EVALUATION OF PERSONAL COOLING SYSTEMS FOR SOLDIERS

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INTRODUCTION

According to body heat balance theory (ASHRAE, 2005), thermal comfort is achieved when the amount of heat produced by the body is approximately equal to the amount of heat lost to the environment. In extremely hot environments and/or at high activity levels, the only way the body can lose excess heat is by the evaporation of sweat from the body surface. The rate of evaporative cooling is dependent upon the vapor pressure gradient between the skin surface and the environment and the rate of air movement around the body and between clothing layers. Unfortunately, protective clothing such as body armor and helmets can inhibit the evaporation of sweat. In addition, the weight, rigidness, and design of protective garments may increase the energy cost associated with wearing them during activity. Consequently, soldiers operating in hot environments often experience heat stress symptoms that affect performance on extended operations. To mitigate these problems, the U. S. Army has been searching for new technological advances in personal cooling systems (PCS) that have been developed by manufacturers in the private sector. The cooling effectiveness of some of these PCS has been quantified using a sweating thermal manikin (Xu et al., 2005). The purpose of this study was to evaluate the cooling effectiveness of selected personal cooling systems using a sweating manikin and human subjects (soldiers) under hot desert conditions.

METHODS

A number of PCS were selected for manikin evaluation based on work completed in the first phase of this project and directives from military personnel. Nine of these PCS were also evaluated on human subjects, and their data are included in this paper. The PCS represented three types: 1) ambient air systems which circulate air under the body armor, 2) phase change materials which absorb body heat for a limited time, and 3) refrigeration systems that circulate chilled water through tubes in a vest. (See Table 1.) Each PCS was evaluated as part of the basic military ensemble which consisted of the Army lightweight desert combat uniform (DCU) with belt, underwear briefs, T-shirt, Kevlar® helmet with internal pads, interceptor body armor, socks, and athletic shoes.

Manikin Tests. Procedures given in ASTM F 2371 “Measuring the Heat Removal Rate of Personal Cooling Systems Using a Sweating Heated Manikin,” (ASTM, 2006) were followed. The manikin (1.80 m² surface area, 177.2 cm height) has 20 independently heated thermal zones equipped with ports for continuous sweating. Power cables, measurement cables, fluid supply tubes, and fluid return tubes connect to his face. The system is computer operated.

The manikin’s skin temperature was controlled at 35ºC, and his skin surface was saturated with water. The environmental conditions for the sweating manikin tests were: ambient air temperature, 35ºC and air velocity, 0.3 m/s. All PCS were tested at 40% relative humidity – the condition specified in the standard. However, ambient air circulation systems were also tested under drier, desert conditions of 26% relative humidity to see if their performance improved. First a baseline test was conducted on each ensemble with the PCS turned off. In the case of phase change materials, a "used" component of the PCS was tested. As soon as steady-state conditions had been reached, a 30 minute test was run. The average power level to the manikin was recorded.

Next the "heat difference" program was opened on the manikin's computer, and the PCS was turned on. This program quantified the cooling rate of the PCS by subtracting the average power level during the baseline test from the power used to keep the manikin's skin temperature at 35°C when the PCS was turned on. Data were collected for two hours. Three replications of the tests were conducted.

Human Subject Tests. The procedures in ASTM F 2300, Standard Test Method for Measuring the Performance of Personal Cooling Systems Using Physiological Testing (ASTM, 2006) were followed except that the environmental conditions were hotter. Groups of four subjects – two in the morning and two in the afternoon – evaluated three personal cooling systems and the baseline condition without a PCS over a seven-day period (including three days for heat familiarization). The design of the experiment was a 4 x 4 Latin square design where subjects and test days serve as blocks. Each subject wore all four PCS treatments in a different order. The Latin square design was repeated two more times for a total of 12 test subjects in a three-week session. This design for a three-week session was conducted three times in so that nine PCS could be evaluated with 36 subjects.

The volunteer subjects were male soldiers from Ft. Riley, Kansas that met the selection criteria. The subjects were Caucasian, African American, Asian, and Hispanic; they ranged in age from 19-38 years, height from 1.70-1.95 m, and weight from 65-100 kg. The environmental conditions in the test chamber were: air temperature, 40°C; relative humidity, 20%; air velocity, 2 m/s (4.5 mph), and mean radiant temperature, 54.4°C (to simulate a solar load).

