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ORIGINAL RESEARCH

Heat Strain Reduction by Ice-Based and Vapor Compression Liquid Cooling Systems with a Toxic Agent Protective Uniform

Bruce S. Cadarette, Leslie Levine, Margaret A. Kolka, Gary N. Proulx, Mathew M. Correa, and Michael N. Sawka

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Background: The purpose of this study was to compare a vapor compression microclimate cooling system (MCC) and a personal ice cooling system (PIC) for their effectiveness in reducing physiological strain when used with cooling garments worn under the impermeable self-contained toxic environment protective outfit (STEPO). A second comparison was done between the use of total body (TOTAL) and hooded shirt-only (SHIRT) cooling garments with both the MCC and PIC systems. It was hypothesized that the cooling systems would be equally effective, and total body cooling would allow 4 h of physical work in the heat while wearing STEPO. ***Methods:*** Eight subjects (six men, two women) attempted four experiments at 38°C (100°F), 30% rh, 0.9 $m \cdot sec^{-1}$ wind, while wearing the STEPO. Subjects attempted 4 h of treadmill walking (rest/exercise cycles of 10/20 min) at a time-weighted metabolic rate of 303 ± 50 W. ***Results:*** Exposure time was not different between MCC and PIC, but exposure time was greater with TOTAL (131 ± 66 min) than with SHIRT (83 ± 27 min) for both cooling systems ($p < 0.05$). Cooling rate was not different between MCC and PIC, but cooling rate while wearing TOTAL (362 ± 52 W) was greater than with SHIRT (281 ± 48 W) ($p < 0.05$). Average heat storage was lower with MCC (39 ± 20 $W \cdot m^{-2}$) than with PIC (50 ± 17 $W \cdot m^{-2}$) in both TOTAL and SHIRT ($p < 0.05$). Also, average heat storage while wearing TOTAL (34 ± 19 $W \cdot m^{-2}$) was less than with SHIRT (55 ± 13 $W \cdot m^{-2}$) for both cooling systems ($p < 0.05$). The Physiological Strain Index (PSI) was lower in MCC-TOTAL (2.4) than MCC-SHIRT (3.7), PIC-SHIRT (3.8), and PIC-TOTAL (3.3) after 45 min of heat exposure ($p < 0.05$). ***Conclusions:*** Total body circulating liquid cooling was more effective than shirt-only cooling under the impermeable STEPO uniform, providing a greater cooling rate, allowing longer exposure time, and reducing the rate of heat storage. The MCC and PIC systems were equally effective during heat exposure, but neither system could extend exposure for the 4 h targeted time.

Keywords: protective clothing, toxic environment, heat stress, human physiology, cooling.

IN THE MANAGEMENT and shutting down of chemical weapons arsenals, the U.S. Army oversees the storage, maintenance, cleanup, and destruction of highly toxic substances. It is essential that workers who routinely clean up spills or otherwise handle toxic munitions wear personal protective equipment. In the years prior to 1988, the toxic agent protective (TAP) suit was the Army standard for use in toxic environments, which pose an immediate danger to life and health. The TAP consisted of a coverall-type, button-up suit fabricated entirely of butyl-coated nylon material. The TAP was worn with butyl rubber boots; a mask for respiratory protection; a butyl rubber hood covering the head, neck, and shoulders; and butyl rubber gloves. The TAP suit was worn over a cotton sateen shirt, trousers, gloves, and three pairs of socks; all impregnated with chlorinated paraffin. When worn under the TAP suit, the impregnated clothing was designed to protect the wearer from small liquid droplets of vapors and blister agents.

By 1987, in accordance with the Occupational Safety and Health Administration safety limits for allowable exposure to chemical warfare agents, Army officials identified the need for a new protective ensemble. The new uniform system, the self-contained toxic environment protective outfit (STEPO) was developed. The STEPO was designed for personal protection in highly toxic, unknown, or oxygen-deficient environments that pose an immediate danger to life and health. In addition, it was to be totally encapsulating and self-contained, not relying on filtered breathing air. An interim STEPO (STEPO-I) was developed and introduced in 1988 to replace the TAP suit in immediate-danger-to-life-and-health environments (6,7,12). The STEPO-I and the TAP suit became the protective systems currently fielded for Army personnel.

The STEPO-I was intended as a single purchase item, but underwent some minor improvements between 1988 and 1995. A new generation of STEPO was designed to provide personal protection for up to 4 h. The newest generation of STEPO was designed to outperform the STEPO-I by reducing heat stress, improving

From the U.S. Army Research Institute of Environmental Medicine, Natick, MA (B. S. Cadarette, L. Levine, M. A. Kolka, M. N. Sawka) and the U.S. Army Research, Development and Engineering Center, Natick, MA (G. N. Proulx, M. M. Correa).

