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EFFECTIVENESS OF AN AIR COOLED VEST USING SELECTED AIR TEMPERATURE, HUMIDITY AND AIR FLOW RATE COMBINATIONS

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U S ARMY RESEARCH INSTITUTE
OF
ENVIRONMENTAL MEDICINE
Natick, Massachusetts

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**EFFECTIVENESS OF AN AIR COOLED VEST USING SELECTED
AIR TEMPERATURE, HUMIDITY AND AIR FLOW RATE COMBINATIONS**

by

Stephen R. Musa, Nancy A. Pimental and Henry M. Cosimini

June 1987

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and

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Natick, Massachusetts 01760-5007

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ABSTRACT

This study evaluated the effectiveness of reducing thermal strain in soldiers by supplying an air-cooled vest with each of four different dry bulb (db) and dew point (dp) temperatures and air flow rate combinations. The four combinations were selected to determine minimal air conditioning requirements for several military vehicles. Six male soldiers attempted four, 300-min heat exposures (49°C db, 20°C dp) at metabolic rates of either 175 and 315 W. The soldiers wore chemical protective clothing over the combat vehicle crewman uniform and the air-cooled vest. Air supplied to the vest ranged from 22.5-27.5°C db, 15.5-21.1°C dp at flow rates of either 10 or 14.5 cfm. Endurance times with the vest were 272-300 min (175 W) and 159-220 min (315 W). In summary, at the 175 W metabolic rate the vest condition which provided the 10 cfm air flow was effective in reducing thermal strain and extending endurance time. At the 315 W metabolic rate, typical of a tank commander or loader, either vest condition would extend endurance time, but would not be as effective in reducing thermal strain as the vest combinations tested in an earlier study.

INTRODUCTION

During nuclear/biological/chemical (NBC) operations, combat vehicle crewmen must wear protective clothing. Such operations may occur in warm to hot environments. The insulation and low moisture permeability of NBC protective clothing severely limits the body's normal heat dissipating mechanism, most markedly the evaporation of sweat. The magnitude of this heat stress problem has been well documented (1,2,5,6). Without microclimate cooling, exposure time while exercising at a moderate intensity in a hot environment in protective clothing may be limited to 60 minutes or less (3,4,8,11).

The U.S. Army Natick Research, Development and Engineering Center (USANRDEC) has developed an air-cooled microclimate vest for soldiers wearing chemical protective clothing. Previous tests of the vest have shown it to reduce thermal strain and increase tolerance time of soldiers wearing protective clothing in the heat (7,8,10,11). During those tests, air supplied to the vest was quite cool and dry, which would require a large capacity air conditioning system if installed in a vehicle. It is desirable to determine minimum air conditioning requirements, which would reduce the space and weight penalties imposed on military vehicles. Furthermore, previous tests supplied a total of 18 cfm air flow to each crewman which also would require the installation of large filters and blower units in vehicles with the microclimate cooling system. If the effectiveness of the microclimate cooling vests in reducing thermal strain

could be maintained using a lower air flow rate, the size of the systems air filters and blower could be reduced.

The present study evaluated the effectiveness of the USANRDEC air-cooled vest when various combinations of vest air dry bulb and dew point temperatures and air flow rates were used. Four combinations of air supplied to the vest were tested: dry bulb (db) temperatures ranged from 22.5-27.5°C and dew point (dp) temperatures ranged from 15.5-21.1°C. Air flow rate to the vest was either 10 or 14.5 cfm. Environmental conditions were constant at 49°C db, 20°C dp, typical for the interior of many combat vehicles in hot environments. Subjects exercised at a low (175 W) and a moderate (315 W) metabolic rate, typical of crewmen operating inside vehicles (12). These studies were designed to expand upon an earlier research study (7) that used similar conditions but lower inlet dew point temperatures with 14.5 cfm air flow to the vest.

MATERIALS AND METHODS

Subjects. Six male soldiers participated in the study. They received a physical examination and were informed of the purpose and procedures of the study, any known risks and their right to terminate participation at will without penalty. Each expressed understanding by signing a statement of informed consent. The physical characteristics of the subjects were: age, 21 ± 2 years; height, 178 ± 8 cm; weight, 76 ± 4 kg; and body surface area, 1.9 ± 0.1 m².

Experimental design. Testing was conducted in June in Natick, Massachusetts. All six subjects had previous experience wearing the chemical protective clothing for at least four hours continuously. Subjects were heat acclimated for four consecutive days by walking on a level treadmill at $1.34 \text{ m}\cdot\text{s}^{-1}$, 3 hours per day, in a 35°C db, 30°C dp environment. During the heat acclimation, they wore shorts, T-shirts, socks and tennis shoes.

Following acclimation, the six subjects attempted four, 300-min heat exposures. Environmental conditions in the climatic chamber were kept constant at 49°C db, 20°C dp, $1.1 \text{ m}\cdot\text{s}^{-1}$ wind speed. During these heat exposures, subjects exercised at time-weighted mean metabolic rates of 175 and 315 W, as can be expected of crewmen operating inside an armored vehicle (12). These two rates were obtained by having the subjects alternate treadmill walking at $1.01 \text{ m}\cdot\text{s}^{-1}$ (metabolic rate ~ 380 W when wearing protective clothing) with seated rest (metabolic rate ~ 105 W). The 175 W metabolic rate was obtained by having the subjects walk for 15 min and rest for 45 min of each hour. The 315 W rate was obtained by having them walk for 45 min and rest for 15 min of each hour.

