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Wearing nuclear, biological and chemical (NBC) clothing or body armor during hot weather operations increases heat strain, can compromise work capacity, and may lead to heat injury. The U.S. Army Natick Soldier Research, Development, and Engineering Center is working to develop a lightweight microclimate cooling system (MCCS) for dismounted Soldiers. This study evaluated a prototype, vapor compression MCCS with an integrated skin temperature sensor to trigger pulsed cooling (PC) cycles. Previous experiments showed PC to be as effective as continuous cooling (CC) while requiring less power, potentially reducing both weight and logistic requirements for MCCS. A 120 W prototype MCCS was tested on volunteers during continuous work wearing either NBC clothing or the Army Combat Uniform (ACU) with body armor. Trials were no cooling, CC, and PC from skin temperature feedback. Volunteers completed three trials at 30°C, 30% rh wearing NBC clothing, and three trials each at 45°C, 20% rh and 35°C, 70% rh wearing the ACU. Skin temperature, core temperature, heart rate, and sweating rate data were collected in all experiments to evaluate heat strain. We found that while the skin temperature feedback worked effectively, the prototype MCCS provided

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PHYSIOLOGICAL RESPONSES TO EXERCISE-HEAT STRESS WITH PROTOTYPE PULSED MICROCLIMATE COOLING SYSTEM

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DISCLAIMER STATEMENTS

The opinions or assertions contained herein are the private views of the authors and are not to be construed as official or as reflecting the views of the Army or the Department of Defense.

The investigators have adhered to the policies for protection of human subjects as prescribed in Army Regulation 70-25, and the research was conducted in adherence with the provisions of 32 CFR Part 219.

Human subjects participated in these studies after giving their free and informed voluntary consent. Investigators adhered to AR 70-25 and the USAMRMC Regulation 70-25 on the use of volunteers in research.

Any citations of commercial organizations and trade names in this report do not constitute an official Department of the Army endorsement of approval of the products or services of these organizations.

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LIST OF ABBREVIATIONS

ACU – Army Combat Uniform

BDU – Battle Dress Uniform

CC – Constant Cooling

IBA – Interceptor Body Armor

IPFU – Improved Physical Fitness Uniform

JSLIST – Joint Service Lightweight Integrated Suit Technology

LCG – Liquid Cooling Garment

MCC – Microclimate Cooling

MCCS – Microclimate Cooling System

MOPP – Mission Oriented Protective Posture

NBC – Nuclear, Biological, and Chemical

NC – No Cooling

NSRDEC – Natick Soldier, Research, Development, and Engineering Center

PC – Pulsed Cooling

PSI – Physiological Strain Index

PPE – Personal Protective Equipment

USARIEM – U.S. Army Research Institute of Environmental Medicine

WBGT – Wet Bulb Globe Temperature

EXECUTIVE SUMMARY

This study supported the U.S. Army Natick Soldier Research, Development, and Engineering Center (NSRDEC) effort to develop a lightweight microclimate cooling system (MCCS) for use by dismounted Soldiers. This development is underway because it is known that military operations in warm and hot environments that require the use of nuclear, biological and chemical (NBC) clothing or body armor pose a thermoregulatory challenge to Soldiers. This challenge results in compromised work capacity and may lead to serious heat injury.

This study evaluated a prototype light weight, circulating liquid, vapor compression MCCS with an integrated skin temperature sensor to trigger on/off cycles (pulsed cooling). We have previously shown in laboratory experiments that using pulsed cooling cools as effectively as continuous cooling, and requires less power than constant cooling, potentially reducing the weight of an individual MCCS, and the logistic trail required to support MCCS. This study focused on the effectiveness of an early prototype pulsed liquid cooling (with small cooling capacity ~120 W) MCCS on volunteers during continuous work when wearing either chemical protective clothing or the Army Combat Uniform (ACU) with body armor.

The early prototype MCCS was tested in both constant and pulsed cooling modes, as well as a no cooling control, in three separate environments to test for functionality and effectiveness. We evaluated heat strain in volunteers during these nine exercise-heat stress experiments. The volunteers completed three tests in one environment (30°C, 30% rh) wearing chemical protective clothing, and a total of six tests, three each in two environments (45°C, 20% rh; 35°C, 70% rh) wearing the ACU.

We evaluated the effectiveness of the prototype MCCS to operate in a pulsed mode in the three environments and found that while the skin temperature system was effective, the prototype MCCS, as currently configured, provided insufficient cooling for our operational scenarios. Skin temperature, core temperature, heart rate, and sweating rate data were collected in all experiments and used to evaluate the MCCS.

INTRODUCTION

This study supported the U.S. Army Natick Soldier Research, Development, and Engineering Center (NSRDEC) effort to develop a lightweight microclimate cooling system (MCCS) for use by dismounted Soldiers. The MCCS evaluated in this study was an early prototype light weight, circulating liquid, vapor compression MCCS with an integrated skin temperature sensor to trigger on/off cycles. The prototype system is based on a USARIEM patent (patent pending) for personalized microclimate cooling that, when configured to operate as a skin temperature feedback pulsed cooling (PC) unit, should delay heat strain as effectively as constant cooling (CC) during exercise-heat stress while reducing the power requirement by ~50%. This prototype system could potentially save the U.S. Army substantial dollars currently being spent on battery acquisition. Additionally, using smaller or fewer batteries would decrease the weight of the system and increase acceptability by dismounted Soldiers. This study was designed to evaluate both the prototype MCC system's capability to be controlled by the skin temperature sensor, and its ability to sufficiently cool subjects under the given heat stress scenarios.

Military operations in warm and hot environments that require the use of body armor or nuclear, biological and chemical (NBC) clothing pose a great thermoregulatory challenge to Soldiers. Compared to wearing only the battle dress uniform (BDU), previous data indicate that body armor increases the effective wet bulb, globe temperature (WBGT) by ~3°C (~5°F). NBC protective clothing reduces the capacity for heat loss resulting in a more rapid rise of core temperature and greater heat strain. Wearing NBC clothing during light and moderate work increases the WBGT penalty by ~6°C (~11°F) and ~12°C (~22°F), respectively (4, 19). Increased heat strain results in compromised work capacity and may lead to serious heat injuries.

Military duty in a combat area requires that personnel wear body armor and helmets over their standard duty uniform. Additionally, some specific military occupations such as disarming explosive ordnance and performing toxic waste clean up require workers to wear additional protective clothing. This personal protective equipment (PPE) has high insulation and low moisture permeability properties and can impose uncompensable heat stress (where the required evaporative cooling exceeds the evaporative cooling capacity of the environment) with resultant heat storage and reduced work capabilities (6, 12, 18). Uncompensable heat stress caused by working in PPE has significant military implications. Specifically, mission performance is severely compromised when wearing chemical protective PPE. Clearly, technological advancement is necessary to increase tolerance time in Soldiers wearing PPE or NBC clothing.

One approach to alleviate heat storage is to enhance heat loss through conduction/convection by using microclimate cooling with a liquid cooling garment (LCG) to sustain cooling capacity. Based on physical principles, optimal cooling should occur with a low perfusate temperature and increased coolant flow, as well as by covering a large proportion of the skin surface. In this way, heat transfer (the product of volumetric flow, specific heat and specific density of the perfusate, and the gradient between the inlet and outlet temperature) is maximized. However, skin blood flow is reduced if the perfusate is too cold. This occurs as cool skin triggers cutaneous vasoconstriction (even with increasing core temperature), which increases insulation, decreases the temperature gradient between the skin and perfusate, and reduces the heat removal efficiency of the LCG (15, 16, 21).

