TOLERANCE FOR INTERMITTENT EXERCISE IN MILITARY CLOTHING IS IMPROVED BY WEARING A VENTILATED VEST IN HOT, DRY CONDITIONS

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INTRODUCTION

There has been much recent research interest in microclimate cooling for individuals working in hot climates whilst wearing protective clothing (Bomalaski et al. 1995; Chen et al. 1997; Cheuvront et al. 2003; Chinevere et al. 2008). Attempts have been made to develop cooling garments that augment convective (air cooled garments), conductive (liquid cooled garments) and evaporative cooling. The purpose of such garments is to delay any heat-related deterioration in physical and cognitive performance and prevent the onset of heat illness. Military personnel (e.g. infantry) and some occupational groups (e.g. emergency services) are particularly vulnerable to heat illness due to the requirement to work whilst wearing protective clothing that impedes heat loss. This requirement creates the need for cooling garments that should form an integrated part of the overall protective clothing assembly.

Relatively few laboratory-based studies have tested the efficacy of microclimate ventilation in air temperatures above 43°C because of the risk of heat gain through forced convection and an increased risk of burning. Additionally, the test protocols used have often been short (e.g. 80 minutes, Hadid et al. 2009; 120 minutes, Verniuew et al. 2008) despite the intended use of garments for longer durations. For example, soldiers deployed with an armoured vehicle require a minimum of 6 h of effective use without battery replenishment. Shorter duration studies can demonstrate the short-term efficacy of microclimate ventilation but do little to inform about the longer term operational significance of using such a garment. A further methodological consideration is that shorter studies can be misleading by being insufficient to allow the clothing assembly to equilibrate in terms of garment temperature and moisture content. Garments like body armour can act as a large heat sink in the early stages of a test if not pre-acclimated to the test environment, and the thermal profile of individuals will alter as the clothing system equilibrates.

For reasons related to battery life, the availability of a suitable heat sink, logistic and operating restrictions (i.e. noise), the tendency has been towards the use of convective/evaporative rather than conductive cooling. The aim of this study was to determine the efficacy of a ventilated vest during long duration exposure to hot, dry conditions. This study tested the hypothesis that the ventilated vest garment would extend exercise time and remain effective during rest and exercise for up to 6 h in hot (45°C), dry (10% RH) ambient conditions.

METHODS

Participants: The study protocol was approved in advance by the University of Portsmouth Ethics committee and the participants gave their written informed consent to participate. Eight healthy males volunteered and were tested (mean [s.d]; Age 19 [1.5] yrs; height 1.78 [.07]m; mass 78.91 [12.35] kg; surface area 1.90 [0.16]m^2(9); body fat 15.6 [1.7]%; (10).

Procedure: Following a 10 day acclimation programme in the same conditions as the main study, each participant completed two 6 h exposures to hot (45°C) dry (10% RH) conditions in a climatic chamber on separate days. During one of the trials they wore a ventilated vest blowing ambient air over the torso (VEST). The other trial served as a control (NOVEST). Throughout the 6 h exposures the clothing worn comprised: t-shirt, desert shirt, combat trousers, socks, training shoes, ballistic vest with two inserts, combat helmet and personal load carriage equipment [PLCE; 19.09kg]). In the VEST condition the ventilated vest was worn in addition to the items listed above and was worn on top of the UBACS tropical desert shirt and beneath the ballistic vest. The total weight of the assembly in the VEST condition approximated 29.3kg and in the NOVEST condition approximated 28kg. A cross-over experimental design was used and all trials commenced at a similar time of day (~0800).

On each day and following instrumentation and dressing, the participants entered the climatic chamber and commenced walking (exercise) on the treadmill at 5km.h^{-1} at a 2% incline. Exercise/rest cycles were based upon deep body temperature thresholds. Upon reaching a T_{rec} of 38.5°C the participant ceased exercise and was seated on a chair on the treadmill. The participant remained seated until T_{rec} had fallen to 38°C they then recommenced exercise. Cycles of exercise and rest were recorded and continued in this manner until 6 h of test time had been completed or volitional withdrawal. The participants were free to stop for any reason, such as soreness in the shoulders due to the load carriage or blisters from walking. The reason and duration of these stops were recorded. Due to the duration of the test, each participant was provided with food in the form of snack bars at approximately 90 minute intervals.

