Strategies to Reduce the Heat Stress of Wearing New Biological and Chemical Protective Combat Uniforms in MOPP 1

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ABSTRACT

Background *The core temperature of the soldier in a MOPP 1 configuration has a substantial impact on how long they can continue to work once they transition to MOPP 4. The higher their temperature at the start of this transition the shorter will be their work time in MOPP 4. New hot weather biological and chemical (BC) protective ensembles have been designed as stand-alone combat uniforms that are intended to replace the concept of an overgarment that is donned only as the threat level increases above MOPP 1. Given that soldiers are also expected to wear fragmentation and assault vests, the heat strain in MOPP 1 can be considerable during work in hot environments. The present study has examined whether vents in the leg and the arm of the BC uniform assist in reducing the heat strain of the soldier under varied wind conditions.* ***Methods*** *Eight males (33.6 ± 7.7 y, 86.8 ± 10.8 kg, 48.9 ± 5.3 ml/kg/min* VO_{2max}*) completed up to 3 hours of treadmill walking at 4 km/h in 40ºC and 30% RH conditions while wearing a new hot weather BC stand-alone uniform, fragmentation and assault vests, and helmet, and carrying an artificial C7 rifle. The total additional weight of the clothing and equipment was 20 kg. Zippered vents on the lateral aspect of the upper and lower leg and the medial aspect of the upper arm were either opened or closed in low (1 m/s) or high (3.5 m/s) wind conditions. Rectal and skin temperatures, heart rate, ratings of perceived exertion and thermal comfort, metabolic rate, and vapour pressures measured at the skin surface and in the clothing layers were determined throughout the heat stress exposures.* ***Results*** *All subjects completed the 3 hours of exercise when the vents were opened regardless of the wind condition. However, when the vents were closed 3 of the subjects were unable to complete the exercise challenge in low wind and 1 in the high wind condition. The change in delta rectal temperature was elevated when the vents were closed (1.8 ± 0.6ºC) compared with open (1.5 ± 0.5ºC) and was lower in high (1.2 ± 0.3ºC) compared with low (2.0 ± 0.5ºC) wind. The vapour pressure within the clothing was significantly reduced when the vents were opened (4.7 ± 0.7 kPa) compared with closed (5.0 ± 0.7 kPa) with the greatest contributor to these differences being found on the leg (4.0 ± 0.6 and 4.3 ± 0.6 kPa for the open and closed condition, respectively) rather than on the torso which was covered by the fragmentation and tactical assault vests (5.6 ± 0.9 and 5.7 ± 0.9 kPa for the open and closed condition, respectively).* ***Conclusion*** *It was concluded that zippered vents on the leg and arm of the CB uniform could significantly reduce the heat strain of the soldier in MOPP 1 while working in hot environments.*

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1.0 INTRODUCTION

Current military deployments involve exposure to hot environments together with the threat of exposure to biological and chemical (BC) agents. Different states of mission oriented protective posture (MOPP) demand various levels of protection from the lowest (MOPP 1) where the protective ensemble is carried to the highest (MOPP 4) where all of the clothing is worn and the respirator is used. Although the use of clothing ensembles protects the soldier from the hazards of exposure to BC agents, the clothing together with the hot temperatures creates a condition of uncompensable heat stress. Under these conditions physiologic tolerance is determined by three factors; the core temperature at the beginning of the exposure, the core temperature tolerated at exhaustion and the rate of increase of core temperature from the beginning to end of the heat stress [for review see 7].

Several nations have designed new BC clothing ensembles with a reduced thermal resistance and increased water vapour permeability in an attempt to lessen the thermal burden when the ensemble is worn in a MOPP 4 configuration [1, 11, 13, 15]. However, these new clothing designs also are worn as a stand-alone combat uniform, which may create greater thermal stress during MOPP 1 when compared to use of the conventional combat uniform. Thus, a true comparison of the effectiveness of the new BC ensembles for reducing thermal strain must include MOPP 1 as well as MOPP 4 comparisons. Any potential advantage of the new ensemble when worn in MOPP 4 may be offset by its disadvantage when worn in MOPP 1. It is well documented that elevations in core temperature at the beginning of heat stress exposure in MOPP 4 will significantly decrease exposure time [5, 6, 20].