Recent engineering approaches for developing optimal liquid MCCS have focused on reducing the weight of the cooling systems by improving the coefficient of performance (COP, the ratio of heat transferred to power consumed) and by reducing the cooling provided, in essence, trading off cooling performance for reduced weight. Unfortunately, traditional engineering approaches for improving cooling effectiveness (i.e., reducing the perfusate temperature and increasing flow) may increase power (and weight) requirements. From a physiologic perspective, these engineering approaches are also potentially self-defeating. Superficial shell insulation (skin and subcutaneous fat) approaches near maximal values at skin temperatures of 30°C, with the onset of vasoconstriction occurring at skin temperatures of 32° – 33°C (21). Thus, the heat loss advantage obtained by widening the core-to-skin temperature gradient with CC is progressively reduced by increased superficial shell insulation as skin temperature drops below 32°C (11, 21).

Recently, we demonstrated that PC effectively reduces heat strain in Soldiers working in the heat when wearing PPE (7). These data support that maintenance of T_{skin} between 33° and 35°C results in increased heat flux without significant additional cardiovascular strain. In contrast, CC reduced T_{sk} to ~32°C with near maximal total insulation (20). The higher T_{skin} afforded by PC increased heat flux with only a small cardiovascular penalty. The ΔHR resulting from an increase in T_{skin} from 32° to 34°C (2°C) was 10 $b{\cdot}min^{-1}$. These data indicated that the PC approach was markedly more efficient (164%–215%) than CC (7). These results showed that power requirements for MCC systems can be reduced using a PC approach.

Subsequently we conducted a follow-up study using a 250 W cooling system that delivered CC, PC at 2-minute on/off intervals, and PC with skin temperature feedback (cooling when skin = 34.5°C and cooling turned off at skin = 33.5°C) (19). Cooling was delivered to the same whole body cooling garment used in the previous study. This study showed that both cooling modes significantly reduced physiological strain and that using skin temperature feedback reduced electrical power requirements by 46% and 28% relative to CC and PC, respectively, without changing the reduction in strain.

Providing microclimate cooling only during rest breaks from moderate exercise has been used to provide a solution to the weight burden imposed by carrying an MCCS on the back or at the waist (9). However, post-exercise cooling in this way created an additional problem of requiring scheduled rest breaks. In addition, cooling during rest breaks did not attenuate the potential for a rapid increase in heat storage during moderate work. Cooling during rest breaks is also problematic, since rest breaks might not be possible on a regular basis. In this case, T_{skin}, core temperature (T_c), and HR would continue to increase during work.

The current study focused on the effectiveness of an early prototype PC liquid cooling system during continuous work when wearing NBC clothing and when wearing the Army Combat Uniform (ACU) with IBA. The prototype MCCS was tested in both constant and PC modes in three separate environments to test for both functionality and effectiveness.

METHODS

EXPERIMENTAL DESIGN, PROCEDURES, AND MEASUREMENTS

Subjects

Seven male Soldiers were recruited to participate as volunteer test subjects in this study. Before testing began, all volunteers were fully briefed, both orally and in writing, on the purpose and risks of the study, and consented to participate in the research. A medical officer cleared the volunteers as healthy after a physical examination and medical history review.

Preliminary Tests

Volunteers completed a heat acclimation program prior to experimental testing to standardize their physiological state and to reduce the risk of exhaustion from heat strain during the experimental trials. On one day the volunteers' age, height, and weight were recorded and percent body fat was estimated from anthropometric measurements collected in accordance with AR600-9.

Volunteers were heat acclimated by performing 10-12 days of exercise in a 45°C, 20% rh (31.3°C WBGT), 1.34 $m \cdot sec^{-1}$ wind speed environment while wearing the Army Improved Physical Fitness Uniform (IPFU). Core temperature (T_c) and heart rate (HR) were measured throughout all heat stress exposures. Treadmill speed was set at 1.56 $m \cdot sec^{-1}$ (3.5 mph) and 4% grade. Volunteers walked continuously for 100 minutes or until rectal temperature reached 39.5°C or voluntary cessation. Volunteers drank 250 ml of water immediately prior to beginning each heat acclimation session. Pre- and post-exercise weights were recorded daily. Each day, at the end of heat acclimation, the volunteers were required to drink sufficient liquid to return within 1% of their first morning weight to assure that they did not undergo a progressive dehydration that would negatively affect T_c and HR responses. Volunteers were also familiarized to three perceptual tests – rating of perceived exertion (RPE) (2), thermal sensation (TS) (10), and thermal comfort (TC) (1) during the heat acclimation program.

<u>Cooling Tests</u>

Volunteers performed nine tests composed of three cooling trials in different uniform configurations and environments. The three trials were 1) CC, 2) PC, and 3) no cooling (NC). The two uniform configurations were 1) NBC clothing at modified Mission Oriented Protective Posture (MOPP 3); and 2) the ACU with sleeves down, Kevlar helmet, and Interceptor Body Armor (IBA). During the NBC trials, volunteers walked continuously on a treadmill at 1.43 $m \cdot sec^{-1}$, 1% grade in a 30°C, 30% rh (21.7°C WBGT), 1.34 $m \cdot sec^{-1}$ wind speed environment for up to 100 minutes, or until rectal temperature reached 39.5°C. For the ACU+IBA trials, volunteers walked continuously on a treadmill at 1.39 $m \cdot sec^{-1}$ in two environments: 45°C, 20% rh (31.3°C WBGT), and 35°C, 70% rh (31.6°C WBGT) 1.34 $m \cdot sec^{-1}$ wind speed environments for up to 2 hours, or until rectal temperature reached 39.5°C. The ambient condition and work load for the MOPP 3 trials were selected to produce significant heat strain while minimizing the likelihood of subjects dropping out as a result of excessive heat strain while encapsulated in chemical protective clothing (3). Additionally, the NBC conditions were designed to match the heat strain induced in the earlier PC experiments (3, 7, 19). The ambient conditions for the ACU trials were selected to represent realistic desert and tropic environments that would produce significant heat strain, but should allow for 2 hours of continuous exercise, as determined by the USARIEM Heat Strain Decision Aid (5).

During PC, monitoring of T_{skin} by the MCCS was made via a skin thermistor placed on the chest. Preset skin temperature values were 34.5°C and 33.5°C to power the MCCS on and off, respectively. The cooling experiments within each environment were presented in a balanced order. Testing was separated by 48-72 hours. See Table 1 for the experimental design summary.

