EFFICIENCY OF COMBINATIONS OF COOLING FOR MICROCLIMATE COOLING SUIT DESIGN, TESTED IN MAN AT 100°F WITH EXERCISE

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INTRODUCTION

A recent concern in hazardous materials containment, removal, and military operations has been the heat and work stress imposed on personnel wearing chemical and biological protective clothing (Chemical and Biological Protection Suit, Carbon Sphere #8415-01-333-7578 and gas mask/cowl, MSA91J012-013; CBR). Several microclimate-cooling systems have been tested as possible solutions (1). Although these systems may extend work time in heat stress environments, many models have limitations that prevent extended use with CBR. These limitations include effectiveness only during conditions of light to moderate work loads, requirement of a significant amount of support materials for sustained operations, removal of protective clothing for re-supply, and necessity of low ambient humidity for evaporative cooling (1-5). The following tests confirmed that several configurations of one model (Flexitherm™ vest, leg panels, and cap, Life Support Systems Inc., Mountain View, CA), in conjunction with a thermoelectric cooling/heating unit (Carlson Technology Inc., Livonia, MI), are effective in reducing cardiovascular load and extending work time during heat stress and moderate work loads (6,7).

METHODS

Data from two separate studies using similar subject populations are presented. Protocols were reviewed and approved by the appropriate agencies. Subjects were screened with an ECG, graded exercise test (8), and % body fat (9). Anthropomorphic data of combined populations is as follows: mean age = 26.7 ± 1.9 yr., height = 178.8 ± 3.6 cm, weight = 78.4 ± 11.1 kg, and body fat = 15.5 ± 5.4%. Subjects were familiarized with the equipment, clothing, and protocols, and given hydration, diet, and sleep instructions. Subjects wore military issue cotton fatigues, CBR suit, gas mask and cowl, cotton socks, and athletic shoes. Exercise consisted of two cycles of 50 minutes treadmill walking (3 mph, 2% grade) followed by 10 minutes rest. Ambient temperature was 100° F and relative humidity 40%.

The experimental conditions consisted of variations in the cooling garments as follows: 1. FATIGUES only; 2. CBR only; 3. VEST; 4. VEST/CAP; 5. VEST/LEG; 6. LEGS; and 7. VEST/CAP/LEGS. VEST, CAP, and LEGS refers to the location of the cooling panels for each protocol. Conditions 3-7 included wearing CBR. Coolant was water + 3% ethylene glycol at a temperature of 14°C with a flow rate of 450 ml min^{-1}. Coolant temperature was maintained by a thermoelectric cooler with an ice bath back-up. Coolant was circulated from bottom to top.

Rectal temperature was measured using a disposable thermocouple inserted 10-12 cm past the anus. Heat flow and temperature were measured at six skin sites- head, arm, chest, back, thigh, and calf using heat flux transducers. Mean heat flow was calculated using a formula weighted on surface area (10). Heart rhythm was measured continuously. Blood pressure, ratings of perceived exertion (RPE), and temperature perception were assessed every 15 minutes (11). Temperature perception was assessed using a 1,000 mm scale (meter stick with numbers covered) where 0 = Intolerably Cold and 1,000 = Intolerably Hot. Subjects were instructed to use their finger as a pointer and indicate how hot or cold they felt relative to the limits presented. The corresponding numerical value was read from the reverse side. Body weights were recorded and timed urine specimens were collected before and after each experiment. Data was analyzed with one-way ANOVA employing the Statistical Package for the Social Sciences.

RESULTS:

In the 54 experiments presented here, only seven were terminated early and all but one termination was in a CBR only, uncooled protocol. The one cooled experiment that was terminated by the subject was due to a feeling of claustrophobia. One experiment was terminated due to exhaustion, one for nausea, one for dizziness, and two for equipment failures.

Mean rectal temperatures as a function of time for the subjects in 5 of the 7 experimental conditions are presented in Figure 1. No significant differences in rectal temperatures were noted between the 5 cooling protocols or the FATIGUES protocol.

The rate of rectal temperature rise up to the first rest period (0-50 minutes), determined by least squares linear regression, is comparable in all seven protocols. With the onset of the second exercise period, however, the mean rectal temperature in the CBR (no cooling) condition increased at a significantly faster rate than during the FATIGUES only and all cooling conditions except VEST (Figure 2).

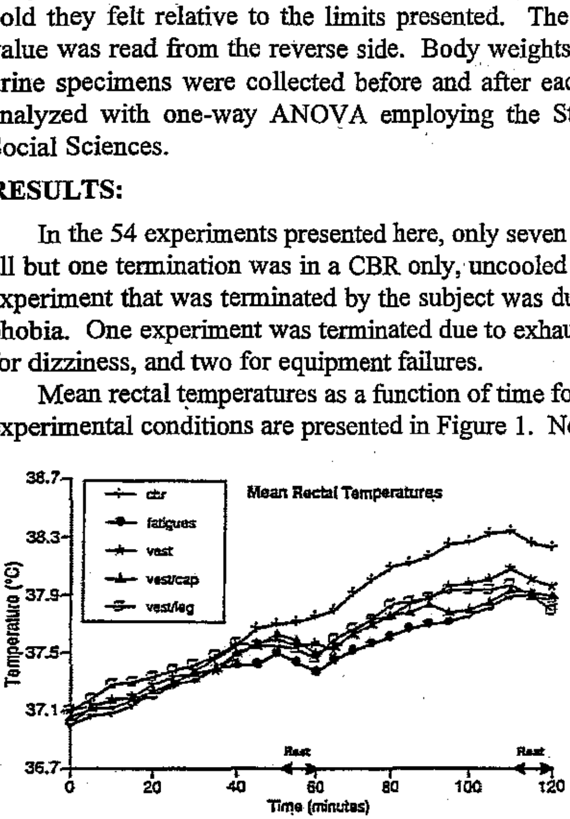

Figure 1. Mean rectal temperature vs time

Weighted values from 6 skin sites were used to calculate mean heat flow for each subject in each condition (10). After reaching the exercise steady state (20 to 30 minutes), changes in heat flow over time during any given experiment were insignificant, therefore average heat flows over each entire experiment were evaluated (Figure 3).