An increased airflow over the skin surface promotes greater convective and evaporative heat transfer [17]. Several sporting companies incorporate zippered vents in their jackets and pants in an attempt to increase airflow over the skin during physical activity. The current study has considered the effectiveness of this same concept during MOPP 1 with the use of a new BC ensemble. In addition, this concept was examined under conditions of low and high wind since the importance of vents in the clothing may be more evident when airflow is low. It was hypothesized that thermal strain would be reduced with the use of vents in the clothing and that this effect would be greatest when airflow was low.

2.0 METHODS

2.1 Subjects

Eight non heat-acclimated males, with mean ± SD values for age of 33.6 ± 7.7 y, height 181 ± 7 cm, body mass of 86.8 ± 10.8 kg and peak aerobic fitness of 48.9 ± 5.3 ml/kg/min, participated in this study. The subjects were fully informed of the details, discomforts and risks associated with the experimental protocol, and following a medical screening and physical exam written informed consent was obtained. The subjects were asked to refrain from heavy exercise and alcohol for 24 hours and to refrain from caffeine or products containing caffeine for 12 hours before each trial. Volunteers were not selected if they were taking any medication or if they had made a blood donation within thirty days of the study. This study was granted approval by the human ethics review committee of Defence R&D Canada.

2.2 Determination of VO_{2peak}

VO_{2peak} was determined on a motor-driven treadmill using open-circuit spirometry [14] 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%/min until subjects were running at a 10% grade. If necessary increases in treadmill speed of 0.22 m/s and grade of 1% were alternated each minute until the subject could no longer continue. VO_{2peak} was defined as the highest oxygen consumption (VO_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}).

2.3 Experimental Design

Subjects performed 4 randomly assigned experimental trials consisting of exposure to either low (1 m/s) or high wind (3.5 m/s) with clothing vents either opened or closed. Subjects walked on a treadmill at 4.0 km/h in a climatic chamber at 40°C and 30% relative humidity. Trials continued until rectal temperature (T_{re}) reached 40°C, HR reached or exceeded 95% of HR_{peak} for 3 minutes, dizziness or nausea precluded further exercise or the subject became exhausted and terminated the session. Subjects consumed 5 ml/kg of warm water every 30 minutes throughout the experimental trials that were separated by a minimum of 7 days. A familiarization session that involved exposure to all of the procedures described below and exercise in the climatic chamber at 40°C preceded the experimental trials by one week. All sessions were conducted during the winter months.

2.4 Dressing and Weighing Procedures

Subject preparation, insertion of the rectal thermistor and placement of skin thermistors have been detailed previously [2, 14]. In addition, humidity sensors and thermistors were placed at 5 locations (upper back, abdomen, upper arm, upper and lower leg) above the skin surface and over a T-shirt (upper back, abdomen and upper arm), shorts (upper leg) or on the inner surface of the uniform (lower leg) to determine vapour pressure (VP) [4]. Upon entering the chamber, the subject's thermistors, humidity sensors and rectal thermistor monitoring cables were connected to a computerized data acquistion system (Hewlett-Packard 3497A control unit, 236-9000 computer and 2934A printer) and the exercise began. Mean values over 1-min periods for T_{re} and skin temperature (T_{sk}) were recorded and printed by the data acquisition system. A 7-point weighted mean T_{sk} [10] was subsequently calculated. An unweighted mean skin and clothing VP was also calculated. HR was recorded every 5 min from the display on the telemetry receiver (Polar® CE0537). 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 subsequent short undressing procedure.

Differences in nude and dressed weights before and after each trial were corrected for respiratory and metabolic weight loss. The rate of sweat production was calculated as the difference between the corrected pre-trial and post-trial nude weights, divided by exercise time that was defined as the difference in time between removal from and entry into the environmental chamber. Evaporative sweat loss was calculated from the differences in pre- and post-trial corrected dressed weights. Although the dripping of sweat from the clothing, face and hands was minimal our calculation of evaporative sweat loss does not account for any of this lost sweat.

