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Mean skin temperature ( $T_{sk}$ ) was also significantly higher in women throughout the exposure. For both sexes, the 4th-h  $T_{re}$ , HR and  $T_{sk}$  were significantly higher than the preceding 3 h. No differences in total sweat rate ( $\dot{m}_{sw}$ ) or sweat sensitivity, as indicated by  $\dot{m}_{sw}/\Delta T_{re}$ , were evident. It was concluded that: (a) prolonged exposure to dry heat does not accentuate physiological differences between the sexes; (b) women are able to secrete sweat at rates comparable to men over a 4-h period; (c) 2-h acclimation sessions do not necessarily acclimate individuals for work of longer duration.

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**Physiological Responses of Men and Women  
to Prolonged Dry Heat Exposure**

**B. A. Avellini, Y. Shapiro, K. B. Pandolf, N.A. Pimental and R. F. Goldman**

**U.S. Army Research Institute of Environmental Medicine  
Natick, Massachusetts 01760**

**Running Head: Extended Heat Exposure: Men & Women**

**Mailing Address: B. A. Avellini, Ph.D.  
Military Ergonomics Division  
U.S. Army Research Institute of Environmental Medicine  
Natick, Massachusetts, 01760**

## Abstract

Heat-acclimated men ( $n = 10$ ) and women ( $n = 9$ ) were exposed to hot-dry conditions ( $49^{\circ}\text{C}$ , 20% rh) for 4 hours to determine the effect of prolonged work in the heat on physiological differences between the sexes. Hourly exposures consisted of 10 min resting and 50 min walking at  $1.34 \text{ m} \cdot \text{s}^{-1}$  (metabolic rate = 195 and  $170 \text{ W} \cdot \text{m}^{-2}$  for men and women, respectively). No significant difference in rectal temperature ( $T_{\text{re}}$ ) was found between the sexes for each hour (h) of exposure. Heart rate (HR) of women, however, averaged 10-17  $\text{beats} \cdot \text{min}^{-1}$  higher than men. Mean skin temperature ( $T_{\text{sk}}$ ) was also significantly higher in women throughout the exposure. For both sexes, the 4th-h  $T_{\text{re}}$ , HR and  $T_{\text{sk}}$  were significantly higher than the preceding 3 h. No differences in total sweat rate ( $\dot{m}_{\text{sw}}$ ) or sweat sensitivity, as indicated by  $\dot{m}_{\text{sw}}/\Delta T_{\text{re}}$ , were evident. It was concluded that: a) prolonged exposure to dry heat does not accentuate physiological differences between the sexes; b) women are able to secrete sweat at rates comparable to men over a 4-h period; c) 2-h acclimation sessions do not necessarily acclimate individuals for work of longer duration.

**Index Terms:** Sex differences in heat tolerance; physiological responses to heat; prolonged heat exposure.

The literature remains somewhat questionable as to whether or not females differ from males in their physiological responses to combined heat and physical work stress. While both sexes demonstrate the same qualitative responses when exposed to thermal stress, that is, increased body temperature, increased heart rate, increased body sweating, and increased blood flow to the periphery, there appear to be some quantitative differences between the responses of men and women. When first exposed to an acute heat stress, unacclimated and relatively unfit women have demonstrated higher heart rates (HR) and rectal temperatures ( $T_{re}$ ) and lower sweat rates ( $\dot{m}_{sw}$ ) than men (2, 3, 5, 6, 16). Following acclimation, however, both HR and  $T_{re}$  were similar in men and women while women still maintained lower rates of sweating (1, 6, 12, 16).

The often-documented lower sweat rate of women has been thought to be responsible for the poorer performance of women during acute heat exposures. However, observations have suggested that the lower  $\dot{m}_{sw}$  in women is evident more in humid than dry environments (8, 12) in which the limiting factor for achieving thermal balance is not the ability to secrete sweat. Rather, tolerance to humid heat is limited by a physical constraint on the ability to evaporate sufficient quantities of sweat needed to maintain thermoequilibrium. Hence their lower  $\dot{m}_{sw}$  should not affect women's ability to thermoregulate in humid environments. However, in hot, dry climates, in which the evaporative capacity of the environment is not a limiting factor to heat tolerance, a lower  $\dot{m}_{sw}$  could prove disadvantageous for women since the evaporation rate needed for attaining thermal equilibrium may not be achieved.