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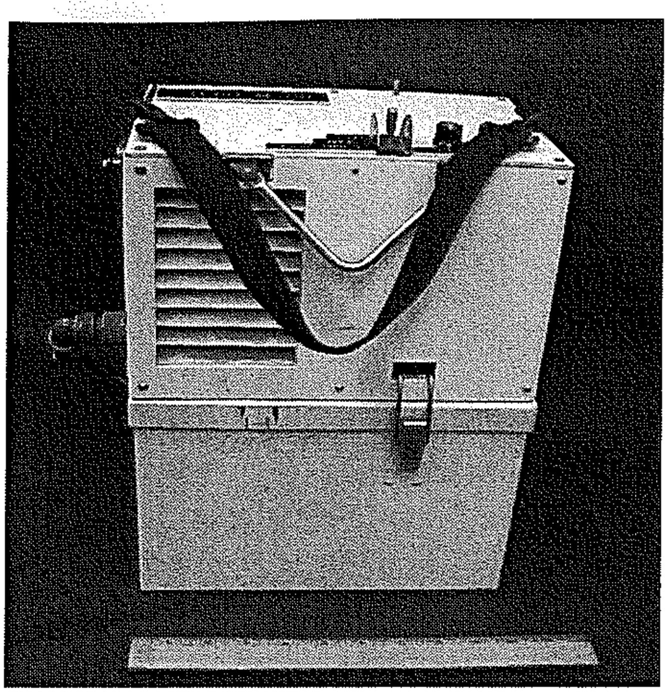

Fig. 1. The 10-kg vapor compression microclimate cooling unit (MCC) was designed to chill and circulate liquid to the total garment seen in Fig. 3.

load carriage, improving flame resistance, and improving industrial chemical and chemical warfare agent protection. These expectations were based on altered fabric, improved weight carrying distribution, and improved total body microclimate cooling system (MCC, vapor compression; **Fig. 1**). The STEPO system was designed to provide a maximal exposure time (including donning to doffing) of 4 h in ambient temperatures up to 38°C. Clothing characteristics determined by thermal manikin for STEPO are clo = 1.95 and I_m = 0.10.

While the STEPO system was being refined, a simplified type of liquid microclimate cooling system was created in a separate developmental program. This system was the personal ice cooling system (PIC; **Fig. 2**). The PIC was designed for shirt-only cooling, inside protective clothing, for a 2-h exposure (1). The PIC design used circulating chilled water with an external ice-filled container as the heat sink, allowing for resupply of the ice without opening the protective clothing. This was an improvement over standard ice vests worn under personal protective equipment that lose cooling efficiency as ice melts.

The purpose of the study was to compare the MCC and PIC cooling systems for their effectiveness in reducing physiological strain when worn under STEPO. A second comparison was done between total body (TOTAL) cooling garments and hooded shirt-only (SHIRT) cooling garments with both the MCC and PIC systems. This allowed comparisons among microclimate cooling, shirt only (MCC-SHIRT); microclimate cooling, total body (MCC-TOTAL); personal ice cooling system, shirt only (PIC-SHIRT); and personal ice cooling system, total body (PIC-TOTAL). It was hypothesized that the cooling systems would be equally effective and total body cooling would allow 4 h of physical work in the heat while wearing STEPO.

METHODS

Clothing/Cooling Systems

The STEPO system includes an impermeable suit encapsulating the entire body. The STEPO outer shell is a one-piece garment with integral booties, back pod (to enclose backpack re-breather), visor, airtight closure, exhaust valves, pass through, support harness, and glove assembly. The material is light in weight and color, is flexible, and is composed of polytetraflouroethylene (Teflon™) and NOMEX™. The fabric has an integrated monomer film which helps decay static charge across the surface. The visor, incorporated into the head portion of the suit, provides a wide field of vision. The visor is a multi-laminate film consisting of a 10 mil fluorinated ethylene polypropylene film which is machine laminated to a 7–10 mil hydrophilic film. The hydrophilic film provides anti-fogging and is permanently welded to the suit. The gloves (viton butyl) for the system are interchangeable, depending on the chemical hazard.

Respiratory protection is provided by use of a self-contained breathing apparatus, with a maximum 4-h capability. The weight of the STEPO breathing system, carried as a backpack under the STEPO shell, is 15 kg. The closed-circuit re-breather circulates exhaled air through a CO_2 scrubber. The effluent is mixed with an O_2 stream supplied from a compressed air bottle, and is then reintroduced into the respirator face piece where it is inhaled. The re-circulated air is cooled, by passing over a frozen gel tube before re-breathing.

The STEPO system was designed to include personal vapor compression MCC. The MCC uses a modified two-piece total body cooling garment (**Fig. 3**) designed

Fig. 2. The 5-kg ice-based personal ice cooling unit (PIC) was designed to chill and circulate liquid to the shirt only.