2.5 Clothing Ensemble

During each trial subjects wore underwear, socks, a T-shirt, shorts and a CB jacket and pants with running shoes (to minimize foot blisters during the exercise). In addition, subjects wore a helmet and a torso fragmentation and a tactical assault vest equipped with weights to simulate ammunition and carried an artificial C7 rifle. The total additional weight of all of the clothing and equipment worn and carried by the subjects approximated 20 kg.

The clothing design incorporated zippered vents on both the left and right front side of the jacket from the juxtanipple to mid-abdomen, on the lateral aspect of the upper chest through the armpit to the medial upper arm, on the lateral aspect of the upper leg from mid thigh to just above the knee and on the lateral aspect of the lower leg from mid-calf to the ankle. The fragmentation vest completely covered the vents on the torso and covered approximately one-third of the vents that ran from the upper chest through the armpit to the upper arm.

2.6 Gas Exchange Analyses

During each trial, open-circuit spirometry was used to determine expired minute ventilation and oxygen consumption (VO_2) using a 2-min average obtained every 15 min. Respiratory water loss was calculated using the VO_2 measured during the trial and the equation presented by Mitchell et al. [16]. Metabolic weight loss was calculated from VO_2 and the respiratory exchange ratio using the equation described by Snellen [19].

2.6 Ratings of Perceived Exertion and Thermal Comfort

Following the gas exchange measurement, subjects were asked to provide a rating of perceived exertion (RPE) between 6 and 20 for the whole body [3] and a rating of thermal comfort (TC) between 1 (so cold I am helpless) and 13 (so hot I am sick and nauseous) for the whole body [8].

2.7 Data Analyses

A two-factor (vents and wind) repeated measures analysis of variance (ANOVA) was used for dependent measures such as exercise time and sweat rate. A three-factor ANOVA (vents, wind and time) was used to analyse the responses during the heat stress for the other dependant measures. When a significant F-ratio was obtained, a Newman-Keuls post-hoc analysis was performed to isolate differences among treatment means. For all analyses, an alpha level of ≤ 0.05 was used for statistical significance.

3.0 RESULTS

3.1 Tolerance Time

All subjects completed the 3 hours of exercise in both wind conditions when the vents in the clothing were opened. Tolerance time was significantly reduced to 172.5 ± 14.5 min when the vents were closed. Three subjects during the low wind trial and one subject during the high wind condition terminated their session due to exhaustion. Respective tolerance times during these trials were 168.8 ± 17.5 min and 176.3 ± 10.6 min.

3.2 Oxygen Uptake (VO_2)

VO_2 was not different among the trials but did increase over time from 11.0 ± 1.1 ml/kg/min at 15 min to 13.1 ± 2.3 ml/kg/min after 165 min of exercise. These values represented approximately 30% of VO_{2peak} remembering that subjects carried an additional 20 kg of clothing and equipment during the trials.

3.3 Heart Rate

Figure 1 presents the HR response during the trials. There was a main effect of wind and vents with values being significantly reduced during the high wind (111.3 ± 17.3 beats/min) versus the low wind trials (118.6 ±

22.1 beats/min) and during the open (112.7 ± 19.6 beats/min) versus the closed vent condition (117.3 ± 20.5 beats/min). The HR also increased more rapidly over time during the low wind trials regardless of whether the vents were opened or closed.

