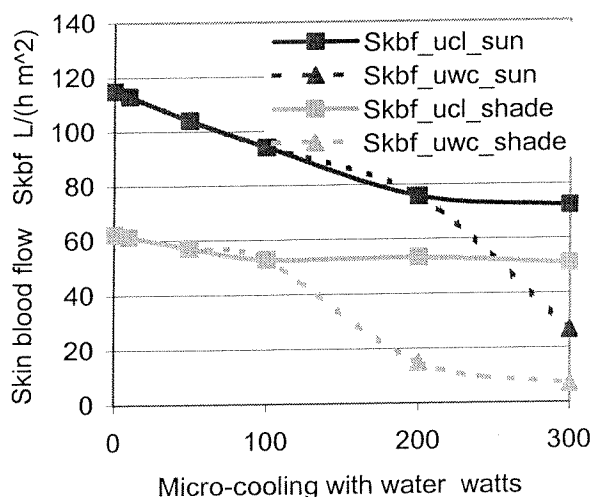


Figure 7. Effect of sun and shade on skin blood flow with water-cooled vest, where _ucl and _uwcv is Skbf under normal clothing and under water-cooled vest. _sun and _shade designate full sun and shade.

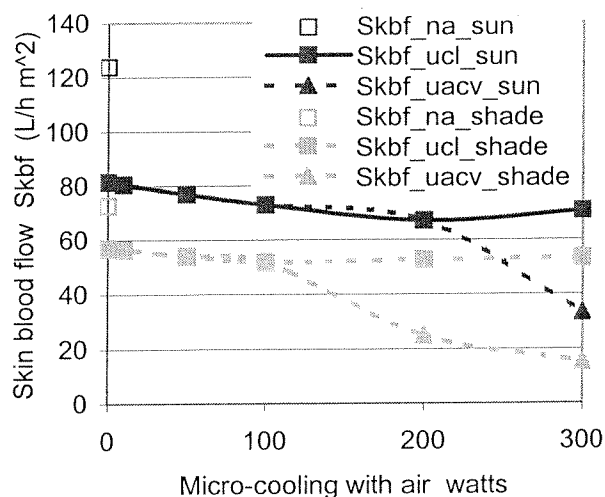


Figure 10. Effect of sun and shade on skin blood flow with air-cooled vest, where _na is no air flow through vest, _ucl and _uacv is under clothing and under air cooled vest with air flow of 10L/s. _sun and _shade designate full sun and full shade.

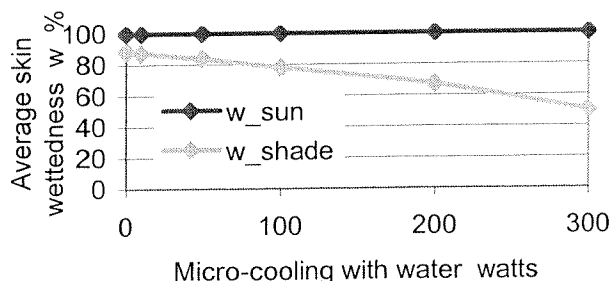


Figure 8. Skin moisture with water-cooled vest.

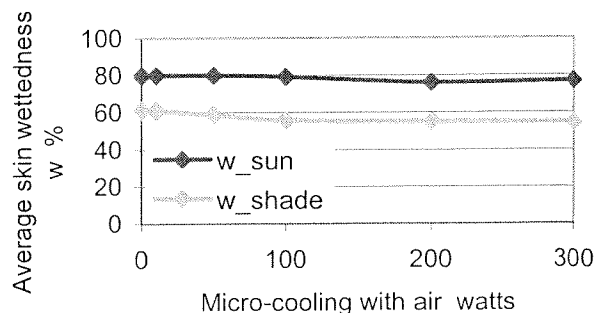


Figure 11. skin moisture with air-cooled vest.

necessary to evaporate the observed sweat rate. Elevated skin moisture decreases the protective capabilities of the skin in many ways and correlates with thermal discomfort in warm conditions. Skin wettedness levels are less under the air-cooled vest, particularly in the sun.