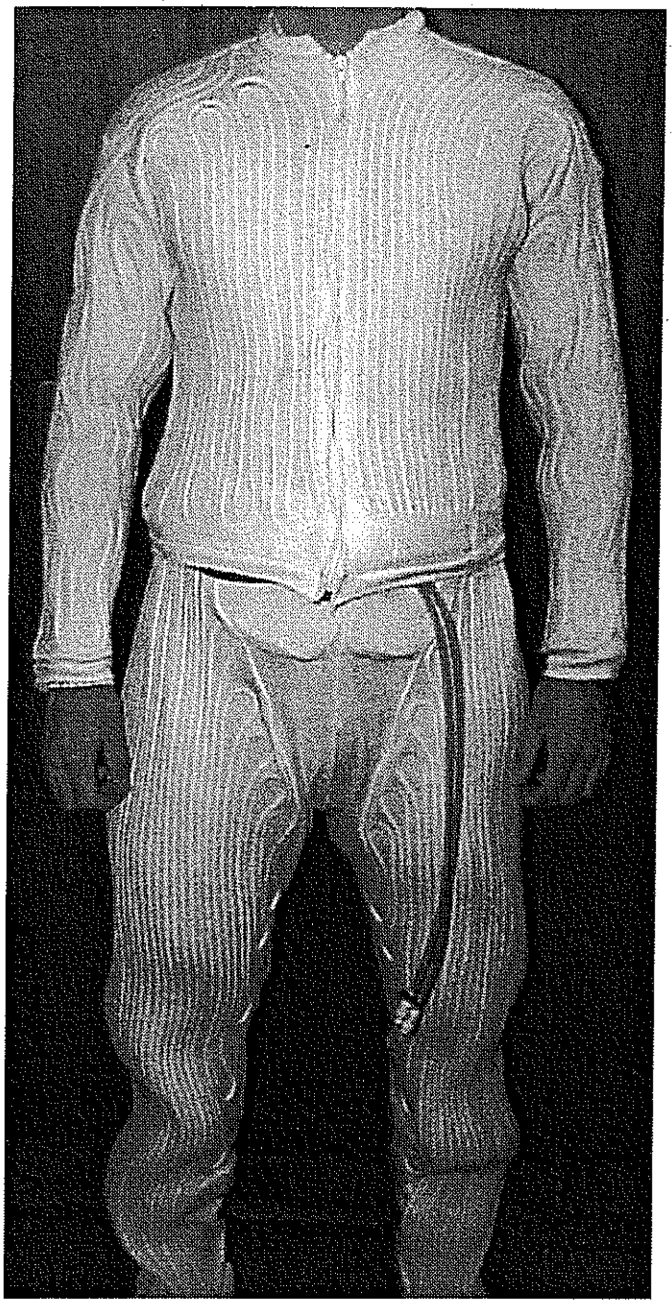

Fig. 3. The two-piece circulating liquid cooling garment

with at least 300 ft of integral, small diameter cooling lines and a rated cooling capacity of 375 W at an ambient temperature of 35°C. The shirt portion of the cooling garment covers the head, torso and arms providing a nominal 150 W of cooling. The pants portion of the cooling garment covers from the waist to the ankles and provides the remaining 225 W of cooling. To provide this cooling for a 4-h mission, the liquid-based cooling system is supplied with coolant at a constant 18°C temperature. The MCC system includes the vapor compression unit, an umbilical hose to the cooling garment, and a power supply (4 BA5590 lithium batteries). Refrigerant in the MCC unit is HFC 134A, and 25% propylene glycol in distilled or de-ionized water in the hoses. The MCC unit was also used with the shirt portion of the two-piece cooling garment for the shirt-only configuration. The cooling unit is carried to the work site and set on the ground during operations. The weight of the cooling unit with batteries is 10 kg. The total STEPO configuration including uniform, cooling garment (without 10 kg MCC unit), and respiratory system weighs approximately 27 kg.

The PIC system was designed to pump chilled water through the tubing system of a long-sleeved cooling garment worn next to the skin, providing a nominal 150 W of cooling with the ice bottle changed every 30 min. It was tested as designed for the shirt-only configuration. The PIC unit was also used with the two-piece total body cooling garment to potentially increase the cooling capacity of the system. The PIC, liquid reservoir, pump, and battery supply are carried by the user, supported by a waist belt system with integral hook, and strapped to the outside of the thigh. Use of the PIC system adds approximately 5 kg to the STEPO system weight for a total weight of 32 kg.

Subjects

Eight volunteers (six men and two women) served as subjects for the experimental trials after completing medical examinations to assure there were no underlying health problems. The mean ± standard deviation (SD) age, height, weight, and % body fat (3) of the subjects were: 23 ± 5 yr, 173 ± 9 cm, 73.0 ± 12.5 kg, and 20.4 ± 3.7% body fat. All subjects were fully informed of the purpose, procedures, and potential risks of the study and signed a statement of informed consent. Investigators obtained appropriate Institutional Review Board approval and adhered to guidelines established for human research.

Procedures/Measurements

Subjects took part in a familiarization day to be fitted to all STEPO and cooling equipment. The same day, subjects practiced walking on the treadmill at 0.9 m · sec^{-1}, 0% grade while wearing the STEPO system and the cooling garment, but without carrying either the MCC or PIC unit. Once subjects were walking comfortably and had been on the treadmill for 15 consecutive minutes, the energy cost of exercise was measured by open circuit spirometry (8). Subjects were then seated for 15 min after which time post-exercise resting energy costs were measured. These measured values were used to calculate time-weighted metabolic rate during the experiments and to validate that they were similar to metabolic rates measured during simulated military hazardous materials handling operations wearing STEPO. A predictive model analysis indicates that carrying the PIC unit adds 20 W to the measured energy cost of walking in STEPO (11). Carrying the MCC unit would add 40 W to the cost of walking in STEPO. However, the amount of time the MCC is carried is mission dependent and it was not carried at all during the experiments.