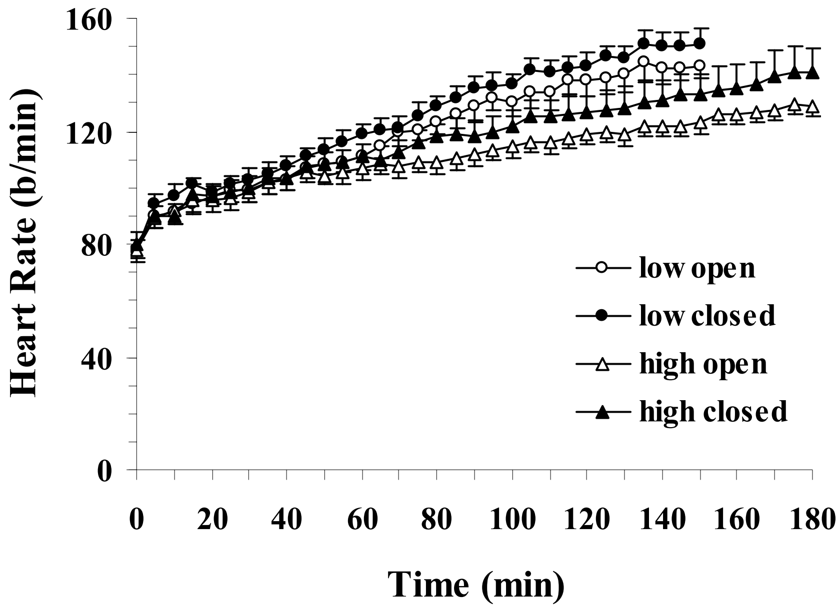

Figure 1: Heart rate response during the exercise and heat stress in low or high wind conditions with vents in the clothing either opened or closed.

3.4 Delta Rectal Temperature

The change in T_{re} from the beginning of the heat stress exposures is presented in Figure 2. During the low wind condition, the opening of the vents significantly slowed the increase in T_{re} after 30 minutes of exercise. Delta T_{re} was significantly reduced during the high wind compared with the low wind trials. Opening the vents in the clothing during the high wind condition caused a further reduction in T_{re} after 135 min of exercise.

The change in T_{re} from the beginning to end of the heat stress exposure was significantly greater during the low (2.03 ± 0.49ºC) versus the high wind (1.22 ± 0.30ºC) trials as well as when the vents in the clothing were closed (1.75 ± 0.61ºC) versus open (1.49 ± 0.52ºC). Similarly, the rate of increase in T_{re} from the beginning to end of the heat stress exposure was greater during low (0.71 ± 0.20ºC/h) compared with high wind (0.41 ± 0.11ºC/h) and closed (0.62 ± 0.24ºC/h) compared with open vent (0.50 ± 0.17ºC/h) conditions.

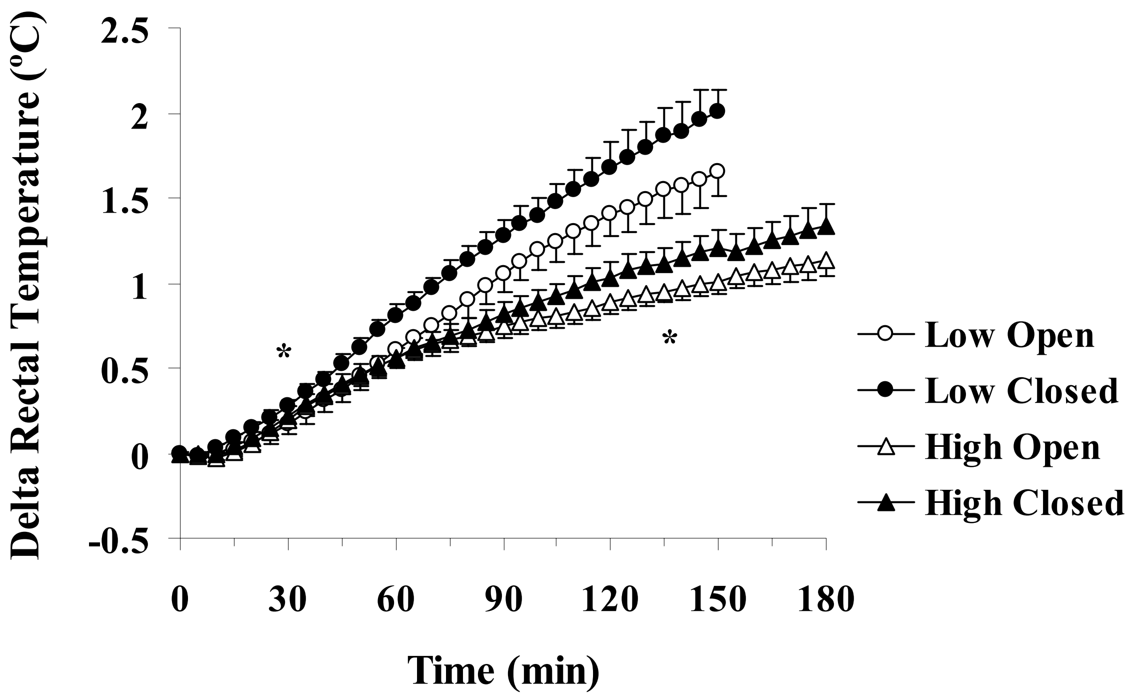

Figure 2: Delta rectal temperature response during the exercise and heat stress in low or high wind conditions with vents in the clothing either opened or closed. The asterisk indicates a significant difference between the open and closed conditions.

