Physiological tolerance to uncompensable heat stress: effects of exercise intensity, protective clothing, and climate

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Montain, Scott J., Michael N. Sawka, Bruce S. Cadarette, Mark D. Quigley, and James M. McKay. Physiological tolerance to uncompensable heat stress: effects of exercise intensity, protective clothing, and climate. *J. Appl. Physiol.* 77(1): 216–222, 1994.—This study determined the influence of exercise intensity, protective clothing level, and climate on physiological tolerance to uncompensable heat stress. It also compared the relationship between core temperature and the incidence of exhaustion from heat strain for persons wearing protective clothing to previously published data of unclothed persons during uncompensable heat stress. Seven heat-acclimated men attempted 180-min treadmill walks at metabolic rates of ~425 and 600 W while wearing full (clo = 1.5) or partial (clo = 1.3) protective clothing in both a desert (43°C dry bulb, 20% relative humidity, wind 2.2 m/s) and tropical (35°C dry bulb, 50% relative humidity, wind 2.2 m/s) climate. During these trials, the evaporative cooling required to maintain thermal balance exceeded the maximal evaporative capacity of the environment and core temperature continued to rise until exhaustion from heat strain occurred. Our findings concerning exhaustion from heat strain are *1)* full encapsulation in protective clothing reduces physiological tolerance as core temperature at exhaustion was lower ($P < 0.05$) in fully than in partially clothed persons, *2)* partial encapsulation results in physiological tolerance similar to that reported for unclothed persons, *3)* raising metabolic rate from 400 to 600 W does not alter physiological tolerance when subjects are fully clothed, and *4)* physiological tolerance is similar when subjects are wearing protective clothing in desert and tropical climates having the same wet bulb globe thermometer. These findings can improve occupational safety guidelines for human heat exposure, as they provide further evidence that the incidence of exhaustion from heat strain can be predicted from core temperature.

heat exhaustion; temperature regulation

FIREFIGHTERS, workers engaged in toxic cleanup, foundry workers, miners, and soldiers on the chemical-biological battlefield are exposed to uncompensable heat stress. This occurs when working in oppressively hot and/or humid areas (7, 22) or when working in protective clothing (13, 25). Uncompensable heat stress exists when the evaporative cooling requirement exceeds the environment's cooling capacity (2, 22). Under these conditions, individuals are unable to achieve thermal steady state and will continue to store heat until exhaustion occurs (23). Because uncompensable heat stress hinders job performance and can lead to exhaustion, it is important to understand the magnitude of physiological strain humans can tolerate and what factors modify tolerance to heat strain. Knowledge of such information will assist in improving occupational safety guidelines for human heat exposure (1, 20).

Although many studies have attempted to estimate exercise duration during heat stress (3–6, 10, 11, 17, 18) and to predict individual tolerance to heat strain (6, 10, 11, 26), there remains little information to predict the incidence of exhaustion from heat strain (7, 12, 23). This information is needed for mathematical models that predict the physiological responses and work capability during heat stress. Recently, we examined the physiological strain tolerated by unclothed persons during uncompensable heat stress (23). We found that exhaustion occurred over a broad range of core temperatures and that there was no threshold core temperature where exhaustion abruptly increased. We also proposed that core temperature might be a physiological index to estimate the incidence of exhaustion as the relationship between core temperature and the incidence of exhaustion was reproducible in a separate set of subjects (7). Additional studies need to determine whether these relationships are valid when subjects are wearing protective clothing during uncompensable heat stress. The low moisture permeability and high insulation properties of protective clothing might result in higher skin temperatures, more wetted skin, and greater subjective discomfort compared with when subjects are unclothed (23); these differences could reduce physiological tolerance to heat strain.

Our previous study also examined factors that modify physiological tolerance to heat strain (23). It was determined that hypohydration reduced and aerobic fitness level did not influence the core temperature when exhaustion from heat strain occurred. Other factors such as exercise intensity, clothing level, and climate could alter tolerance to heat strain. High-intensity compared with moderate-intensity exercise will result in a smaller cardiac reserve to support thermoregulation and, therefore, may decrease physiological tolerance to heat strain. Workers fully encapsulated in protective clothing will remove clothing when possible to improve heat loss. This practice might also improve physiological tolerance to heat strain. Whether exposing small areas of skin (i.e., removal of face mask and hood) will sufficiently reduce cutaneous venous compliance, reduce cardiovascular strain, and improve physiological tolerance has not been determined. Finally, because dry heat loss is the primary avenue for heat exchange when protective clothing is worn, persons might have greater tolerance when working in lower ambient temperatures at a given wet bulb globe thermometer (WBGT).