Table 1. Experimental Design

Preliminary	Environment	Experimental Trials		
Heat Acclimation 45°C, 20% rh (31.3°C WBGT) 1.56 m/sec, 4% grade IPFU	NBC Clothing – MOPP Level 3 (modified) 30°C, 30% rh (21.7°C WBGT)	CC 100 min continuous exercise (Metabolic cost ~225 $W \cdot m^{-2}$)	PC 100 min continuous exercise (Metabolic cost ~225 $W \cdot m^{-2}$)	NC 100 min continuous exercise (Metabolic cost ~225 $W \cdot m^{-2}$)
	ACU+IBA, Kevlar helmet 45°C, 20% rh (31.3°C WBGT)	CC 120 min continuous exercise (Metabolic cost ~225 $W \cdot m^{-2}$)	PC 120 min continuous exercise (Metabolic cost ~225 $W \cdot m^{-2}$)	NC 120 min continuous exercise (Metabolic cost ~225 $W \cdot m^{-2}$)
	ACU+IBA, Kevlar helmet 35°C, 70% rh (31.6°C WBGT)	CC 120 min continuous exercise (Metabolic cost ~225 $W \cdot m^{-2}$)	PC 120 min continuous exercise (Metabolic cost ~225 $W \cdot m^{-2}$)	NC 120 min continuous exercise (Metabolic cost ~225 $W \cdot m^{-2}$)

Clothing and Equipment. Uniform configuration during the NBC trials consisted of modified MOPP Level 3 configuration worn over the Army IPFU and athletic shoes. The modified MOPP Level 3 configuration consists of a JSLIST overgarment (top and bottom), cotton glove liners, butyl gloves, and an M-40 chemical-biological (CB) field mask with hood. USARIEM copper manikin data collected at 1.0 $m \cdot s^{-1}$ wind speed shows that this uniform configuration provides approximate insulative (Clo) and vapor permeability (i_m) characteristics of 1.65 and 0.39, respectively.

Uniform configuration during the ACU trials consisted of ACU with sleeves down worn over underwear and t-shirt, Kevlar helmet, athletic shoes to reduce blisters, and the IBA vest with small arms protective inserts. The total weight of the IBA is ~8 kg, and it covers ~22% of body surface area. USARIEM copper manikin data collected at 1.0 $m \cdot s^{-1}$ wind speed shows that this uniform configuration provides approximate insulative (Clo) and vapor permeability (i_m) characteristics of 1.30 and 0.42, respectively.

The MCCS prototype is a light-weight, vapor compression cooling system that circulates chilled water through tubes in a torso cooling garment worn against the skin to reduce skin temperature and enhance convective cooling. It consists of a cooling unit, battery, skin temperature thermistor, and the LCG that, together, weigh approximately 3.6 kg. The LCG design consists of cotton or Nomex® aramid fabric woven or laminated around small diameter Tygon® tubing (2.5mm, I.D.) divided into multiple parallel circuits. Continuous power provides ~500 ml/min of 22°C water delivered through the cooling garment yielding ~120 watts of cooling to the torso vest (LCG) at an ambient temperature of 35°C. Flow rate and inlet temperature (22°C) are similar to previous studies (3, 7).

Procedures. In all experiments, HR was measured every 5 min using a Polar HR monitor. All body temperatures were measured at 1-minute intervals. Rectal temperature (T_{re}) was measured using a flexible rectal thermistor (Measurement Systems Inc.) inserted 10 cm beyond the anal sphincter. T_{skin} was measured by thermistor from five sites (forearm, back, chest, thigh, and calf) and calculated using the equation: $0.15 (T_{chest}) + 0.15 (T_{back}) + 0.3 (T_{forearm}) + 0.2 (T_{thigh} + T_{calf})$ (17). One additional skin thermistor was placed on the chest to provide skin temperature feedback to the MCCS. Body mass was recorded pre- and post-testing in the nude and with the complete uniform configuration.

The volunteers drank 250 ml of water approximately 1 h before starting exercise. As in previous studies (7), subjects did not drink during the NBC experiments conducted at 30°C, 30% rh. In the ACU+IBA experiments conducted at 45°C, 20% rh and 35°C, 70% rh, subjects were asked to drink 400 ml of water every 30 minutes. Volunteers whose post-exercise weight loss was >1% of their baseline weight were required to drink sufficiently following each exercise-heat trial until they reached ≤1% of their baseline weight before being released for the day. This assured that they did not progressively dehydrate over the course of testing.

Sweating rate was determined by calculating water balance using a modified Peters-Passmore equation (7):

$$\text{sweat loss} = \Delta \text{ body mass} + (\text{Fluids}_{in} - \text{Fluids}_{out}) - (\text{Gases}_{in} - \text{Gases}_{out});$$

where Δ body mass is the difference in nude body mass pre-to-post exercise, fluids in = water, fluids out = urine and respiratory water losses (13), and gases represent CO_2-O_2 exchange (8, 13). The sum of the equation represents actual sweat losses (kg), which were then expressed as a rate (volume per unit time, ml/min).

During the ACU+IBA trials, metabolic rate was determined from 90-second samples of expired air collected using indirect calorimetry via Douglas Bags, dry gas meter, and TrueMax metabolic cart. Expired gas samples were collected on the subjects at ~30 min of exercise each test day. For the NBC trials, metabolic rate could not be collected during tests because volunteers were wearing the M-40 masks. Therefore, metabolic rate was determined on a day after the heat acclimation procedure, but prior to initiating the experimental trials. Volunteers wore the NBC uniform while carrying the M-40 mask on their hips and walking on the treadmill at a speed and grade pre-calculated to approximate an energy cost of ~225 $W \cdot m^{-2}$. After ~15 minutes of exercise, a 90-second sample of expired air was collected in the same manner as described above. The technique was repeated at different speeds and grades as needed to achieve an energy cost of ~225 $W \cdot m^{-2}$.

Heat balance was computed using the following equation:

$$S\ (W \cdot m^{-2}) = M \pm Wk \pm (R + C) - E$$

where: S is the rate of storage of body heat, M is rate of metabolic energy production, Wk equals work, E is the rate of evaporative heat transfer, R equals the rate of radiant heat exchange, and C is the rate of convective heat transfer. All values were calculated using known methods (3, 7). Calculating heat balance provided definitive evidence for the cooling capability of the MCCS during exercise heat stress.

RPE, TC, and TS were recorded upon entering the chamber and then every 20 minutes during all experiments. In addition, the Physiological Strain Index (PSI) was calculated (14).

STATISTICAL ANALYSIS

Analyses were made only among cooling conditions (PC, CC, and NC) for each uniform configuration within each environment. Core and skin temperature, sweating rate, RPE, TC, TS, PSI and metabolic data from all trials were compared using a two-way repeated measure ANOVA. Significance was set at $p<0.05$. A significant *F*-test was further analyzed with Tukey's post hoc test to detect differences among means.

RESULTS

Seven male volunteers were studied. All results are reported as the mean ± standard deviation (SD). The age, height, weight, body surface area (A_D), and percent body fat of the volunteers were 19±1 years, 173±6 cm, 75.3±6.4 kg, 1.89±0.09 m^2, and 15±4% body fat.

NBC (30°C, 30% rh)

All seven subjects performed the three 100 min treadmill walking tests in each of the three cooling configurations while wearing chemical protective clothing. While not all subjects completed the entire 100 minutes in each test, there were no significant differences in total time among the three tests (Table 2). There were no differences in metabolic rate among the cooling configurations and overall mean metabolic rate was 238±19 $W \cdot m^{-2}$. Cooling (W) provided by the MCCS in the three configurations were all significantly different from each other (Table 2), with PC providing highest values. Additionally, the percent of total exercise time that cooling was provided in each configuration were all significantly different (Table 2). The MCCS cycled on and off at least three times and as many as 11 times on the individual subjects during PC in this environment.