Most of the research that has been done comparing the responses of men and women in dry heat involved relatively short exposures (less than 2 hours). It would be expected that the physiological differences between the sexes would be

accentuated by increasing the duration of the exposure to the heat stress. In environments in which the rate of sweating could be the limiting factor to heat tolerance, a lower capacity for sweat output and/or a more rapid suppression of sweating would result in higher HR and body temperatures for the women over the course of the exposure. The purpose of this study therefore was to expose acclimated males and females to extended periods of work in dry heat to determine if physiological differences between the sexes would become more obvious.

### MATERIALS AND METHODS

Nine women and ten men, who were informed of experimental risk and subsequently gave their written consent to participate, served as subjects in this study during the early spring months. Both sexes were similar in age ( $21.1 \pm 0.6$  and  $22.0 \pm 1.0$  yr, for men and women respectively), while males were taller ( $178.6 \pm 2.1$  cm), heavier, ( $75.6 \pm 4.2$  kg) and had a higher body surface area ( $1.93 \pm .06$  m<sup>2</sup>) than did women ( $161.5 \pm 2.3$  cm,  $56.6 \pm 2.6$  kg, and  $1.59 \pm .04$  m<sup>2</sup>, respectively). As expected, women had a significantly higher percentage of body fat than men ( $29.6 \pm 1.5$  and  $17.7 \pm 1.6\%$ , respectively). The mean maximal oxygen consumption ( $\dot{V}O_2$  max) of  $52.3 \pm 2.2$  ml  $\cdot$  kg<sup>-1</sup>  $\cdot$  min<sup>-1</sup> for men was significantly higher than the  $\dot{V}O_2$  max of  $40.5 \pm 1.5$  ml  $\cdot$  kg<sup>-1</sup>  $\cdot$  min<sup>-1</sup> for the women.

Following preliminary measurements of anthropometric parameters and  $\dot{V}O_2$  max, all subjects were heat-acclimated for six consecutive days by walking on a level treadmill at  $1.34$  m  $\cdot$  s<sup>-1</sup> in an environmental chamber maintained at  $49^\circ\text{C}$   $T_{\text{db}}$ ,  $19.8^\circ$   $T_{\text{wb}}$  (20% rh),  $1$  m  $\cdot$  s<sup>-1</sup> wind speed. Exposure during acclimation lasted two hours with each hour consisting of 10 min rest, 50 min walk. After the criteria for heat-acclimation had been achieved (levelling off of

final daily  $T_{re}$  and HR), the subjects were exposed for four hours to the same environmental conditions and work-rest cycle.

Each subject was tested at the same time every day. During all heat exposures, both men and women were dressed in shorts, T-shirt, socks and tennis shoes. Initial values of  $T_{re}$ , HR, and mean skin temperature ( $T_{sk}$ ) were obtained during the first rest period. Rectal temperature was continuously monitored with a Y.S.I. thermistor probe inserted ~ 10 cm beyond the anal sphincter. Skin temperatures were measured with uncovered copper-constantan thermocouples attached to the skin at three sites: chest, calf, and forearm. Mean weighted skin temperature was calculated according to Burton (4). Both  $T_{sk}$  and  $T_{re}$  were recorded at 2-min intervals using an on-line system consisting of a Hewlett-Packard 9825A calculator and a 9862A Plotter. Heart rate was measured by radial artery palpation during each rest period and after each 25 min of walking. Total body sweat rate was determined from the changes in nude body weight measured on a K-120 Sauter precision electronic balance (accuracy of  $\pm 10$  g) before and after the heat exposure while evaporation rate was calculated as the change in clothed body weight. Adjustment was made for water ingested. Water intake was encouraged during all heat exposures. Two-minute expired air samples, for determination of rate of oxygen consumption, were collected in Douglas bags during the initial rest period and again at 50 min of each hour. The air samples were analyzed for  $O_2$  and  $CO_2$  content with an Applied Electrochemistry Model S-3A  $O_2$  Analyzer and Beckman LB-2 infrared  $CO_2$  Analyzer, respectively; and volume was measured in a Collins Spirometer and then corrected to STPD. Rates of heat exchange were calculated according to conventional formulae (7, 9).