During the heat exposures, subjects wore the combat vehicle crewman uniform, fragmentation protective vest and MOPP level 4 protective clothing (overgarment, overboots, M25 mask/hood, gloves) and the USANRDEC air-cooled vest. This clothing ensemble had a clo value of 1.75 in still air. The air to the cooling vests was provided by an air conditioning unit located

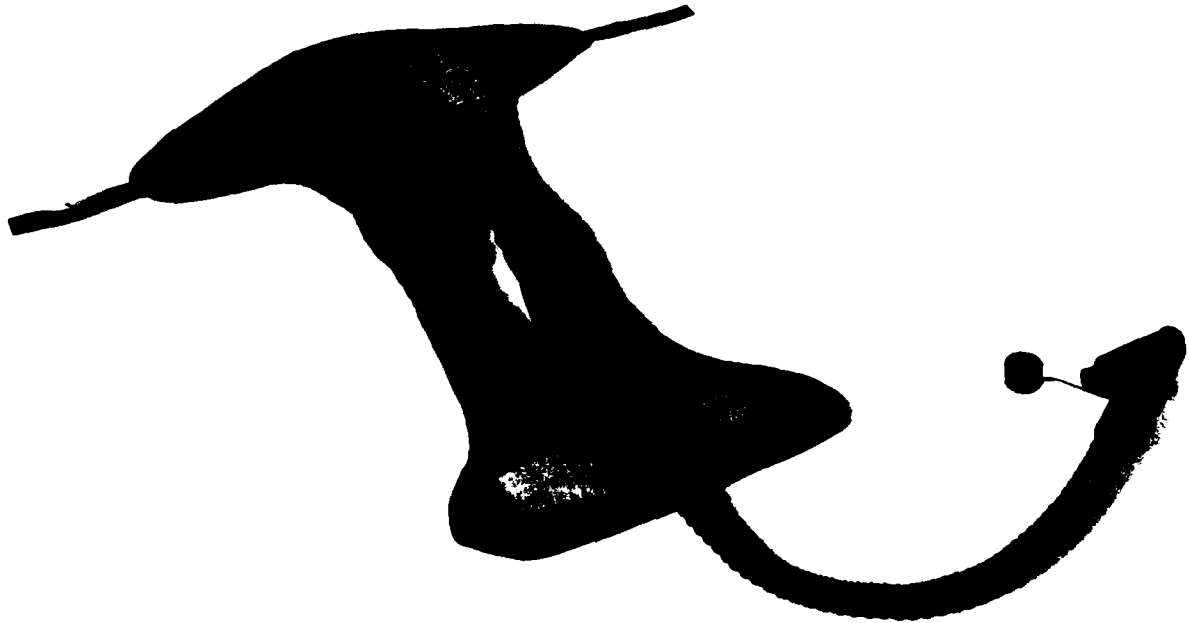
outside the climatic chamber. Four combinations of dry bulb and dew point temperatures and air flow rates were supplied to the vest. Dry bulb temperatures ranged from 22.5-27.5°C and dew point temperatures ranged from 15.5-21.1°C at air flows of 10 or 14.5 cfm to the vest. The conditioned air combinations and the test schedule are provided in Table 1.

TABLE 1. COOLING VEST TEST COMBINATIONS.

COMBINATION	TEST DAY	VEST TARGET DB/DP (°C)	VEST DB/DP OBTAINED	AIR FLOW RATE (CFM)	METABOLIC RATE (W)	POTENTIAL COOLING* (W)
F	3	26.7/15.5	26.1/15.6	10	315	196
G	1	29.4/21.1	27.5/21.1	14.5	315	360
H	2	26.7/15.5	22.5/15.5	10	175	218
I	4	29.4/21.1	24.4/21.1	14.5	175	391

* POTENTIAL COOLING CALCULATED FROM OBTAINED DB/DP TEMPERATURES.

Description of microclimate system. The USANRDEC vest is designed to provide chest, neck and back cooling via a hose and manifold system mounted on an open weave fabric (see Figure 1). The hoses are lightweight, crush-resistant and maintain a constant inside diameter upon bending. The air is distributed through the chest and back manifolds and holes in the hoses at a ratio of approximately 40% to the chest, 20% to the neck and 40% to the back. The ventilated facepiece (M25 CB mask) can be used without the vest. The vest side of the air connector is self-sealing when disconnected to prevent the entry of chemical agents. The inlet air flow is split by an air connector into 10 cfm to the vest and 3.5 cfm to the facepiece at 13.5



**Figure 1. Air-cooled vest developed by the US Army Natick Research
Development and Engineering Center, Natick, MA.**

cfm total air flow, and 14.5 cfm to the vest and 3.5 cfm to the facepiece at 18 cfm total flow. The air exits diffusely, primarily at the waist. The vest is worn over the undershirt and under the body armor and weighs 0.45 kg.

Cooling capacity of vest. Maximal theoretical cooling capacities of the vest when supplied with the four different air combinations are shown in Table 1. The maximal dry convective cooling capacity was calculated as the product of flow rate, density and specific heat of air, and gradient between inlet air temperature and an assumed skin temperature of 35°C. The evaporative cooling capacity was calculated as the product of flow rate, latent heat of evaporation of water at 35°C, and gradient between moisture content of inlet air and air saturated at an assumed skin temperature of 35°C.

Physiological measurements. Rectal temperatures were measured with thermistor probes, inserted approximately 10 cm beyond the anal sphincter. The electrocardiogram was obtained from chest electrodes (CM5 placement) and displayed on an oscilloscope and cardiometer unit. Total body sweating rates were calculated from pre- and post- test nude body weights, adjusted for water intake. Subjects were encouraged to drink water during the heat exposures. Since the M25 CB mask has no drinking tube, a plastic tubing "straw" was threaded under the hood and mask.