The purposes of this study were to *1)* examine the influence of exercise intensity, clothing level, and climate on physiological tolerance to heat strain and *2)* compare the relationship between core temperature and the incidence of exhaustion for persons wearing protective clothing to that published for unclothed persons during uncompensable heat stress. It was hypothesized that lowering exercise intensity, decreasing encapsulation level, and lowering ambient temperatures would each improve tolerance to heat strain during uncompensable heat stress. In addition, we hypothesized that full encapsulation would alter the usual relationship between physiological strain and the incidence of exhaustion.

METHODS

Subjects. Seven healthy male soldiers [age 21 ± 3 (SD) yr, body wt 80.1 ± 10.7 kg, body surface area 2.0 ± 0.2 m^2, and maximal oxygen uptake ($\dot{V}O_{2\,max}$) 52 ± 6 $ml \cdot kg^{-1} \cdot min^{-1}$] completed the experimental testing. Before participating they provided their voluntary and informed consent. The study had been approved by the appropriate Institutional Review Boards, and investigators adhered to AR 70–25 and US Army Research Institute of Environmental Medicine 70–25 on Use of Volunteers in Research.

Experimental protocol. Before experimental testing was completed, each subject's height, weight, subcutaneous skinfold thickness, and $\dot{V}O_{2\,max}$ were obtained. $\dot{V}O_{2\,max}$ was determined by a continuous effort treadmill test (23). On separate days, the treadmill speed and grade combinations to elicit metabolic rates of ~425 and 600 W were determined for each subject while he was fully and partially clothed in protective clothing. The fully clothed ensemble consisted of pants, coat, overboots, gloves, and face mask with hood [insulation (clo) = 1.5 and vapor permeability (im) = 0.33 at wind speed 2.2 m/s]. The partial clothing ensemble consisted of pants and coat (clo = 1.3 and im = 0.55 at wind speed 2.2 m/s).

The subjects then completed a 10-day heat acclimation program. Each day the subjects walked on a treadmill at 1.56 m/s at a 4% grade for 120 consecutive min in a hot dry environment (40°C, 20% relative humidity, wind speed 2.2 m/s) while wearing shorts, socks, and boots. The heat acclimation sessions were conducted at the same time of day, and subjects were allowed to drink ad libitum. This heat acclimation protocol resulted in similar final exercise rectal temperatures (T_{re}) and heart rate values during the last 3 days of acclimation. The subjects were also habituated to wearing a chemical protective mask and wore the mask continuously during the initial 60 min of exercise on *days 6–10* of heat acclimation.

Experimental testing consisted of eight trials; the first four trials were in a desert climate (43°C dry bulb, 20% relative humidity, wind speed 2.2 m/s, 29.9°C WBGT), and the last four trials were in a tropical climate (35°C dry bulb, 50% relative humidity, wind speed 2.2 m/s, 28.9°C WBGT). The two climates were matched for WBGT but had different ($P < 0.05$) evaporative heat capacities (Table 1). In each climate, the subjects attempted a 180-min treadmill walk at metabolic rates of ~425 and 600 W while wearing partial or full clothing ensembles. The trial order was counterbalanced across subjects. The trials were conducted on weekday mornings with ~45 h of recovery between tests. An experimental trial was terminated when a subject completed 180 min of exercise, a subject achieved the predetermined endpoint criteria for T_{re} (40°C) or heart rate (95% maximal heart rate), or physiological symptoms forced the subject to discontinue exercise. Subjects were considered exhausted from heat strain if they discontinued exercise due to impending syncope, ataxia, headache, and/or disorientation. Subjects ingested 300 ml of water on arrival to the laboratory and 300 ml every 20 min throughout exercise to minimize effects of dehydration by providing sufficient fluid to prevent loss of >2% body weight during exercise. The rate of fluid replacement was determined from the equation of Shapiro et al. (24).