Criteria for termination of any heat exposure were a HR of  $180 \text{ beats} \cdot \text{min}^{-1}$  during exercise and/or a  $T_{re}$  greater than  $39.5^{\circ}\text{C}$ ; or dizziness, nausea or dry skin.

Statistical Treatment: All variables, ( $T_{re}$ , HR,  $\dot{m}_{sw}$ , etc) were statistically evaluated with a mixed factorial analysis of variance. However, when the subjects were separated into subgroups, a one-way analysis of variance was utilized. Tukey's LSD procedure was used as a follow-up if significant F-values ( $P < 0.05$ ) were found.

## RESULTS

During heat acclimation, the mean final  $T_{re}$  dropped  $0.46^{\circ}\text{C}$  and  $0.70^{\circ}\text{C}$  for males and females, respectively, while mean final HR decreased  $30 \text{ beats} \cdot \text{min}^{-1}$  for females and  $27 \text{ beats} \cdot \text{min}^{-1}$  for males over the six days. The mean sweat rate, however, remained unchanged from day 1 to day 6 of acclimation in both men and women. There were no significant differences in the final HR or  $T_{re}$  for days 5 and 6 in either the males or females indicating that the subjects were successfully acclimated to the dry heat conditions for this two-hour period.

Oxygen consumption during rest or exercise for both males and females did not change significantly over the course of the four-hour exposure. The work rate reflecting the weighted time averages of all work (0.833) and rest (0.167) periods was similar for both sexes when expressed per kg of body weight ( $13.5$  and  $12.8 \text{ ml} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$  for the men and women, respectively). However, when the metabolic heat production was expressed as a function of body surface area, the males, due to their lower surface area-to-mass ratio, had a significantly higher weighted rate of metabolism ( $175$  and  $151 \text{ W} \cdot \text{m}^{-2}$  for males and females, respectively). During exercise in the heat, women were working at an average of  $36 \pm 1\%$  of their  $\dot{V}O_2 \text{ max}$  which was significantly higher than the relative work load of  $29 \pm 1\% \dot{V}O_2 \text{ max}$  for men.

Figure 1 demonstrates the time course of  $T_{re}$ , HR and  $T_{sk}$  responses for the men and women at the end of each hour of exposure. No significant differences in  $T_{re}$  were noted between men and women at any time period. The  $T_{re}$  values for each sex were the same at hours 1 and 2, indicating the individuals were in thermoequilibrium. It was found, however, that after the second hour in the heat, the  $T_{re}$  continued to rise until the end of the exposure for both sexes, with the fourth hour  $T_{re}$  being significantly greater than any of the other previous hours. From hour 2 until the end of the exposure, the  $T_{re}$  rose  $0.28^{\circ}\text{C}$  and  $0.31^{\circ}\text{C}$  in the females and males, respectively.

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INSERT FIGURE 1 HERE

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Heart rate showed the same response as body temperature, that is, reaching steady state after one hour and then rising again after two hours so that the fourth-hour value was significantly higher than any of the preceding hours. Unlike the  $T_{re}$  response, however, the females demonstrated significantly higher HR values than males at hours 2, 3, and 4, with the difference ranging from 10-17 beats  $\cdot$  min $^{-1}$ .

The  $T_{sk}$  was seen to increase gradually with time in the heat, with the fourth-hour value being significantly higher than the previous three hours. Except for the initial value, the females demonstrated significantly higher  $T_{sk}$  than males at each time period.

Both sexes lost similar percentages of their body weight over the four-hour exposure. For the males, the water deficit averaged 1.6% of body weight while

females lost 1.8% ( $p > 0.05$ ). Evaporation and sweat loss data averaged over the four-hour period are presented in Figure 2. The females were found to have a significantly lower rate of evaporative weight loss per unit surface area than did the males, with the men evaporating about 8% more sweat than the women. There was no significant difference in rates of sweating between the sexes, although the women tended to sweat about 7% less than the males. Despite their lower  $\dot{m}_{sw}$ , women demonstrated as sensitive a sweat mechanism to changes in body temperature as men (Figure 3). The similarity of  $\dot{m}_{sw}/\Delta T_{re}$  between the sexes was mainly a reflection of the smaller rise in  $T_{re}$  of women during the exposure. Similarly, women demonstrated the same evaporative cooling capacity per  $^{\circ}\text{C}$  change in  $T_{re}$  as men.