Vest Condition: The VEST comprised a pump that distributed ambient air around the torso through a series of vented ducts woven into the vest across the front and back of the garment covering approximately 33% of the body surface. To ensure the pump maintained consistent performance, checks of pump power supply (volts), pressure (pa) and air flow (L·s^{-1}) were recorded at the start and end of each trial and subsequently confirmed consistent pump performance.

Measurements: Exercise/rest periods were noted (minutes) and the ratio of exercise to rest was calculated. Cool tap water (19°C) was consumed *ad libitum* throughout the study and was recorded using digital weighing scales. Fluid intake and pre and post trial naked and clothed body weights were used to estimate sweat production. Deep body temperature was measured with a calibrated rectal thermistor (T_{re}) inserted 15cm beyond the anal sphincter. Skin temperature (T_{sk}) was measured using thermistors attached to the skin by tape at four sites: chest, arm, thigh and calf. T_{re} and T_{sk} were recorded each minute on a data logger. Subjective responses were recorded during the 6 h trials at baseline, every 15 minutes during exercise and every 5 minutes during rest. Thermal comfort for the torso (TC_{torso}) and then the whole body (TC) using a 20cm sliding scale where: v*ery comfortable (20cm)*, *comfortable (16cm)*, just *comfortable (12cm)*, *just uncomfortable (10.5cm)*, *uncomfortable (4cm)*, *very uncomfortable (0cm)*.

Calculations: Mean skin temperature (T_{msk}) was calculated according to the formula: $T_{msk} = 0.3 (T_{chest} + T_{arm}) + 0.2 (T_{thigh} + T_{calf})$ (Ramanathan 1964)

Mean body temperature (T_b): $T_b = 0.8T_{re} + 0.2T_{msk}$ (Colin et al. 1971)

Stored heat (S) was calculated for each exercise and rest period: $S = (\Delta T_b \times 3.48 \times mass)/t$

The average specific heat of body tissues was assumed as 3.48kJ.kg^{-1}°C^{-1} (Pembrey 1898). Any absolute error compared with partitional calorimetry (Vallerand et al. 1992) was assumed equal between trials.

Data Analyses: Data were assessed for normality of distribution using a Kolmogorov-Smirnov test. Due to the difference in exercise and rest completed in each condition, data were averaged for each of the following: exercise performance (% of time spent exercising against total exposure time), exercise/rest ratio, ΔT_{sk}, ΔT_{rec} and ΔT_b (°C·hr^{-1}) heating (exercise; Watts) and cooling rate (rest; Watts) and perceptual measures (TC, TC_{torso}) during rest and exercise. Site specific T_{sk} (chest & back) and heart rate were averaged across the total exposure time. These variables, and the overall sweat responses (Produced [L]; Evaporated [L; %]) were compared using paired samples t-tests. For all statistical tests the α level was set at 0.05. Data are presented as mean [SD].

RESULTS

Significant performance data are summarised in Table 1.

Table 1. Performance, thermal and perceptual indicators of exercise and rest periods in the NOVEST and VEST conditions. * denotes significant difference between conditions.

	NOVEST		VEST		
	Mean	SD	Mean	SD	p value
Exercise Time (min)	138	[38]	179	[56]	0.065
Rest Time (min)	151	[74]	91	[56]	0.085
Percentage Exercise	51	[16]	69	[12]	0.028*
ΔT_b Exercise (°C.hr^{-1})	1.64	[0.34]	1.26	[0.37]	0.001*
ΔT_b Rest (°C.hr^{-1})	-1.06	[0.20]	-2.07	[0.66]	0.001*
ΔT_{rec} Exercise (°C.hr^{-1})	1.41	[0.28]	1.19	[0.37]	0.132
ΔT_{rec} Rest (°C.hr^{-1})	-1.00	[0.26]	-1.69	[0.71]	0.048*
Average T_{chest} (°C)	37.55	[0.51]	35.33	[1.00]	0.002*
Average T_{back} (°C)	36.85	[0.83]	35.84	[0.88]	0.041*
$TC_{rest\ Torso}$	8	[3]	10	[4]	0.053
Stops due to $T_{rec} \geq 38.5$°C	3	[2]	1	[2]	0.006*