Electrocardiographic activity was continuously monitored with chest electrodes (CM5 placement) and radiotelemetered to an oscilloscope-cardiotachometer unit (Hewlett-Packard). During the $\dot{V}O_{2\,max}$ tests, an automated system (Sensormedics 2900) was used to measure oxygen uptake. During the experimental trials in the heat, expired air was collected in 150-liter Douglas bags for 2 min at 15 min of exercise to measure caloric expenditure. The volume of expired gases was measured with a Tissot gasometer, and oxygen and carbon dioxide concentrations were measured with an electrochemical oxygen analyzer (Applied Electrochemistry S 3-A) and an infrared carbon dioxide analyzer (Beckman LB-2), respectively. T_{re} was obtained from a thermistor inserted ~10 cm beyond the anal sphincter. Skin temperatures (T_{sk}) were obtained with a four-point thermocouple skin harness (chest, arm, thigh, and calf), and mean $\bar{T}_{sk}$ was calculated (21). The change in mean body temperature ($\bar{T}_b$) was calculated every 10 min of exercise by using a 9:1 weighting for T_{re} and $\bar{T}_{sk}$, respectively. Body weights were determined on a K-120 Sauter electronic balance (accuracy ±10 g). Total body sweating rates were calculated from nude body weight loss adjusted for water intake and urine output. Required evaporative cooling and evaporative capacity were calculated with the formulas of Gagge and Nishi (8) and modified by Kraning and Gonzalez (13). Sweat evaporation was not calculated because any sweat dripping from the uniform would result in overestimation of sweat evaporation.

Statistical analysis. Physiological responses at exhaustion from heat strain were analyzed by a two-way analysis of variance with repeated measures for the independent variables of clothing level with environment and exercise intensity with environment. Tukey's post hoc test was performed when statistical differences between means were found ($P < 0.05$). Data are presented as means ± SD.

RESULTS

The moderate- and high-intensity exercise elicited metabolic rates of 421 ± 41 and 595 ± 50 W ($P < 0.05$) and oxygen uptakes of 16 ± 2 and 22 ± 3 $ml \cdot kg^{-1} \cdot min^{-1}$ or 30 ± 4 and 43 ± 7% $\dot{V}O_{2\,max}$, respectively. Many subjects (9 of 14 trials) completed 180 min of exercise when wearing partial clothing during moderate-intensity exercise. Of the five trials that were not completed, one was terminated due to exhaustion from heat strain, two were because of orthopedic problems, one was because of illness, and one was because of technical problems. During the partial clothing moderate-intensity trials, final T_{re} and heart rate were 38.2 ± 0.5°C and 142 ± 19 beats/min, respectively. Because exhaustion from heat strain did not occur during the partial moderate trials, they are not discussed further. Exhaustion from heat strain occurred in 38 of the 42 remaining trials. Of the four trials that did not result in exhaustion from heat strain, three were discontinued because of orthopedic problems and one was stopped because T_{re} rose to 40.0°C. This latter trial was included in the statistical analysis as the data were a conservative estimate of this subject's ability to tolerate heat strain.

Exercise intensity. Tables 1 and 2 present data for moderate- and high-intensity exercise experiments when subjects were dressed in full clothing. Mean body temperature rose more rapidly ($P < 0.05$) during high-intensity than during moderate-intensity exercise. Sweating rates were lower ($P < 0.05$; 26 ± 6 vs. 33 ± 6 g/min) during moderate- than during high-intensity exercise. However,

TABLE 1. *Partition of heat transfer while wearing full or partial protective clothing during moderate- and high-intensity exercise in desert and tropical climates*

