USE OF ENCAPSULATED PHASE CHANGE MATERIAL (EPCM) AS A COOLING AGENT IN MICROCLIMATE COOLING GARMENTS

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INTRODUCTION

Clothing designed to protect an individual from chemical, biological and radiological (CBR) contamination reduces heat dissipation. Garments have been designed which allow cooling fluids to be delivered near the body surface, removing heat and averting hypothermia. This microclimate cooling approach to limit heat stress has been evaluated in our laboratory. Experiments presented here represent the application of a new technology to provide cooliig. The conventional coolant has been water; therefore the heat removed is a function of the specific heat of water (1 $cal \cdot g^{-1} \cdot {}^{\circ}C^{-1}$) and the temperature gradient between the coolant and the **skin.** The new approach utilizes small capsules that contain material that changes phase at a specific temperature. This phase change will absorb more heat and maintain a larger gradient for heat transport than water alone. The experimental design was such that the effect of adding the phase change material to the coolant could be evaluated by comparing this protocol to water alone as the coolant and a no cooling condition. Since the phase change material is contained in the microcapsules, this system will be referred to as "encapsulated phase change material" or EPCM.

MATERIALS AND METHODS

Experimental protocols were reviewed and approved by appropriate agencies. Screening volunteers included receiving informed consent to participate, a medical history; a 12-lead electrocardiogram, % body fat , and a graded exercise test. The ten subjects selected for the project had an average age of 22 years; body fat of 15.3%; height, 167 cm and weight, 76.2 kg. Subjects were briefed on the experimental protocol, laboratory, equipment, and risks associated with participation and reimbursement arrangements. Each subject participated in three experimental protocols: two with supplemental cooling (EPCM slurry or water alone), one without. Protocols were separated by at least 5 days and counterbalanced. After being instrumented and dressing, subjects performed moderate exercise (treadmill walking at 3 mph at a 2% grade) for 120 min. at an ambient temperature of **98** to 100°F. When coolant was employed, it was delivered at 515 $cc \cdot min^{-1}$, and temperature of 14°C.

The subject inserted a disposable thermocouple into the rectum 10-cm past the anus and provided a urine sample. The subject was weighed and **was** instrumented as follows: ECG electrodes, four **skin** thermocouples and a blood pressure cuff. Subjects began dressing by donning the microclimate-cooling suit (Paul Webb, Yellow Springs, OH). This mesh garment consists of capillary-like plastic tubing network between the liner and mesh. **Cotton** coveralls were **worn** over the cooling suit and the CBR pants; shoes and rubber boots were donned. Control measurements were obtained and cooling initiated when appropriate. The remained of the clothing was donned (CBR jacket and gloves) to complete modified Mission Oriented Protective Posture (MOPP) III configuration. The jacket hood was worn without the gas mask or cowl. At the end of the experiment, the subject was undressed, weighed, and provided a urine sample.

The cooling system consisted of a chilled inflow reservoir, four-parallel input pumps, an output reservoir, and a fifth pump to circulate the coolant through the heat exchangers. Flow rate, input and output temperatures were monitored. The fluid containing EPCM was mixed **as** follows: 20% EPCM, and 1% Triton X-100 by weight. EPCM was cooled to 7°C, to ensure a solid phase before reheating it to achieve the desired inflow temperature.

RESULTS

Of the 30 experiments, 13 were terminated early. In this group of 13, 10 were the no-cooling protocol. No-cooling protocol termination ranged **from 45** to **90** minutes (mean was **68** minutes). The mean heart rate was 161 beats/min and the rectal temperature was 39.2°C at termination.

The mean rectal temperatures vs. time, for the ten subjects and three conditions, are presented in Figure 1. Statistical analysis reveals significant differences only between the no-cooling protocol and the water and EPCM protocols.

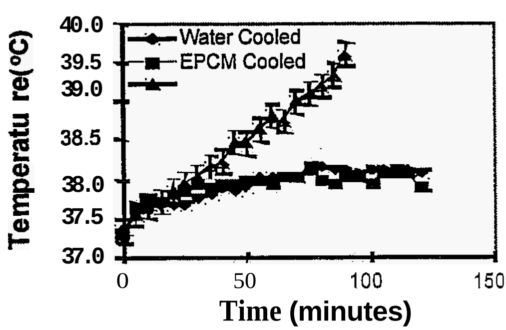


Figure 1. Mean rectal temperature vs. time

If one evaluates the subjects' responses in Figure 1, it is evident that the change in rectal temperature **vs.** time can be divided into two phases: The first phase consists of the iuitial 20 minutes of transient increase in rectal temperature. A second phase includes the responses from 20 minutes to the end **of** the protocol during which the rectal temperature vs. time relationship is essentially linear. **This** data, for each subject **and** protocol was fit by least squares linear regression analysis for phase 2. Slopes representing the rate of rectal temperature change (TR/t) for each protocol are presented in Table 1. Statistical analysis of the slopes indicated significant **dif**ferences among the three protocols ($P < 0.05$ for all pairwise comparisons).