The test was terminated for any subject: whose rectal temperature reached 39.5°C, whose heart rate exceeded 180 b·min⁻¹ for five minutes continuously, who voluntarily withdrew, or who was removed at the discretion of the medical monitor or principal investigator.

Statistical analysis. A one-way repeated measures analysis of variance was used to compare endurance times among the four experimental (cooling combination) tests. Rectal temperatures and heart rate data at each metabolic rate were analyzed using two-way (time by cooling combination) repeated measures analyses of variance. For both the 175 and 315 W data, sweating rates were analyzed using one-way (cooling combination) repeated measures analyses of variance. Significance was accepted at the $p < 0.05$ level.

RESULTS AND DISCUSSION

This series of tests evaluated the effectiveness of an air-cooled vest in reducing thermal strain when supplied with four different combinations of dry bulb/dew point temperatures (db/dp) and air flow rate. Due to mechanical problems, the air conditioning system did not accurately deliver the desired db/dp temperatures. The air conditioning system was positioned in a separate room adjacent to the climatic chamber. Due to variations in this room's temperature, the dry bulb temperature of the air conditioner's output varied. The desired dew point temperatures were achieved on each test day. But, since the dry bulb temperatures were not on target, we decided to treat each test day as a separate vest condition (ie., F,G,H,I). The desired vest db/dp temperatures and the actual db/dp temperatures obtained are listed in Table 1. Vest condition F was on target and condition G was only 2 °C db below target. However, conditions H and I were 4 and 5°C db lower respectively than desired. Due to these lower db temperatures, the cooling capacity of combinations G, H and I were higher than desired.

Figure 2 presents the endurance times for the four cooling combination tests. At the low metabolic rate (175 W), between vest conditions H and I there were no significant differences in endurance time. All 6 test subjects completed the 300 min test with cooling combination H. Although only 5 subjects (Table 2) completed the entire test using combination I, the test subject who left at the end of the second rest period did so because of problems with his feet.

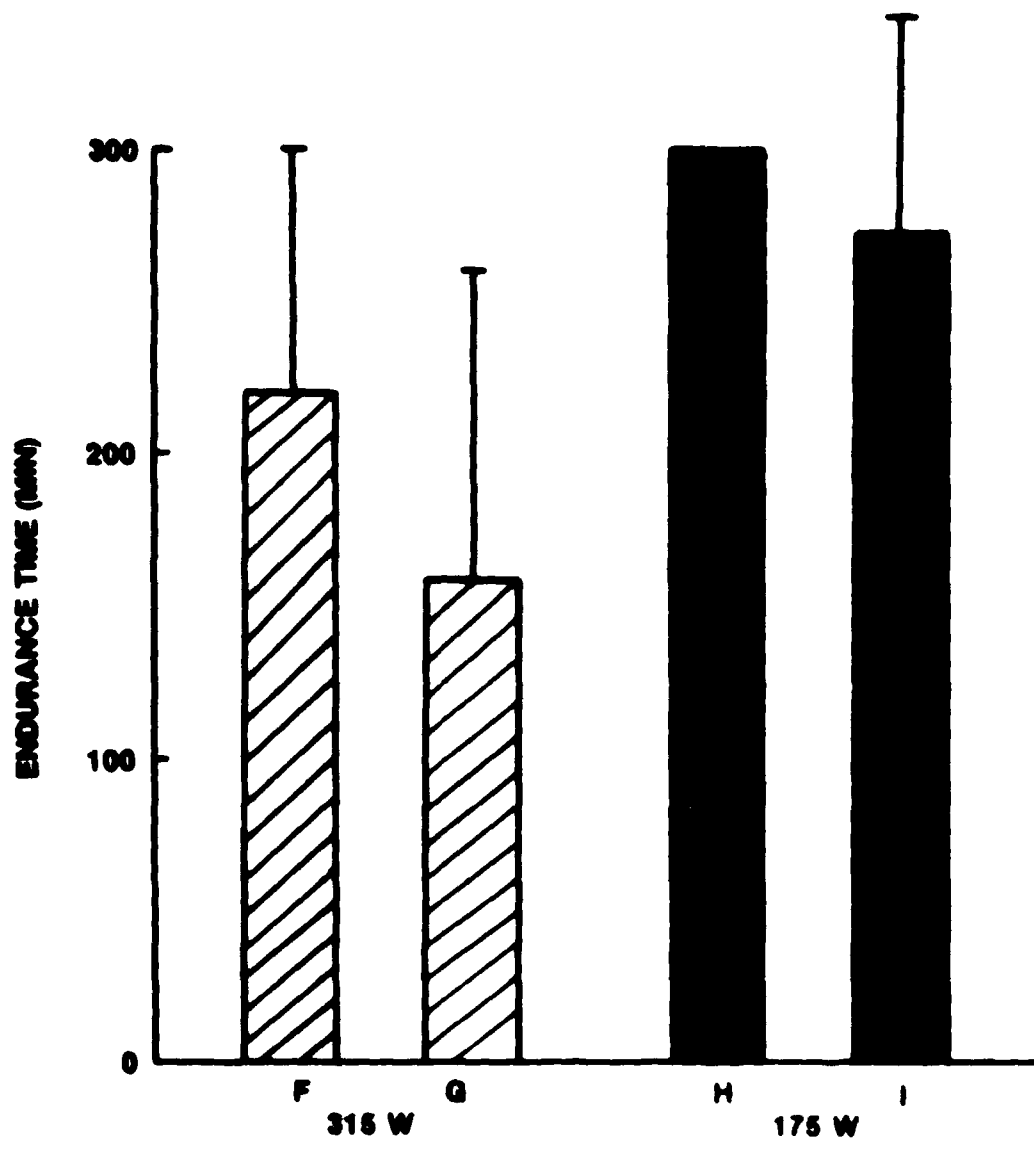


Figure 3. Endurance times (\bar{X} , \pm SD) for the four cooling vest conditions, 175 W and 315 W.