Variable	Full Clothing		Partial Clothing	
	Moderate intensity	High intensity	Moderate intensity	High intensity
	Desert climate (43°C db, 20% rh, wind 2.2 m/s)			
$\Delta\bar{T}_b$, °C/10 min	0.31±0.06	0.47±0.11	0.11±0.03	0.26±0.08
Sweating rate, g/min	27±7	33±7	18±5	26±4
R + C, W/m²	37±2	37±2	47±2	47±2
E_{req}, W/m²	254±18	324±22	249±11	316±17
E_{max}, W/m²	131±4	132±4	262±7	265±6
HSI, %	195±13	248±18	95±5	119±6
	Tropical climate (35°C db, 50% rh, wind 2.2 m/s)			
$\Delta\bar{T}_b$, °C/10 min	0.24±0.03	0.44±0.11	0.08±0.02	0.22±0.07
Sweating rate, g/min	26±5	33±6	18±4	27±3
R + C, W/m²	−5±2	−6±3	−4±1	−6±3
E_{req}, W/m²	211±15	274±31	191±15	258±25
E_{max}, W/m²	94±3	96±5	183±2	193±8
HSI, %	226±19	288±36	105±8	134±13

Values are means ± SD; $n = 7$ men. $\Delta\bar{T}_b$, change in mean body temperature; R + C, radiation and convective heat loss; E_{req}, evaporation required for heat balance; E_{max}, maximal evaporative capacity; HSI, heat strain index = $E_{req} \cdot E_{max}^{-1} \cdot 100$; db, dry bulb; rh, relative humidity.

because of the greater exercise duration during moderate-intensity exercise ($P < 0.05$; 75 ± 19 vs. 46 ± 11 min), the magnitude of dehydration was similar between the two exercise intensities (0.9 ± 0.4 vs. 0.9 ± 0.5% body wt loss for moderate- and high-intensity exercise, respectively).

Exhaustion occurred at a similar T_{re} and T_{sk} during the moderate- and high-intensity exercise trials. Heart rate at exhaustion was higher ($P < 0.05$) during high-intensity than during moderate-intensity exercise (176 ± 14 vs. 163 ± 10 beats/min). Figure 1 presents the effect of exercise intensity on the cumulative incidence of exhaustion from heat strain. During moderate exercise in full clothing, 25, 50, and 75% of the persons were exhausted at a T_{re} of 38.2, 38.8, and 39.0°C, respectively, and at a heart rate of 154, 165, and 170 beats/min, respectively. During high-intensity exercise in full clothing, 25, 50, and 75% of the persons were exhausted at a T_{re} of 38.1, 38.6, and 38.8°C, respectively, and at a heart rate of 166, 176, and 185 beats/min, respectively.

Clothing level. Tables 1 and 3 present data for the effects of clothing level. $\bar{T}_b$ rose faster ($P < 0.05$) when subjects were fully clothed than when they were partially clothed during high-intensity exercise, whereas sweating rates were 33 ± 6 and 27 ± 4 g/min, respectively ($P < 0.05$). Wearing partial clothing resulted in longer exercise time compared with full clothing ($P < 0.05$; 95 ± 27 vs. 46 ± 11 min). Percent body weight loss at exhaustion was higher ($P < 0.05$) when subjects were in partial than in full clothing (1.4 ± 0.5 and 0.9 ± 0.5%, respectively).

T_{re} was higher ($P < 0.05$) and T_{sk} and heart rate were lower ($P < 0.05$) at exhaustion when subjects were wearing partial compared with full clothing. Figure 2 presents the effect of clothing level on the cumulative incidence of exhaustion from heat strain during high-intensity exercise. When wearing full clothing, 25, 50, and 75% of the persons were exhausted at a T_{re} of 38.1, 38.6, and 38.8°C and at a heart rate of 166, 176, and 185 beats/min, respectively. When subjects wore partial clothing, 25, 50, and 75% of the persons were exhausted at a T_{re} of 38.5, 38.8, and 39.2°C and at a heart rate of 166, 169, and 173 beats/min, respectively.

Climate. Tables 1–3 present the effects of climate on the change in $\bar{T}_b$, sweating rate, T_{re}, mean T_{sk}, heart rate, and exercise time. The desert climate resulted in a slightly faster ($P < 0.05$) increase in $\bar{T}_b$ compared with the tropical climate, despite similar sweating rates with each combination of clothing and exercise intensity (Table 1). Exercise time was similar when subjects were fully clothed during high-intensity exercise (Table 3) but was longer ($P < 0.05$) when subjects were fully clothed during moderate-intensity exercise in the tropical compared with the desert climate (Table 2). At exhaustion, T_{re} was similar in both climates but T_{sk} and heart rate were higher ($P < 0.05$) in the desert than in the tropical climate.