Figure 1 illustrates the impact of the three cooling configurations on torso temperature and mean skin temperature. CC lowered both the T_{torso} (Figure 1a) and T_{skin} (Figure 1b) temperatures lower than either PC or NC throughout the course of exercise. Throughout exercise T_{torso} with PC trended lower than with NC but was significantly lower only at minutes 45 and 75 (Figure 1a). At no time was the T_{skin} with PC significantly lower than with NC (Figure 1b).

Figure 2 illustrates the impact of the three cooling configurations on core temperature, HR and the PSI. There were no significant differences in core temperature among the three conditions at any time (Figure 2a). Starting with minute 30, heart rates with both CC and PC trended lower than with NC, but only at minute 75 and 90 were HRs significantly lower in both cooling configurations than in the NC configuration (Figure 2b). There were no significant differences in the PSI among the three conditions (Figure 2c).

There were no significant differences in heat storage or sweating rate among the three conditions at any time (Table 2). Additionally, there were no significant differences among the three configurations for either perceived exertion (RPE) or perceived thermal strain (TC and TS) throughout the experiments.

Table 2. Exercise time, cooling parameters, and calculated heat storage and sweating rates during all three cooling tests at 30°C, 30% rh.

	Exercise Time (min)	Cooling (W)	% Time Cooled	Heat Storage ($W \cdot m^{-2}$)	Sweating Rate ($g \cdot min^{-1}$)
NC	99±3	0±0*	0±0*	20±6	10±3
CC	96±11	106±30*	100±0*	12±8	10±3
PC	100±0	134±27*	53±21*	21±8	10±3

*All significantly different from each other (p<0.05).

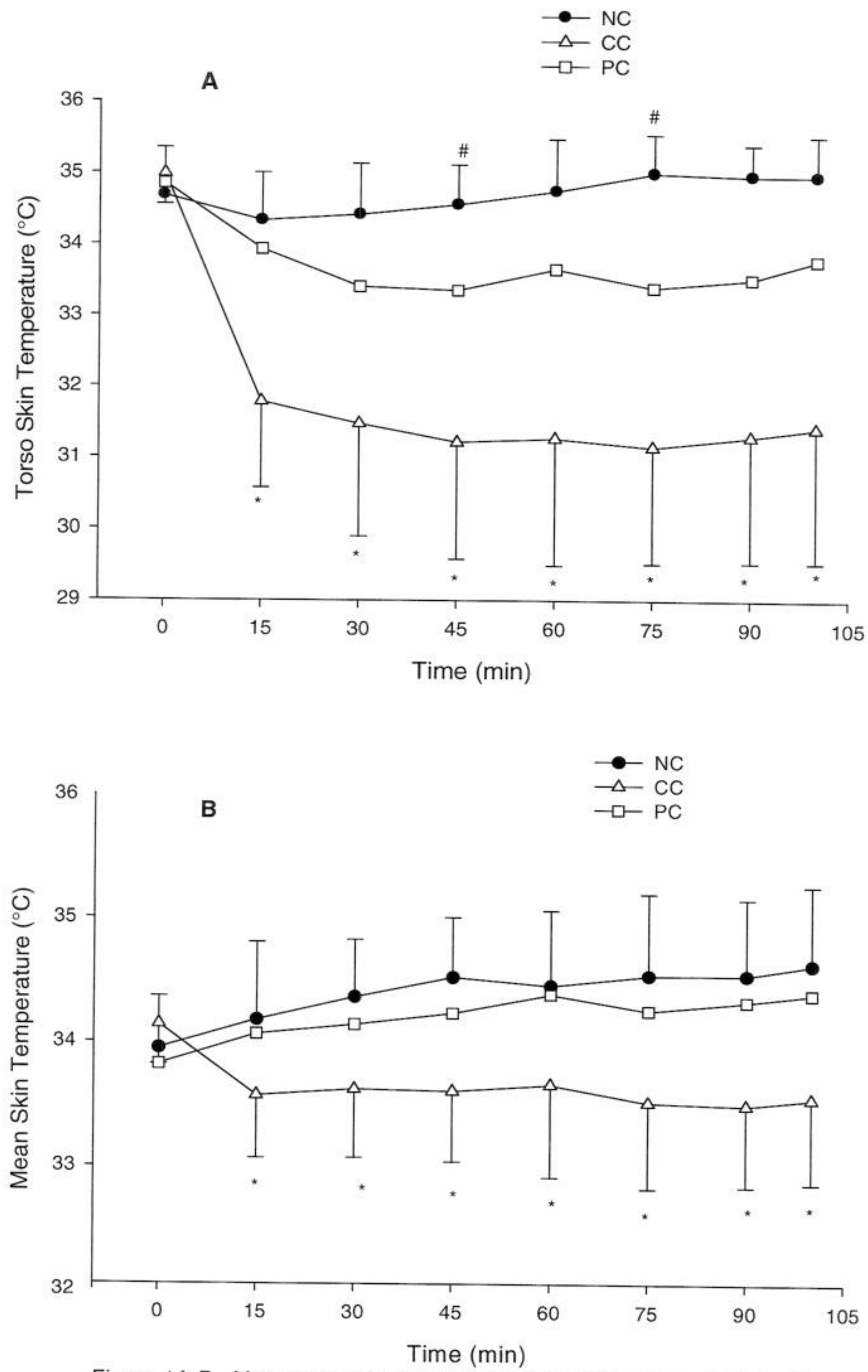


Figure 1A-B. Mean torso skin temperature (A) and mean weighted skin temperature (B) across time in all three cooling tests at 30°C, 30% rh. *Significantly different from PC and NC (p<0.05). #Significantly different from PC (p<0.05).

