Chemical-Biological Protective Clothing: Effects of Design and Initial State on Physiological Strain

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Purpose: This study examined whether heat strain during low states of chemical and biological protection (CB_{low}) impacted tolerance time (TT) after transition to a high state of protection (CB_{high}) and whether vents in the uniform reduced heat strain during CB_{low} and increased TT. ***Methods:*** There were eight men who walked at 35°C in CB_{low} and then transitioned to CB_{high}. Subjects wore fatigues in CB_{low} with an overgarment during CB_{high} (F+OG) or a new 1-piece (1PC) or 2PC uniform throughout CB_{low} and CB_{high}. One condition also tested opened vents in the torso, arms, and legs of the 2PC uniform ($2PC_{vent}$) during CB_{low}; these vents were closed during CB_{high}. Also worn were fragmentation and tactical vests and helmet. ***Results:*** Heart rates were reduced significantly during CB_{low} for F+OG and $2PC_{vent}$ (114 ± 13) vs. 1PC and 2PC (122 ± 18). Rectal temperature (T_{re}) increased least in CB_{low} for F+OG (0.86 ± 0.23°C) and was significantly lower for $2PC_{vent}$ (1.02 ± 0.25°C) vs. 2PC (1.11 ± 0.27°C). T_{re} increased rapidly during CB_{high} for F+OG, which had the shortest TT (40 ± 9 min). Increased thermal strain during CB_{low} for 1PC negated its advantage in CB_{high} and TT (46 ± 21 min) was similar to F+OG. Differences in T_{re} between 2PC and $2PC_{vent}$ remained during CB_{high} where TT was increased during $2PC_{vent}$ (74 ± 17 min) vs. 2PC (62 ± 19 min). ***Conclusions:*** It was concluded that heat strain during CB_{low} impacted TT during CB_{high}, and use of vents reduced heat strain during CB_{low}, thereby increasing TT.

Keywords: uncompensable heat stress, physiological strain, wind, evaporative heat loss.

UNDER CERTAIN conditions of high ambient temperature and/or relative humidity, or with the wearing of protective clothing that restricts evaporative heat loss, the evaporative heat loss required to maintain a thermal steady state (E_{req}) can exceed the maximal evaporative capacity of the environment (E_{max}), creating a condition of uncompensable heat stress (UHS) (9). Often overlooked in establishing heat stress tolerance time (TT) to UHS is the impact of the initial core temperature. For example, factors such as aerobic fitness (6), heat acclimation (3,6), and pre-exercise cooling (11), which lower the initial core temperature, are associated with increased total heat storage and TT during UHS. Conversely, factors such as hypohydration (6,32), the postovulatory phase of the menstrual cycle (35), or prior immersion in warm water (11), which raise the initial core temperature, lower total heat storage and reduce TT.

Military chemical and biological (CB) protective ensembles are designed to protect the soldier from the hazards of the environment and, as such, have high thermal resistance and low water vapor permeability characteristics. Traditional designs involved the donning of a protective garment that was worn over the combat fatigues, which exacerbated heat transfer due to the additional air layers trapped within the protective ensemble (13). In contrast, new CB protective garments have been designed that are intended to replace the combat fatigues and be worn as a stand-alone uniform throughout the transition from a low (CB_{low}) to a high (CB_{high}) level of protection (1). In theory, the improved heat transfer during CB_{high} would increase TT and, thus, improve the operational effectiveness of soldiers working in a contaminated environment. Amos and Hansen (1) correctly included CB_{low} and CB_{high} in their determinations of the physiological strain of wearing a new CB garment. However, comparisons during either condition were independent from one another and subjects began all heat stress exposures in a rested thermoneutral state. Thus, the true impact of the new garment design on its operational utility was not determined. Certainly, if the new CB garments are intended to replace the combat fatigues and overgarment concept then comparisons should include the transition through protection levels that represent that entire concept.

The potential for elevations in core temperature and body heat storage while wearing these new CB uniforms for prolonged periods during compensable heat stress during CB_{low} would be a disadvantage as the soldier transitions to CB_{high} and UHS. This disadvantage, therefore, could offset the intended advantage of these stand-alone uniforms on rates of heat storage during encapsulation such that heat stress TT during CB_{high} would be no different than the use of the traditional overgarment concept. Further, if sweat rates and fluid losses are increased while wearing these new CB uniforms in hot environments during CB_{low}, then fluid replacement guidelines (26) would need to be appropriately adjusted to ensure that soldiers were not becoming dehydrated

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prior to transitioning to CB_{high}. Improper fluid replacement can reduce heat stress TT during encapsulation due to a reduction in heat storage capacity (23) and a reduction in the core temperature that can be tolerated at exhaustion (32), and place individuals at a greater risk of orthostatic intolerance (5).

Heat transfer through protective clothing is determined by its thermal resistance and water vapor permeability, and the impact of wind velocity upon the air exchange within the microenvironment of the clothing ensemble and the external environment (2,13,30). Goldman (10) reported that a vent inserted under a flap across the shoulder area reduced heat storage during treadmill exercise at 35°C when impermeable but not permeable clothing was worn. The incorporation of clothing vents into the design of these new CB uniforms may be one option to assist with heat transfer when the uniform is worn in CB_{low}, especially if additional impermeable body armor needs to be worn to provide protection from blast and fragmentation particles. CB_{low} is a protective state that does not require filtration of the air exchange with the environment and would permit the opening of the vents. In this context, the use of clothing vents in the CB uniform may reduce the rise in core temperature during exercise in CB_{low}. If so, the initial core temperature upon transition to CB_{high} (or full encapsulation) would likely be more similar to what is observed when the combat fatigues are worn alone. Heat exposure TT would then be able to more fully exploit the advantage of these new CB uniform designs in slowing the rate of heat storage and the operational effectiveness of the soldier would be maximally extended.

