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INFLUENCE OF A NEW VAPOUR PROTECTIVE CLOTHING LAYER ON PHYSICAL WORK TOLERANCE TIMES AT 40°C AMBIENT TEMPERATURE

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EXECUTIVE SUMMARY

Canadian Forces personnel must be able to sustain operations in an environment contaminated with nuclear, biological and/or chemical (NBC) agents. Clothing has been designed that protects the individual from a hostile NBC environment. This clothing, however, impairs body heat loss due to its overall insulative qualities. A new vapour protective clothing ensemble is under development at the Defence Research Establishment Ottawa. This new clothing is thinner and more close-fitting to the body than the present NBC protective ensemble. The purpose of the present study, therefore, was to examine the influence of this new vapour protective clothing on physical work performance in a hot environment.

Eleven males were allocated to exercise at either a light intermittent (L) (15 min exercise followed by 15 min rest, N = 6), or heavy continuous (H) (N = 5) metabolic rate. For group L, exercise involved walking on a treadmill at 4 $km \cdot h^{-1}$ with a 0% grade. Group H walked continuously at 4.8 $km \cdot h^{-1}$ with a 3% grade. Trials were conducted in a environmental chamber at 40°C and 25% relative humidity. Subjects were tested wearing three levels of protective clothing: the present NBC High level of protection worn over combat clothing (TH + CC); the present NBC High level of protection without clothing (TH - CC); and, the new vapour protective clothing ensemble (NPC). Work tolerance time (WTT) was defined as the time-period until body temperature increased to 39.3°C (normal being 37°C), heart rate reached 95% of an individual's maximum (~ 190 beats/min with resting values being ~ 70 beats/min), dizziness or nausea precluded further exercise or 3 hours had elapsed.

For group L, WTT was similar for the present NBC protective ensemble worn with or without combat clothing (120 min) but was significantly increased for the new clothing. All subjects completed 3 h in the environmental chamber in the new clothing. For group H, WTT was significantly increased from TH + CC (46 min) to TH - CC (60 min) and to the new clothing ensemble (85 min). The evaporative efficiency of the clothing (calculated as the ratio of sweat evaporated from the clothing to sweat produced) was increased 2-3 fold in the new clothing compared with the other clothing configurations. This improved evaporation of sweat from the clothing was reflected by a lower heart rate and core temperature during the exposure to the hot environment. The results of this experiment clearly show the benefits of the new vapour protective clothing on physical work performance in a hot environment.

ABSTRACT

A new vapour protective clothing ensemble is under development at the Defence Research Establishment Ottawa. This clothing is thinner and more close-fitting to the body than the present nuclear, biological and chemical (NBC) protective garment. The purpose of the present study was to examine the influence of this new vapour protective clothing on physical work performance in a hot environment (40°C and 25% relative humidity). Eleven unacclimatized males (28 ± 6 y, 79 ± 8 kg, 1.76 ± 0.06 m) were assigned to exercise at either a light intermittent (L) (N = 6), or heavy continuous (H) (N = 5) metabolic rate. Group L alternated between 15 min of walking on a treadmill at 1.11 $m \cdot s^{-1}$ with a 0% grade and 15 min of rest. Group H walked continuously at 1.33 $m \cdot s^{-1}$ with a 3% grade. Subjects were tested wearing three clothing configurations: full NBC protection (TOPP High) with the combat clothing worn under the NBC garment (TH + CC); full NBC protection without combat clothing (TH - CC); the new vapour protective clothing together with the NBC gloves, boots and respirator (NPC). WTT was the time-period until rectal temperature (T_{re}) reached 39.3°C, heart rate reached 95% maximum, dizziness or nausea precluded further exercise, or 3 h had elapsed. For group L, WTT was similar for TH + CC (113 ± 12 min) and TH - CC (139 ± 18 min). WTT was significantly increased for NPC where all subjects completed the 3 h in the climatic chamber. The rate of increase for T_{re} was significantly reduced for NPC (0.3 ± 0.1 $°C \cdot h^{-1}$) compared with both TH + CC (0.9 ± 0.1 $°C \cdot h^{-1}$) and TH - CC (0.8 ± 0.2 $°C \cdot h^{-1}$). The evaparative efficiency of the new clothing ensemble (76 ± 4%) was also significantly increased compared with both TH + CC (36 ± 17%) and TH - CC (46 ± 9%). For group H, WTT significantly increased from TH + CC (46 ± 15 min) to TH - CC (60 ± 21 min) and to NPC (85 ± 28 min). The rate of increase in T_{re} was not different among the three clothing configurations. Evaporative efficiency was significantly different among the three clothing trials (19 ± 8%, 34 ± 4% and 57 ± 7% for TH + CC, TH - CC and NPC, respectively). For both groups, mean skin temperature and heart rates reflected the differences in the evaporative efficiency of the clothing comparisons. The results of this experiment clearly show the benefits of the new vapour protective clothing on physical work performance in a hot environment. Also, the data strongly suggest that, if possible, the combat clothing should not be worn under the present NBC garment.

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1.0 INTRODUCTION

The Canadian Forces (CF) must be able to sustain operations in an environment contaminated with nuclear, biological, and/or chemical (NBC) agents. To protect personnel working in this environment from the effects of contaminating agents, an individual protective ensemble has been developed which consists of a facial mask/respirator, a clothing overgarment, overboots and gloves. The components of the NBC protective clothing are either semi-permeable or impermeable to moisture penetration; thus the ability to evaporate sweat from the skin surface is severely impaired. Since sweat evaporation is the major avenue by which humans dissipate body heat which otherwise accumulates during physical work in a hot environment, debilitating heat strain is the likely outcome of attempting to maintain normal work rates while wearing the protective clothing. Such an effect is described in several documents and reports for both the Canadian (McLellan et al. 1990; McLellan 1991) and Allied Forces (Avellini 1983; Bergh and Danielsson 1987; Carter and Cammermyer 1985; Fine and Kobrick 1985; Joy and Goldman 1968; Tilley et al. 1981).

Farnworth and Crow (1983) have suggested that the heat stress caused by wearing the protective clothing can be attributed partially to the fact that the garment is loose-fitting and that the air layers between the skin, underwear, combat clothing and NBC overgarment all contribute to the thermal insulation and vapour resistance of the ensemble. If the air layers were removed, the thermal insulation and vapour resistance would be reduced. Also, the layers of clothing worn under the NBC overgarment (i.e, underwear, t-shirt and combat clothing), together with the bulkiness of the NBC overgarment itself, impede the movement and evaporation of sweat from the body and the clothing. In full NBC protection, the evaporative efficiency (calculated as the ratio of sweat evaporated from the clothing to sweat produced) of the clothing ensemble is less than 20% during exercise at 30° or 40°C with 50% relative humidity (McLellan et al. 1990; McLellan 1991). Therefore, reducing the thickness of the NBC garment and/or reducing the layers of clothing worn under the garment should improve the efficiency of sweat evaporation from the clothing and reduce heat strain during exercise in a hot environment.

The current Canadian Forces NBC overgarment was developed to be used in a central European theater, where ambient temperature rarely exceeds 30°C. The heat stress associated with wearing the NBC ensemble at temperatures above 30°C is well documented (McLellan, 1991). A new concept of NBC undergarment, aimed at reducing heat stress by eliminating air layers, is under development at Defence Research Establishment Ottawa. This concept allows the soldier to remove the outerlayers as the ambient temperature rises or as his metabolic rate increases. The prototype clothing consists of a semi-permeable charcoal impregnated lycra worn over polyester knit (DuPont Solarmax®) long underwear. Both fabrics are, out of necessity, stretchable because of the close-fitting nature of the garment. The charcoal layer provides vapour protection only. In a very hot environment, liquid protection (which the present NBC ensemble also provides) is not necessary since liquid agents would evaporate before they reached the surface of the clothing. The purpose of the present investigation, therefore, was to examine the effectiveness of this new vapour protective clothing system on work tolerance in a hot environment, and to compare it with the current NBC ensemble.

2.0 METHODS

2.1 Subjects

Following approval from the Institute's Human Ethics Committee, eleven unacclimatized males (27.7 ± 6.0 y, 79.0 ± 8.0 kg, 1.76 ± 0.06 m) volunteered to participate in the study. They were informed of all details of the experimental procedures and the associated risks and discomforts. After a medical examination to ensure that there were no medical contraindications to their participation in the experiments, they gave their informed consent prior to the first day of data collection.