Each group of four subjects exercised on treadmills in the environmental chamber for three days prior to the collection of data to familiarize themselves with the hot conditions and the experimental protocol. Then they wore three PCS and the ensemble with no PCS in a random order during the next four days. Each subject walked on the treadmill for two hours at a pre-determined speed and 1% incline that would result in a metabolic heat production of 350-360 W at the beginning of the experiment. A nurse monitored the subjects constantly inside the chamber and an engineer monitored the soldiers' physiological responses and environmental conditions with the data acquisition system. The following dependent variables were measured:

- exposure time (duration of test if the subject was removed prior to two hours)
- core temperature measured continuously with a rectal sensor
- mean skin temperature measured continuously with thermocouples taped to the skin in seven locations
- oxygen consumption measured periodically with the met cart
- metabolic rate measured periodically with the met cart
- whole body sweat rate measured by weighing the subjects before and after the experiment (accounting for water input and urine output)
- heart rate measured every minute with a Polar™ S810i heart rate strap and watch
- soldiers' perceptions of comfort and their opinions about each PCS.

The soldiers were removed from the experiment early if they reached any of the removal criteria, and the time was recorded. The subjects' clothing and instrumentation was cleaned between test sessions.

RESULTS

Manikin Tests. We calculated the cooling rate two ways: 1) the time the system was drawing 50 W or more of power, as the standard specified, and 2) the average cooling rate over two hours – even though this is somewhat meaningless if a system did not cool for very long. Table 1 provides a description of the PCS by type and a summary of the data collected.

Table 1. Cooling Effectiveness of Personal Cooling Systems Measured with a Sweating Manikin

		120 Minute Test		50 Watt Cut-off Test	
Personal cooling system (worn over T-shirt under DCU shirt unless indicated) [a]	RH (%)	Cooling effectiveness (W) [b]	Power level at 120 min. (W)	Cooling effectiveness (W) [c]	Time to 50 W cut-off (min)
Ambient air systems which circulate air under the body armor, increasing the evaporation rate					
1. ClimaTech Safety ForcedAIR Vest (worn over DCU shirt)	40 26	69.5 88.3	69.6 87.7	Never achieved 50 Watts.	
2. ClimaTech Safety ForcedAIR Vest	40 26	109.5 195.3	109.9 195.9		
3. Prototype Active Cooling System (worn over DCU shirt)	40 26	29.6 37.5	29.1 37.8		
4. Global Secure Safety Products Body Ventilation System	40 26	119.7 134.1	118.1 135.2		
Phase change materials which absorb body heat for a limited time					
5. Prototype Passive Self-charging Device	40	13.6	7.8	Never achieved 50 Watts.	
6. First Line Technology Cooling Vest	40	25.2	13.9	61.2	6.3
Refrigeration systems that circulate chilled water through tubes in a vest					
8. Aspen Thermal Personal Cooling System - low setting with chilled water at 21.1°C	40	124.2	124.1		
9. Aspen Thermal Personal Cooling System - high setting With chilled water at 15.6°C	40	147.0	148.0		

[a] PCS #12 (Foster Miller Compact Vapor Cooling System) was not available for manikin testing.
[b] Time-average of the power input to the manikin from the start of the test until the completion of 120 minutes of testing.
[c] Time-average of the power input to the manikin from the start of the test until the power level decreased to 50 Watts.

Ambient air circulation systems (#1 – 4) that work by blowing air between the body armor and the clothing layers increase convective and evaporative heat losses. Three of the four ambient air flow systems provided more than 50 W of cooling for two hours. At the dry 26%

relative humidity condition, these systems provided more evaporative cooling than they did at 40%. This result was expected since the vapor pressure gradient between the skin surface and the air was higher at the lower humidity condition. The ForcedAir vest worn over the T-shirt (#2) provided the highest amount of cooling in the study – 195 W at 26% humidity. However, it is unlikely that a soldier would experience the same amount of heat removal due to evaporation because a human would not experience continuous sweating from a 100% saturated skin surface like the manikin does during a test. The results also confirmed that ambient air systems provide more evaporative cooling when they are worn close to the body surface (#2) as opposed to over other garments (#1).