3.5 Skin Temperature

Overall, mean T_{sk} was significantly reduced during the high wind (36.1 ± 0.9ºC) compared with the low wind trials (36.6 ± 1.1ºC). Opening or closing the vents had no effect on the calculated mean T_{sk}. However, the reader must remember that the wearing of the fragmentation vest largely influenced the abdomen and upper arm temperature sites that would reflect the effectiveness of the torso and arm vents, respectively. The influence of the upper and lower leg vents on leg skin temperature is shown in Figure 3. A significantly lower leg skin temperature was observed during the low wind condition when the vents were opened (36.2 ± 0.9ºC) compared with the closure of the vents (36.7 ± 1.0ºC). For the high wind condition, a lower leg skin temperature was observed following 130 min of exercise.

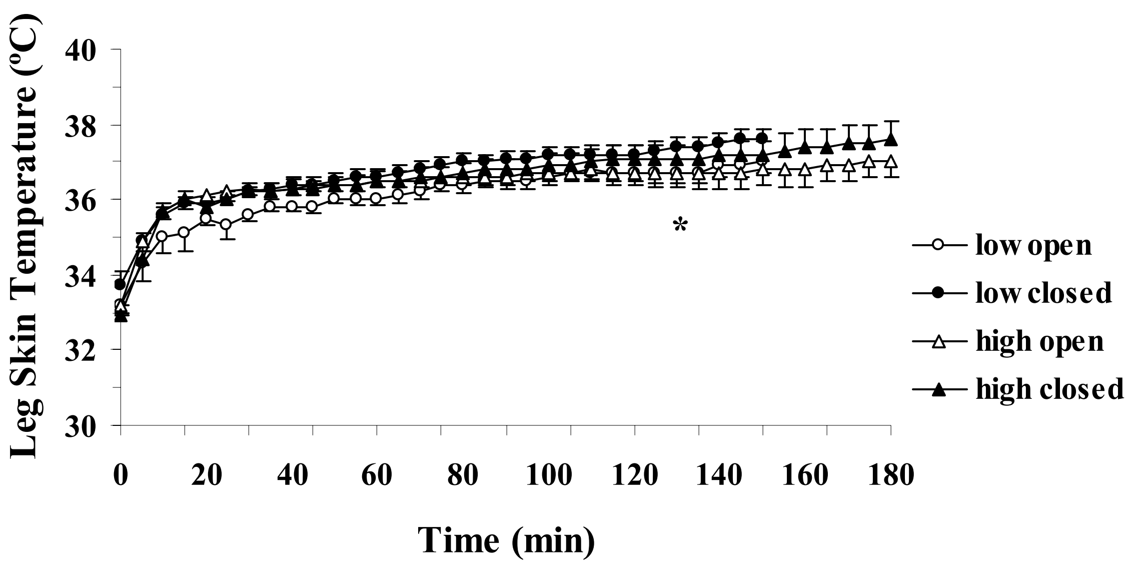

Figure 3: Leg skin temperature response during the exercise and heat stress in low or high wind conditions with vents in the clothing either opened or closed. The asterisk indicates a significant difference during the high wind condition when the vents were either opened or closed.

3.6 Vapour Pressure

Mean vapour pressure above the skin surface was significantly reduced during the high wind (5. 16 ± 0.66 kPa) compared with the low wind trials (5.46 ± 0.80 kPa) and these differences were consistent regardless of the site of measurement (i.e., abdomen, upper arm or leg). Overall, skin vapour pressure was significantly different among the abdomen (6.00 ± 0.80 kPa), the upper arm (5.25 ± 0.90 kPa) and leg (4.71 ± 0.65 kPa) sites reflecting the influence of the coverage of the fragmentation vest. Opening or closing the vents had no measurable effect on the vapour pressure immediately over the skin surface.