TABLE 2. NUMBER OF SUBJECTS COMPLETING EACH WORK/REST PERIOD.

COMBINATION	EX	REST	EX	REST	EX	REST	EX	REST	EX	REST
	1	1	2	2	3	3	4	4	5	5
F	6	6	6	5	4	4	3	3	2	-
G	4	4	3	3	2	2	2	2	-	-
H	6	6	6	6	6	6	6	6	6	6
I	6	6	6	6	5	5	5	5	5	5

NOTE: ONLY 5 SUBJECTS STARTED

Figure 3 illustrates the rectal temperature responses at the 175 W metabolic rate for cooling combinations H and I. After the second walk, the T_{re} did not increase significantly ($p > 0.05$) over time with either cooling condition. Rectal temperatures were higher ($p < 0.05$) at the end of each exercise bout than at the end of each subsequent rest period. However, vest combination H resulted in significantly ($p < .05$) higher T_{re} than I approximately 150 to 200 minutes into the exercise heat stress.

The mean heart rates during the 175 W tests are presented in Figure 4, for the end of the first and final exercise bouts (walk 1 and 5) and for the first and final rest periods (rest 1 and 5). Heart rates increased ($p < 0.05$) over time and were higher at the end of each exercise bout than at the end of each subsequent rest period. There were no significant differences in the heart rates between cooling combinations H and I during either the exercise bouts or rest periods.

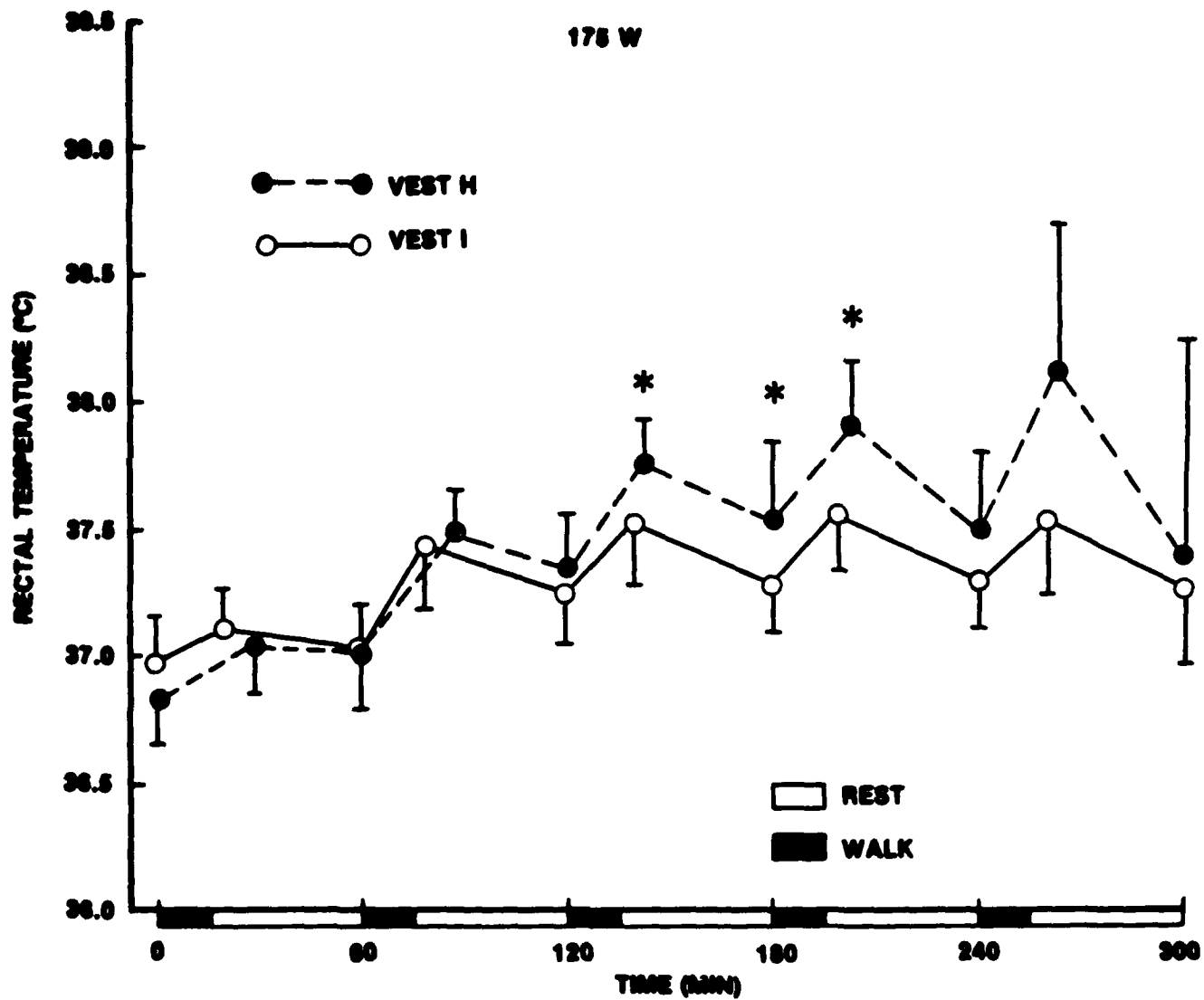


Figure 3. Mean rectal temperatures (\bar{X} , \pm SD) plotted across time for two cooling vest conditions, 175 W.