The purposes of this study, therefore, were twofold. Firstly, it was the intent to reveal the impact of the thermoregulatory strain during CB_{low} with the use of stand-alone CB uniforms on TT during CB_{high}, and, secondly, to investigate whether the incorporation of vents in the uniform would reduce the thermoregulatory and cardiovascular strain during exercise in CB_{low} such that TT would be extended after the transition to CB_{high}.

METHODS

All trials were conducted within the climatic facility at Defense Research and Development Canada (DRDC) - Toronto following approval from the human research ethics committee of DRDC. Subjects were medically screened with a 12-lead ECG and physical exam and a full explanation of procedures, discomforts, and risks was given prior to obtaining written informed consent. Eight men volunteered to participate in the study. Respective mean values and SD for age, height, weight, peak aerobic power, and peak heart rate were 30.6 ± 10.6 yr, 1.81 ± 0.09 m, 80.0 ± 15.8 kg, 52.6 ± 7.5 ml · kg^{-1} · min^{-1}, and 194 ± 12 bpm.

Determination of Peak Aerobic Power ($\dot{V}o_{2peak}$)

$\dot{V}o_{2peak}$ was determined on a motor-driven treadmill using open-circuit spirometry before the series of experiments in the climatic chamber. Following 2 min of running at a self-selected pace, the treadmill grade was increased 1% · min^{-1} until subjects were running at a 10% grade. Treadmill speed was then increased 0.22 m · s^{-1} (0.8 km · h^{-1}) each minute until the subject could no longer continue. $\dot{V}o_{2peak}$ was defined as the highest 30-s averaged $\dot{V}o_2$ observed during the incremental test. Heart rate (HR) was monitored throughout the incremental test from a telemetry unit (Polar Electro PE3000, Stamford, CT). The heart rate value recorded at the end of the exercise test was defined as the individual's peak value (HR_{peak}).

Experimental Design

Subjects completed a familiarization session and four randomly assigned experimental sessions, all separated by a minimum of 7 d to reduce the carry-over effects of acute heat stress exposure. Sessions involved 90 min of treadmill exercise and heat stress at 35°C, 30% relative humidity, and a wind speed of 1 m · s^{-1} in CB_{low}, a 10-min transition period, and a further maximum of 90 min of the same exercise and heat stress in CB_{high}. During the familiarization session the treadmill speed and grade were individually set to create a rise in rectal temperature (T_{re}) between 0.5°C and 1.0°C by the end of the 90 min of exercise in CB_{low}. Thereafter the speed and grade were constant for the completion of the familiarization session and all experimental sessions. End-point criteria for all trials included 190 min of heat stress, T_{re} reaching 40.0°C, heart rate reaching or exceeding 95% of maximum for 3 min, dizziness or nausea precluding further exercise, or subject exhaustion. TT during CB_{high} was defined as the elapsed time from the beginning of the treadmill exercise following the 10-min transition period to the attainment of one or more of the end-point criteria that resulted in removal from the chamber.

Clothing Ensembles

Common clothing items for all sessions were undershorts, T-shirt, socks, running shoes, helmet, tactical assault vest, and fragmentation vest without the armor plates inserted. Simulated ammunition magazines were inserted into the pockets of the assault vest. Subjects also carried a simulated rifle. The total weight of these items was approximately 15 kg. For the familiarization session subjects wore combat clothing over their underwear and T-shirt with the combat jacket worn under the fragmentation and tactical assault vests to represent CB_{low}. For the transition to CB_{high} for this session, subjects first removed the helmet and doffed the fragmentation and assault vests. They then donned the current Canadian Forces CB protective garment over their combat fatigues and reattached the fragmentation and tactical assault vests over the torso. In addition, protective over-boots and gloves were worn together with the current respirator and canister. The attached hood then covered the remainder of the head and the subject redonned the helmet and carried the rifle.

One experimental trial was a repeat of the familiarization session and was designated F+OG for the wearing of the combat fatigues plus the CB overgarment to represent the traditional protection design concept. For the other three experimental trials subjects wore new CB protective uniforms designed to replace the combat fatigues in CB_{low} during hot-weather deployments. One of these uniforms was a one-piece (1PC), whereas for the other trials subjects wore a two-piece (2PC) jacket and pant design that included a 15-cm overlap of the jacket over the waist area of the pant. The closures at the neck, wrist, and ankle were open when these new uniforms were worn during CB_{low} but closed during CB_{high}. The 1PC uniform had an attached hood that draped down over the back during CB_{low}, whereas the 2PC uniform worn had a detachable hood that was removed during CB_{low}. For the transition to CB_{high} all closures were sealed and the gloves, hood, respirator, and canister were donned. The CB over-boots were not worn as part of the 2PC uniform during CB_{high}. The fragmentation and assault vests were worn over the 1PC and 2PC uniforms during both CB_{low} and CB_{high}.