TABLE 2. *Rectal and mean skin temperatures, heart rate, and exercise time at exhaustion from heat strain when fully clothed during moderate- and high-intensity exercise in a desert or tropical climate*

Variable	Moderate Intensity-Desert	Moderate Intensity-Tropical	High Intensity-Desert	High Intensity-Tropical	Moderate vs. High Intensity	Desert vs. Tropical	Interaction
Rectal temperature, °C	38.6±0.4	38.7±0.5	38.5±0.6	38.5±0.5	NS	NS	NS
Mean skin temperature, °C	37.4±0.5	36.7±0.3	37.5±0.5	37.1±0.5	NS	$P < 0.01$	NS
Heart rate, beats/min	166±11	160±9	178±13	173±14	$P < 0.01$	$P < 0.03$	NS
Exercise time, min	66±14	85±20	46±11	46±11	$P < 0.01$	$P < 0.02$	$P < 0.04$

Values are means ± SD; $n = 7$ men except for moderate intensity-tropical ($n = 6$).

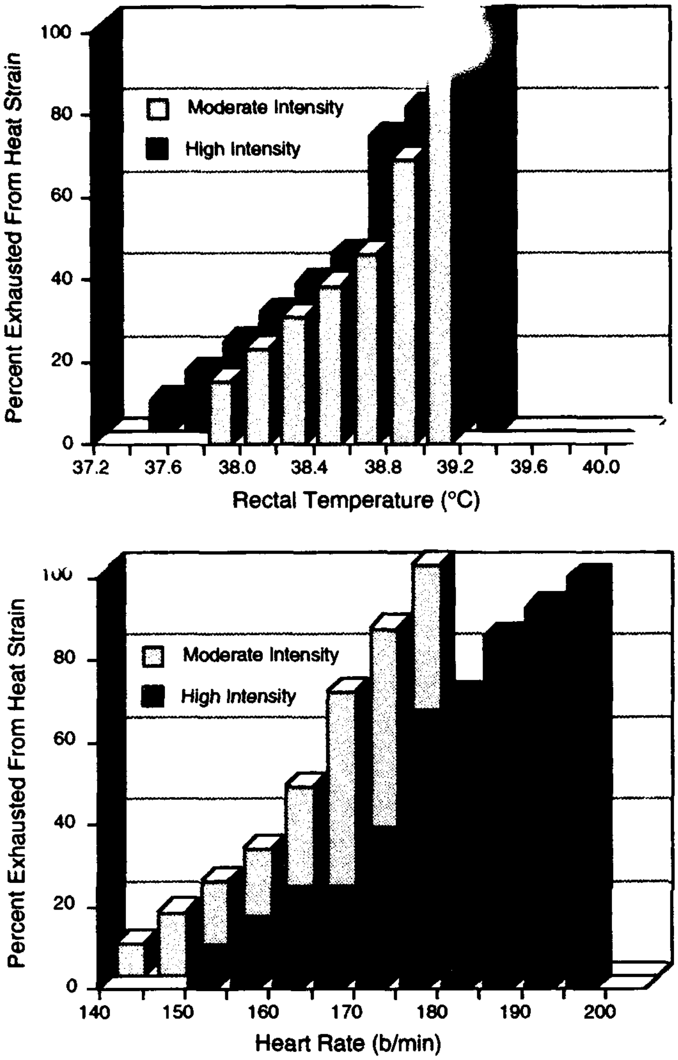

FIG. 1. Influence of exercise intensity (moderate, 13 trials; high, 14 trials) on incidence of exhaustion from heat strain relative to rectal temperature and heart rate at exhaustion when wearing full protective clothing in tropical and desert climate. b/min, Beats/min.

Validity. Figure 3 compares this study's incidence of exhaustion from heat strain to the studies of Eichna et al. (7) and Sawka et al. (23) for unclothed persons. The combined results of these studies show that 25, 50, and 75% of subjects were exhausted at a T_{re} of 38.5, 38.8, and 39.1°C, respectively. Our data for persons wearing full clothing (combined from moderate- and high-intensity trials) indicate that 25, 50, and 75% of the subjects were exhausted at a T_{re} of 38.2, 38.6, and 38.9°C, respectively. Therefore, it appears that wearing full clothing lowers T_{re} quartiles by 0.2–0.3°C. Wearing partial clothing resulted in T_{re} quartiles nearly identical to those of the studies using unclothed subjects, as 25, 50, and 75% were exhausted at a T_{re} of 38.5, 38.8, and 39.2°C, respectively. However, unlike for unclothed persons, wearing partial clothing produced a rightward shift in the relationship between exhaustion and core temperature below the 25th and above the 75th percentile of T_{re}.