The sweating rates for the four cooling combinations are presented in Figure 5. At 175 W there were no significant differences in the sweating rates between cooling combinations H and I. The sweating rates ranged between 301-454 $\text{g}\cdot\text{m}^{-2}\cdot\text{h}^{-1}$ for combination H and 270-563 $\text{g}\cdot\text{m}^{-2}\cdot\text{h}^{-1}$ for combination I.

At the higher metabolic rate (315 W), between cooling combinations F and G there were no significant differences in endurance time (Figure 2). As shown in Table 2, no subjects were able to complete the 300 min heat exposure using either cooling combination F or G. During the test of combination G, one subject quit during the first walk due to a severe headache which may not have been associated with the exercise heat stress.

Figure 6 illustrates the rectal temperature responses at the 315 W metabolic rate for cooling combinations F and G. Rectal temperatures were higher ($p < 0.05$) at the end of each exercise bout compared to the end of the previous exercise bout. The T_{re} did not significantly drop during the short rest periods between walks. Vest combination F did result in lower ($p < 0.05$) T_{re} than G at the end of the second walk and rest periods. With both cooling combinations, prior to terminating the exercise heat stress the average T_{re} had exceeded 39.0°C.

The mean heart rates during the 315 W metabolic rate tests are presented in Figure 7, for the end of the first and fourth exercise bouts (walk 1 and 4) and for the first and fourth rest periods (rest 1 and 4).

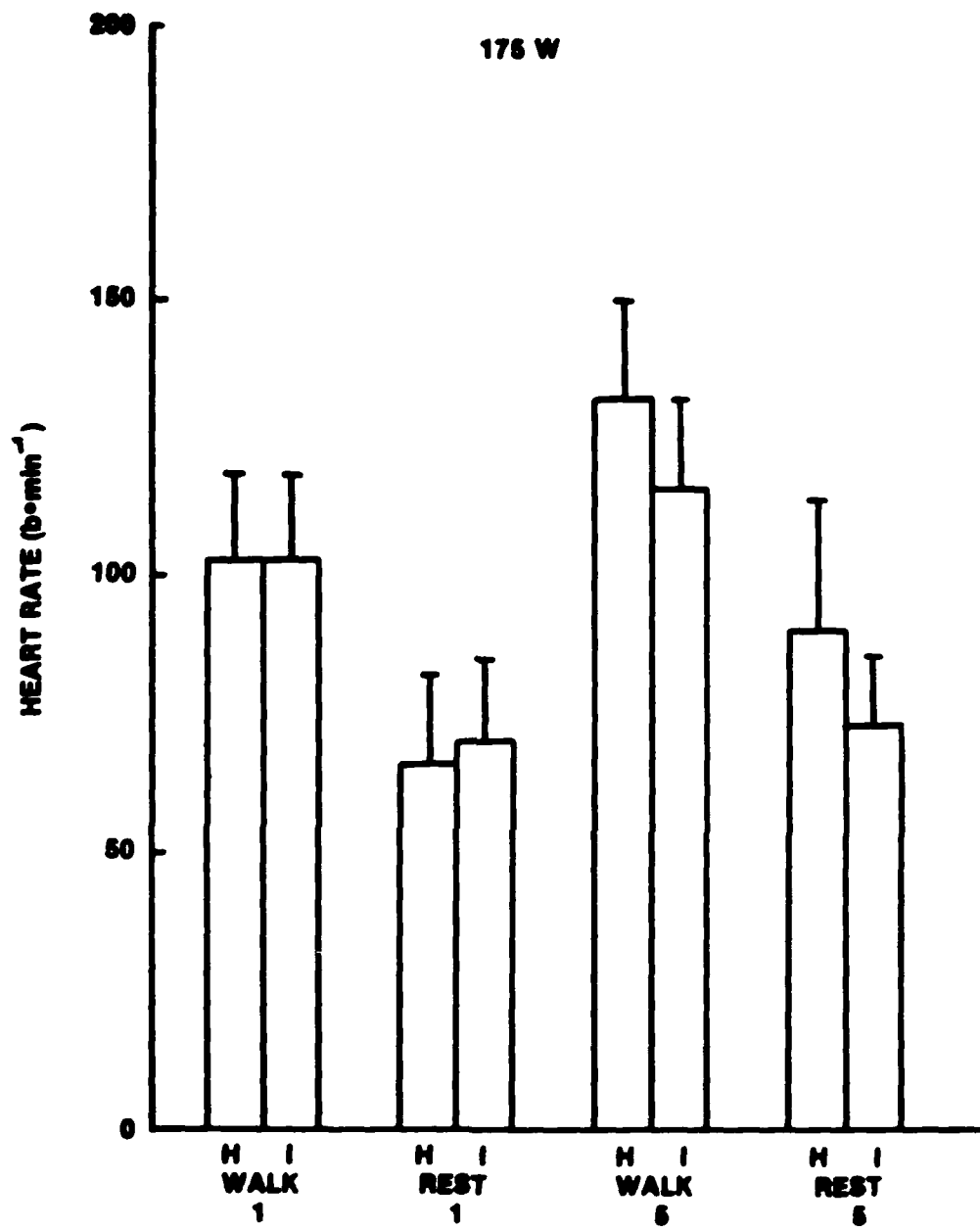


Figure 4. Heart rates (\bar{X} , \pm SD) at end of first and fifth exercise and rest periods for two cooling vest conditions, 175 W.

Heart rates increased ($p < 0.05$) over time and were higher at the end of each exercise bout than at the end of the subsequent rest period. During the exercise bouts at the 315 W metabolic rate, several subjects were removed from the climatic chamber due to heart rates exceeding $180 \text{ b} \cdot \text{min}^{-1}$ while testing cooling combinations F and G. There were no significant differences in the heart rates between cooling combinations F and G during either the exercise bouts or rest periods.