Following familiarization and measurement of energy cost, the subjects completed four experimental tests always wearing the STEPO, but with a different cooling configuration each day; MCC-SHIRT, MCC-TO-

TAL, PIC-SHIRT, and PIC-TOTAL. Tests were conducted in a counterbalanced design to avoid an order effect on results. Each morning, subjects drank at least 500 ml of a glucose electrolyte drink immediately after their initial weights. This was the only liquid consumed until the completion of the test. All tests were completed in an environmental chamber set at 38°C, 30% rh, with wind at 0.9 m · sec^{-1}.

Measurements of physiological values were collected daily to monitor the subjects' status and determine differences between treatments. Rectal temperature (T_{re}) was measured by a flexible thermistor probe (Yellow Springs Instruments, Yellow Springs, OH) inserted approximately 10 cm beyond the anal sphincter. Individual skin temperatures (T_{sk}) were measured with a four-site skin thermocouple harness (chest, arm, thigh, calf). Mean skin temperature was calculated as 0.6 for upper body (chest + arm) and 0.4 for lower body (thigh + calf) using the weighting system of Ramanathan (13). Heart rate (HR) was obtained from an electrocardiogram (chest electrodes, CM5 placement). Average heat storage (S) in W · m^{-2} for each experiment was calculated from the equation $S = [(m_b \cdot c_b)/A_D] \cdot (\Delta T_b/\Delta t)$, where m_b is the mean body weight (kg) during the experiment; c_b is the specific heat constant (0.965 W · h^{-1} · °C^{-1} · kg^{-1}); A_D is the DuBois surface area (m^2); ΔT_b is the change in mean body temperature (°C) where $T_b = 0.2 \cdot T_{sk} + 0.8 \cdot T_{re}$; and Δt is the exposure time (h). Heat storage was also calculated in kJ · kg^{-1} · h^{-1} both to adjust for differences in body mass and to indicate the probability of heat casualty as a function of heat storage (4). Neither heat storage calculation assumes a change in the proportion of core to skin as a function of time. Whole body sweating rates were calculated from changes in pre- to post-experiment nude weights with correction for any liquids ingested or urine voided subsequent to the first morning weight.

After complete instrumentation and donning of STEPO, subjects entered the environmental chamber and sat for a 10-min rest followed by 20 min walking at 0.89 m · sec^{-1} on a level treadmill. This pattern was repeated for up to 4 h. Ice packs for the PIC cooling system were changed every 30 min regardless of whether the cooling garment was worn in the SHIRT or TOTAL configuration. Tests were terminated at the predetermined endpoint of heat exposure (240 min), predetermined core temperature endpoint (39.5°C), or heart rate endpoint criteria (90% age predicted maximal HR). Tests could also be terminated at the discretion of the medical monitor, investigator, or by subject choice. All test sessions were conducted in the morning with approximately 2 d between tests.

A Physiological Strain Index (PSI) was calculated at 10-min intervals to assess the relative level of heat strain among the four configurations. The PSI is based on rectal temperature and heart rate and calculated on a universal scale of 0–10 (9). The PSI was calculated by the equation: $PSI = 5(T_{ret} - T_{re0}) \cdot (39.5 - T_{re0})^{-1} + 5(HR_t - HR_0) \cdot (180 - HR_0)^{-1}$, where T_{ret} and HR_t are simultaneous measurements taken at any time during heat exposure, T_{re0} and HR_0 are the initial resting values, and 39.5 and 180 represent maximal core temperature and heart rate respectively.

The cooling rates were calculated for each of the four test configurations using the difference between inlet and outlet temperatures of the coolant and the flow rate of the circulating coolant. The flow rate and temperature of the coolant supplied to the cooling garments was continuously monitored using Omega Engineering model FTB601 Ultra-Low Flow Sensors (Omega Engineering, Stamford, CT) with a range of 1 to 2 L · min^{-1} and Type-T (copper constantan) thermocouples.

Statistical Analysis

Analyses of variance were done for endurance time (ET), final core temperature (T_{reF}), final mean skin temperature (T_{skF}), final upper body skin temperature (upper T_{skF}), final lower body skin temperature (lower T_{skF}), final heart rate (HR_F), cooling rates, average rate of heat storage (S) in W · m^{-2}, average heat storage in kJ · kg^{-1} · h^{-1}, and sweating rate (SR) among the four cooling system configurations. Analyses of variance were also conducted for core temperature (T_{re50}), upper body skin temperature (upper T_{sk50}), lower body skin temperature (lower T_{sk50}), mean weighted skin temperature (T_{sk50}), heart rate (HR_{50}), average heat storage (S_{50}) in W · m^{-2}, and average heat storage in kJ · kg^{-1} · h^{-1} at 50 min of heat exposure, before subject attrition occurred. If significant main effects (cooling system or surface area cooled) were found at the $p < 0.05$ level then post hoc analyses were conducted using the Tukey Test. There were no differences in the results between the cooling configurations when examining the data from male subjects separate from the female subjects, so results are reported on all eight subjects.