The 2PC uniform worn for two of the experimental trials also incorporated zippered vents on the torso, arms, and legs. These vents were open in one trial ($2PC_{vent}$) but closed for the other (2PC) during CB_{low}. On both the left and right front side of the jacket 20-cm vents were located from the juxtanipple to midabdomen and 40-cm vents from the shoulder over the medial aspect of the arm to the midforearm. The vents on the torso were covered when the fragmentation vest was worn. In addition, 40-cm vents were located on the medial aspect of both pant legs from the midthigh to the calf. A porous meshed fabric was sewn on the inside of the uniform over the vented areas that permitted a maximum midpoint opening of 4 cm for the torso and 9 cm for the arm and leg vents. All vents were zippered closed during the transition to CB_{high}. Normalized values at a wind speed of 1.0 $m \cdot s^{-1}$ for thermal resistance and the Woodcock water vapor permeability coefficient are presented in **Table I** for the four experimental configurations worn in CB_{low} and CB_{high}. These determinations were made on a heated and wetted non-articulating manikin at wind speeds of 0.6, 1.12, and 2.24 $m \cdot s^{-1}$ (J. Giblo, Navy Clothing and Textile Research Facility, Natick Labs, personal communication; 2007).

TABLE I. NORMALIZED VALUES AT A WIND SPEED OF 1.0 $m \cdot s^{-1}$ FOR THERMAL RESISTANCE (CLO) AND THE WOODCOCK WATER VAPOR PERMEABILITY COEFFICIENT (i_m, DIMENSIONLESS UNITS) MEASURED ON A HEATED AND NON-ARTICULATING WETTED MANIKIN FOR THE CHEMICAL AND BIOLOGICAL UNIFORMS WORN IN A LOW (CB_{LOW}) AND HIGH (CB_{HIGH}) LEVEL OF PROTECTION.

	CB_{low}		CB_{high}	
Uniform	Clo	i_m	Clo	i_m
F+OG	1.06	0.41	1.90	0.27
1PC	1.17	0.37	1.62	0.31
2PC	1.17	0.36	1.53	0.31
$2PC_{vent}$	1.07	0.41	1.53	0.31

1 Clo unit is equal to 0.155 $m^2 \cdot °C^{-1} \cdot W^{-1}$. The chemical and biological protective uniforms represent the traditional combat fatigues plus overgarment design (F+OG) and a new one-piece (1PC) or two-piece (2PC) stand-alone protective uniform. For the 2PC uniform, zippered vents in the torso, arm, and leg were open during CB_{low} for $2PC_{vent}$ but closed during CB_{high}. For 2PC, the vents were closed during both CB_{low} and CB_{high}.

Dressing and Weighing Procedures

To control for the effects of circadian rhythm on core temperature, all trials began at approximately 0800 (22). Subject preparation and dressing procedures are described in detail previously (22). Subjects were given 5 $ml \cdot kg^{-1}$ body mass (approximately 400 ml) of cool water (at approximately 15°C) to drink prior to beginning the heat stress exposure and every 30 min throughout the session. If T_{re} was above 39°C or if the subject felt that he could not continue for another 10 min, water was not administered for the remainder of the test. This procedure was adopted to reduce the likelihood that the bolus of water administered was not absorbed prior to the termination of the trial.

Physiologic Measurements

Mean values over 1-min periods for T_{re}, and mean skin temperature ($\bar{T}_{sk}$) were calculated, recorded, and printed by a computerized data-acquisition system. T_{re} was measured using a flexible vinyl-covered rectal thermistor (YSI Philips model 21090A, Philips Medical Systems, Andover, MA) inserted approximately 15 cm beyond the anal sphincter. $\bar{T}_{sk}$ was calculated using a weighted equation (16) from seven temperature thermistors (Mallinckrodt, Medical Inc, St. Louis, MO) taped on the head, abdomen, medial deltoid, hand, anterior thigh, shin, and foot. The change in mean body temperature ($\Delta\bar{T}_b$) during CB_{low}, CB_{high}, and from the beginning to the end of the exercise and heat stress exposure was calculated using the weighted coefficients of 0.9 and 0.1 for the change in T_{re} and $\bar{T}_{sk}$, respectively (15). HR was monitored using a transmitter (Polar Vantage XL, Waltham, MA) clipped to an elasticized belt that was fitted around the chest and taped in place. The receiver was taped to the outside of the clothing, allowing for a continuous HR display. HR was recorded manually every 5 min during the heat stress test. Open-circuit spirometry was used to determine expired minute ventilation ($\dot{V}_E$), $\dot{V}o_2$, and carbon dioxide production ($\dot{V}co_2$) every 30 min beginning after 15 min of exercise from values averaged over a 2-min sampling period. An adapter was placed on the exhaust valve of the respirator to allow for collection of gas exchange during CB_{high}. The physiological strain index (PSI) was calculated according to the equation originally presented by Moran et al. (27) but modified by Tikuisis et al. (36) as follows:

$$PSI = 5(T_{re(t)} - T_{re(i)}) \cdot (40.0 - T_{re(i)})^{-1} + 5(HR_{(t)} - HR_{(i)}) \cdot (HR_{peak} - HR_{(i)})^{-1} \quad \text{Eq. 1}$$

where the subscripts (i) and (t) represent measurements taken at the start of the exposure and at some time after the start, respectively, and 40.0 and HR_{peak} represent limits to T_{re} and HR, respectively.

Sweat Measurements

Differences between nude and dressed body masses before and after each trial were corrected for respiratory (24) and metabolic weight losses (34), and for fluid intake. The rate of sweat produced was calculated as the sum of pretrial nude body mass and fluid given minus post-trial (corrected) nude body mass, divided by the total heat stress exposure time. Unfortunately it was not possible to determine nude body mass after the heat stress exposure during CB_{low} and prior to the initiation of heat stress during CB_{high}.