2.2 Determination of Maximal Aerobic Power ($\dot{V}O_2max$)

$\dot{V}O_2max$ was determined on a motor-driven treadmill using open-circuit spirometry before the series of experiments in the climatic chamber. Following two minutes of running at a self-selected pace, the treadmill grade was increased $1\%\cdot min^{-1}$ until subjects were running at a 10% grade. Treadmill speed was then increased 0.22 $m\cdot s^{-1}$ ($0.8\ km\cdot h^{-1}$) each minute until the subject could no longer continue. $\dot{V}O_2max$ was defined as the highest oxygen consumption ($\dot{V}O_2$) observed during the incremental test. Heart rate (HR) was monitored throughout the incremental test from a transmitter/receiver telemetry unit (Polar Electro PE3000). The value recorded at the end of the exercise test was considered to be the individual's maximal heart rate.

2.3 Experimental Design

Subjects were allocated to exercise at either a light intermittent (L, N = 6) or heavy continuous (H, N = 5) metabolic rate. All clothing trials in the climatic chamber were performed at 40°C and 25% - 30% relative humidity. Those subjects exercising at the light intensity walked on the treadmill at 1.11 $m\cdot s^{-1}$ with a 0% grade for 15 min and then sat quietly and rested for 15 min. This 15 min exercise and 15 min rest schedule was continued for the duration of each trial for group L. The heavy exercise group walked continuously at 1.33 $m\cdot s^{-1}$ with a 3% grade.

Each subject was tested wearing each of the following three levels of clothing protection, corresponding to the standard Canadian Forces "threat-oriented protective postures" (TOPP):

(a) TOPP High with Combat Clothing (TH + CC), i.e., underwear, t-shirt, fatigues, webbing, NBC garment, gloves, boots and respirator.

(b) TOPP High without Combat Clothing (TH - CC) i.e., underwear, t-shirt, webbing, NBC garment, gloves, boots and respirator.

(c) TOPP High as New Protective Clothing (NPC) i.e., underwear, top and bottom thermal long underwear (Solarmax), close-fitting vapour protective layer, webbing, NBC gloves, boots and respirator.

The order of wearing the various clothing configurations was assigned randomly.

2.3.1 Work Tolerance Time

Work tolerance time (WTT) for all trials was defined as the time-period until any of the following criteria first occurred: rectal temperature reached 39.3°C; heart rate remained at or above 95% of maximum for 3 min; dizziness or nausea precluded further exercise or 3 h had elapsed.

2.4 Dressing and Weighing Procedures

At the beginning of each test day in the climatic chamber, subjects first inserted a rectal thermistor (Pharmaseal APC 400 Series) approximately 0.12 m beyond the anal sphincter. They were then weighed nude on an electronic scale sensitive to the nearest 0.01 kg (Electroscale Model 921). To measure skin temperature, thermistors (Yellow Springs Instruments thermistor bead 44004) were taped to the following 12 sites: forehead, chest, upper back, lower back, forearm, wrist, abdomen, front thigh, rear thigh, calf, shin, and foot.

For HR measurements, a transmitter telemetry unit (Polar Electro PE3000) was clipped to an elasticized electrode belt around the chest; the receiver was taped to the outside of the clothing and displayed HR continuously for the duration of each trial.

Subjects then completed the next stage of dressing which included socks, combat boots, a t-shirt, combat clothing or long underwear depending on the particular clothing configuration (i.e., TH + CC, TH - CC or NPC). Approximately 15 min before entry into the chamber, subjects donned the NBC garment for the TH + CC and the TH - CC trials or the new vapour protective layer for the NPC trial. NBC protective gloves and boots were put on at this time. Standard issue webbing was worn over the NBC garment or the new vapour protective layer. Subjects also carried one canteen filled with cool water (approximately 1 L). They were instructed to drink *ad libitum* from the canteen but the canteen would not be refilled. The canteen was weighed to the nearest 0.001 kg before and after each trial. Both nude and total dressed weight (which included the NBC respirator) were recorded prior to entry into the chamber. For all trials the respirator and hood were donned 1 min before chamber entry. Immediately upon entering the climatic chamber, the subject's skin and rectal thermistor monitoring cables were connected to a computerized data acquisition system (Hewlett-Packard 3497A control unit, 236-9000 computer and 2934A printer) and the exercise began. After the completion of each trial, dressed weight was recorded within 1 min after exit from the chamber and nude weight was recorded following a 5 min undress procedure. Any urine which was collected in bottles during the experiment was weighed to the nearest 0.001 kg.

Differences in nude and dressed weights before and after each trial were corrected for urine, respiratory and metabolic weight losses (see below). The amount of sweat produced (P) was calculated as follows: pre-trial minus post-trial nude weight (corrected) plus the weight of the water drunk during the trial. Evaporative sweat loss (E) from the clothing was calculated as the ratio of the difference in corrected dressed weight to the amount of sweat produced, and was expressed as a percentage (i.e., $(E/P) \cdot 100$). This percentage was termed evaporative efficiency of the clothing. Subjects were not instructed to void prior to the experiment. Therefore, the above description for the calculation of the amount of sweat produced (P) does not take into account urine volume in the bladder and the transit time involved for the absorption of water from the stomach. The reader should be aware of these limitations when the data are presented for the evaporative efficiency of the clothing. To determine which layer of clothing retained the greatest amount of sweat, all clothing was weighed before and after each trial in plastic bags according to the following groupings: socks, t-shirt and underwear (including the long underwear for the NPC trial); combat clothing; combat boots and webbing without the canteen; NBC gloves, boots and respirator; and, the NBC garment or the new vapour protective layer.

Each minute, T_{re} and the individual skin temperatures were displayed, printed and recorded by the data acquistion system. A weighted mean skin temperature ($\overline{T}_{sk}$) was calculated from a 12-point weighted equation (Hody, 1973). Heart rate values were recorded every five minutes from the display on the telemetry receiver.

2.5 Gas Exchange Analyses

During each trial, open-circuit spirometry was used to determine expired minute ventilation ($\dot{V}_E$), oxygen consumption ($\dot{V}O_2$) and carbon dioxide production ($\dot{V}CO_2$) during minutes 10-15, 25-30 and 40-45 of each hour. Values were averaged from a 2-min sampling period obtained for each subject.

For all trials, an adaptor was attached to the respirator which allowed expired air to be collected. Expired gases were directed into a 5 L mixing-box and through an Alpha Technologies VMM 110 Series Ventilation Module for the determination of $\dot{V}_E$. A sampling line directed dried gases from the mixing-box to S-3A O_2 and CD-3A CO_2 Ametek analyzers. The gas analyzers were calibrated before each collection period with a precision-analyzed gas while the ventilation module was calibrated with a syringe of known volume. After conversion of the analogue voltage outputs from the ventilation module and gas analyzers into digital signals (Hewlett-Packard 59313 A/D Converter) $\dot{V}_E$, $\dot{V}O_2$ and $\dot{V}CO_2$ were calculated and printed on-line every 60 s using appropriate software on a Hewlett-Packard >825A microcomputer.

Respiratory water loss was calculated using the $\dot{V}O_2$ measured during the treadmill walk and the equation presented by Mitchell et al. (1972). Metabolic weight loss was calculated assuming an energy equivalent of 21 $kJ \cdot L^{-1} O_2$ consumed (a 0.1 kg weight loss would require ~3200 kJ of energy expenditure or the consumption of ~150 L of O_2).

2.6 Statistics

Data are presented as mean values and standard error of the mean. An independent t-test was used to compare group values for $\dot{V}O_2$max and maximal heart rate. A two-factor (clothing and time) repeated measures analyses of variance (ANOVA) was used to analyze gas exchange, heart rate, T_{re}, and $\overline{T}_{sk}$ changes at a given metabolic rate (light or heavy). A one-factor (clothing) repeated measures ANOVA was used to compare changes in nude, dressed and clothing weights at each metabolic rate. When a significant F-ratio (corrected for the repeated measures factor) was obtained, a Newman-Keuls post-hoc analysis was performed to isolate differences among treatment means. For all statistical analyses, the 0.05 level of significance was used.

3.0 RESULTS

$\dot{V}O_2$max was not significantly different between the two exercise groups (47.7 ± 2.1 and 48.8 ± 2.9 $mL \cdot kg^{-1} \cdot min^{-1}$ for group L and H, respectively). Similarly, maximal heart rates were similar between the two groups (198.8 ± 4.8 and 189.6 ± 7.1 $b \cdot min^{-1}$ for L and H, respectively).