RESULTS

The time-weighted mean ± SD energy cost of the subjects in STEPO was 303 ± 50 W. Mean endurance times (± SD) for the four configurations were 86 ± 32 min for MCC-SHIRT, 152 ± 69 min for MCC-TOTAL, 81 ± 22 min for PIC-SHIRT, and 110 ± 61 min for PIC-TOTAL. There was no significant difference in endurance time between MCC and PIC systems. Endurance time for total body cooling systems (131 ± 66 min) was significantly greater than for shirt-only cooling (83 ± 27 min) ($p < 0.05$). The entire 4-h exposure was completed by two subjects wearing MCC-TOTAL and by one subject wearing PIC-TOTAL.

Table I provides the reason for test termination in each of the four configurations. Tests were stopped as a result of perceived discomfort by the subjects in 21 of the 32 individual tests. Six of the 32 tests were stopped by reaching pre-determined heart rate limits. One test was stopped for mechanical failure and three subjects completed the full test.

Table II shows the mean ± SD final values, range, and statistical significance for core temperature, mean weighted total body skin temperature, upper body (chest + arm) and lower body (thigh + calf) mean skin temperature, heart rate, sweating rate, and PSI for the four cooling configurations. The T_{reF} for total body cool-

TABLE I. REASONS FOR TEST TERMINATION EITHER AS A MEASURED PHYSIOLOGICAL VALUE OR AS REPORTED BY THE SUBJECT.

	MCC-SHIRT	MCC-TOTAL	PIC-SHIRT	PIC-TOTAL
T_{re} limit	0	0	0	0
HR limit	2	1	2	1
Hard to breathe/ hot air	2	1	2	4
Feel hot	3	1	1	1
Exhausted by work	1	2	2	1
Mechanical failure	0	1	0	0
No reason	0	0	1	0
Finishes test	0	2	0	1

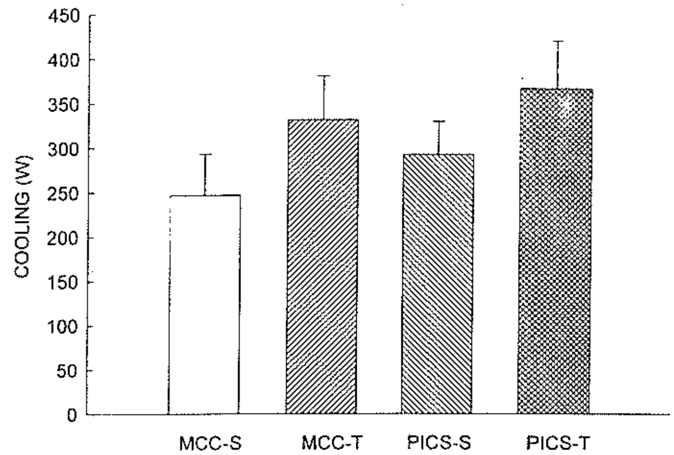

Fig. 4. Mean ± SD cooling in watts provided by both the vapor compression microclimate cooling system (MCC) and personal ice cooling system (PIC) worn with either hooded cooling shirt (SHIRT) or total body cooling garment (TOTAL) in STEPO during exercise at 38°C, 30% rh.

ing (38.2 ± 0.5°C) was significantly lower than the T_{reF} for shirt-only cooling (38.6 ± 0.4°C) ($p < 0.05$). Final upper body skin temperature for total body cooling (36.5 ± 1.4°C) was significantly higher than the upper T_{skF} for shirt-only cooling (34.9 ± 1.5°C) ($p < 0.05$). Final lower body skin temperature for total body cooling (35.6 ± 1.4°C) was significantly lower than the lower T_{skF} for shirt-only cooling (38.1 ± 0.5°C) ($p < 0.05$). There were no significant differences shown among the final values of any of the other measured variables either between PIC and MCC cooling or TOTAL and SHIRT coverage at the end of exposure.

Fig. 4 shows the mean total cooling rates ± SD calculated for the four cooling configurations. The cooling rate for TOTAL (362 ± 52 W) was significantly greater than cooling rates for SHIRT (281 ± 48 W) ($p < 0.05$). Cooling rate was not different between MCC and PIC. **Fig. 5** shows the avetage rate of heat storage ± SD in $W \cdot m^{-2}$ over the entire test calculated for the four cooling configurations. The average rate of heat storage for MCC (39 ± 20 $W \cdot m^{-2}$) was significantly lower than for PIC (50 ± 17 $W \cdot m^{-2}$) ($p < 0.05$). The average rate of heat storage for TOTAL (34 ± 19 $W \cdot m^{-2}$) was significantly lower than rate of heat storage for SHIRT (55 ± 13 $W \cdot m^{-2}$) ($p < 0.05$). The average heat storage calculated relative to body weight for MCC (3.53 ± 1.72 $kJ \cdot kg^{-1} \cdot h^{-1}$) was significantly less than for PIC (4.56 ± 1.43 $kJ \cdot kg^{-1} \cdot h^{-1}$). Average heat storage relative to body weight for TOTAL (3.09 ± 1.61 $kJ \cdot kg^{-1} \cdot h^{-1}$) was significantly less than for SHIRT (5.01 ± 1.00 $kJ \cdot kg^{-1} \cdot h^{-1}$).