Statistical Analyses

A 1-factor (uniform) repeated measures analysis of variance (ANOVA) was performed on dependant measures such as TT, sweat rate, and $\Delta\bar{T}_b$. For dependant measures collected over time, a 2-factor (uniform and time) repeated measures ANOVA was conducted. To correct for violations in the assumption of sphericity with the repeated factors, the Huynh-Feldt correction was applied to the F-ratio. When a significant F-ratio was obtained, post hoc analyses used a Newman-Keuls procedure to isolate differences among the treatment means. All ANOVAs were performed using statistical software [SuperAnova V.1.11 (1991), Abacus Concepts, Inc., Berkley, CA]. For all statistical analyses, an alpha level of 0.05 was used. Data are presented as mean values ± SD.

RESULTS

Nude body weights were similar at the beginning of each trial. Sweat rates were also not different among the sessions with values averaging between 0.8–0.9 $kg \cdot h^{-1}$. $\dot{V}O_2$ was similar for all trials throughout the exercise and heat stress with values averaging 12.5–13.0 $ml \cdot kg^{-1} \cdot min^{-1}$. There was a progressive rise in $\dot{V}O_2$ over time from the initial measure of 12.3 ± 1.5 $ml \cdot kg^{-1} \cdot min^{-1}$ after 15 min of exercise and heat stress in CB_{low} to the value of 13.4 ± 1.8 $ml \cdot kg^{-1} \cdot min^{-1}$ recorded after 15 min of exercise and heat stress in CB_{high}.

Cardiovascular Strain

The changes in heart rate throughout the heat stress trials are depicted in **Fig. 1**. The responses were not different between uniforms F+OG and $2PC_{vent}$ or between 1PC and 2PC during CB_{low} with significantly higher heart rates observed while wearing the latter two uniforms after 45 min of exercise. After the transition to CB_{high} HRs remained significantly reduced for uniform $2PC_{vent}$, whereas the response while wearing uniform F+OG quickly increased to levels that matched the response in the other uniforms. HRs remained significantly elevated for 2PC compared with $2PC_{vent}$ despite the fact that the CB_{high} configuration was identical. Final HRs at the end of the heat stress trial for $2PC_{vent}$ were significantly lower compared with F+OG and 2PC but similar to 1PC (**Table II**). These HRs represented 90.9 ± 6.5, 88.3 ± 6.0, 90.4 ± 5.3, and 86.9 ± 6.5% HR_{peak} for F+OG, 1PC, 2PC, and $2PC_{vent}$, respectively.

Thermal Strain

The change in $\bar{T}_{sk}$ throughout the heat stress exposure is presented in **Fig. 2**. During CB_{low} there were no differences in $\bar{T}_{sk}$ among the four uniforms, although values tended ($P < 0.07$) to be lower for F+OG (35.4 ± 1.0°C) and $2PC_{vent}$ (35.4 ± 1.0°C) compared with 1PC (35.7 ± 1.0°C) and 2PC (35.7 ± 1.0°C). Average skin temperatures of the head, hand, abdomen, and foot indicating regions of the body unaffected by the vents in the clothing were not different among the uniforms during CB_{low}. In contrast, average skin temperatures for the arm and leg were not different between F+OG (35.3 ± 0.8°C) and $2PC_{vent}$ (35.3 ± 0.8°C), but their values were significantly lower than the other uniforms (35.6 ± 0.9°C and 35.7 ± 0.9°C for 1PC and 2PC, respectively). During CB_{high}, $\bar{T}_{sk}$ was significantly reduced for $2PC_{vent}$ compared with the other uniforms (Fig. 2). In addition, $\bar{T}_{sk}$ increased quickly for F+OG, becoming significantly greater than 2PC and equal to 1PC after 10 min of exercise and heat stress

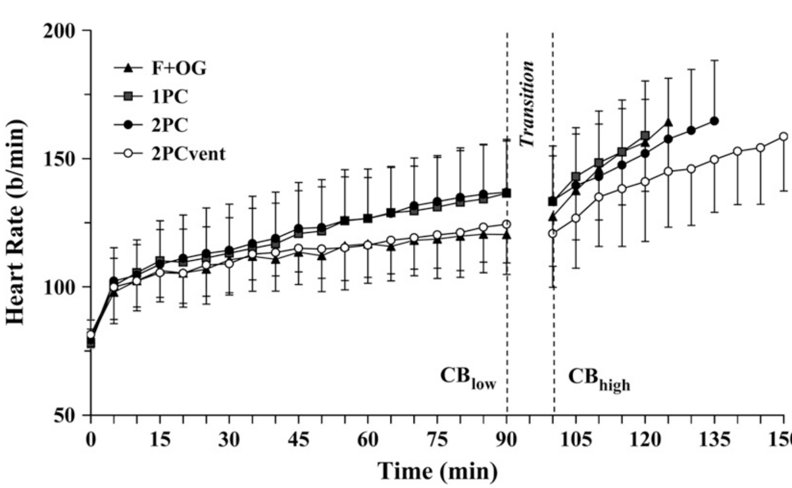

Fig. 1. Changes in heart rate during treadmill walking at 4.5 $km \cdot h^{-1}$ and exposure to 35°C and 50% relative humidity. Values are means ± SD for $N = 8$ in all conditions.