3.1.1 Work Tolerance Time (WTT).

Figure 1 presents WTT for the three clothing configurations for both the light and heavy metabolic rates. For group L, all subjects completed 3 h during the NPC trial which was significantly longer than the WTT for either TH - CC (138.7 ± 17.6 min) or TH +CC (113.2 ± 11.5 min). These latter WTT values were not significantly different. For group H, WTT was significantly increased from TH + CC (46.2 ± 6.5 min) to TH - CC (60.4 ± 9.6 min) and to NPC (85.0 ± 12.6 min).

3.1.2 Gas Exchange.

The data for $\dot{V}O_2$ and $\dot{V}_E$ during the trials are presented in Table 1 for the two groups. $\dot{V}O_2$ is presented in both $L \cdot min^{-1}$ and $mL \cdot kg^{-1} \cdot min^{-1}$ since the weight of the clothing differed slightly among the three configurations (i.e., ~ 10, 9 and 8 kg for the TH + CC, TH - CC and NPC clothing conditions, respectively). For group L, $\dot{V}O_2$ during the exercise periods did not increase with time and there was no effect of clothing. $\dot{V}_E$ was lower for the NPC trial and did increase from one exercise period to the next for all clothing configurations. For NPC, $\dot{V}O_2$ did not change significantly from one walk period to the next or during the different rest periods for the duration of the 3 h. $\dot{V}_E$ was significantly increased at 105 min compared with the value at 15 min during the first walk period. Also, $\dot{V}_E$ was increased at 90 and 150 min compared with the first resting measurement at 30 min. For group H, $\dot{V}O_2$ ($L \cdot min^{-1}$ and $mL \cdot kg^{-1} \cdot min^{-1}$) was significantly higher for TH + CC compared with the other trials. There was no difference for $\dot{V}O_2$ between TH - CC and NPC. Also there was no effect of time for $\dot{V}O_2$. $\dot{V}_E$ increased from 15 to 30 min for all clothing configurations. For NPC, there was no further increase in $\dot{V}_E$ at 45 min.

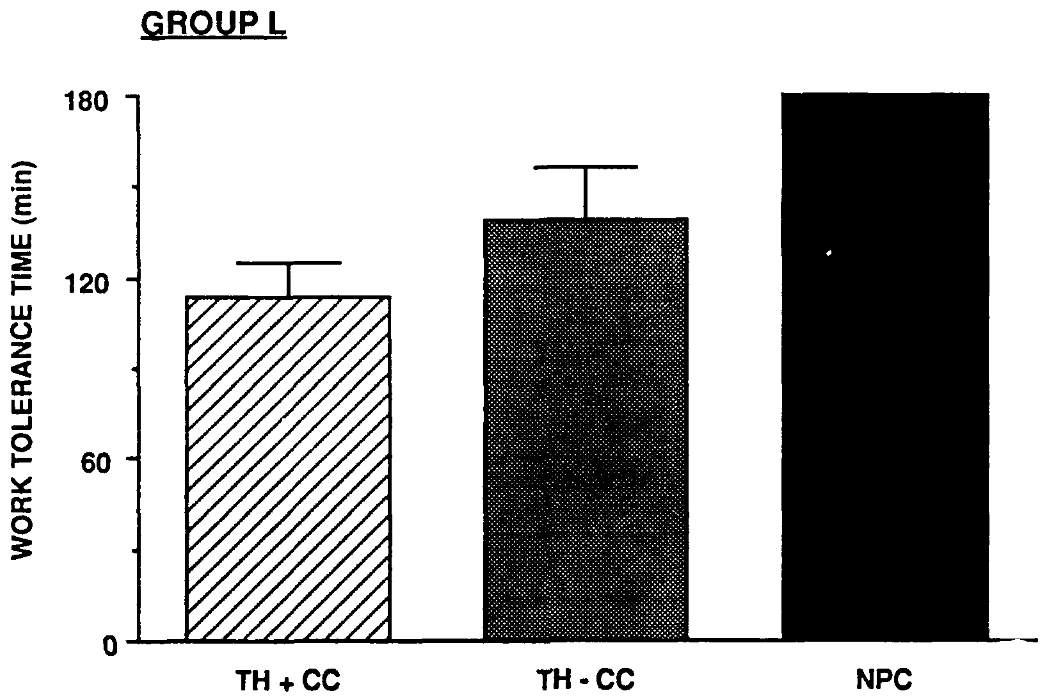
3.1.3 Heart Rate (HR).

The changes in HR for the different clothing trials are presented in Figure 2 for both exercise groups. For the group L, there was no effect of clothing on the changes in HR during the first 25 min of the trials. From 35 min to the end of the comparative data presented in Figure 2, the HR for NPC was significantly lower than the values for TH + CC. At 80 min and beyond, HR for NPC was also significantly lower than the TH - F trial. HR continued to increase with time for the duration of the NPC trial. For group H, HR was significantly higher for TH + CC compared with the other two clothing configurations from 5 to 30 min. In addition, HR for TH - CC was greater than for NPC from 15 to 30 min.

3.1.4 Rectal Temperature (T_{re}).

The increase in T_{re} for the three clothing configurations is shown in Figure 3 for both groups. During the first 30 min of the comparisons shown for group L, there was no effect of clothing on the increase in T_{re}. However, at 35 min T_{re} was significantly lower for the NPC trial compared with the other two clothing configurations and this difference was evident for the remainder of the comparative data presented in Figure 3. Also, T_{re} was significantly lower for TH - CC compared with TH + CC during the second hour of comparative data that are shown. For NPC, T_{re} continued to increase during the last hour of the trial. For group H, the rate of increase in T_{re} during the first 30 min of the trials was significantly greater for TH + CC compared with the other

Figure 1. Work tolerance times at 40°C for TOPP High with combat clothing (TH + CC) or without (TH - CC) or the new vapour protective clothing layer (NPC) for the light (L, n=6) or heavy (H, n=5) exercise groups. For group L, all subjects completed 180 minutes in NPC.



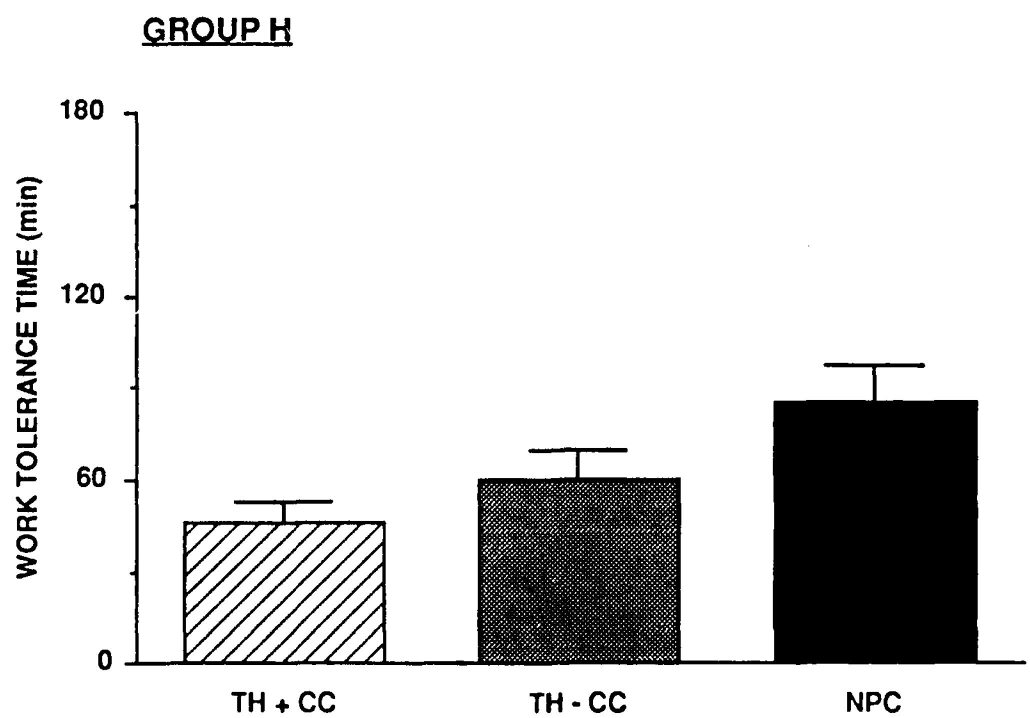


Table 1. Gas exchange measurements ($\dot{V}O_2$ and $\dot{V}_E$) at 40°C for the light (L) and heavy (H) exercise groups while wearing TOPP High with combat clothing (TH + CC) or without (TH - CC) or the new vapour protective clothing layer (NPC).