The physiological responses at 50 min, representing the final time when all subjects were present, are shown in **Table III**. The T_{re50} for total body cooling (37.6 ± 0.3°C) was significantly lower than the T_{re50} for shirt-only cooling (37.9 ± 0.2°C) ($p < 0.05$). The mean T_{sk50} for total body cooling (34.8 ± 1.2°C) was significantly lower than for shirt-only cooling (35.4 ± 1.0°C) ($p < 0.05$). The mean upper T_{sk50} for total body cooling (35.1 ± 1.4°C) was significantly higher than for shirt-only cooling (34.0 ± 1.7°C) ($p < 0.05$). The mean lower T_{sk50} for total body cooling (34.3 ± 1.4°C) was significantly lower than for shirt-only cooling (37.6 ± 0.3°C) ($p < 0.05$). The HR_{50} for MCC (122 ± 20 bpm) was significantly lower than the HR_{50} for PIC (132 ± 15 bpm), and HR_{50} for total body cooling (121 ± 17 bpm)

TABLE II. MEAN FINAL VALUES (±SD) FOR CORE TEMPERATURE (T_{RE}), UPPER BODY AND LOWER BODY SKIN TEMPERATURE (T_{SK}), HEART RATE (HR), SWEATING RATE (SR), AND PHYSIOLOGICAL STRAIN INDEX (PSI) IN THE FOUR COOLING CONFIGURATIONS.

	MCC-SHIRT	MCC-TOTAL	PIC-SHIRT	PIC-TOTAL	AREA OF COVERAGE T/S
T_{re} (°C)	38.5 (0.5)	38.2 (0.5)	38.7 (0.3)	38.3 (0.6)	
Range	38.1–39.3	37.6–38.5	38.1–39.3	37.1–39.0	T < S
Mean T_{sk} (°C)	36.0 (1.3)	35.9 (1.6)	36.2 (0.8)	36.4 (0.9)	
Range	34.0–37.7	33.6–38.0	35.3–37.7	35.2–37.9	N.S.
T_{sk} (°C) (chest + arm)	34.7 (1.9)	36.0 (1.6)	35.1 (1.1)	37.0 (1.0)	
Range	31.3–37.3	33.6–38.1	33.6–37.1	35.7–38.5	T > S
T_{sk} (°C) (thigh + calf)	38.1 (0.6)	35.6 (1.4)	38.1 (0.4)	35.6 (1.5)	
Range	37.2–39.2	33.4–37.6	37.4–38.7	32.8–37.3	T < S
HR ($b \cdot min^{-1}$)	154 (21)	145 (27)	158 (24)	156 (21)	
Range	126–182	109–178	139–182	124–184	N.S.
SR ($g \cdot min^{-1}$)	14 (6)	11 (5)	16 (6)	14 (8)	
Range	7–23	3–21	6–27	7–31	N.S.
PSI	6.5 (1.8)	5.4 (2.1)	7.1 (1.2)	6.2 (1.8)	
Range	4.8–9.6	2.9–7.6	5.9–9.1	3.7–8.8	N.S.

T < S and T > S indicate differences in physiological response between receiving total body cooling (T) and shirt-only cooling (S) ($p < 0.05$).

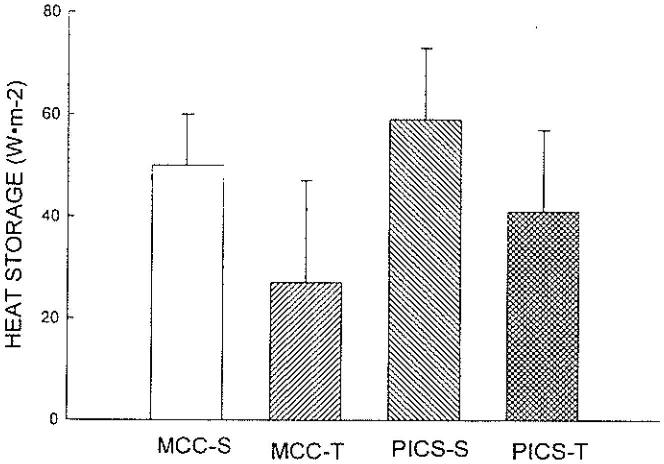

Fig. 5. Mean ± SD heat storage with cooling provided by both the vapor compression microclimate cooling system (MCC) and personal ice cooling system (PIC) worn with either hooded cooling shirt (SHIRT) or total body cooling garment (TOTAL) in STEPO during exercise at 38°C, 30% rh.