A significant difference occurred between cooling combinations F and G in the total body sweating rates. As presented in Figure 5, at the 315 W metabolic rate cooling combination F resulted in significantly lower ($p < 0.05$) sweating rates than combination G. The average sweating rates for combination F and G were 662 ± 113 and $842 \pm 136 \text{ g} \cdot \text{m}^{-2} \cdot \text{h}^{-1}$ respectively.

TABLE 3. COMPARISON OF COOLING POTENTIAL, MEAN ENDURANCE TIMES AND MEAN RECTAL TEMPERATURES.

COMBINATION*	POTENTIAL COOLING (W)	175 W		315 W	
		ENDURANCE (MIN)	T_{re}^{**} ($^{\circ}\text{C}$)	ENDURANCE (MIN)	T_{re}^{***} ($^{\circ}\text{C}$)
CONTROL	---	118	39.0	73	39.4
A	687	300	37.4	293	37.9
B	631	300	37.2	300	38.2
C	620	300	37.6	275	38.6
D	564	300	37.5	281	38.3
E	498	300	37.6	242	38.5
F	196	---	---	220	38.9
G	360	---	---	159	39.3
H	218	300	38.1	---	---
I	391	272	37.5	---	---

* DATA FOR CONTROL AND COMBINATIONS A-E FROM PIMENTAL ETAL. (8)

** END OF WALK 5

*** END OF WALK 4

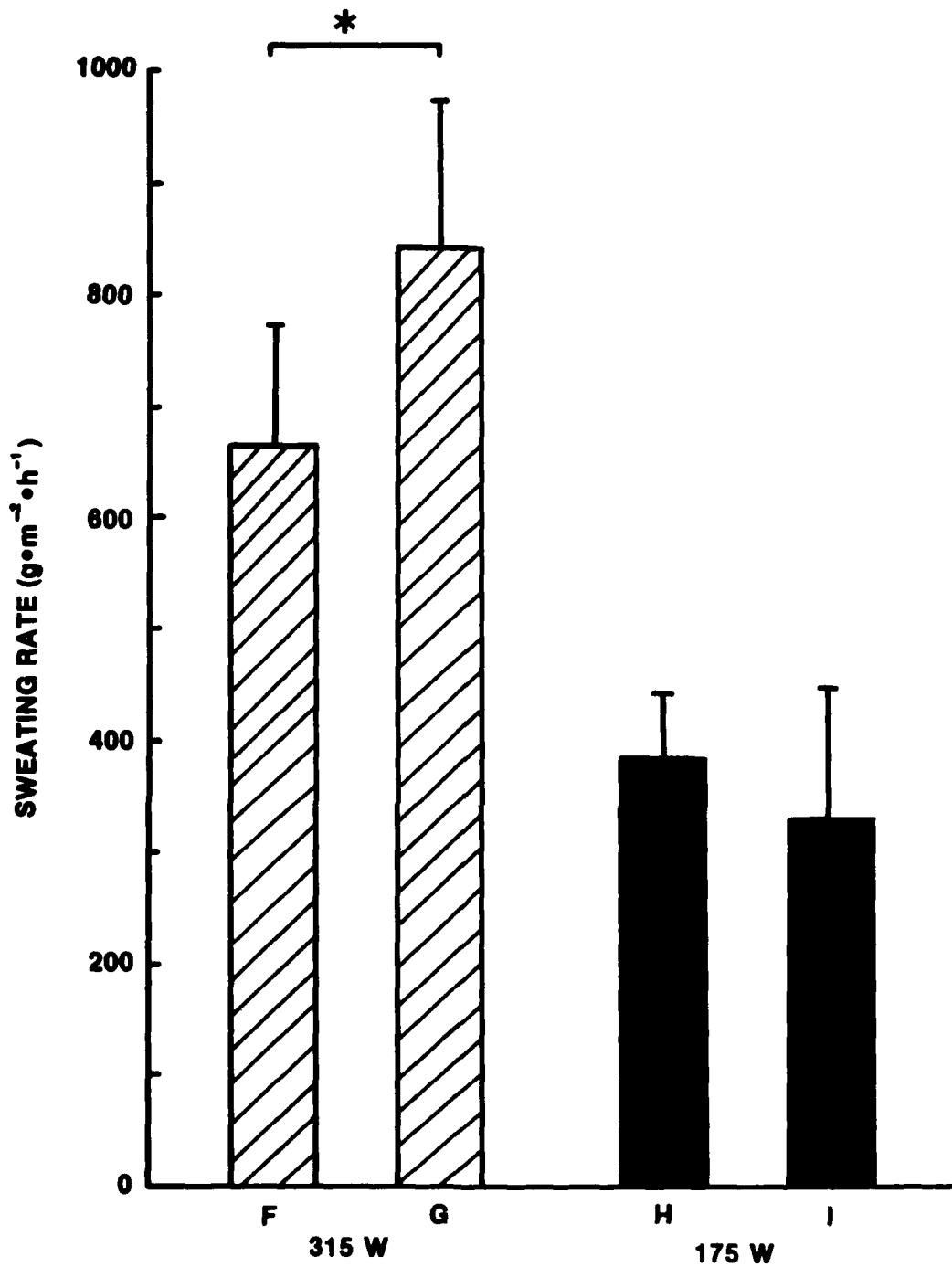


Figure 5. Sweating rates (\bar{X} , \pm SD) for the four cooling vest conditions, 175 W and 315 W.