TABLE II. MEAN TOLERANCE TIME (TT ± SD) DURING THE HIGH LEVEL OF PROTECTION (CB_{HIGH}), AND FINAL RECTAL (T_{RE}) AND MEAN SKIN ($\bar{T}_{sk}$) TEMPERATURES AND FINAL HEART RATE (HR) DURING CB_{HIGH} FOR THE CHEMICAL AND BIOLOGICAL UNIFORMS AND THE REASONS FOR TERMINATION OF THE HEAT-STRESS TRIALS.

	F+OG	1PC	2PC	$2PC_{vent}$
TT (min)	40.4 (8.9)†	46.0 (20.7)†	62.1 (19.3)	74.4 (17.0)*
Final T_{re} (°C)	38.7 (0.5)	39.0 (0.5)	38.8 (0.5)	38.9 (0.5)
Final $\bar{T}_{sk}$ (°C)	37.7 (0.9)	37.8 (0.8)	37.4 (0.7)	36.8 (0.8)
Final HR ($b \cdot min^{-1}$)	176.8 (21.1)	171.4 (16.9)	176.3 (17.5)	168.5 (17.1)†‡
Reasons for Trial Termination				
T_{re}	0	0	0	0
Exhaustion	4	5	3	3
HR	4	3	3	1
Time	0	0	2	4

Values represent the number of subjects during each trial that attained a rectal temperature (T_{re}) of 40.0°C, ended due to exhaustion, reached or exceeded a heart rate (HR) of 95% HR_{peak} for 3 min, or attained the time limit of 90 min for CB_{high}. † significantly different from 2PC. * significantly different from the other uniforms. ‡ significantly different from F+OG. Abbreviations for clothing uniforms are as in Table I.

exposure in CB_{high}. Final $\bar{T}_{sk}$ at the end of CB_{high} was similar among uniforms (Table II).

Initial T_{re} values were not different among the four experimental trials (36.9 ± 0.3°C, 36.9 ± 0.3°C, 37.0 ± 0.3°C, and 37.0 ± 0.3°C for F+OG, 1PC, 2PC, and $2PC_{vent}$, respectively), but in order to normalize small individual variations, the increase in T_{re} from the initial value throughout the heat stress for CB_{low} and CB_{high} is shown in **Fig. 3**. Rectal temperature was the lowest for F+OG throughout CB_{low}, with the increase being significantly less than 2PC and $2PC_{vent}$ after 30 min of heat stress and less than 1PC after 65 min. There was no difference in the change in T_{re} throughout CB_{low} for 1PC and $2PC_{vent}$, but the increase was less for $2PC_{vent}$ compared with 2PC after 75 min of heat stress exposure. Differences in T_{re} among the uniforms persisted throughout the transition period such that values were significantly reduced for F+OG at the start of CB_{high}. However, T_{re} increased rapidly for F+OG during CB_{high} such that the response after 20 min of additional heat stress exposure was greater than that observed for $2PC_{vent}$ and similar to 2PC, but still reduced compared with 1PC. Differences in T_{re} between 2PC and $2PC_{vent}$ that were evident at the start of CB_{high} remained evident throughout the additional heat stress. Final T_{re} at the end of the heat stress exposure during CB_{high} was not different among the uniforms (Table II).

During CB_{low} the change in $\bar{T}_b$ was significantly reduced for F+OG compared with 1PC and 2PC (**Table III**). Further, the change was significantly less for $2PC_{vent}$ compared with 2PC. The change in $\bar{T}_b$ during CB_{high} and from the very beginning to the end of the heat stress exposure was not different among the uniforms.

Physiological Strain Index

The increase in the calculated PSI was significantly greater for 1PC and 2PC compared with F+OG and $2PC_{vent}$ after 45 min of heat stress exposure during CB_{low} (**Fig. 4**). In addition, the increase in PSI was greater for $2PC_{vent}$ compared with F+OG during the last 5 min of exposure during CB_{low}. Following the transition to CB_{high}, PSI increased most rapidly for F+OG, being significantly greater than $2PC_{vent}$ after 5 min and similar to the values calculated for 2PC after 15 min and 1PC after 25 min (data not shown for $N = 7$) of additional heat stress exposure. The PSI for 1PC was greater than that calculated for 2PC after 15 min of exposure in CB_{high}. Differences that were evident in PSI between 2PC and $2PC_{vent}$ after the transition to CB_{high} remained constant

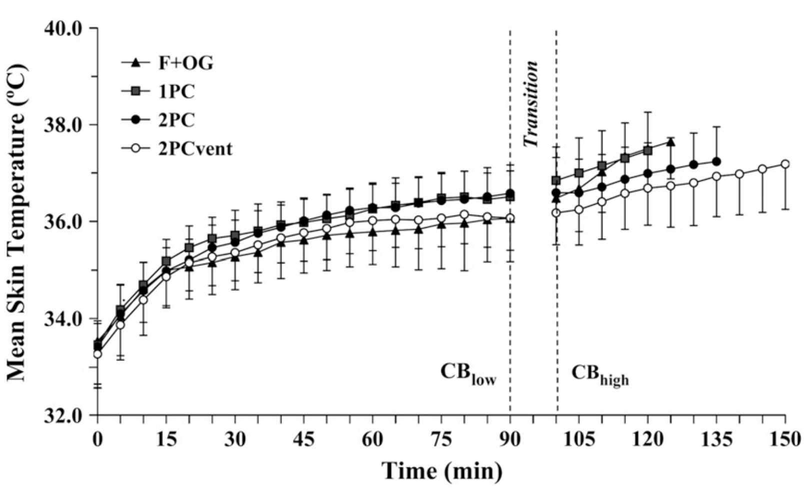

Fig. 2. Changes in mean skin temperature during treadmill walking at 4.5 $km \cdot h^{-1}$ and exposure to 35°C and 50% relative humidity. Values are means ± SD for $N = 8$ in all conditions.