			Time (min)								
		Clothing	15	30	45	75	90	105	135	150	165
L	$\dot{V}O_2$ ($L \cdot min^{-1}$) (STPD)	TH + CC	1.18 (0.03)	0.33 (0.02)	1.13 (0.05)	1.17 (0.04)	0.40 (0.02)				
		TH - CC	1.18 (0.05)	0.35 (0.04)	1.17 (0.06)	1.14 (0.08)	0.38 (0.02)				
		NPC	1.10 (0.04)	0.33 (0.02)	1.08 (0.05)	1.10 (0.04)	0.33 (0.02)	1.12 (0.04)	1.08 (0.05)	0.34 (0.02)	1.08 (0.05)
	$\dot{V}O_2$ ($mL \cdot kg^{-1} \cdot min^{-1}$)	TH + CC	13.2 (0.3)	3.6 (0.3)	12.6 (0.4)	13.1 (0.4)	4.4 (0.3)				
		TH - CC	13.3 (0.5)	3.9 (0.1)	13.2 (0.5)	12.8 (0.6)	4.2 (0.2)				
		NPC	12.6 (0.4)	3.7 (0.2)	12.4 (0.4)	12.6 (0.3)	3.8 (0.2)	12.7 (0.2)	12.3 (0.4)	3.9 (0.2)	12.3 (0.3)
	$\dot{V}_E$ ($L \cdot min^{-1}$) (STPD)	TH + CC	24.6 (1.7)	9.3 (0.6)	25.7 (1.6)	27.3 (1.4)	12.0 (0.8)				
		TH - CC	25.4 (1.2)	10.1 (0.8)	26.8 (1.4)	26.2 (1.6)	11.0 (1.0)				
		NPC	22.8 (1.0)	8.4 (0.5)	23.9 (1.3)	24.5 (1.3)	9.4 (0.6)	25.1 (0.8)	23.9 (1.2)	9.9 (0.7)	24.2 (1.3)
H	$\dot{V}O_2$ ($L \cdot min^{-1}$)	TH + CC	1.72 (0.06)	1.73 (0.10)							
		TH - CC	1.47 (0.05)	1.53 (0.06)							
		NPC	1.55 (0.09)	1.60 (0.09)	1.61 (0.10)						
	$\dot{V}O_2$ ($mL \cdot kg^{-1} \cdot min^{-1}$)	TH + CC	19.5 (0.8)	19.6 (1.3)							
		TH - CC	17.0 (0.8)	17.6 (1.0)							
		NPC	18.0 (1.2)	18.6 (0.9)	18.8 (1.2)						
	$\dot{V}_E$ ($L \cdot min^{-1}$)	TH + CC	35.9 (2.1)	37.7 (2.9)							
		TH - CC	32.2 (1.9)	34.8 (2.2)							
		NPC	33.2 (2.9)	34.1 (2.8)	34.5 (3.4)						

Values are means (SEM); For group L, N = 6 until 75 min. N = 5 at 90 min and N = 6 for the NPC trial from 105 to 165 min. N = 5 for the data presented for group H.

Figure 2. Changes in heart rate at 40°C during the exercise and rest periods for the light (L, n=6) exercise group and during continuous exercise for the heavy (H, n=5) exercise group while wearing TOPP High with combat clothing (TH + CC) or without (TH - CC) or the new vapour protective clothing layer (NPC).

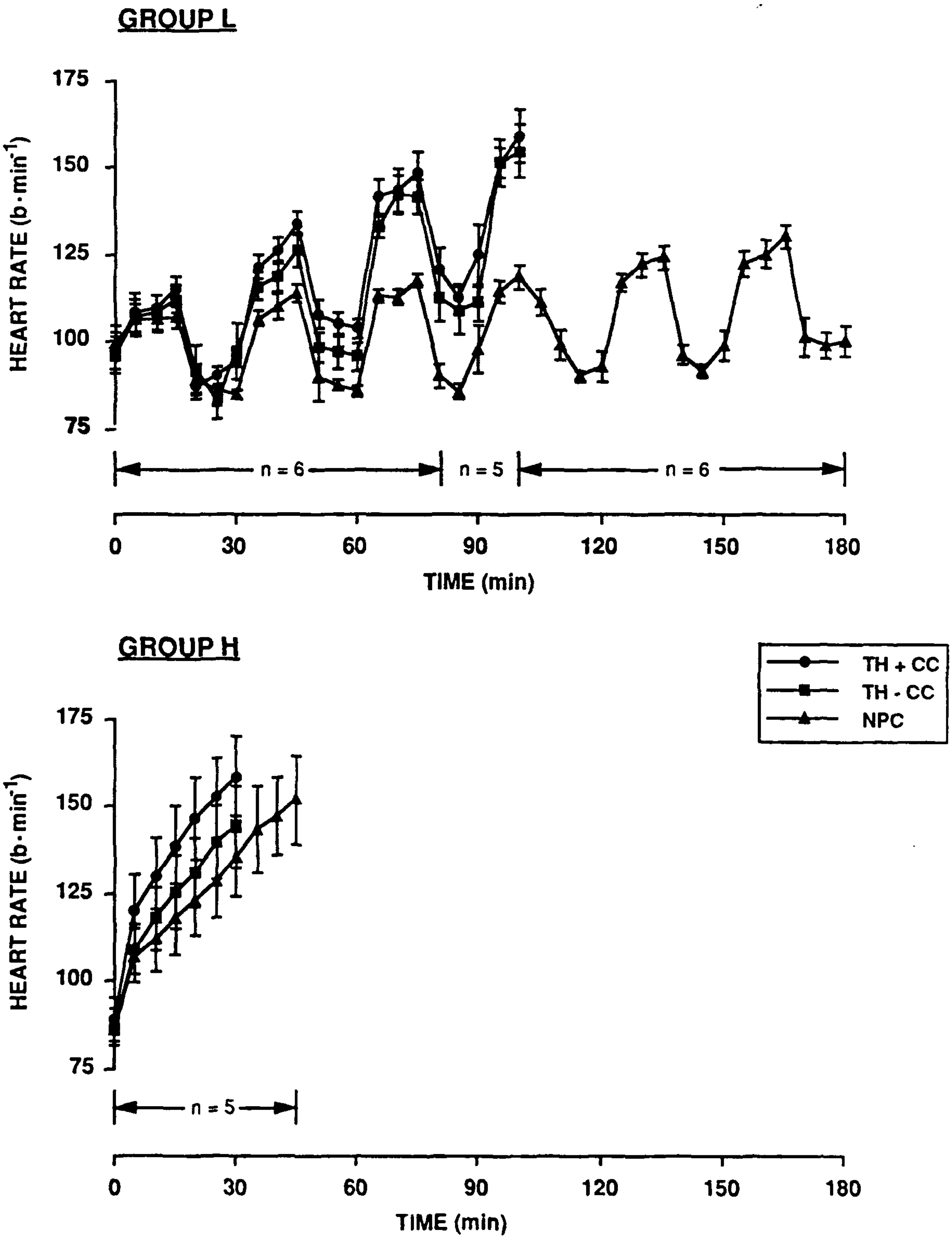
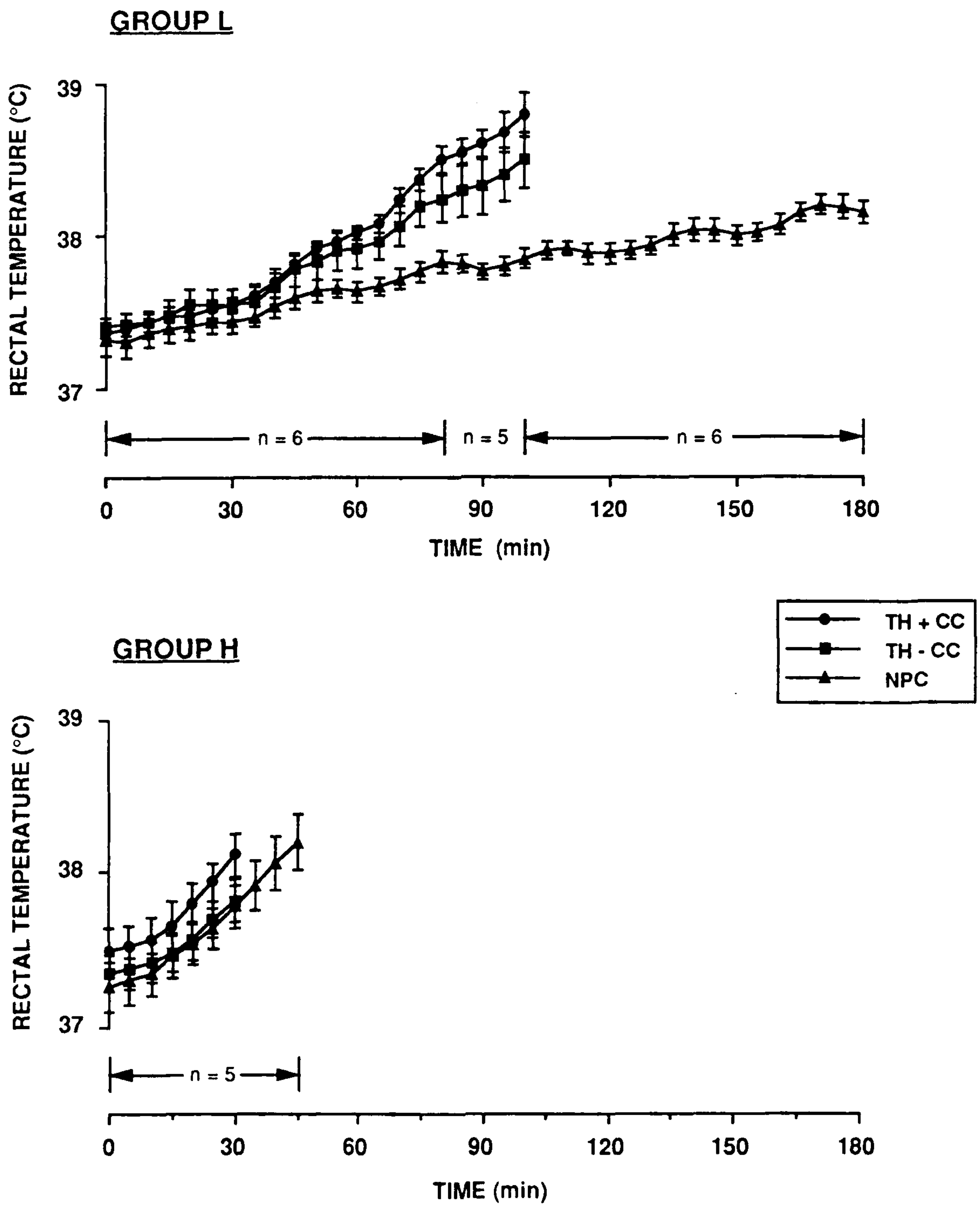