The amount of exercise and consequently rest completed whilst wearing the VEST approached a greater and lesser amount respectively in the VEST condition (see Table 1). Not all participants completed the whole 6 h exposure (NOVEST: 4 completed; VEST: 3 completed), but 18% more exercise was performed in the VEST vs. NOVEST condition (as a percentage of total exposure time NOVEST: 289 [96] min; VEST 270 [97] min). The difference in total exercise time between conditions was 41 minutes (23%) in favour of the VEST condition. The ratio of exercise to rest was 1 [1] in the NOVEST condition and 3 [2] in the VEST condition.

Using change in T_b as the measure of heat storage (ΔT_b), the rate of heat gain during exercise and heat loss during rest was significantly lower and greater in the VEST condition respectively. Estimated heat storage was 28W lower during exercise but the rate of cooling was 73W greater during rest between exercise bouts. This difference was not reflected in the quantity of sweat produced (NOVEST: 3.57 [0.44]L, VEST: 3.75 [1.19]L; $p = 0.816$) and evaporated (NOVEST 2.94 [0.47]L & 83 [12]%, VEST 3.38 [1.22]L & 89 [8]%; $p = 0.386$). An example of a typical exercise/rest profile in the NOVEST and VEST conditions is displayed in Figure 1.

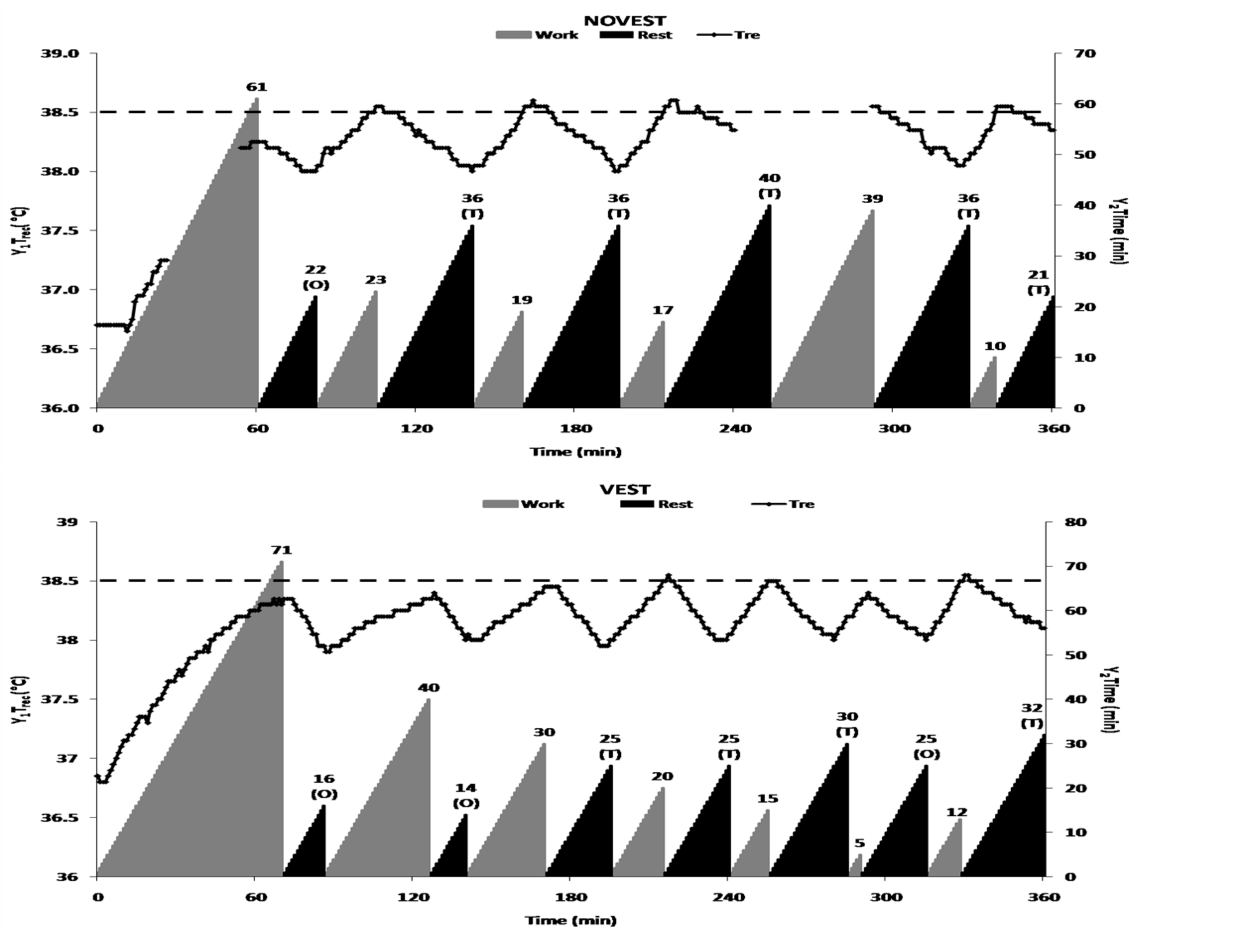

Fig 1. Rectal temperature response (Y_1 axis) and exercise/rest cycle (Y_2 axis) during the NOVEST and VEST condition over time (X axis) in one participant. The quantity (minutes) of exercise (grey bars) and rest (black bars) completed in each exercise/rest bout is printed at the top of the highest bar. T and O denote the reasons for stopping exercise due to temperature (T_{rec} >38.5°C) or other reasons respectively. Anomalous T_{rec} data have been removed from the figure.

TC did not differ significantly between conditions either during rest (TC_{rest}: NOVEST: 8 [3]; VEST 9 [3], $p = 0.420$) or exercise ($TC_{exercise}$: NOVEST: 7 [1]; VEST 6 [1], $p = 0.809$). TC_{torso} during rest approached being significantly lower (improved comfort) in the VEST condition.