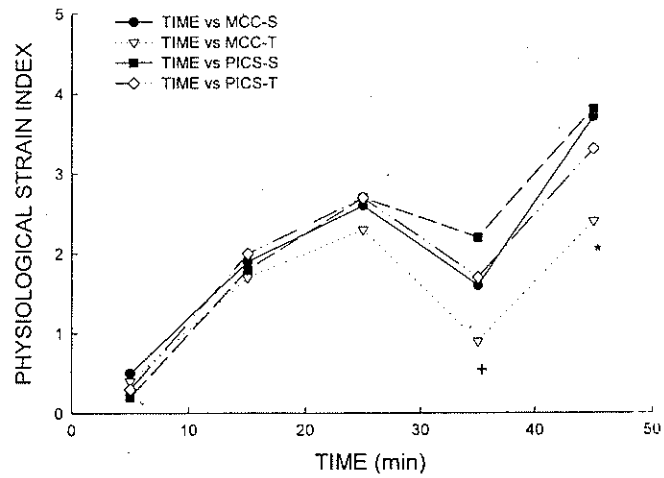

Fig. 6. Mean Physiological Strain Index values calculated during the first 45 min of heat exposure with both the vapor compression microclimate cooling system (MCC) and personal ice cooling system (PIC) with either a shirt-only (SHIRT) or total body cooling garment (TOTAL) worn under STEPO during rest and exercise at 38°C, 30% rh. + less than PIC-SHIRT; * less than other three configurations ($p < 0.05$).

was significantly lower than for shirt-only cooling (132 ± 18 bpm) ($p < 0.05$). The average S_{50} for MCC (44 ± 17 $W \cdot m^{-2}$) was significantly lower than for PIC (54 ± 18 $W \cdot m^{-2}$), and average S_{50} for total body cooling (40 ± 16 $W \cdot m^{-2}$) was significantly lower than for shirt-only cooling (59 ± 14 $W \cdot m^{-2}$) ($p < 0.05$). These patterns were similar to those of heat storage calculated for the entire test times (Fig. 4). Average heat storage calculated relative to body weight at 50 min for MCC (4.14 ± 1.30 $kJ \cdot kg^{-1} \cdot h^{-1}$) was significantly less than for PIC (4.97 ± 1.52 $kJ \cdot kg^{-1} \cdot h^{-1}$). Average heat storage relative to body weight at 50 min for total body cooling (3.69 ± 1.18 $kJ \cdot kg^{-1} \cdot h^{-1}$) was significantly less than for shirt-only cooling (5.41 ± 1.17 $kJ \cdot kg^{-1} \cdot h^{-1}$).

The Physiological Strain Index at 5, 15, 25, 35, and 45 min of heat exposure including both resting (5 and 35 min), and exercising (15, 25, and 45 min) values is shown in **Fig. 6.** There were no differences among the four configurations through the first 25 min of heat exposure. After 35 min of heat exposure (rest), PSI for MCC-TOTAL (0.9) was less than PIC-SHIRT (2.2) ($p < 0.05$). After 45 min of heat exposure (exercise), PSI for MCC-TOTAL (2.4) was less than all other configurations: MCC-SHIRT (3.7), PIC-SHIRT (3.8), and PIC-TOTAL (3.3) ($p < 0.05$).

DISCUSSION

This study showed similar effectiveness of the personal ice cooling system (PIC) and the vapor compression microclimate cooling (MCC) in reducing heat storage and enhancing performance while working in the STEPO impermeable toxic cleanup system. Additionally, the expectation that heat strain would be lower and endurance longer when liquid cooling was delivered to the total body compared with shirt-only cooling was observed. Unfortunately, neither cooling system was effective in allowing a 4-h heat exposure in the conditions of the study.

TABLE III. MEAN 50-MINUTE VALUES (±SD) FOR CORE TEMPERATURE (T_{RE}), UPPER BODY AND LOWER BODY SKIN TEMPERATURES (T_{SK}), HEART RATE (HR), AND HEAT STORAGE (S) IN THE FOUR COOLING CONFIGURATIONS.

	MCC-SHIRT	MCC-TOTAL	PIC-SHIRT	PIC-TOTAL	AREA OF COVERAGE T/S
T_{re} (°C)	37.8 (0.2)	37.6 (0.3)	38.0 (0.2)	37.6 (0.4)	
Range	37.5–38.0	37.2–37.9	37.6–38.2	37.3–38.0	T < S
Mean T_{sk} (°C)	35.3 (1.3)	34.5 (1.2)	35.6 (0.7)	35.1 (1.2)	
Range	33.0–37.1	32.8–36.5	35.0–37.2	32.4–37.7	T < S
T_{sk} (°C) (chest + arm)	33.8 (2.1)	34.7 (1.2)	34.3 (1.2)	35.5 (1.6)	
Range	29.8–36.4	33.2–36.7	33.0–36.7	32.4–37.7	T > S
T_{sk} (°C) (thigh + calf)	37.5 (0.3)	34.1 (1.5)	37.6 (0.3)	34.5 (1.4)	
Range	37.0–38.1	32.1–36.2	37.1–38.1	32.4–36.5	T < S
HR ($b \cdot min^{-1}$)	129 (20)	115 (18)	136 (15)	128 (15)	
Range	111–173	95–146	114–157	111–149	T < S
S ($W \cdot m^{-2}$)	54 (11)	35 (16)	64 (16)	45 (14)	
Range	44–72	19–69	48–92	18–59	T < S
S ($kJ \cdot kg^{-1} \cdot h^{-1}$)	4.96 (0.81)	3.31 (1.18)	5.86 (1.35)	4.08 (1.13)	
Range	3.93–6.11	2.40–5.83	4.38–8.48	1.88–5.25	T < S

T < S and T > S indicate differences in physiological response between receiving total body cooling (T) and shirt-only cooling (S) ($p < 0.05$).