DISCUSSION

This study is the first to examine in the same subjects the effects of exercise intensity, clothing level, and climate on the limits of physiological strain a person can tolerate during uncompensable heat stress. This was accomplished by having the subjects exercise to volitional exhaustion on repeated occasions while the exercise intensity, clothing level, and climate were varied. Metabolic rates were selected to represent moderate and heavy exercise for soldiers wearing chemical protective clothing during military operations (20); in addition, the rates are within the range of metabolic rates reported for toxic cleanup (14) and firefighting (16) activities performed in protective clothing. The climatic conditions are common tropical and desert climates that maximize differences (8°C) in dry bulb temperature and yet are matched for WBGT. Neither of these climates alone is an uncompensable heat stress condition, but wearing protective clothing and performing exercise can create uncompensable heat stress conditions (see Table 1). The full and partial clothing levels represent the military mission-oriented protective posture protective clothing levels 1 and 4, which are employed in anticipation of chemical agent exposure and presence of chemical agent, respectively.

This study found that full protective clothing reduced the physiological strain a person can tolerate during uncompensable heat stress. Numerous studies have examined the impact of wearing protective clothing on thermoregulation and exercise tolerance time (13, 14, 17, 18, 25–27). However, these studies did not determine whether clothing affected the ability of the person to tolerate heat strain. We found that the wearing of full clothing lowered the core temperature at exhaustion compared with the wearing of partial clothing. Exposure of only the face, neck, and hands by using partial clothing increased the average core temperature at exhaustion to 38.8°C, which is very similar to the mean core temperature at exhaustion reported for unclothed subjects during

TABLE 3. *Rectal and mean skin temperatures, heart rate, and exercise time at exhaustion from heat strain when partially and fully clothed in a desert or tropic climate during high-intensity exercise*

Variable	Partial Clothing-Desert	Partial Clothing-Tropical	Full Clothing-Desert	Full Clothing-Tropical	Partial vs. Full Clothing	Desert vs. Tropical	Interaction
Rectal temperature, °C	39.1±0.6	38.8±0.6	38.5±0.6	38.5±0.5	$P < 0.03$	NS	NS
Mean skin temperature, °C	37.0±0.7	36.6±0.7	37.5±0.5	37.1±0.5	$P < 0.03$	$P < 0.02$	NS
Heart rate, beats/min	171±8	167±4	178±13	173±14	$P < 0.02$	$P < 0.02$	NS
Exercise time, min	100±27	88±28	46±11	46±11	$P < 0.01$	NS	NS

Values are means ± SD; $n = 7$ men except during partial clothing-tropical ($n = 5$).