CONCLUSIONS

This study demonstrated the efficacy of a ventilated vest cooling garment in temperature conditions that exceed mean skin temperature in exercising participants. At no point did skin temperature, measured at five separate sites across the body, approach the ambient temperature conditions. Furthermore, the skin temperatures reached did not induce irritation or burning. As a consequence of wearing the ventilated vest, participants exercised for significantly longer and reached the experimental cut-off for rectal temperature significantly less frequently thereby reducing their risk of heat-illness. This was facilitated by the evaporation of sweat on the torso producing, an average, significantly lower skin temperatures throughout the 6 h experiment. These beneficial effects could only be discerned when the duration of exposure exceeded 90 minutes before which the 'heat sink' potential of the clothing was substantial (figure 1).

The lower skin temperatures experienced by the participants in the ventilated vest condition markedly improved their thermal comfort rating. These findings are consistent with those listed in other studies utilising ventilated ambient air cooling (Chinevere et al. 2008; Hadid et al. 2009; Muza et al. 1988). It is clear from the present study that, when the evaporative heat loss potential of the environment is high (dry conditions), the ambient temperature threshold for adding heat to the body lies in excess of 45°C. Shapiro et al (1982) noted a risk of skin burning and added thermal strain in hot (49°C) dry (20%RH) conditions with a radiative component (T_{globe}: 68°C) where heat loss due to ventilated cooling was negligible. This implies that the upper limit for the potential thermal benefit from ventilated cooling is closer to 49°C. The results, continue to suggest that a ventilated vest may reduce thermal load and potentially enhance exercise time in certain real-world military and civilian environments.

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