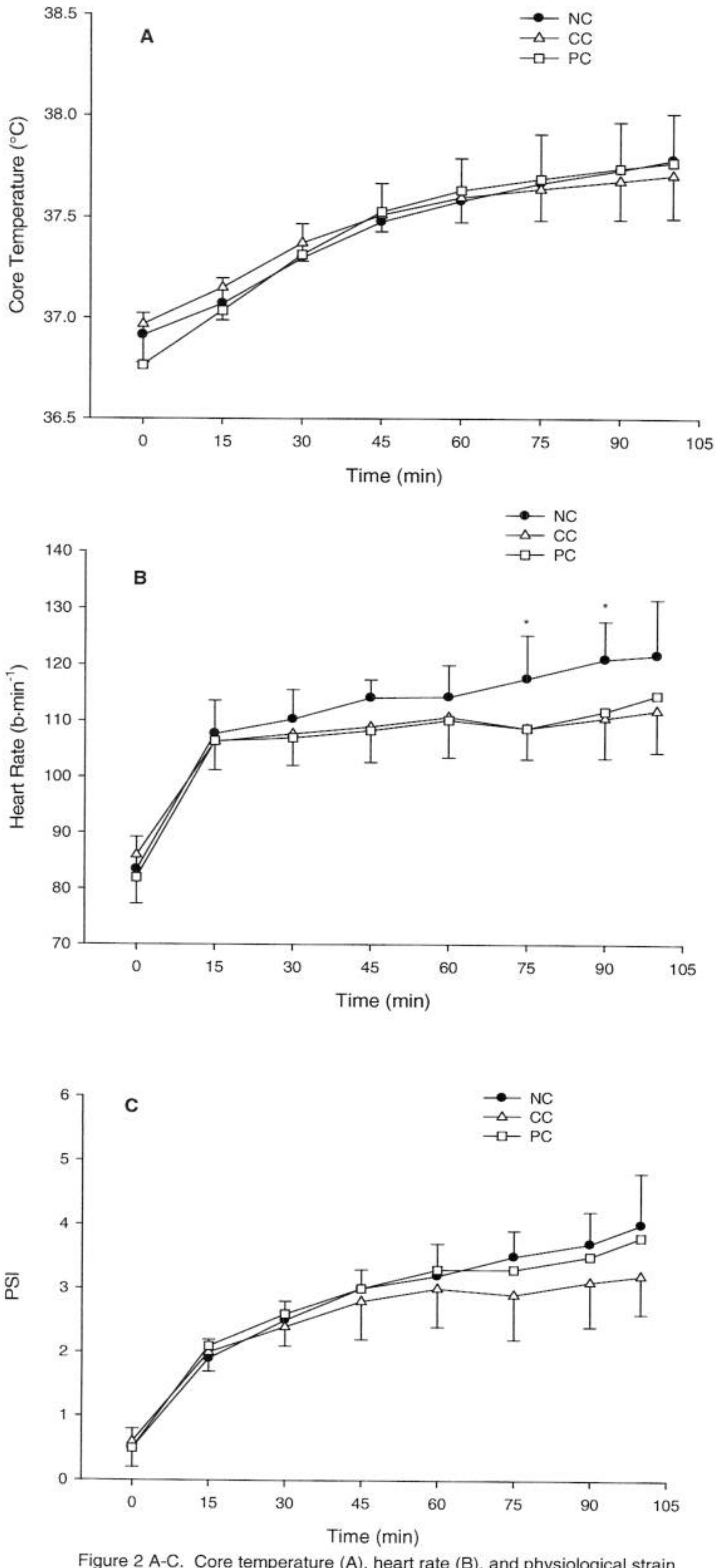


Figure 2 A-C. Core temperature (A), heart rate (B), and physiological strain index (PSI) (C) across time in all three cooling tests at 30°C, 30% rh.
*Significantly different from PC and CC ($p<0.05$).

ACU (45°C, 20% rh)

All seven subjects performed the three hot/dry, 120 min treadmill walking tests in each of the three cooling configurations while wearing the ACU with helmet and body armor. While not all subjects completed the entire 120 minutes in each test, there were no significant differences in total time among the three tests (Table 3). There were no differences in metabolic rate among the cooling configurations, and overall mean metabolic rate was 229±17 W·m^{-2}. Cooling provided by the MCCS was not significantly different between PC and CC in this environment, while both were greater than NC (Table 3). During PC, the MCCS on one subject cycled off a single time with the remainder of the PC trials serving functionally as CC tests. There was no difference in the percent of exercise time that subjects received cooling between PC and CC in this environment, while both were greater than NC (Table 3).

Figure 3 illustrates the impact of the three cooling configurations on torso temperature and mean skin temperature. CC and PC resulted in T_{torso} temperatures lower than NC throughout the course of exercise, and CC resulted in T_{torso} less than PC at minute 15 (Figure 3a). CC and PC also resulted in T_{skin} temperatures lower than NC from minute 30 on throughout the course of exercise (Figure 3b).

Figure 4 illustrates the impact of all three cooling configurations on core temperature, heart rate, and the PSI. CC resulted in lower core temperature than NC from minute 75 through the remainder of exercise (Figure 4a). There were no differences in HR among the three configurations at any time (Figure 4b). CC resulted in lower PSI than NC at minutes 105 and 120 of exercise (Figure 4c).

There were no significant differences in heat storage or sweating rate among the three conditions at any time (Table 3). Additionally, there were no significant differences among the three configurations for RPE, TC, and TS throughout the experiments.

Table 3. Exercise time, cooling parameters, and calculated heat storage and sweating rates during all three cooling tests at 45°C, 20% rh.

	Exercise Time (min)	Cooling (W)	% Time Cooled	Heat Storage (W·m^{-2})	Sweating Rate (g·min^{-1})
NC	107±23	0±0	0±0	37±15	18±4
CC	107±24	85±33 †	96±8 †	31±19	17±3
PC	106±25	79±22 †	92±8 †	36±18	18±3

† Significantly different from NC (p<0.05).