Mean vapour pressure over the first clothing layer was significantly lower during the high wind (4.66 ± 0.6 kPa) versus the low wind (5.01 ± 0.87 kPa) trials and also significantly lower when the clothing vents were opened (4.72 ± 0.78 kPa) rather than closed (4.96 ± 0.80 kPa). The effect of wind was again consistent regardless of the site of measurement. Also, differences among the abdomen (5.66 ± 0.93 kPa), upper arm (4.45 ± 0.96 kPa) and leg (4.17 ± 0.67 kPa) were again observed. A differential effect depending on the site of measurement was observed for whether the vents were opened or closed. Whereas no effect during either high or low wind conditions was observed for the abdomen or upper arm when the vents were opened or closed, Figure 4 shows the significant reduction in leg vapour pressure when the vents were opened during both the low and high wind trials.

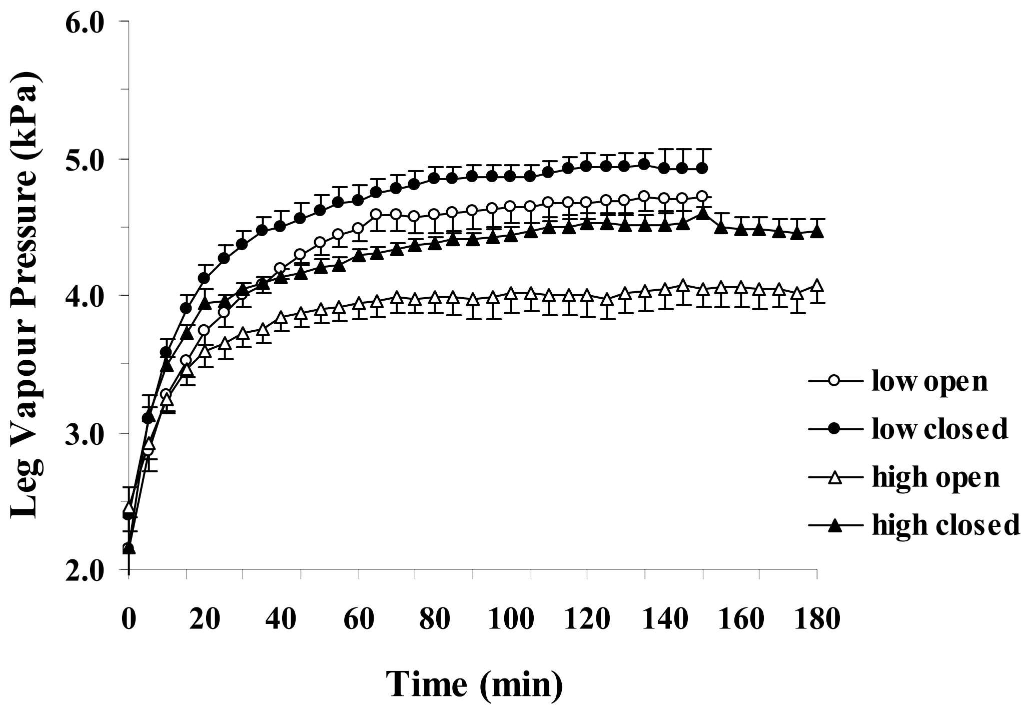

Figure 4: Average leg vapour pressure determined from a reading over the shorts and inside the lower pant leg during the exercise and heat stress in low or high wind conditions with vents in the leg either opened or closed.

3.7 Sweat and Evaporation Rates

Sweat rates were similar among all of the trials averaging approximately 1.1 kg/h. Evaporation rates were significantly increased during the high (0.82 kg/h) compared with the low (0.68 kg/h) wind trials. There was also a trend ($p < 0.09$) for higher evaporation rates when the vents were opened (0.78 kg/h) rather than closed (0.72 kg/h).

3.8 Ratings of Perceived Exertion

RPE was significantly reduced during the high wind condition after 90 min of exercise. Opening or closing the vents had no effect on RPE although there was a trend ($P < 0.08$) for lower values when the vents were open in the high wind trials.