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INSERT FIGURES 2, 3 ABOUT HERE

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The rates of heat exchange, averaged for the four-hour exposure and expressed as  $\text{W} \cdot \text{m}^{-2}$ , are presented in Figure 4. The rate of heat gained by radiation and convection ( $R + C$ ) was constant throughout the four-hour exposure for each sex; but at each hour, females were found to have about a 7% lower heat gain by  $R + C$  than the males ( $p < 0.05$ ). Both sexes stored heat at the same rate over the course of the four hours ( $p > 0.05$ ), with the largest amount of heat accumulated during the first hour ( $p < 0.05$ ). The rate of heat storage declined during the second hour, only to rise again during hours 3 and 4. The rate of heat storage during the fourth hour was significantly higher than the second-hour value for both men and women.

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INSERT FIGURE 4 ABOUT HERE

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### DISCUSSION

The results of this study suggest that prolonged exposure to dry heat does not accentuate physiological differences between men and women. Women are able to secrete sweat at rates comparable to men over a four-hour period and hence can effectively produce sufficient evaporative cooling to prevent a larger rise in core temperature than men. There were, however, apparent sex-related differences in heart rate which were evident from the second hour to the end of the exposure (Figure 1). The magnitude of the difference in HR between males and females did not increase with duration of exposure. The higher HR of women could be explained by the fact that women were working at a significantly higher percentage of their aerobic capacity compared to men (36% compared to 29%  $\dot{V}O_2$  max). As HR levels off at a value relative to the individual's maximum capacity (11), it is not surprising that the females' HR would be higher than males when they were working at a metabolic rate which was the same for both sexes per kg body weight but which represented a higher relative thermal load for the women.

Since cardiorespiratory physical fitness apparently plays a role in explaining previously noted sex-related differences in response to hot environments (1, 10, 14), the subjects were divided into subgroups based on  $\dot{V}O_2$  max values (Table I). When the most fit females ( $\dot{V}O_2$  max =  $43.7 \text{ ml} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$ ) were compared to the least fit males ( $\dot{V}O_2$  max =  $46.3 \text{ ml} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$ ), both groups were found

to be working at similar relative work loads and subsequently demonstrated the same HR. This further supports the growing opinion that some of the previously-reported differences between men and women can be eliminated if account is made for differences in fitness levels between the two sexes. That is, when the same relative internal thermal stress is applied to both, there appear to be no sex-related physiological differences between men and women (1, 10, 14).

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INSERT TABLE I

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There were no qualitative differences in rates of heat exchange between the men and women (Figure 4). However, by virtue of their higher  $T_{sk}$  (Figure 1), women had a lower dry heat gain by  $R + C$  than did men. This, coupled with their lower rate of metabolic heat production, effectively gave the women a lower total heat load ( $M + R + C$ ) to be dissipated. Hence their rate of evaporative cooling was necessarily lower than that of men. But, since the women experienced a smaller change in  $T_{re}$  over the four hours ( $0.99^{\circ}\text{C}$  compared to  $1.10^{\circ}\text{C}$  for men), their evaporative cooling per unit change of body temperature was very similar to that found in men ( $502$  and  $487 \text{ g} \cdot \text{m}^{-2} \cdot \text{h}^{-1} \cdot ^{\circ}\text{C}^{-1}$  for men and women, respectively; see Figure 3).

A noteworthy point from this study was that the six consecutive exposures to dry heat for two hours per day apparently did not fully acclimate the subjects to the four-hour dry heat exposure. From the second hour to the fourth hour,  $T_{re}$  increased  $0.28^{\circ}\text{C}$  and  $0.31^{\circ}\text{C}$  in the females and males, respectively, while the HR rose by 18 and 20  $\text{beats} \cdot \text{min}^{-1}$ . In a previous study in which men and women were acclimated to humid heat for 10 consecutive days for four hours per

day (16), the  $T_{re}$  and HR of both sexes remained at the same level for the duration of the four hours during the tenth exposure. In a more recent study, men and women were acclimated to humid heat for two hours per day for 10 days, following which they were exposed to a humid heat stress for three hours (1). Similar to what was found in this present study, the  $T_{re}$  and HR, particularly in the males, continued to demonstrate a gradual increase after thermo-equilibrium had been established. It appears therefore that two-hour acclimation sessions do not acclimate individuals for work in the heat of much longer duration.