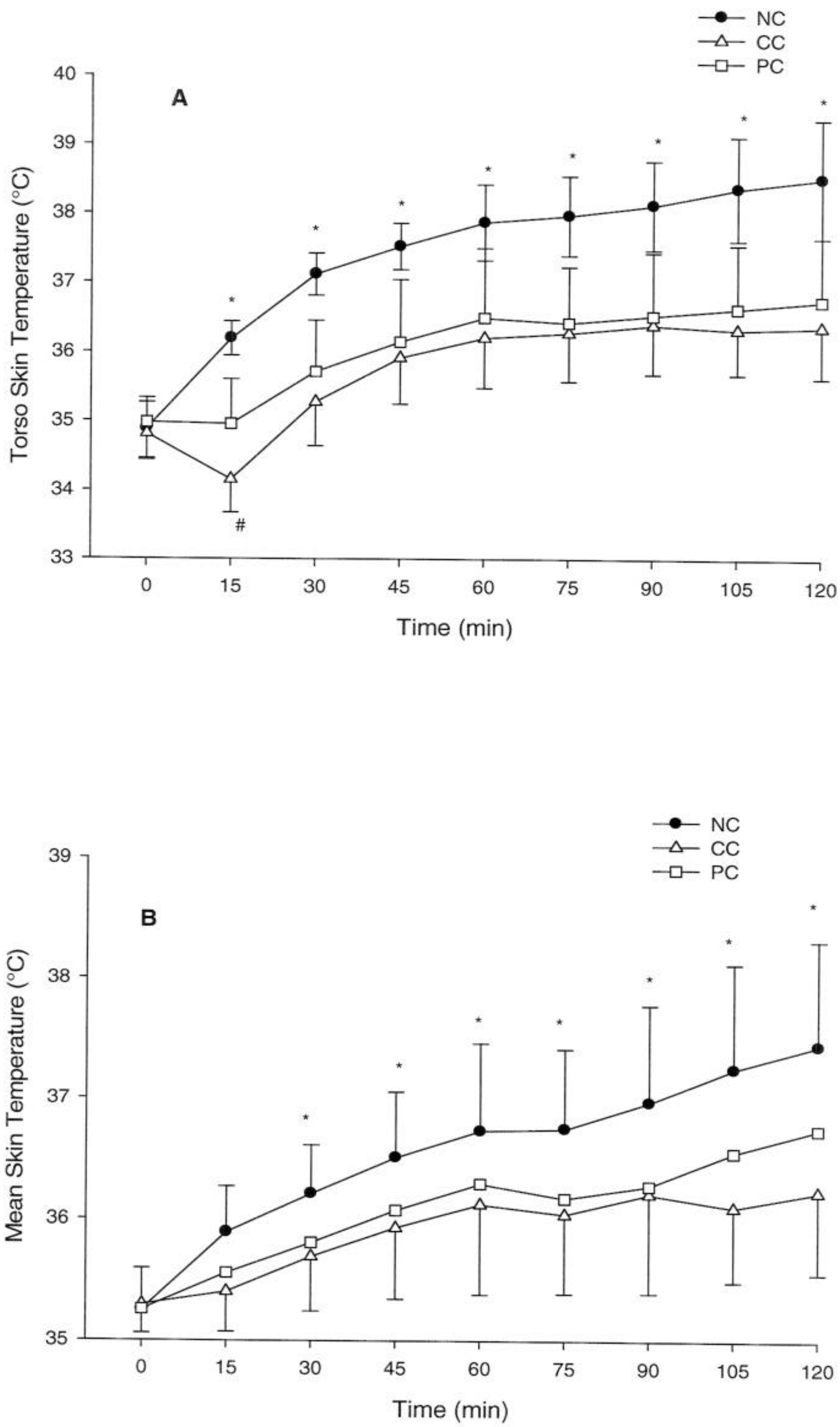


Figure 3A-B. Mean torso temperature (A) and mean weighted skin temperature across time in all three cooling tests at 45°C, 20% rh. *Significantly different from PC and CC ($p<0.05$). #Significantly different from PC ($p<0.05$).

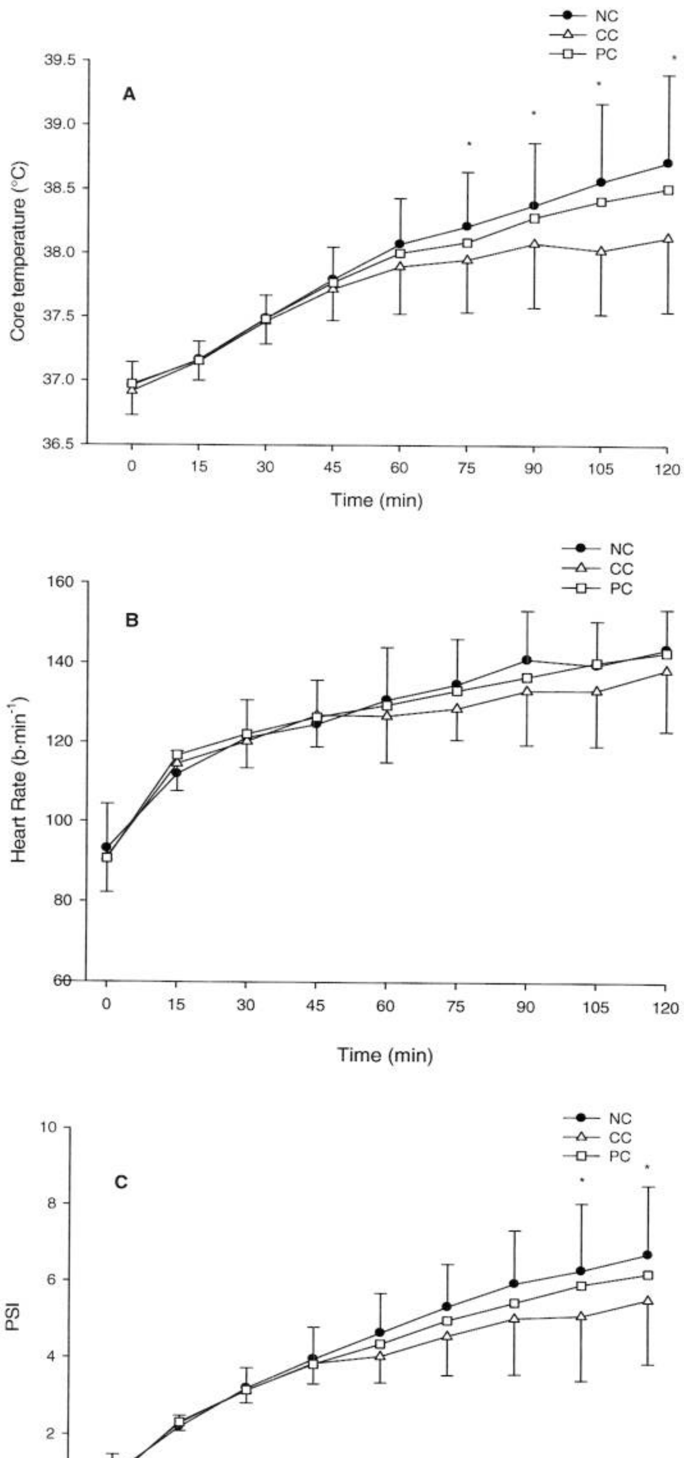


Figure 4A-C. Core temperature (A), heart rate (B), and physiological strain index (PSI) (C) across time in all three cooling tests at 45°C, 20% rh. *Significantly different from CC ($p<0.05$).

ACU (35°C, 70% rh)

Six subjects performed the three hot/humid 120 min treadmill walking tests in each of the three cooling configurations while wearing the ACU with helmet and body armor. While not all subjects completed the entire 120 minutes in each test, there were no significant differences in total time among the three tests (Table 4). There were no differences in metabolic rate among the cooling configurations, and overall mean metabolic rate was 221±19 $W \cdot m^{-2}$. Cooling provided by the MCCS was not significantly different between PC and CC in this environment, while both were greater than NC (Table 4). However, the percent of total exercise time that cooling was provided in each configuration were all significantly different (Table 4). The MCCS cycled off either once or twice in five of the six subjects during the first 30 minutes of PC before remaining on for the rest of the experiment for all subjects.

Figure 5 illustrates the impact of the three cooling configurations on torso temperature and mean skin temperature. Because one subject did not routinely complete the 120 minutes in all of the trials, his data is excluded from these four variables that were analyzed across time. CC and PC resulted in T_{torso} temperatures lower than NC throughout the course of exercise, and CC resulted in T_{torso} lower than PC at every time period except minute 105 when there was no difference between the two (Figure 5a). CC and PC also resulted in T_{skin} temperatures lower than NC throughout the course of exercise, as well as CC resulting in T_{skin} less than PC at minute 15 (Figure 5b).

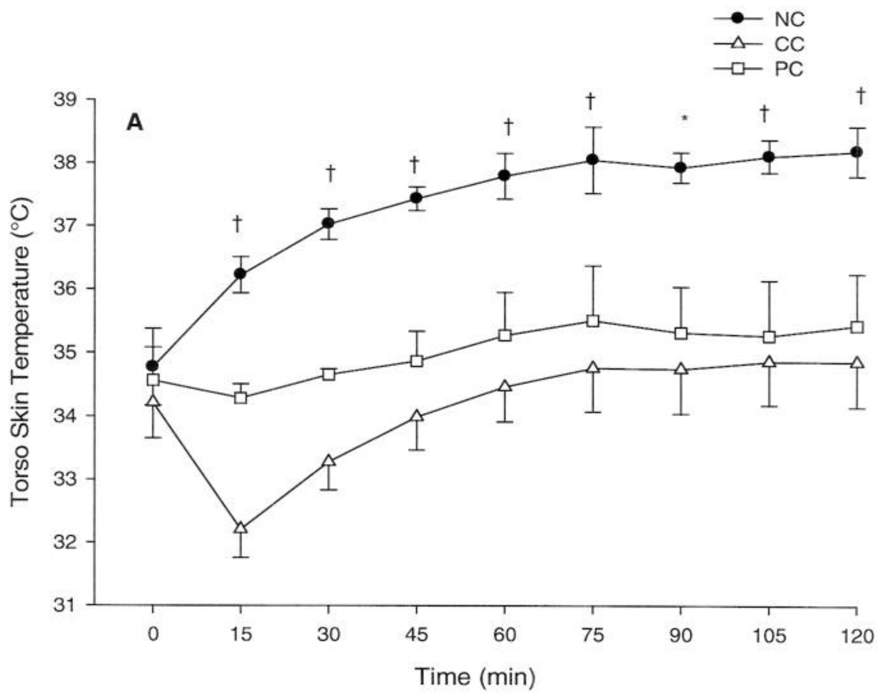
Figure 6 illustrates the impact of the three cooling configurations on core temperature, heart rate, and the PSI. PC resulted in lower core temperature than NC at minute 60, and both PC and CC resulted in lower core temperature than NC from minute 75 through the remainder of exercise (Figure 6a). CC and PC resulted in HR lower than NC from minute 90 through the end of exercise (Figure 6b). Similarly, PC resulted in lower PSI than NC at minute 60, and both PC and CC resulted in lower PSI than NC through the remainder of exercise (Figure 6c).