3.9 Ratings of Thermal Comfort

RTC was significantly lower during the high wind condition after 75 min of exercise. Opening or closing the vents had no effect on RTC.

4.0 DISCUSSION

The results from this study have shown the impact of wind and the importance of vents in the clothing for reducing the thermal strain of exercising in hot environments. The former effect is well substantiated in the literature as both the convective and calculated evaporative heat transfer coefficients are affected by wind speed [17, 18]. This is also true when clothing ensembles are worn as has been demonstrated using articulating manikins [9] and humans [12]. The latter effect is less clear despite its obvious use in athletic apparel. Generally, studies have shown that as wind speed increases clothing apertures at the wrist, ankle and neck have little impact on ventilation diffusion and heat transfer through air permeable garments but a substantial effect when impermeable garments are worn [12]. Certainly, for the soldier who may be wearing an impermeable fragmentation vest and other equipment that covers 40-50% of their surface area, the use of vents in the clothing on other regions of the body, not so encumbered, appear to reduce thermal strain. In the present study, this was evident from the reduction in heart rate and core temperature, leg skin temperature and leg clothing vapour pressure when the vents were opened rather than closed. We were unable to differentiate an effect of the vents between the low and high wind conditions despite the obvious greater thermal strain that was evident in the low wind condition. Possibly, with more extensive openings on areas of the body not covered by impermeable clothing and equipment the importance of vents in the clothing would be more apparent during low wind conditions.

4.1 Operational Significance

The physiological evidence certainly would support the use of vents in new BC clothing ensembles on areas of the body not encumbered with the wearing of impermeable layers of other protective equipment. The question remains, however, if the physiological changes that were observed would be of operational significance during the transition from MOPP 1 to MOPP 4. Several nations have designed new BC clothing ensembles that have a lower thermal resistance and increased water vapour permeability compared with older clothing configurations in order to reduce the resultant thermal and cardiovascular stain during MOPP 4 [1, 11, 13, 15]. However, these new ensembles also are intended to serve as a stand-alone duty uniform and thus would be worn during MOPP 1 rather than the traditional combat uniform. A true comparison of the effectiveness of the new BC ensembles for reducing thermal strain, therefore, should include MOPP 1 as well as MOPP 4. Any potential advantage of the new ensemble when worn in MOPP 4 may be offset by its disadvantage when worn in MOPP 1. Amos et al. [1] have shown that the new Australian hot-weather BC clothing does not elevate the thermal strain when worn in MOPP 1 but significantly reduces the strain in MOPP 4 when compared with an older overgarment protective ensemble. However, it was noted that evaporative efficiency was reduced during MOPP 1 when their new clothing was compared to a conventional duty uniform. Also, their laboratory trials did not include the wearing of a fragmentation vest or helmet, impermeable equipment that would further restrict evaporative heat loss over those regions of the body.

It is well documented that elevations in core temperature at the beginning of heat stress exposure in MOPP 4 will significantly decrease exposure time. Previous findings have clearly demonstrated that elevated core temperatures at the beginning of heat stress exposure in MOPP 4, such as during the luteal phase of the menstrual cycle [20] or as a result of previous dehydration [5, 6], significantly decrease heat tolerance. The effects can be as great as 20% when tolerance times exceed one hour [6]. For soldiers marching at 4 km/h with tolerance times in MOPP 4 around 90 minutes [5], a 20% reduction in heat tolerance would decrease the total distance covered by more than 1 km. If soldiers were required to move from a contaminated to a clean area before transitioning back to a reduced protective posture, this reduction in work output would be operationally significant and impact on the success of the mission objective.

5.0 CONCLUSION

In summary, the present study has revealed an advantage of vents in the clothing for reducing thermal and cardiovascular strain during exercise in a hot environment. The changes in skin temperature and clothing vapour pressure were most evident when the vents were open on regions of the body not encumbered by the wearing of impermeable clothing and equipment. Thus, it is recommended that future clothing designs consider the use of larger vented regions over the legs and arms that could assist with maintaining temperature regulation in hot environments prior to transitioning to a MOPP 4 configuration.

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