The increase in  $T_{re}$  and HR after two hours during the acute four-hour exposure may have been a consequence of the duration of the preceding acclimation period. While the six-day procedure appeared to acclimate the individuals to two-hour work bouts in the heat, as judged by the same final  $T_{re}$  and HR on days 5 and 6, subjects may not have actually been fully acclimated to these hot-dry conditions. The Human Sciences Laboratory in South Africa has demonstrated that the duration of the acclimation procedure is the determining factor as to whether or not thermoequilibrium can be maintained for prolonged periods of time (13, 15). They found that five- and seven-day acclimation procedures are inadequate for full acclimation to work under high environmental heat stress for more than two hours. Their data showed that when the acclimation procedure of daily four-hour work bouts in the heat was less than eight days, subjects appeared to be fully acclimated for two hours only. After two hours, core temperatures and heart rates were significantly higher than the values found at three and four hours of exposure on days 9 through 12 of acclimation. It is not known, however, whether an individual acclimated for two hours per day for eight days or more would be classified as fully acclimated for periods of work lasting up to 8 hours per day.

In summary, it appears that prolonged exposure does not enhance any sex-related physiological differences in response to dry heat exposure. Women can maintain sufficiently high sweat rates over four hours to reach and maintain thermoequilibrium. The apparently higher cardiovascular strain of women throughout the heat exposure, as evidenced by their higher HR, could have been attributed to the relatively higher thermal stress under which they worked at the same absolute work load. In addition, it appears that an acclimation procedure of two hours per day for six days does not fully acclimate an individual for longer periods of work in the heat.

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1. The views, opinions, and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy, or decision, unless so designated by other official documentation.

2. Human subjects participated in these studies after giving their free and informed voluntary consent. Investigators adhered to AR 70-25 and USAMRDC Regulation 70-25 of Use of Volunteers in Research.

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### Figure Legends

Fig. 1. Time course of rectal temperature ( $T_{re}$ ), heart rate (HR), and mean skin temperature ( $T_{sk}$ ) for the 4-h heat exposure.

Fig. 2. Average rates of sweating and evaporation for men and women for the 4-h exposure.

Fig. 3. Sweat sensitivity ( $\dot{m}_{sw}/\Delta T_{re}$ ) and evaporative cooling per unit change in rectal temperature for men and women over the 4-h exposure.

Fig. 4. Average rates of energy exchange for men and women over the 4-h exposure.

TABLE I. PHYSICAL FITNESS AND PHYSIOLOGICAL RESPONSES TO 4-HOUR HEAT EXPOSURE.

		4th-hour values					
n	$\dot{V}O_2$ max	% $\dot{V}O_2$ max	$T_{re}$	HR	$\bar{T}_{sk}$	$\dot{m}_{sw}$	
	$ml \cdot kg^{-1} \cdot min^{-1}$	%	$^{\circ}C$	beats $\cdot min^{-1}$	$^{\circ}C$	$g \cdot m^{-2} \cdot h^{-1}$	
<b>MOST FIT</b>							
Males	58.34 $\pm$ 1.69*	26.6 $\pm$ 1.0	38.21 $\pm$ 0.09	132 $\pm$ 6*	36.2 $\pm$ 0.3	518 $\pm$ 25	
Females	43.70 $\pm$ 1.26*†	32.9 $\pm$ 1.6*†	38.24 $\pm$ 0.10	145 $\pm$ 6*	36.8 $\pm$ 0.2	475 $\pm$ 11	
<b>LEAST FIT</b>							
Males	46.30 $\pm$ 0.58	31.3 $\pm$ 1.0	38.23 $\pm$ 0.08	144 $\pm$ 5	36.3 $\pm$ 0.3	514 $\pm$ 12	
Females	36.55 $\pm$ 1.12†	39.3 $\pm$ 0.6†	38.31 $\pm$ 0.16	154 $\pm$ 4	36.9 $\pm$ 0.1	493 $\pm$ 17	

\*Significant difference between fitness groups within sex ( $p < 0.05$ )

†Significantly different from males within fitness group ( $p < 0.05$ )