This study evaluated the effectiveness of reducing thermal strain in soldiers by supplying an air-cooled vest with each of four different dry bulb and dew point temperatures and air flow rate combinations. The various air-cooled vest conditions tested reduced but did not prevent body heat storage. In Table 3, the cooling capacity, mean endurance times and mean rectal temperatures are presented for the control and five vest conditions tested by Pimental et al. (8) and the four vest conditions tested by us. The previous study (8), with identical environmental and exercise conditions, demonstrated that without auxiliary cooling endurance time at the 175 W metabolic rate was 118 ± 27 minutes. This demonstrated the intolerance of wearing protective clothing in hot environments to even short-term, light intensity work. In the current study, vest combinations H and I yield longer endurance times (300 ± 0 and 272 ± 68 min respectively) suggesting that these two combinations of air flow rate and db/dp temperatures were effective in reducing the thermal strain of the subjects. But vest condition H with the lower air flow rate was associated with a greater thermal strain than vest condition I. From Table 3 it can be seen that the potential cooling of vest condition H (218 W) was about 66% lower than vest condition A and B which previously (8) had demonstrated to be the most effective (physiologically) in reducing thermal strain. In actual use, the evaporative and convective cooling rates of the vests were both probably lower than the calculated maximal values. But, since we could not measure the dry bulb and dew point temperatures of the air leaving the vest, we cannot compute the actual cooling rates. It is possible that at the lower air flow rate (10 cfm) the vest was more

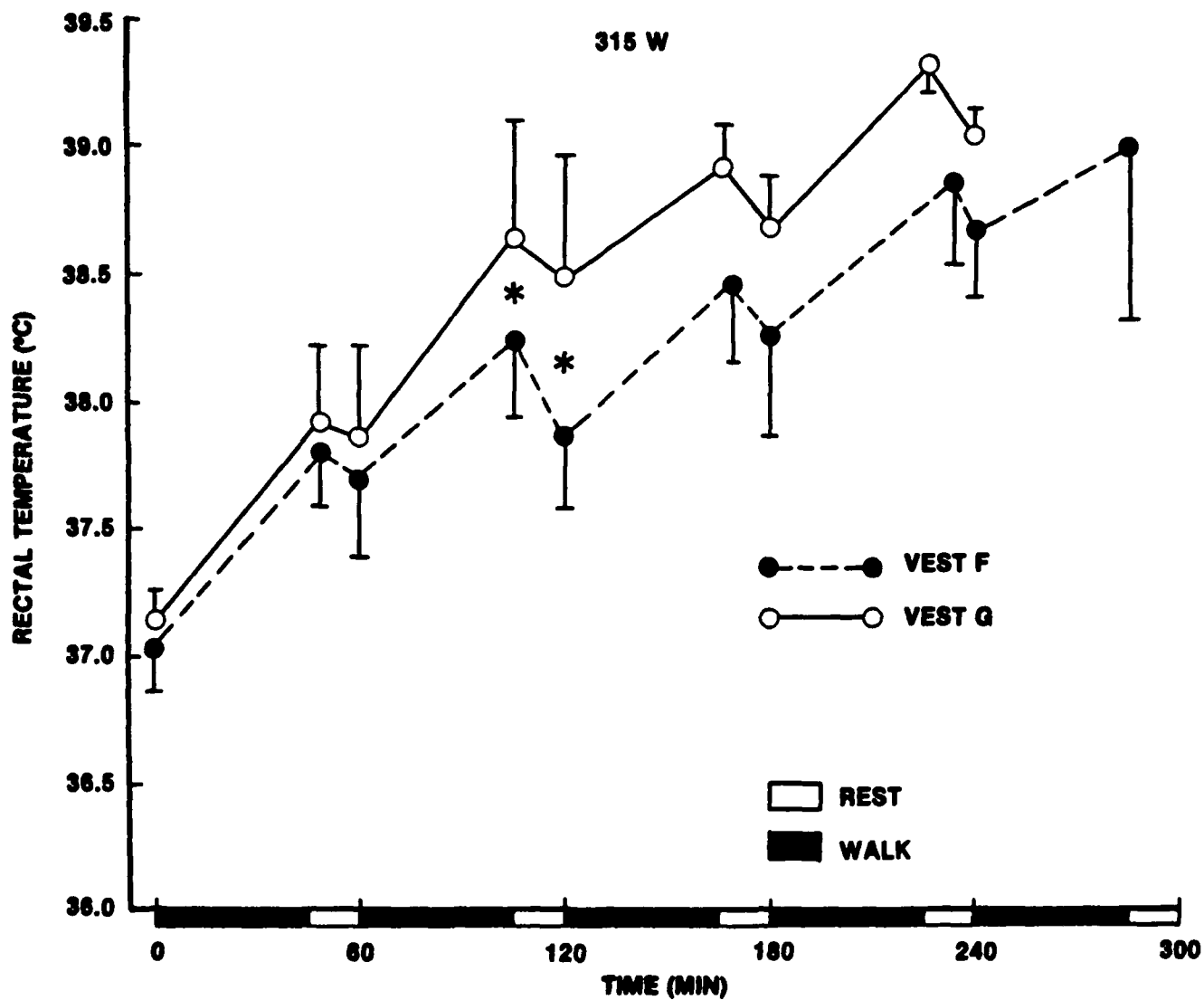


Figure 6. Mean rectal temperatures (\bar{X} , *SD) plotted across time for two cooling vest conditions, 315 W.

efficient. If the air flow past the skin is too high, the dry bulb and dew point temperatures of the air exiting the protective garment may not equilibrate with those of the skin. Lowering the air flow rate may, by increasing the transit time across the skin, have improved heat transfer thus making vest condition H effective in reducing the thermal strain of the subjects at the 175 W metabolic rate.