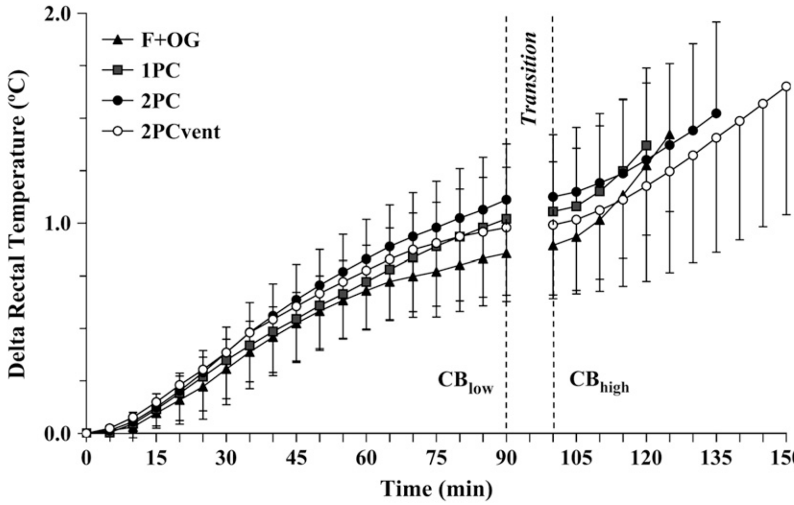

Fig. 3. The increase in the rectal temperature from rest (delta) during treadmill walking at 4.5 km · h^{-1} and exposure to 35°C and 50% relative humidity. Values are means ± SD for $N = 8$ in all conditions.

throughout the remaining exercise and heat stress exposure.

Tolerance Time

Tolerance time was significantly greater in CB_{high} for $2PC_{vent}$ compared with the other conditions (Table II). In addition, TT for 2PC was also greater than the values recorded for F+OG and 1PC. The significant difference in the mean TT of 12 min between 2PC and $2PC_{vent}$ during CB_{high} could be attributed to the difference in T_{re} at the beginning of this heat stress exposure (0.13°C) given their similar mean rates of increase for T_{re} of 0.01°C · min^{-1} (see Fig. 3). Tolerance time was underestimated for 2PC and $2PC_{vent}$ where two and four subjects, respectively, ended their CB_{high} exposure due to the 90-min time limit imposed by the experimental design (Table II).

DISCUSSION

The present study has revealed two major findings. First, it was evident that the thermal strain imposed with the wearing of new CB protective ensembles (1PC, 2PC, $2PC_{vent}$) during CB_{low} significantly impacted TT after the transition to CB_{high}. Typically, heat exposure limits with the wearing of protective clothing in UHS conditions have been defined both in the laboratory (1,6,25) and the field (17,33) with subjects beginning from a rested thermoneutral state. However, in many occupational settings workers are not in a rested state prior to donning their protective clothing, but rather are required to transition from a lower to a higher state of protection while continuing to perform certain tasks. This prior work activity will raise body temperature, which will decrease the expected TT compared with tests that begin at a lower resting body temperature (11,31).

TT during UHS is determined by the initial T_{re}, the T_{re} that can be tolerated at exhaustion, and the rate of increase in T_{re} from the beginning to the end of the heat stress exposure (7). Although the importance is often overlooked, numerous investigations have reported conditions where the change in the initial T_{re} is the principal determinant of TT (3,11,28,35). These new CB uniforms are intended to slow the rate of heat storage and the rate of increase in T_{re} during CB_{high}, but their impact on the initial T_{re} cannot and should not be overlooked when assessing their effect on work performance.

For the military, protective dress levels are intended to protect the soldier against the toxic hazards in the environment and safely ensure that sufficient time is available to transition from the lowest to the highest state of protection as required. Traditional CB protective ensembles employ an overgarment concept where the outer charcoal impregnated garment together with rubber gloves, over-boots, mask, and canister confer the desired level of protection. However, these ensembles, as represented by configuration F+OG in the present study, have a high thermal resistance and low water vapor permeability (see Table I) and compromise soldier performance when worn in hot environments such as the Middle East (20,25). As a result, similar to 1PC and 2PC in the present study, several nations have incorporated new carbon sphere technology to develop protective garments that are designed to be worn as a stand-alone uniform and replace the need for the use of an overgarment concept (1,8). These stand-alone protective

TABLE III. THE CHANGE IN MEAN BODY TEMPERATURE CALCULATED FROM THE CHANGE IN RECTAL AND SKIN TEMPERATURES DURING THE 90 MIN OF EXERCISE AND HEAT STRESS DURING THE LOW LEVEL OF PROTECTION (CB_{LOW}), FROM THE BEGINNING TO THE END OF THE EXERCISE AND HEAT STRESS IN THE HIGH LEVEL OF PROTECTION (CB_{HIGH}), AND FROM THE BEGINNING TO THE END OF THE ENTIRE HEAT STRESS EXPOSURE (TOTAL) FOR THE CHEMICAL AND BIOLOGICAL UNIFORMS.