None of the phase change systems (#5 and #6) provided 50 W of cooling for two hours. A new prototype system (#5) developed for the military never even achieved 50 W of cooling.

The refrigeration systems that circulate chilled water through tubes in a vest provided high amounts of cooling to the body for two hours. The Aspen Thermal Cooling System on the high cooling setting (#9) circulated water at 15.6°C and provided 147 W of cooling. The system on the low cooling setting (#8) circulated water at 21.1°C and provided 124 W of cooling.

Human Subject Tests. Most of the soldiers were able to complete the two-hour test session. Six soldiers reached the 39°C cut off for rectal temperature prior to 120 minutes – usually when wearing the baseline ensemble. The metabolic rates of the soldiers increased slightly as they walked for two hours, so they were between 350-400 W at the end of the experiment. The final values for the dependent variables were taken at 120 minutes or when the subject met one of the removal criteria and the experiment was stopped. Analysis of variance and Tukey post hoc comparison tests were used to determine the effect of PCS type on the physiological responses of the soldiers. (See Table 2.) Prior to analysis, data were normalized based on the subjects' responses wearing the basic military ensemble with no PCS.

Core temperature is the most important variable to consider when evaluating the effectiveness of PCS. The four ambient air circulation systems only decreased body core temperature 0.1-0.2°C. However, they significantly lowered the subjects' heart rates and skin temperature under the body armor as compared to wearing no PCS. All of these PCS except #3, significantly lowered oxygen consumption as well. In addition, the soldiers were able to perceive differences in their comfort while wearing the air circulation systems.

The two phase change systems provided some initial cooling, but the soldiers' perceptions and physiological responses indicated that the cooling was not sufficient to offer any significant improvement over the baseline condition of wearing no PCS at all.

The refrigeration systems were the most effective in cooling the body. All three of these systems significantly reduced the subjects' heart rates, oxygen consumption, sweat rates, and skin temperatures under the body armor. The Aspen water-circulating cooling system also provided enough sustained cooling to significantly lower body core temperature 0.3°C.

CONCLUSIONS

The manikin tests indicated that three of the four air circulation systems and the refrigeration systems provided the highest amount of evaporative cooling. However, the human subject evaluation indicated that only the Aspen system (PCS #8 and 9) significantly lowered body core temperature (as compared to not using a PCS). The ambient air circulation systems (except for PCS #3) and the other refrigeration system (PCS #12 CVCS) significantly improved other physiological responses, but not core temperature. Some of the soldiers could perceive

Table 2. Physiological Responses of Soldiers Wearing Personal Cooling Systems as Compared to Wearing No PCS

Personal cooling systems (worn over T-shirt under DCU shirt unless indicated)	Final core temperature (°C)	Oxygen consumption (ml/kg/min)	Final heart rate (bpm)	Final torso skin temperature (°C)
0. Baseline ensemble, no PCS	38.4	11.6	123.3	37.4
1. ClimaTech Safety ForcedAIR Vest (worn over DCU shirt)	38.3	11.0*	115.0*	35.9*
2. ClimaTech Safety ForcedAIR Vest	38.2	11.2*	114.9*	36.4*
3. Prototype Active Cooling System (worn over DCU shirt)	38.4	11.4	122.7*	36.4*
4. Global Secure Safety Products Body Ventilation System	38.2	11.1*	112.4*	35.7*
5. Prototype Passive Self-charging Device	38.4	11.5	120.4	37.0
6. First Line Technology Cooling Vest	38.4	11.1*	117.6	37.1
8. Aspen Thermal Personal Cooling System - low setting with chilled water at 21.1°C	38.1*	10.8*	110.6*	32.1*
9. Aspen Thermal Personal Cooling System - high setting with chilled water at 15.6°C	38.1*	10.6*	105.0*	29.1*
12. Foster Miller Compact Vapor Cooling System	38.3	11.2*	113.1*	35.2*

* Indicates that the responses of the subjects wearing a PCS were significantly different from their responses when not wearing a PCS; $p < 0.05$.

differences in their comfort while wearing these systems. Therefore, we recommend that the refrigeration systems (#8 or #9 and #12) and air circulation systems (#2 and #4) be studied on soldiers in the field where an ergonomic evaluation is conducted in addition to measuring the soldiers' physiological and subjective responses.

REFERENCES

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