Figure 3. Changes in rectal temperature temperature at 40°C during the exercise and rest periods for the light (L, n=6) exercise group and during continuous exercise for the heavy (H, n=5) exercise group while wearing TOPP High with combat clothing (TH + CC) or without (TH - CC) or the new vapour protective clothing layer (NPC).



two clothing configurations.

The rate of change in T_{re} or core temperature, calculated as the final minus the initial T_{re}, divided by WTT and multiplied by 60 (expressed as $°C \cdot h^{-1}$), is depicted in Figure 4. For group L, the rate of change in T_{re} for the NPC trial of approximately $0.3°C \cdot h^{-1}$ was significantly less than the value of either $0.8°C \cdot h^{-1}$ for TH - CC or $0.9°C \cdot h^{-1}$ for TH + CC. For group H, there was no effect of clothing on the rate of change in T_{re} which averaged 1.8, 1.5 and $1.4°C \cdot h^{-1}$ for TH + CC, TH - CC and NPC, respectively.

3.1.5 Mean Skin Temperature ($\overline{T}_{sk}$)

Figure 5 presents the changes in $\overline{T}_{sk}$ for both groups during the different clothing trials. For group L, there was no effect of clothing on the increase in $\overline{T}_{sk}$ during the first 30 min of data collection. Thereafter, $\overline{T}_{sk}$ was significantly lower for NPC compared with the other clothing configurations. $\overline{T}_{sk}$ was also significantly lower during the TH - CC trial compared with TH + CC after 50 min of exposure in the climatic chamber. The difference in $\overline{T}_{sk}$ between TH + CC and TH - CC was quite small compared with the differences between these two clothing configurations and NPC. $\overline{T}_{sk}$ continued to increase during the last hour of the NPC trial. For the comparative data presented in Figure 5 for group H, $\overline{T}_{sk}$ was significantly different among the three clothing configurations.

3.1.6 Rate of Sweat Production and Evaporative Efficiency.

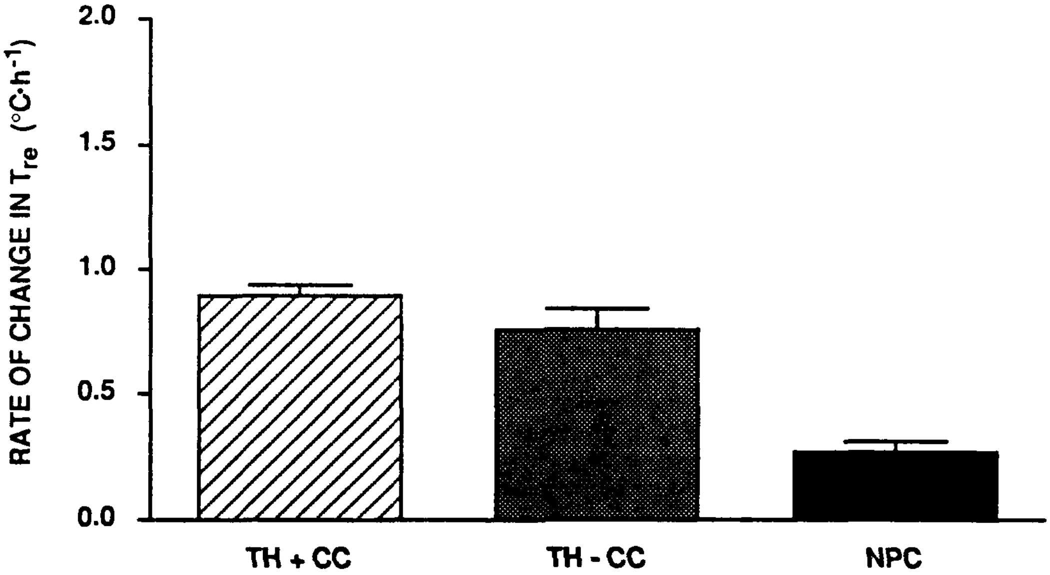
The rate of sweat production of the body is presented in Figure 6 for both exercise groups with the three clothing configurations. For group L, the rate of sweat production for TH + CC (~ 0.8 $L \cdot h^{-1}$) was significantly greater than for TH - CC (~ 0.7 $L \cdot h^{-1}$). The rate of sweat production for NPC (~ 0.5 $L \cdot h^{-1}$) was significatly less than the other two clothing configurations. Similarly for group H, the rate of sweat production for TH + CC (~ 1.2 $L \cdot h^{-1}$) was greater than the value of ~ 1.1 $L \cdot h^{-1}$ for TH - CC. These values were also significantly greater than the value of 0.9 $L \cdot h^{-1}$ for NPC.

The evaporative efficiency of the different clothing configurations for both exercise groups is presented in Figure 7. For group L, the evaporative efficiency of 76% for NPC was significantly greater than the values of 46% and 36%, respectively, for TH - CC and TH + CC. Evaporative efficiency was not different between these latter two clothing configurations. For the heavy exercise group, evaporative efficiency was significantly different among each of the three clothing configurations. Values approximated 19%, 34% and 57% for TH + CC, TH - CC and NPC, respectively.

For both exercise groups, Table 2 presents the amount of sweat that was produced but not evaporated from the different layers of the clothing configurations. For example, for group L, of the 0.94 kg of sweat not evaporated in the TH + CC clothing configuration, 0.33 kg remained in the combat clothing, 0.18 kg in the socks, t-shirt and underwear, 0.14 kg remained in the NBC garment, 0.10kg remained in the combat boots and webbing, 0.07 kg in the NBC gloves, boots and respirator, and 0.13 kg was unaccounted for and represented sweat evaporation during the undressing procedure and/or sweat in the skin thermistor harness or heart rate telemetry belt which were not weighed before and after each trial. For TH - CC, 0.82 kg of the sweat produced was not evaporated. Of this amount, the greatest proportion (0.46 kg) remained in the socks, t-shirt and underwear, and in the NBC garment. For the NPC clothing configuration only 0.36 kg of the sweat produced was not evaporated. Of this

Figure 4. Rate of change in rectal temperature (T_{re}) at 40°C during the exercise and rest periods for the light (L, n=6) exercise group and during continuous exercise for the heavy (H, n=5) exercise group while wearing TOPP High with combat clothing (TH + CC) or without (TH - CC) or the new vapour protective clothing layer (NPC).