PC and CC resulted in lower heat storage than NC, and PC resulted in a lower sweating rate than NC (Table 4). There were no significant differences among the three configurations for RPE, TC, and TS throughout the experiments.

Table 4. Exercise time, cooling parameters, and calculated heat storage and sweating rates during all three cooling tests at 35°C, 70% rh.

	Exercise Time (min)	Cooling (W)	% Time Cooled	Heat Storage ($W \cdot m^{-2}$)	Sweating Rate ($g \cdot min^{-1}$)
NC	103±27	0±0	0±0*	42±12	19±5
CC	117±7	93±8 †	100±0*	24±13 †	16±6
PC	113±18	98±9 †	90±6*	26±11 †	13±5 †

* All significantly different from each other ($p<0.05$). † Significantly different from NC ($p<0.05$).



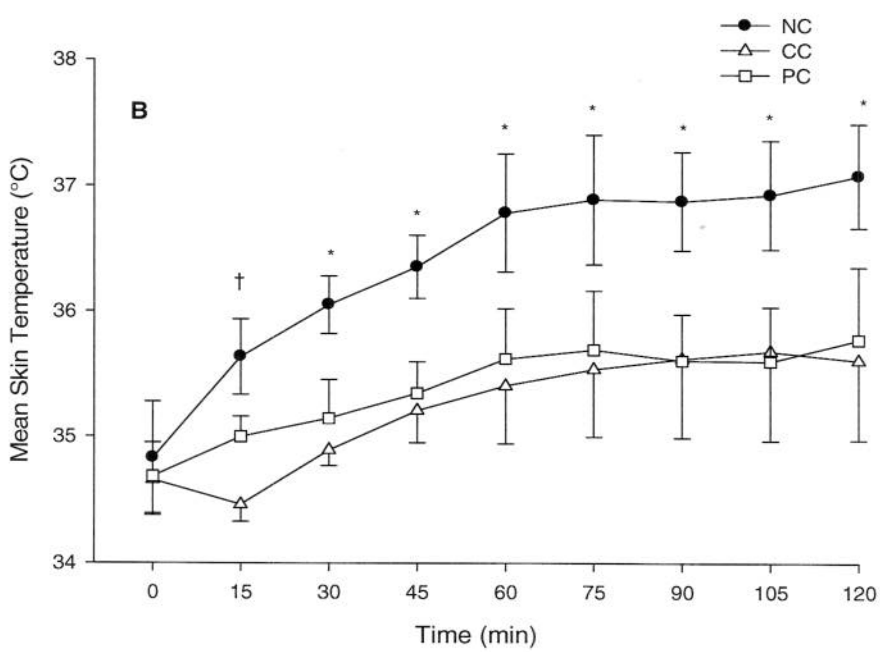


Figure 5A-B. Mean torso skin temperature (A) and mean weighted skin temperature (B) across time in all three cooling tests at 35°C, 70% rh. †All conditions significantly different from each other ($p<0.05$). *Significantly different from PC and CC ($p<0.05$).

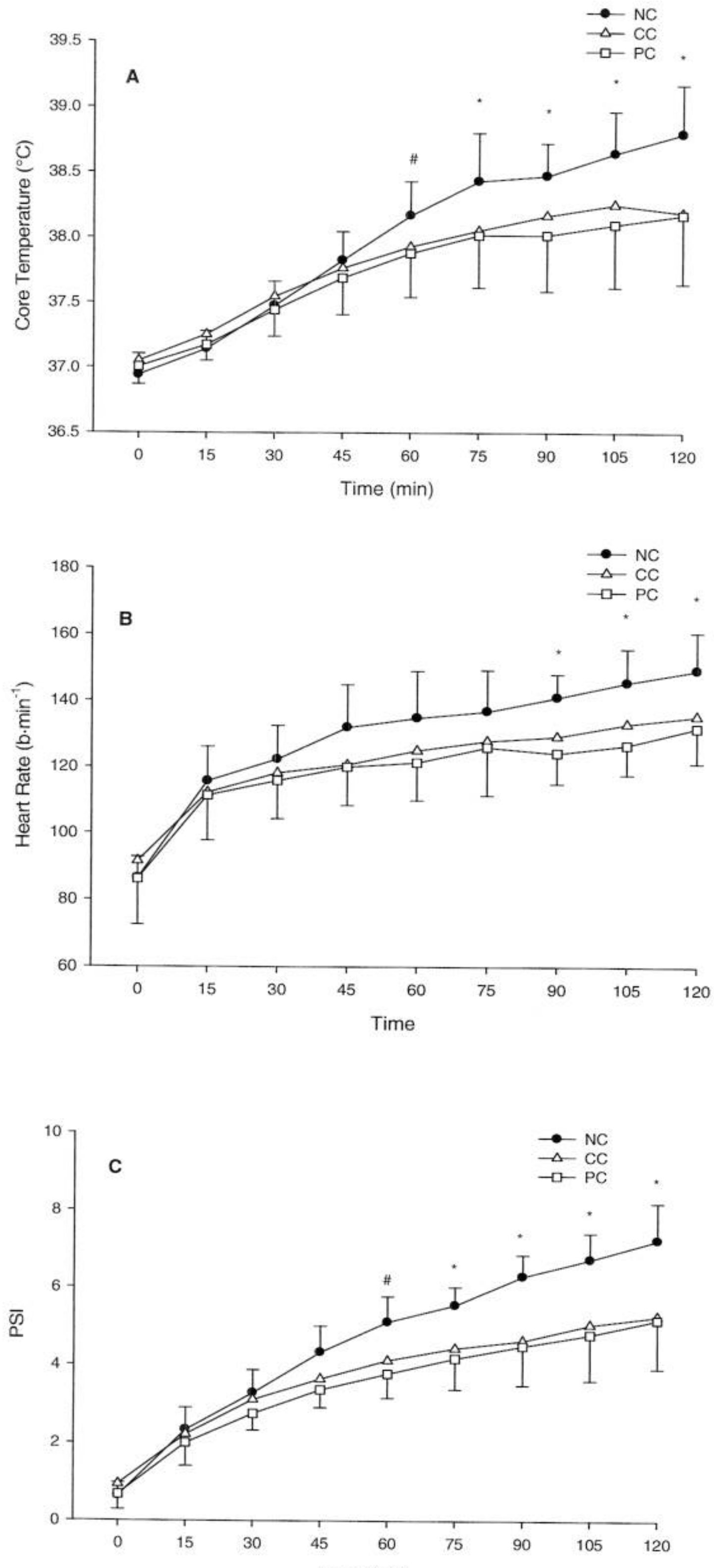


Figure 6A-C. Core temperature (A), heart rate (B), and physiological strain index (PSI) (C) across time in all three cooling tests at 35°C, 70% rh. *Significantly different from PC and CC ($p<0.05$). #Significantly different from PC ($p<0.05$).