	Change in Mean Body Temperature (°C)		
Uniform	CB_{low}	CB_{high}	Total
F+OG	1.03 (0.22)†	1.00 (0.37)	2.03 (0.40)
1PC	1.23 (0.26)‡	0.99 (0.40)	2.21 (0.45)
2PC	1.32 (0.26)	0.80 (0.29)	2.11 (0.33)
$2PC_{vent}$	1.16 (0.27)†	1.04 (0.36)	2.19 (0.52)

Values are means ± SD. † Significantly different from 2PC. ‡ Significantly different from F+OG. Abbreviations for clothing uniforms are as in Table I.

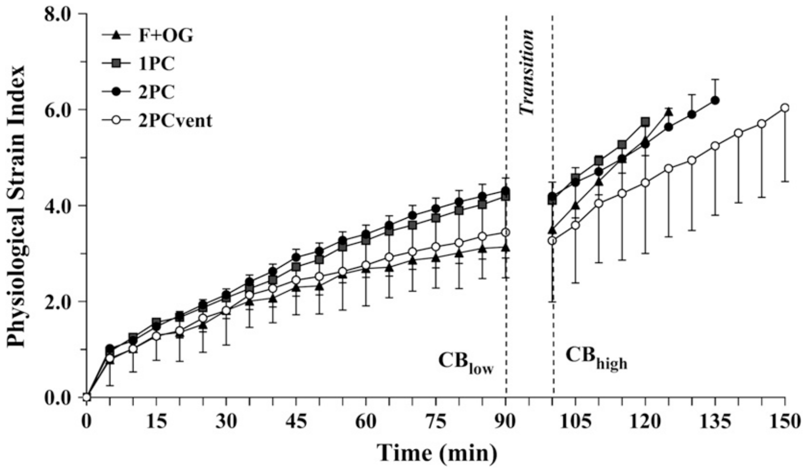

Fig. 4. Changes in the physiological strain index during treadmill walking at 4.5 km · h^{-1} and exposure to 35°C and 50% relative humidity. Values are means ± SD for $N = 8$ in all conditions.

uniforms have a reduced thermal resistance and increased water vapor permeability when worn in CB_{high}, but this is not necessarily the case when they are worn in their lowest state of protection (see Table I). It is important to realize that the requirement to protect the individual against the hazards in the environment limits the extent of the improved heat transfer characteristics that can be expected in these stand-alone protective uniforms during CB_{high} with the incorporation of new carbon absorptive technology. Indeed, most of the improved heat transfer characteristics during CB_{high} for these new CB protective ensembles reflects the removal of the air and clothing layer represented by the normal combat fatigues which are traditionally worn under the protective overgarment as represented in F+OG (21).

Since the requirement for protection constrains the extent of the improvement in heat transfer characteristics with these new uniforms during CB_{high}, it becomes critical to consider the impact of wearing these uniforms during CB_{low} when operational conditions require the use of a lower level of protection for the majority of time and only occasional demands to transition to CB_{high}. Failure to consider this impact would generate misleading guidance about the potential benefit of these stand-alone CB uniforms. For example, mean rates of increase in T_{re} during CB_{high} were 0.212, 0.158, and 0.011°C · min^{-1} for F+OG, 1PC, and 2PC, respectively (Fig. 4). If these rates of increase together with an assumed initial resting T_{re} of 37.0°C and the final T_{re} shown in Table II were used, then TT would approximate 80, 125, and 160 min for the three uniforms, respectively, or a walking distance of 6.0, 9.4, and 12.0 km given the average treadmill speed of 4.5 km · h^{-1} that was used in the present study. The relative improvement in TT during CB_{high} for 1PC and 2PC compared with the use of the traditional overgarment concept (F+OG) would be 56% and 100%, respectively. These changes are far different than the actual 15% and 55% improvements demonstrated in the current study with the prior use of these respective stand-alone uniforms during exercise and heat stress in CB_{low}. Indeed, 1PC failed to significantly extend TT during CB_{high} compared with the use of the traditional overgarment concept. Clearly, if environmental temperature, humidity, metabolic rate, or the duration of heat stress exposure increased, then differences in thermal strain would widen during CB_{low} with the use of these stand-alone CB uniforms compared with the use of the combat fatigues; these larger differences would further reduce the impact of these new uniforms on TT during CB_{high}.

The second major finding from the present study was that the opening of zippered vents in the clothing reduced the thermal and cardiovascular strain experienced during CB_{low} such that TT was increased during CB_{high}. The effectiveness of these vents for promoting heat loss from the body are influenced by their location, since the requirement to wear other protective equipment could reduce their utility, type of activity, and wind speed (2), and the environmental temperature and humidity. Dry and wet heat transfer are affected by the thermal characteristics of clothing layers that cover the skin surface (14). As environmental temperature increases above 35°C and begins to exceed skin temperature, a lower thermal resistance of the clothing will actually promote greater sensible heat gain. Thus the approximate 10% reduction in thermal resistance afforded by the opening of the vents in $2PC_{vent}$ (Table I) would, by itself, promote greater heat storage in hot environments. However, at any given wind speed, it is the ratio of the water vapor permeability coefficient to the thermal resistance of the clothing ensemble together with the vapor pressure gradient between the skin and the environment that determines evaporative heat loss at the skin surface (14). Thus the approximate 25% improvement in this ratio for $2PC_{vent}$ compared with 2PC (Table I) would counter the negative effect of the lowered thermal resistance on sensible heat gain when exposed to hot environments. A summary of the impact of the open vents during CB_{low} on the estimated sensible and insensible heat transfer in a temperate, humid (25°C and 80% relative humidity), tropical (35°C and 75% relative humidity), and desert (50°C and 10% relative humidity) environment is depicted in **Table IV**. These calculations are not entirely correct since they assume steady-state conditions throughout the heat stress exposure with similar $\bar{T}_{sk}$ (see Fig. 2.) and maximal skin