GROUP L



GROUP H

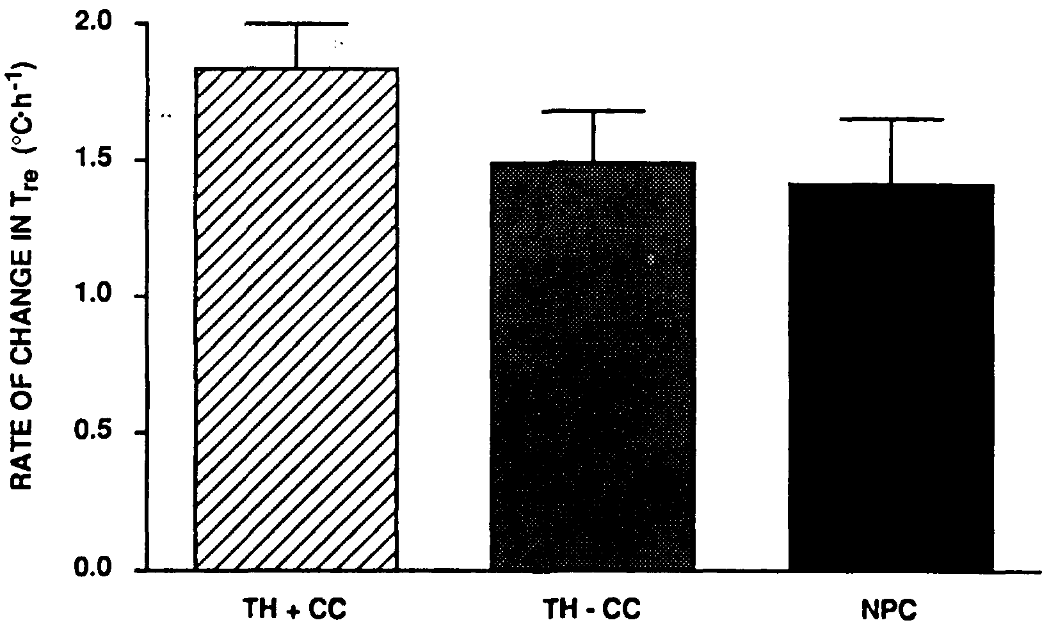


Figure 5. Changes in mean skin temperature at 40°C during the exercise and rest periods for the light (L, n=6) exercise group and during continuous exercise for the heavy (H, n=5) exercise group while wearing TOPP High with combat clothing (TH + CC) or without (TH - CC) or the new vapour protective clothing layer (NPC).

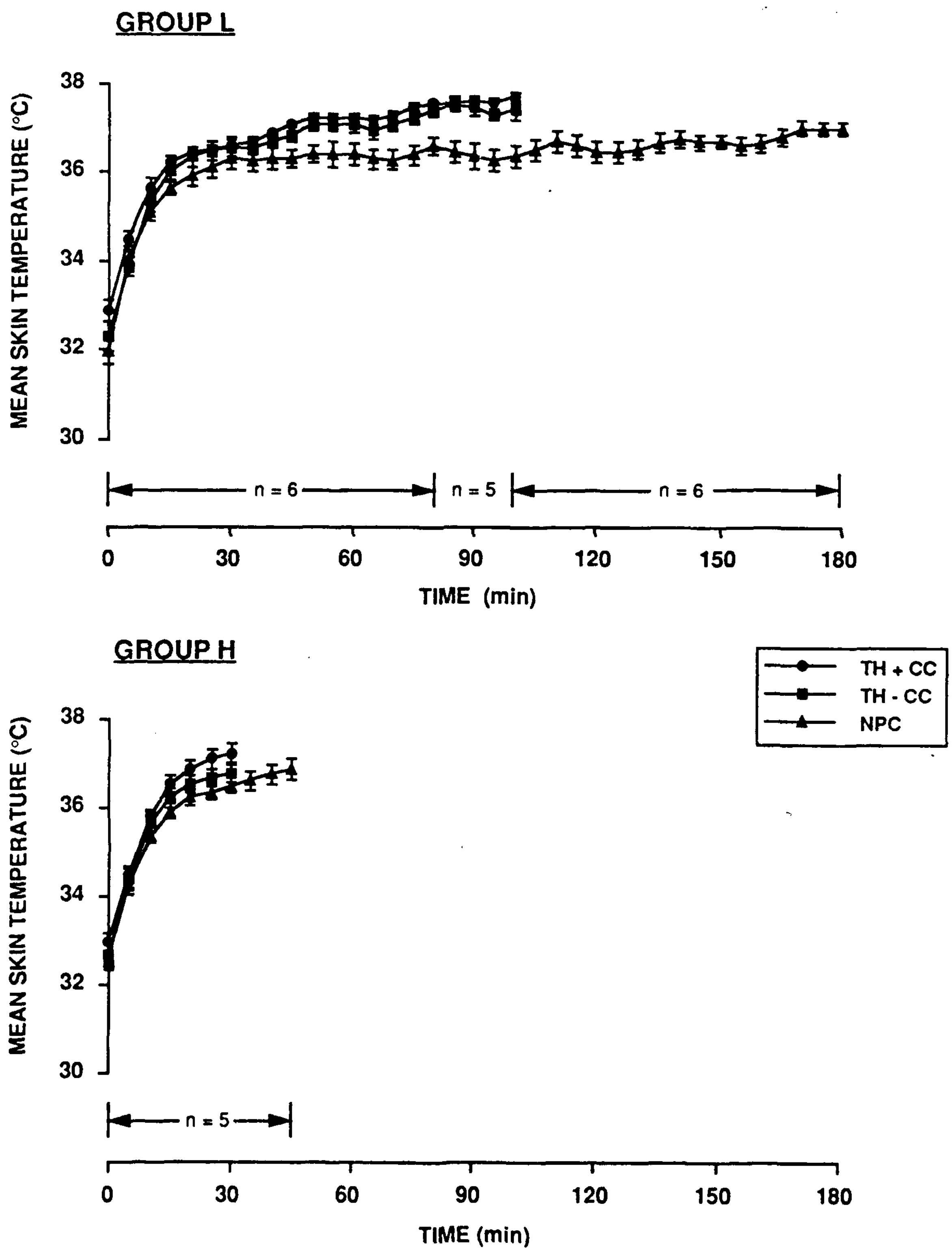


Figure 6. Rate of sweat production at 40°C for the exercise and rest periods for the light (L, n=6) exercise group and during continuous exercise for the heavy (H, n=5) exercise group while wearing TOPP High with combat clothing (TH + CC) or without (TH - CC) or the new vapour protective clothing layer (NPC).