There was no advantage, based on the physiological data from this study, between PIC and MCC cooling technologies. The method of removing heat from the body, primarily through convection, was identical whether the PIC or MCC was used. The differences between the two systems exists at the level of the cooling unit itself with either a vapor compression refrigeration technology acting as the heat sink with the MCC, or a simple ice bottle acting as the heat sink as water is circulated around it with the PIC. Once the circulating liquid is chilled, it is pumped through the same cooling garment with both systems. Data presented at the end of exposure (52–240 min, Table II) and after 50 min of exposure (Table III) were similar between the two cooling technologies covering the same surface area.

There were physiological differences as the surface area receiving liquid cooling increased. The circulating liquid in these microclimate cooling systems removed heat from the body surface by convection, and to a lesser degree by conduction, providing a temperature gradient for metabolic heat dissipation. The design of the STEPO uniform with a clo of 1.95 and I_m of 0.10 for all intents eliminated any evaporative cooling effect. Obviously, whole body cooling provided a greater surface area to dissipate heat from the core, significantly reducing core temperatures and resulting in lower calf and thigh skin temperatures at both 50 min and the end of exercise (Tables II and III).

The advantage of total body liquid cooling was also apparent by 50 min, with reduced heart rates and reduced mean weighted skin temperatures compared with values with shirt-only cooling. Endurance time was longer, cooling rates were greater, and calculated rates of heat storage measured in $W \cdot m^{-2}$ were lower with total body cooling regardless of cooling technology. Similarly, in calculations over the first 50 min, heat storage rates measured in $kJ \cdot kg^{-1} \cdot h^{-1}$ were also lower with total body cooling compared with the shirt-only cooling. Additionally, at 50 min the heat storage values with shirt-only cooling were above 4.78 $kJ \cdot kg^{-1} \cdot h^{-1}$ which is identified as the threshold for feelings of thermal discomfort (4). This rate of heat storage with shirt-only cooling at 50 min (5.41 $kJ \cdot kg^{-1} \cdot h^{-1}$), while not by itself high enough to result in heat casualties, could be a contributing factor to shortened work time when wearing the heavy, fully encapsulating STEPO uniform.

Even though endurance times were longer for total body cooling configurations, subjects sometimes withdrew from experiments when physiological heat strain was relatively low. This indicates that other factors might affect endurance in STEPO. The effects caused by the work intensity and load carriage of STEPO are one possibility. The feelings of thermal discomfort sensed while wearing protective masks is another. The re-circulated air in STEPO passes over a frozen gel pack, with the effect of both cooling the face under the respiratory mask and providing some respiratory cooling. As the gel pack thaws, the air returning to the respiratory mask becomes increasingly warmer. Thirty percent of the experiments were self-terminated because the subjects perceived breathing to be hot or difficult (Table I). It has been shown that as air temperature measured under the facemask of exercising subjects approaches 31°C, feelings of facial discomfort increase and overall acceptability of whole body sensation decreases (2,5,10). In our study, a total of 21 of the 32 experiments were self-terminated due to subject discomfort or sensation of feeling hot or exhausted. It is possible that if a continuous flow of cooled air was provided to the facemask, the perception of discomfort might be more closely related to actual level of heat strain experienced at any given time.

In general, the level of heat strain as indicated by the final mean physiological values shown in Table II indicate that the subjects endured an equivalent heat strain in all four configurations. The calculated cooling rates, endurance time, and sweating rates were similar between the MCC and PIC technologies. The lower rate of heat storage in MCC than in PIC may have been a result of the transient (1–2 min) shut down of circulating liquid during ice changeouts every 30 min in PIC. It is also possible that the predicted 20 W greater metabolic cost of carrying the PIC could have resulted in a greater rate of heat storage in that configuration (11). However, there clearly was not an effect on any performance responses between the two technologies. Further, the mean physiological data at the end of exposure in each configuration are consistent with those reported at exhaustion by soldiers exercising in chemical protective uniforms during uncompensable heat stress (8).

CONCLUSIONS

It can be concluded from the results of the current study that convective cooling from a total body circulating liquid garment was more effective than shirt-only cooling in providing a greater overall cooling rate in the impermeable STEPO uniform, allowing longer exposure time, and reducing the rate of heat storage. The MCC and PIC systems were equally effective in providing cooled liquid to the garments during heat exposure, but neither system could extend exposure for the 4-h targeted time. The study also indicated that something other than the measured physiological heat strain parameters might result in shortened work performance in the STEPO system.

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