At the 315 W metabolic rate vest combinations F and G yield endurance times 2-3 fold longer than the previously reported control test (9) with no auxiliary cooling. However, the five previously tested cooling vest combinations (Table 3, combinations A, B, C, D and E) yield mean endurance times ranging from 242 to 300 minutes. In the present study, vest combination F had the longest endurance time, which was 220 ± 78 minutes. This is shorter than the previously reported values listed in Table 3. Furthermore, vest combination F was associated with a greater thermal strain (higher rectal temperatures and sweating rates) than the previously tested cooling vest combinations (8). It is important to note that none of our subjects were able to complete the 5 hour heat exposures, whereas in the previous study (8) subjects completed the heat exposures 70% of the time.

Compared to previous reported control tests using a ventilated facepiece only (8), use of the microclimate cooling vest combinations F, G, H and I reduced the sweating rates by an average of 39, 22, 48 and 55%

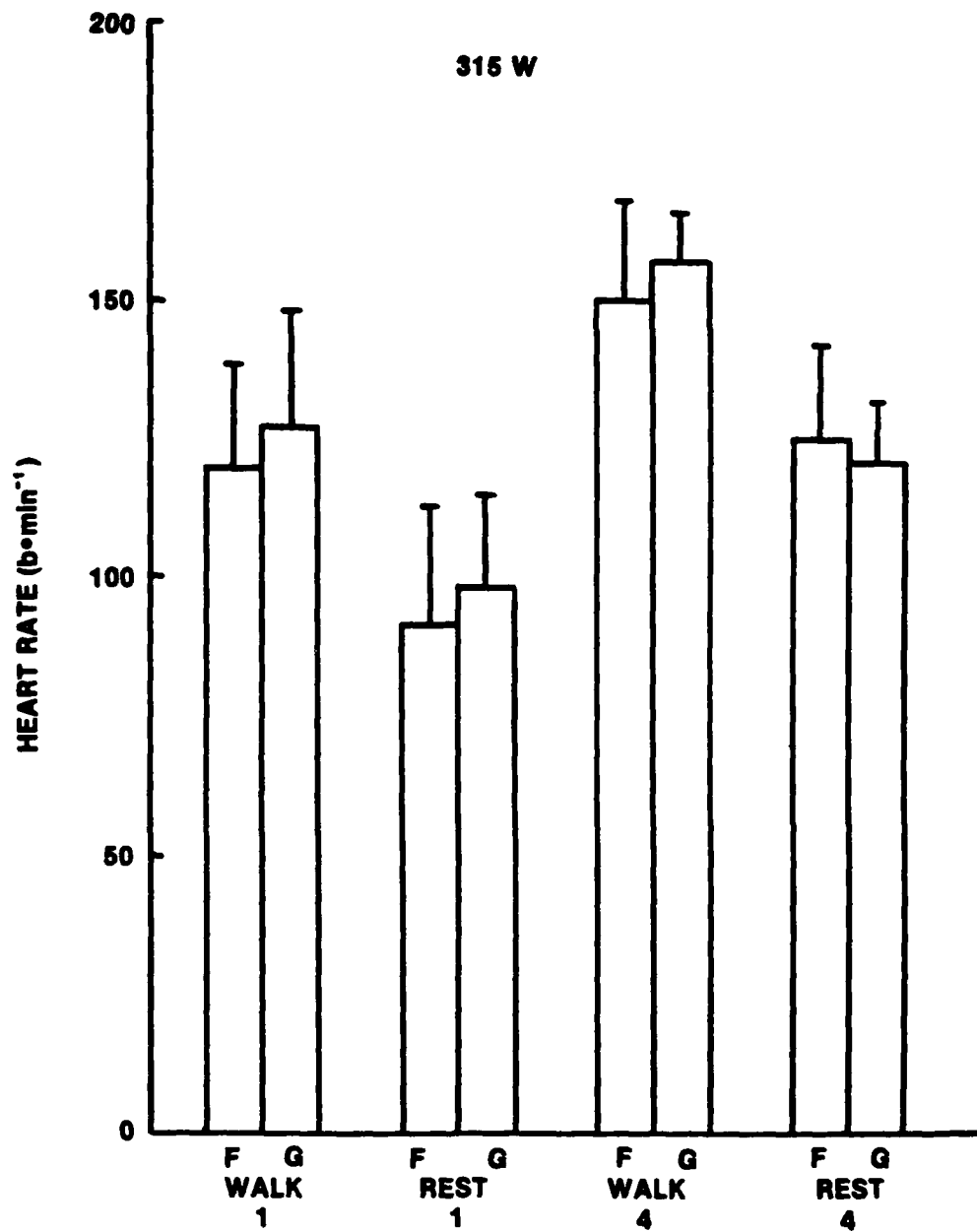


Figure 7. Heart rates (\bar{X} , \pm SD) at end of first and fourth exercise and rest periods for two cooling vest conditions, 315 W.

respectively. These sweating rate reductions represent significant water savings. A recent study (unpublished) conducted at our Institute observed nearly a 40% decrease in ad libitum water consumption during walking while wearing a M17A2 chemical protective mask equipped with a drinking tube. Therefore, microclimate cooling will help avoid dehydration which even at moderate levels will cause increased exercise heat storage (9). Additionally, logistic constraints may limit the supply of available drinking water making its conservation essential to sustain operations.

CONCLUSIONS

At the lower metabolic rate, combination H, which provided the 10 cfm air flow to the vest, would enable subjects working at 49°C db in protective clothing to thermoregulate at a relatively constant but elevated body temperature. Both cooling combinations H and I were effective in reducing thermal strain and extending endurance time at a 175 W metabolic rate. At the higher metabolic rate (315 W), typical of a tank commander or loader, vest combination F or G would extend endurance time, but would not be as effective in reducing thermal strain as the previously tested vest combinations.

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