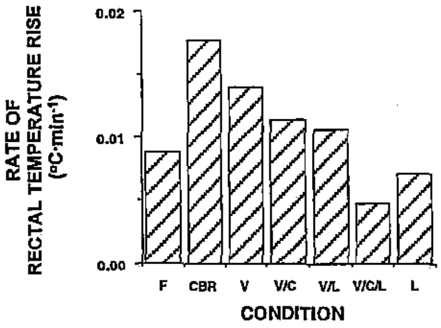

Figure 2. Rate of rectal temperature rise as a function of condition.

The greatest increase in mean heart rate occurred in the No-cooling (CBR) protocols. During both rest periods, the heart rate in the cooling and the FATIGUES protocols decreased to control levels or below, while in the no-cooling protocols heart rates remained about 25% higher than control levels. All other cardiovascular-respiratory parameters monitored during these experiments show similar trends with no significant differences.

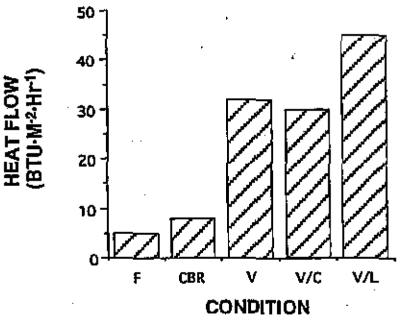

Figure 3. Rate of heat flow as a function of condition.

Fluid losses were estimated by changes in body weight (loss by perspiration and respiration) and by urine production. The largest weight loss (2.4%) occurred in the CBR no-cooling protocol, with the lowest weight losses observed in the VEST/LEGS and VEST/CAP/LEGS protocols (1.9% and 1.8%, respectively). This indicates a significant reduction *($P< 0.05$)* in fluid loss during these 2 cooling conditions. The other cooling conditions show similar but not significant trends.

Temperature perceptions recorded in conditions 1-5 indicate that subjects felt as cool with any of the three cooling configurations wearing the CBR as they did in FATIGUES alone. By 30-45 minutes in the CBR alone protocol they felt significantly *($P < 0.05$)* warmer than during the cooling conditions. Ratings of Perceived Exertion (RPE), did not show significant differences between conditions, although the trends indicate improvement with cooling.

DISCUSSION

At high ambient temperature, evaporative cooling is the only physiological mechanism for heat loss. The CBR suit prevents evaporative heat loss in addition to its insulating effects and weight. Under the above conditions several microclimate cooling configurations effectively compensated for CBR use resulting in core temperature, cardiovascular, and perception changes equivalent to exercise without CBR. Of the 5 cooling protocols, the VEST/LEG and VEST/CAP/LEG protocols were most effective. All but the VEST cooling significantly reduced core temperature rise. All reduced heart rates when compared to CBR. Recovery of heart rate during rest periods was also improved with cooling. RPE paralleled temperature perception, with both cooling and absence of CBR decreasing perception of workload. There were no significant differences in systolic, diastolic, or mean blood pressure across conditions and no abnormal rhythms were detected.

The maximum mean heat flow (43 BTU·ft^{-2}·hr^{-1}) occurred when the vest and leg panels were worn. This configuration was the most effective heat removal arrangement for two reasons: (a) it provided the maximum surface area for heat transport of approximately 3,770 cm^2 (vest = 2,070 cm^2, leg panels = 1,700 cm^2) and (b) the leg panels are either covering or in close proximity to the exercising muscles. This arrangement results in high efficiency of heat transfer. The VEST and the VEST/CAP configuration had heat flow values approximately 75% of the VEST/LEG arrangement with about 54% and 70% of the cooling surface when compared to VEST/LEG, respectively.

The head has been presented as a high heat loss region (1,5,12). However, the data presented here indicates that it was not a very effective cooling site for the following reasons: (1) it has a relatively small surface area (28% and 33% of the surface area of the vest and leg panels, respectively), (2) it is not the site of the greatest heat production, and (3) coolant flow through the cap is difficult to maintain. Obtaining an effective seal on the gas mask often reduced flow in the inlet and outlet tubing, which makes the functioning of the cap and gas mask questionable and difficult to maximize. However, the temperature perception data indicate that the cap, due to its location, may give the subject a feeling of coolness.

In summary, the addition of microclimate cooling, in any of the combinations tested here, to the CBR ensemble, decreases core temperature rise, cardiovascular stress, and perception of heat associated with exercise in hot environments. In this way, the addition of microclimate cooling may increase work performance and endurance while wearing CBR in a hot environment. Cooling with the vest and leg panels was the most effective combination. The effectiveness of the leg panels alone may in part be due to the fact that the exercise consisted of walking, and much of the muscle mass producing the heat was in near proximity to the cooling source. Finally, the cap cooling system does not afford sufficient additional cooling to justify the added complexity involved with its use.

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