TABLE IV. ESTIMATED RADIATIVE AND CONVECTIVE (R+C) DRY HEAT TRANSFER, THE MAXIMUM EVAPORATIVE POTENTIAL OF THE ENVIRONMENT (E_{MAX}), AND TOTAL HEAT LOSS DURING A LOW LEVEL OF PROTECTION FOR 2PC AND $2PC_{VENT}$, WITH THE LATTER UNIFORM INCORPORATING OPEN ZIPPERED VENTS IN THE TORSO, ARMS, AND LEGS.

	R+C ($W \cdot m^{-2}$)		E_{max} ($W \cdot m^{-2}$)		Total Heat Loss ($W \cdot m^{-2}$)		%Gain [($2PC_{vent}$ − 2PC)/PC]*100
Environment	2PC	$2PC_{vent}$	2PC	$2PC_{vent}$	2PC	$2PC_{vent}$	$2PC_{vent}$ vs. 2PC
Temperate & Humid (25°C, 80% RH)	−60.6	−66.3	−111.6	−139.1	−172.2	−205.4	+19.3
Tropical (35°C, 75% RH)	−5.5	−6.0	−56.5	−70.4	−62.0	−76.4	+23.3
Desert (50°C, 10% RH)	+77.2	+84.4	−154.2	−192.1	−77.0	−107.7	+39.9

A positive value indicates a source of heat gain, whereas a negative value indicates heat loss. Also shown is the relative gain in heat loss that could be achieved with the use of the open vents as represented by $2PC_{vent}$.

Details of the equations used to estimate sensible and insensible heat transfer were taken from Gonzalez et al. (14). R+C was estimated as $(T_a - 36) \cdot I_T^{-1}$ where T_a represented the ambient temperature, 36 was the assumed mean skin temperature, and I_T was the total insulative value of the uniform as represented in Table I, but expressed in $m^2 \cdot °C^{-1} \cdot W^{-1}$. E_{max} was estimated as $16.5 \cdot (i_m \cdot I_T^{-1}) \cdot (5.94 - P_a)$, where 16.5 is the Lewis relation expressed in $°C \cdot kPa^{-1}$, i_m is the Woodcock water vapor permeability coefficient from Table I, 5.94 is the saturated skin vapor pressure at 36°C, and P_a represents the ambient vapor pressure. Abbreviations for clothing uniforms are as in Table I.

vapor pressures (4). Nevertheless, given these limitations, the extent of the advantage of incorporating open vents into the clothing to promote greater heat transfer away from the body will depend on the environmental conditions.

It appears that the biophysics of heat transfer (12) and the well documented "pumping" effect of wind and physical movement on clothing insulation (29,37) has provided sufficient evidence to convince manufacturers of athletic apparel to include vents in some of their clothing designs. Evidenced-based research from experimentation with human subjects to directly support this approach is limited. Goldman (10) did report reduced heat storage during treadmill walking at 35°C for eight subjects when an impermeable raincoat inserted a vent under a flap across the shoulders. Nielsen et al. (29) reported that opening the front zipper of a jacket did not further reduce the clothing insulation of an ensemble consisting of jacket, shirt, trousers, socks, shoes, underwear, and a T-shirt compared with the effects of walking on a treadmill or exposed to wind of $1.1\ m \cdot s^{-1}$. However, their conclusions were obtained from testing only four subjects. Lotens and Havenith (18) reported the advantage of designing vents into rainwear for the purpose of preventing condensation on the inner surface of the garment. They reported an improvement of about 30% in the ventilation of the garment for only three subjects who were walking at $5\ km \cdot h^{-1}$ and exposed to a wind speed of $2\ m \cdot s^{-1}$. No physiological data were collected in this study. Lotens and Wammes (19) demonstrated that the opening of apertures on a 2-piece ensemble at the neck, wrist, leg, and bottom of the jacket significantly improved vapor transfer from the skin to the environment for garments of low but not high air permeability. Thus, as the air permeability of the clothing ensemble increases, the advantage of incorporating vents into the design eventually becomes maximized for promoting heat transfer. In the present study, the wearing of the tactical and fragmentation vests together with the helmet would have restricted vapor transfer from these regions of the body, which might approximate 35–40% of the total surface area (16). Over the remaining surface area, the opening of vents in the arms and legs successfully reduced the clothing insulation and increased the water vapor permeability of the ensemble in the CB_{low} configuration (Table I). In certain conditions the use of the fragmentation vest may not be necessary and thus the opening of vents on the torso may further assist heat transfer away from the body during heat stress exposure.

In summary, the present findings have demonstrated the importance of considering the physiological strain associated with wearing CB stand-alone uniforms during CB_{low} on determining TT after the transition to CB_{high}. Failure to consider these carry-over effects will falsely increase the expected benefits of these new hot-weather uniforms on extending TT during CB_{high}. In addition, the study has revealed that incorporating zippered vents into areas of the uniform that are not impeded by the wearing of additional impermeable protective items will assist with heat transfer during a lower protective state and extend TT after transitioning to higher protective states that necessitate the closure of these vents.

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