The simulation indicates that sweat rates (Figure 12) decrease with micro-cooling. A person working in the hot sun while wearing the air-cooled vest can be expected to sweat substantially less and this contributes to the drier skin of Figure 11. Any sweat reduction in turn would reduce the drinking water needs of the task.

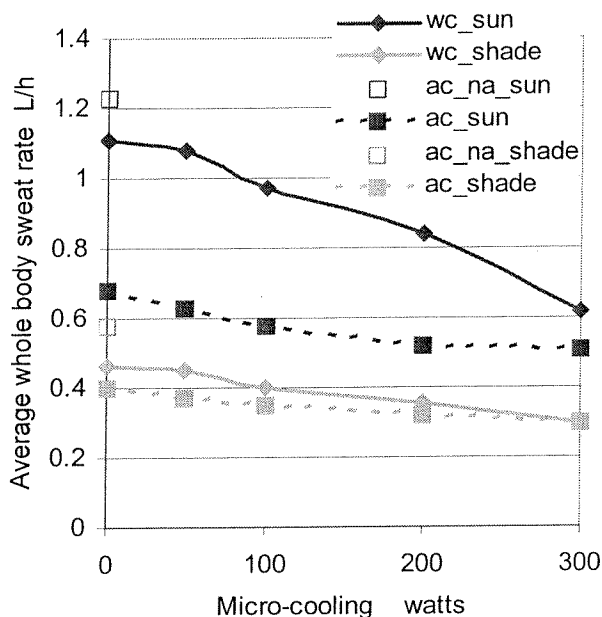


Figure 12. Comparison of simulated sweat rates with water (wc) and air-cooled (ac) vests in sun and shade. _na indicates no airflow.

The physiological effort of body temperature regulation imposed by the environment and activity as indicated by increases in blood flow, sweat rate, body temperatures and skin moisture lead and correlate with feelings of thermal discomfort. The simulated discomfort responses show (Figure 13) that for these environments and activity, this feeling is less with air micro-cooling system.

CONCLUSION

Bio-thermal simulation indicates that micro-cooling is beneficial for hot conditions. However excessive local cooling can cause local vasoconstriction reducing the effectiveness of the cooling. The simulation further indicates that micro-cooling the skin with air is probably superior to water-cooling because blood flow to the skin is generally less and the air movement over the skin better enables the evaporative cooling capabilities of the body to function resulting in drier skin with less discomfort.

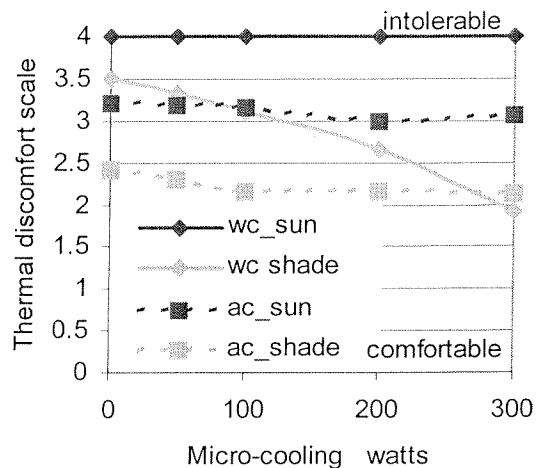


Figure 13. Comparison of thermal discomfort resulting with water (wc) and air-cooled (ac) micro-cooling systems in sun and shade.

These results are from computer simulation and as yet are unverified by measurements on humans. But the work indicates the value of bio-thermal simulation to initially quantify and refine design approaches while reducing the need and risks of exploratory experiments with humans.

DISCLAIMER

The views, opinions and/or findings in this paper are those of the author and should not be construed as an official Department of the Army position, policy or decision, unless so designated by other official documentation. Approved for public release; distribution is limited.

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