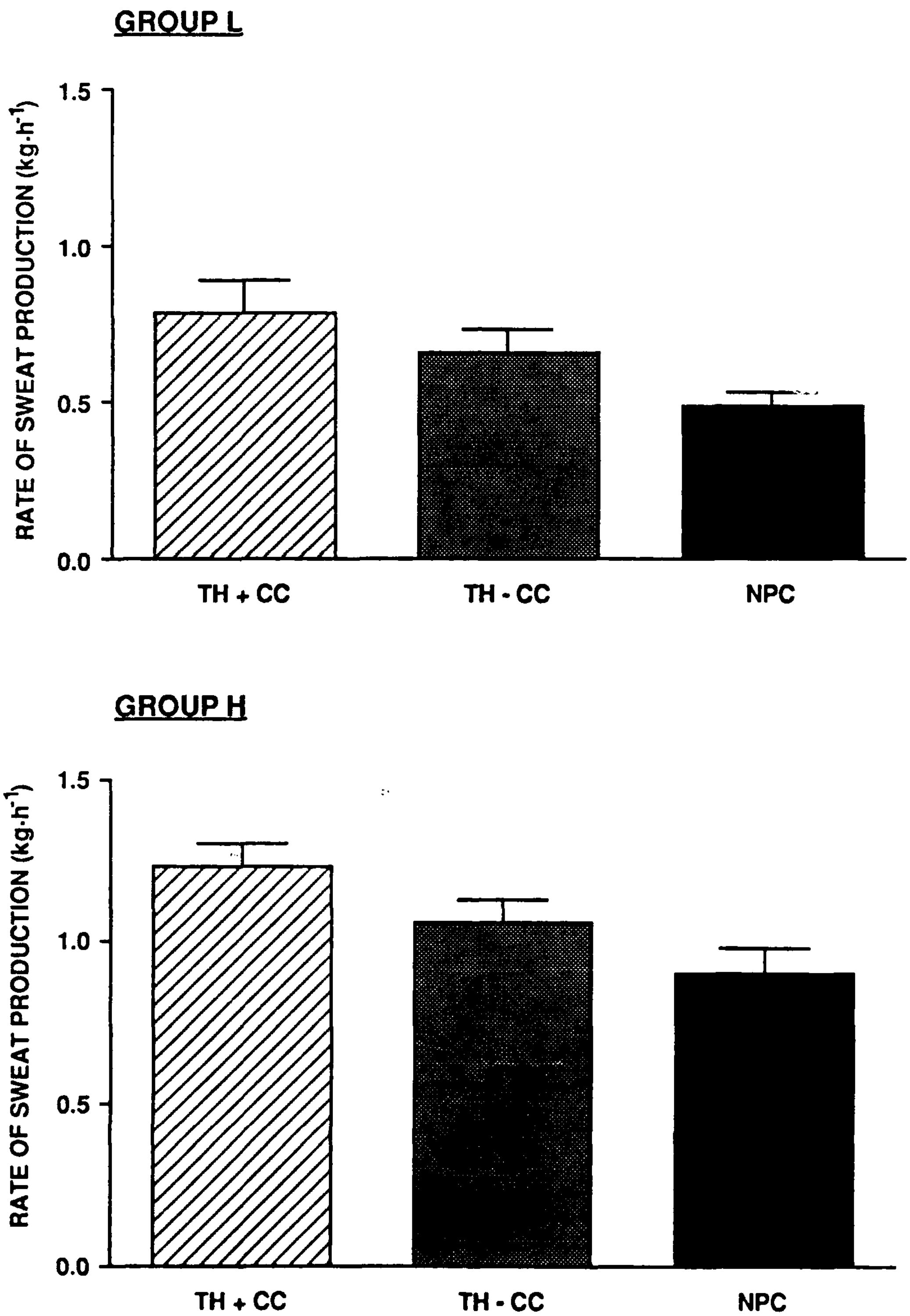
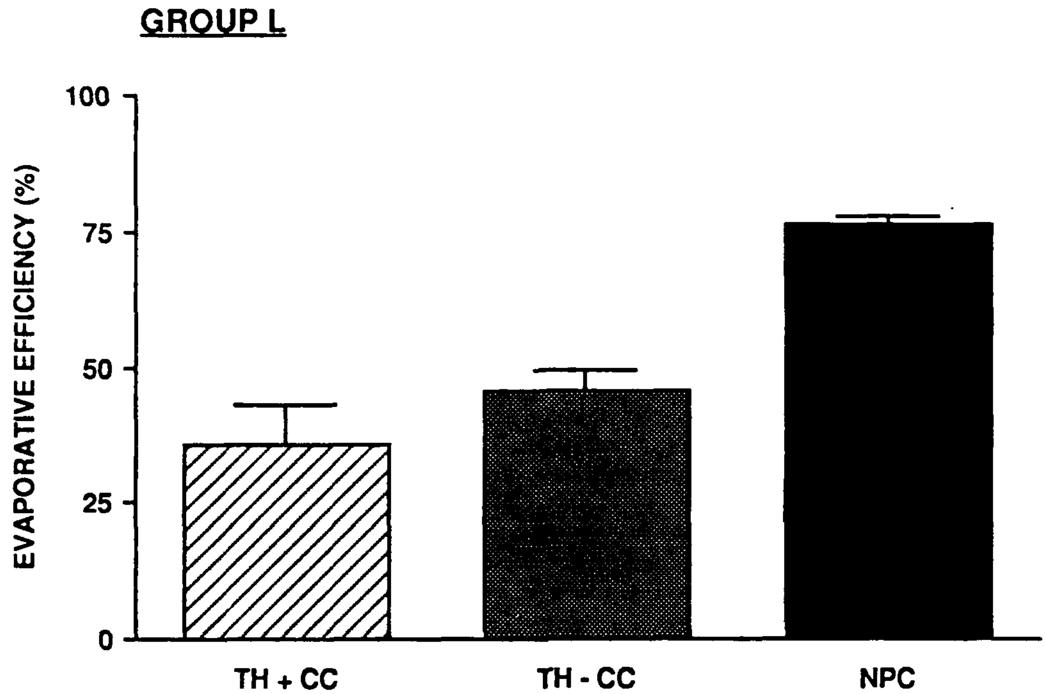
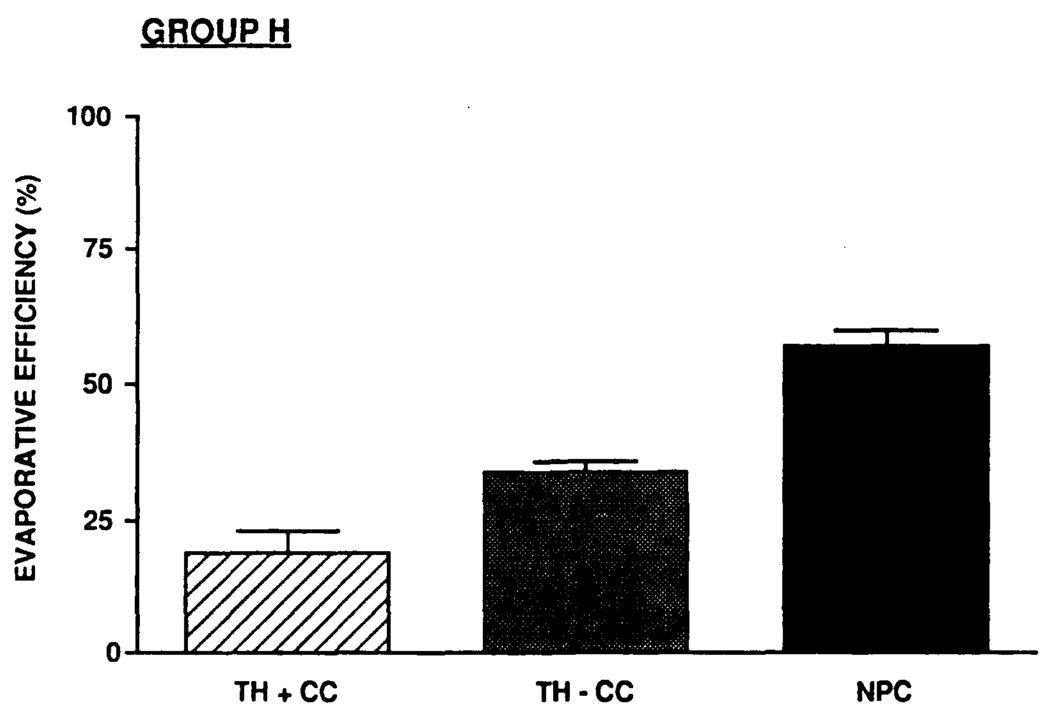


Figure 7. Evaporative efficiency at 40°C for TOPP High with combat clothing (TH + CC) or without (TH - CC) or the new vapour protective clothing layer (NPC) during the exercise and rest periods for the light (L, n=6) exercise group and during continuous exercise for the heavy (H, n=5) exercise group.





amount, 0.09 kg remained in the underwear, socks and long underwear, and only 0.03 kg remained in the new vapour protective layer.

Table 2. The amount of sweat produced but not evaporated at 40°C for the light (L) and heavy (H) exercise groups while wearing TOPP High with combat clothing (TH + CC) or without (TH - CC) or the new vapour protective clothing layer (NPC).