DISCUSSION

Two main conclusions can be drawn from the results of this study. The first is that the skin feedback technology devised by NSRDEC for the prototype MCCS worked effectively. Second, the MCCS cooling capacity, as currently engineered, was insufficient cooling for the subjects in the more severe environmental conditions.

NBC (30°C, 30% rh)

Under these environmental conditions, the skin temperature feedback feature of the prototype cooling system worked as designed. The cooling portion of the MCCS was designed and tested by the developers to deliver 120 W of cooling in a 35°C environment. Actual cooling power measured during the study showed that the prototype MCCS provided 106 W of cooling during CC and 134 W during PC. Even with this low level of cooling, the torso temperatures were able to cycle through the pre-designed range of 34.5° – 33.5°C, allowing the cooling system to cycle on and off. This resulted in higher torso and mean weighted skin temperatures during PC versus CC. However, while skin temperatures differed between CC and PC, there was no difference in core temperature, HR or sweating rate among any of the three trials. These observations differ from previous PC studies while wearing NBC equipment carried out at USARIEM (3, 7, 19).

The exercise rates and environmental conditions in the current study were designed to approximate those used in the previous PC studies. These studies showed lower core temperatures and HRs using PC delivered either on timing sequence (3, 7) or by skin temperature feedback (19). These studies also used more powerful cooling systems distributed to whole body and head cooling garments. These earlier studies were designed as proof of concept studies to show that PC would provide equivalent heat strain relief while using less power than CC. However, these systems were not practical for use by the dismounted Soldier.

In addition to having less cooling provided over a smaller surface area in the PC and CC experiments, there were also two differences in the NC mode between this study and the earlier ones. Those studies used the Battle Dress Overgarment, an earlier generation of NBC protective clothing, which created more insulation and reduced permeability compared with the JSLIST garment worn in the current study. Additionally, in the previous studies, the subjects wore the full body cooling suit without any water pumped through it during the non-cooling tests. This also served to increase the thermal barrier between the subjects and the environment compared to wearing the JSLIST with no cooling garment in the NC phase of the current study. These variables lowered thermal strain in the subjects in the current study, as they had a final mean core temperature of 37.8°C in NC compared with 38.7 in the first PC study (7). It is unknown whether the MCCS used in this study would be sufficient to reduce heat strain at either higher metabolic rates or under more extreme environmental conditions during NBC experiments.

ACU AND BODY ARMOR

In the two tests conducted with the ACU and body armor, the MCCS were incapable of providing the 120 W of anticipated cooling based on laboratory bench tests conducted at 35°C. It appears that the increased environmental stress limited the cooling provided by the MCCS. The metabolic rates in the ACU tests were, if anything, marginally lower than those in the NBC tests, and the barriers to heat transfer as measured by Clo and i_m were less in these tests.

The measured cooling in both these environments was well below the expected cooling of 120 W. In the dry 45°C, 20% rh environment, the cooling for CC was 84.5±33.4 W and for PC was 79.1±22.1 W. In the 35°C, 70% rh environment, the cooling for CC was 92.8±8.3 W and for PC was 97.8±8.8 W. These levels of cooling were inadequate to remove enough heat from the torso to lower skin temperature to 33.5°C. Consequently, during the PC tests the MCCS ran continuously. Despite the low level of cooling in these environments, some heat strain relief was observed.

ACU (45°C, 20% rh)

At 45°C, 20% rh, there would be considerable evaporative cooling, but there would be concomitant environmental convective and radiant heat gain. Even with this level of heat stress and the low level of cooling provided by the MCCS in this environment, both torso and mean weighted skin temperatures with PC and CC were lower than NC for the majority of walk time. However, even though lower than NC, they remained above 35°C for all but the first 15 minutes with CC and the entire test with PC. Of interest is that from minute 75 to 120, core temperature in CC was significantly lower than NC and marginally lower than PC. During this time both torso and mean skin temperatures with CC were marginally lower than PC. It may be that even the slight difference in cooling temperatures provided by the MCCS (84 W for CC and 79 W for PC) may have had a physiological impact over a long time period.

ACU (35°C, 70% rh)

At 35°C, 70% rh, the ambient temperature was close to initial skin temperature, but the inability to evaporate sweat resulted in increasing skin temperatures and heat strain in the volunteers without supplementary cooling. While the MCCS did not provide enough cooling to trigger the on-off cycles, the approximately 95 W of cooling delivered in both CC and PC had sufficient impact on both torso and skin temperature in this environment that mean skin temperature remained significantly lower than NC throughout exercise at around 35°C versus around 36.5°C with NC. This impact by the MCCS during CC and PC was sufficient to provide a core-to-skin transient to significantly reduce heat strain, as measured by core temperature and HR during the last 45 minutes of exercise relative to NC.

CONCLUSIONS

There were design problems with the early prototype MCCS that prevented it from delivering the level of cooling for which it was engineered. Also, the surface area of cooling garment in contact with skin is limited by use of tubing and the amount of tubing that can be fit into a torso vest. Design changes that would result in larger surface area coverage could enhance the heat removing capabilities of the system. It is unknown at this time whether this can be accomplished without creating a greater weight burden.

Additionally, while the skin temperature feedback system did work, there were problems with maintaining consistent contact from the small thermistor used (Figure 7). Integrating the skin sensor into the cooling garment could be one way to increase the likelihood of contact. Also, using multiple sensors to either direct flow to an individual hot spot or just to start the flow as soon as one area reaches the criterion temperature could increase the reliability of future skin temperature feedback MCCS.

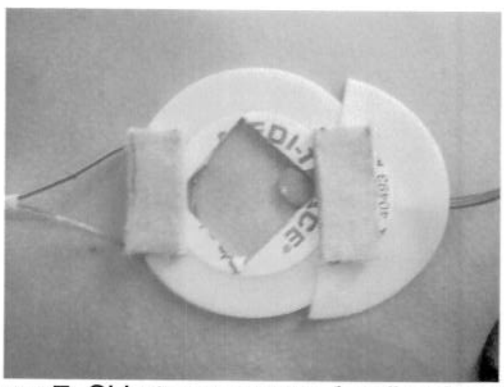


Figure 7. Skin temperature feedback sensor.

Finally, based on the marginal improvements observed with this 120 watt MCCS, it may be necessary to design a system with higher cooling capacity and then determine what the trade-off would be in performance for the increased weight of the system. It may be that a combination of using more sensor sites, increased contact area of cooling channels with skin and a larger cooling capacity will achieve the capability of providing sufficient cooling, with the energy saving pulsed capability, to increase tolerance time in Soldiers under extreme conditions.

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