Table 1. Rectal Temperature as a Function of Time **During** Phase 2

Protocol	$\Delta T_R/\Delta t$ (°C/min.)	&
No Cooling	0.0304	0.99
Water Cooled	0.0037	0.62
EPCM	0.0008	0.65

In the no-cooling experiments heart rate increases rapidly as the exercise heat stress is initiated, see Figure 2. The heart rate continued to rise as long as the subject exercised. In the cooling protocols the secondary increase in heart rate did not occur. After the first 40 minutes, mean heart rate in the water-cooled experiments was consistently higher **than** that in the EPCM cooled experiments, indicating that the stress level was less in the EPCM experiments. Statistical analysis of the heart rate data for the three conditions yielded a significant difference for all three comparisons.

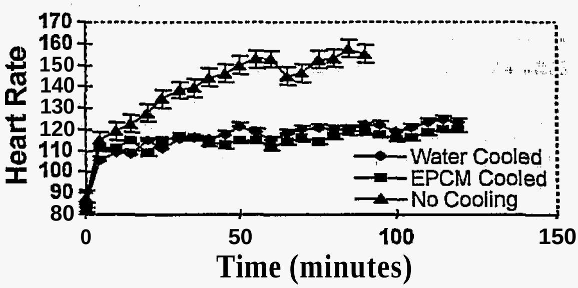
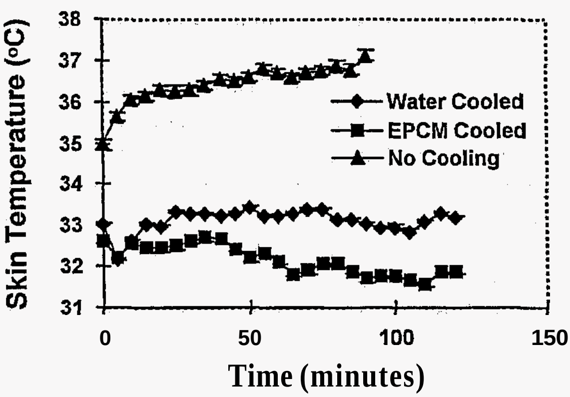


Figure 2. Mean heart rate vs. time



.Figure 3. Mean skin temperature vs. time.

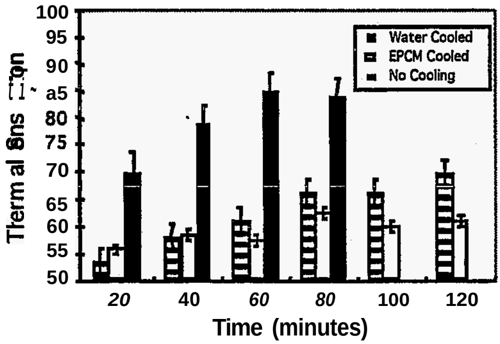


Figure 4. Mean thermal sensation vs. time

Mean skin temperature (T_{msk}) was calculated using the formula of Ramanathan . T_{ms} values are presented in Figure 3 as a function of time for the three conditions. Statistical analysis of mean skin temperatures indicated that a siguificant difference existed between all three conditions. After about ten minutes, T_{msk} for the EPCM experiments dropped below that of the water-cooled protocol.

Subjects were requested to give their opinion of how hot they felt throughout the protocol. Subject perception of temperature, in the set of experiments during which no cooling was employed, far exceeded the evaluations given in either cooling conditions, see Figure 4. There was a progressive increase in the heat perception, which was less for the EPCM than for the water-cooled protocol.

The no-cooling protocol was associated with a larger water loss, both total body sweat water loss, than either of the cooling protocols. However, no significant difference between conditions was found.

DISCUSSION

The primary objective of these tests was to determine if the use of an EPCM slurry as a coolant is more efficient than the water alone. It is evident from the data presented that the microclimate cooling arrangement used in these experiments was very efficient in retarding the rise in core temperature and reducing when either water or the EPCM slurry was used. With cooling, the subjects perceived the work as less demanding and the ambient temperature less extreme. When the two coolants are compared, water alone and EPCM slurry, there is a significant advantage to EPCM as a coolant. However, under the design employed here, the advantage is relatively small. When cooling was not present, the subjects were severely limited in the length of time they could work under the imposed load and ambient temperature. In the EPCM protocols the skin temperatures were lower than those during the water-cooled experiments. This could contribute to the observation by the subjects that the environment was not as hot as it seemed to be in the experiments in which water alone was the coolant. The lower skin temperature may or may not be an advantage. Low skin temperatures may induce cutaneous vasoconstriction and actually reduce heat loss. This point should be addressed in further studies.

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