Group	Clothing Configuration	Total Sweat Produced	Sweat Produced but not Evaporated (kg)						
			Total	Socks,t-shirt underwear	combat clothing	combat boots, webbing	NBC gloves, boots, mask	NBC garment	other
L	TH + CC	1.43	0.94	0.18	0.33	0.10	0.07	0.14	0.13
		(0.19)	(0.17)	(0.04)	(0.07)	(0.02)	(0.02)	(0.02)	(0.04)
	TH - CC	1.50	0.82	0.24	0.00	0.07	0.07	0.22	0.22
		(0.24)	(0.14)	(0.07)	(0.00)	(0.02)	(0.01)	(0.05)	(0.04)
	NPC	1.47	0.36	0.09	0.00	0.08	0.03	0.03	0.13
		(0.12)	(0.05)	(0.02)	(0.00)	(0.02)	(0.01)	(0.01)	(0.02)
H	TH + CC	0.97	0.77	0.16	0.24	0.04	0.05	0.08	0.21
		(0.18)	(0.12)	(0.03)	(0.07)	(0.01)	(0.01)	(0.02)	(0.02)
	TH - CC	1.10	0.72	0.27	0.00	0.06	0.07	0.18	0.15
		(0.22)	(0.13)	(0.04)	(0.00)	(0.02)	(0.01)	(0.05)	(0.02)
	NPC	1.30	0.53	0.20	0.00	0.07	0.06	0.06	0.15
		(0.23)	(0.08)	(0.04)	(0.00)	(0.02)	(0.02)	(0.01)	(0.02)

Values are means (SEM)

4.0 DISCUSSION

The results from the present investigation show conclusively the advantages of the new vapour protective clothing ensemble on physical work tolerance times at 40°C. It must be stated that the present study has not considered the influence of solar radiation or the colour of the clothing on WTT in a hot environment. Nevertheless, for both the light and heavy exercise groups, WTT was significantly increased compared with the current NBC ensemble worn with or without combat clothing (i.e., TH + CC or TH - CC). The improvements in work performance are also of operational significance for CF personnel since the real-time increases in WTT would translate into quantifiable differences in the amount of work completed at a given metabolic rate. For example, at the 4.8 km·h^{-1} walking speed for group H, subjects, on average, would have covered a distance of 3.7 km in TH + CC. With the new clothing ensemble, subjects covered a distance of 6.8 km. These differences in the total distance walked could influence a commander's decision of whether personnel should move to a new location to escape a hostile NBC environment with the expectation of arriving with minimal heat-stress casualties.

The evaporative efficiency of the new clothing was increased 2-3 fold compared with the other clothing trials. The greater evaporation of sweat from the body and the layers of the new clothing ensemble resulted in a lower heart rate, mean skin temperature and rectal temperature in the hot environment compared with the other clothing configurations (see Figures 2 to 5). Since the evaporation of sweat represents the major avenue of metabolic heat dissipation during exercise (Åstrand and Rodahl 1977), any change in the efficiency of sweat evaporation will be reflected by a change in other variables that indicate the extent of the thermal stress. For example, if the evaporative efficiency is increased, the heat load on the body will be reduced. This will be reflected by a smaller redistribution of cardiac output to the periphery, an enhanced venous return and, therefore, stroke volume, and a lower heart rate (see Rowell, 1974). The improved evaporative efficiency for the new clothing ensemble was reflected also by a lower rate of sweat production (see Figure 6). If the availability of "clean" water is at a minimum, then this lower sweat rate for the new clothing would be accompanied by a slower rate of body dehydration. Dehydration levels as low as 2% of body weight may begin to affect performance (Jacobs, 1987).

It is important to note that the above discussion would also apply for the comparison between TH + CC and TH - CC. The additional layer of clothing represented by the combats significantly affected work tolerance times, evaporative efficiency and the rate of sweat production for the heavy exercise group. Consistent differences among the subjects in the light exercise group were not as evident. Nevertheless, the present data is sufficiently strong to recommend that, if operationally feasible, the combat clothing should not be worn under the NBC garment during exercise in a hot environment. The present guidelines given to the U.S. Forces for sustaining operations in a desert environment provide separate tables for their NBC ensemble worn over combats or underwear (USARIEM 1990). However, the work tolerance times predicted from the USARIEM heat stress model (Pandolf et al. 1986) reveal little, if any, difference between the two clothing configurations. This is in direct contrast with the findings of the present study.

It is difficult to compare the work tolerance times for the different clothing configurations in the present investigation with results from previous studies. The WTT values for TH + CC compare reasonably well with the values predicted by Rich (1985) for the U.S. MOPP IV worn over combat clothing at 38°C and 20% R.H. For both exercise groups in TH + CC, WTT was greater than what has been reported for the same clothing configuration, metabolic rate and ambient temperature (McLellan, 1991). However, with this previous investigation the humidity was set at 50% which could account for the differences in work performance. As stated above, our findings for TH - CC exceed the tolerance times predicted by the USARIEM heat stress model (USARIEM 1990). Finally, to our knowledge, there are no previous reports available that have documented the benefits of a close-fitting vapour protective clothing ensemble on work performance in a hot environment.

For group H, $\dot{V}O_2$ was significantly increased during the treadmill walk for TH + CC compared with the other clothing configurations. This could be viewed as a decrease in mechanical efficiency since a greater $\dot{V}O_2$ was required to produce the same amount of external work. However, differences in $\dot{V}O_2$ among the clothing configurations were not evident at the slower walking speed of 4.0 km·h^{-1}. Therefore, either differences in mechanical efficiency only are evident at higher walking speeds or the $\dot{V}O_2$ kinetics for TH + CC are different than the other clothing configurations during the heavy exercise condition. Clarification of these possible explanations would require the measurement of $\dot{V}O_2$ throughout the initial 10 to 15 min of the exercise session.

5.0 CONCLUSIONS

Based upon the results obtained from the present study, the following conclusions are evident:

1. The new vapour protective clothing ensemble, under development at the Defence Research Establishment Ottawa, significantly prolonged physical work performance by as much as 85% at 40°C and 25% R.H.

2. The evaporative efficiency of sweat was increased at least 2-fold with this new clothing ensemble compared with the current NBC TOPP High configuration.

3. For the heavy exercise group, wearing combat clothing under the NBC garment significantly affected physical work performance.

6.0 RECOMMENDATIONS FOR FURTHER STUDY

Further evaluation of the new vapour protective clothing ensemble should focus on the following:

1. Whether the mechanical efficiency is improved during exercise wearing the new clothing; and,

2. Identifying which factors among fitness level, body size, body fatness and gender contribute the greatest to the variability in work performance that is observed at any given metabolic rate.

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ABSTRACT

A new vapour protective clothing ensemble is under development at the Defence Research Establishment Ottawa. This clothing is thinner and more close-fitting to the body than the present nuclear, biological and chemical (NBC) protective garment. The purpose of the present study was to examine the influence of this new vapour protective clothing on physical work performance in a hot environment (40°C and 25% relative humidity). Eleven unacclimatized males (28 ± 6 y, 79 ± 8 kg, 1.76 ± 0.06 m) were assigned to exercise at either a light intermittent (L) (N = 6), or heavy continuous (H) (N = 5) metabolic rate. Group L alternated between 15 min of walking on a treadmill at 1.11 $m \cdot s^{-1}$ with a 0% grade and 15 min of rest. Group H walked continuously at 1.33 $m \cdot s^{-1}$ with a 3% grade. Subjects were tested wearing three clothing configurations: full NBC protection (TOPP High) with the combat clothing worn under the NBC garment (TH + CC); full NBC protection without combat clothing (TH - CC); the new vapour protective clothing together with the NBC gloves, boots and respirator (NPC). WTT was the time-period until rectal temperature (T_{re}) reached 39.3°C, heart rate reached 95% maximum, dizziness or nausea precluded further exercise, or 3 h had elapsed. For group L, WTT was similar for TH + CC (113 ± 12 min) and TH - CC (139 ± 18 min). WTT was significantly increased for NPC where all subjects completed the 3 h in the climatic chamber. The rate of increase for T_{re} was significantly reduced for NPC (0.3 ± 0.1 $°C \cdot h^{-1}$) compared with both TH + CC (0.9 ± 0.1 $°C \cdot h^{-1}$) and TH - CC (0.8 ± 0.2 $°C \cdot h^{-1}$). The evaparative efficiency of the new clothing ensemble (76 ± 4%) was also significantly increased compared with both TH + CC (36 ± 17%) and TH - CC (46 ± 9%). For group H, WTT significantly increased from TH + CC (46 ± 15 min) to TH - CC (60 ± 21 min) and to NPC (85 ± 28 min). The rate of increase in T_{re} was not different among the three clothing configurations. Evaporative efficiency was significantly different among the three clothing trials (19 ± 8%, 34 ± 4% and 57 ± 7% for TH + CC, TH - CC and NPC, respectively). For both groups, mean skin temperature and heart rates reflected the differences in the evaporative efficiency of the clothing comparisons. The results of this experiment clearly show the benefits of the new vapour protective clothing on physical work performance in a hot environment. Also, the data strongly suggest that, if possible, the combat clothing should not be worn under the present NBC garment.

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