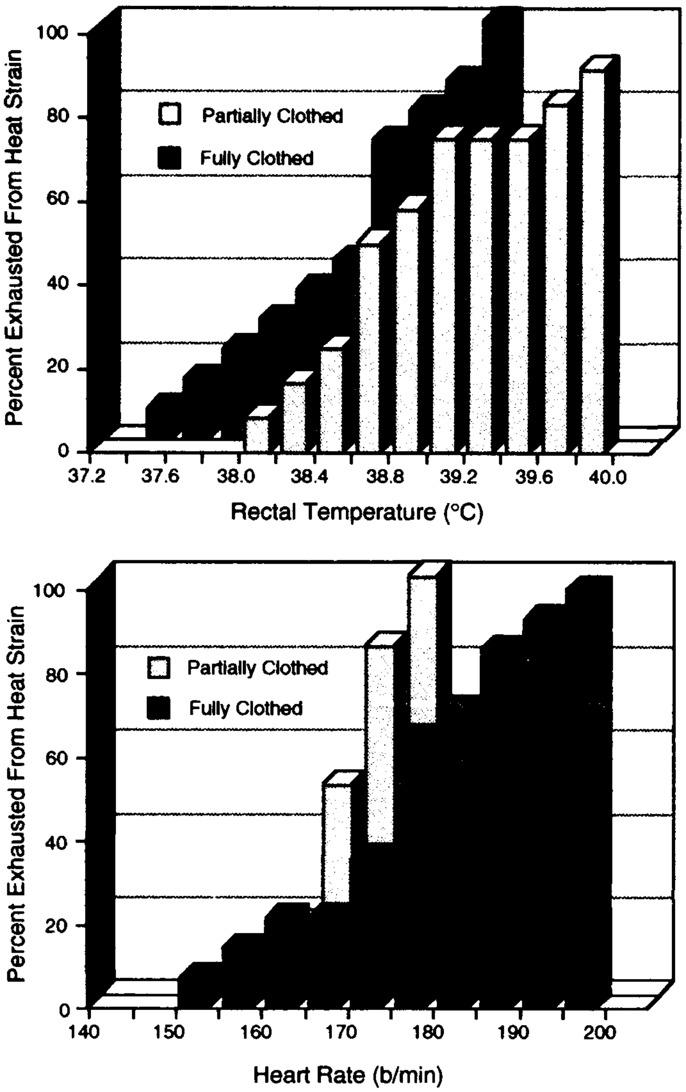

FIG. 2. Influence of protective clothing level (partial, 12 trials; full, 14 trials) on incidence of exhaustion from heat strain relative to rectal temperature and heart rate at exhaustion when performing high-intensity exercise (~600 W) in tropical and desert climate.

uncompensable heat stress (5–7, 15, 23). The use of partial clothing also resulted in a similar incidence of exhaustion from heat strain at a given core temperature when compared with values from unclothed persons during uncompensable heat stress (see Fig. 3; 25, 50, and 75th percentile nearly identical). Although there is some indication that our subjects may have been more tolerant to heat strain than the subjects from the studies of Sawka et al. (23) and Eichna et al. (7) based on the lower incidence of exhaustion at low and high T_{re} (below the 25th and above the 75th percentile), it is likely that this is due to the limited sample size in the studies and the large interindividual tolerance to heat strain (3, 5). Finding that 25, 50, and 75% of persons wearing partial clothing were exhausted at core temperatures similar to the other studies suggests that there is a reproducible relationship between the incidence of exhaustion and core temperature and that algorithms can be developed to predict the incidence of exhaustion from core temperature.

The present study found that heart rates at exhaustion were influenced by the exercise intensity, clothing level, and climate. One explanation for the variable heart rate responses may be $\bar{T}_{sk}$. Heart rates at exhaustion were elevated whenever exercise intensity, clothing level, or climate independently elevated $\bar{T}_{sk}$. A high $\bar{T}_{sk}$ could increase cardiovascular strain and heart rate as a consequence of increased skin blood volume. It is unlikely that exhaustion occurred during moderate-intensity exercise due to muscle fatigue rather than physiological strain due to incompensable heat stress, as there were no complaints of muscle fatigue and the exercise intensity elicited only 31% of $\dot{V}O_{2\,max}$. Under conditions of compensable heat stress, subjects would be able to exercise much longer than 100 min before exhaustion at this exercise intensity. In addition, during moderate-intensity exercise in the desert and tropical climates, the heart rates at exhaustion were 46 ± 16 and 54 ± 10 beats/min higher than the 10-min exercise value, respectively, indicating substantial cardiovascular strain during the exercise periods. Regardless of the reason for the variable heart rates at exhaustion, the current results and other research (15, 23, 25) clearly demonstrate that heart rate alone is an inadequate variable for modeling the incidence of exhaustion during uncompensable heat stress.

The lower physiological tolerance of subjects while wearing full clothing was possibly due to cardiovascular instability accompanying cutaneous vasodilatation and increased venous compliance. Covering the head, neck, and hands removed 12% of the surface area available for evaporative cooling (9) and reduced evaporative capacity by ~132 and ~97 W/m^2 in the desert and tropical climates, respectively. This lower evaporative cooling capability resulted in a ~0.4°C higher $\bar{T}_{sk}$, which likely increased cutaneous compliance and reduced central blood volume, cardiac filling, and mean arterial pressure. Another possibility for the lower physiological tolerance of subjects while fully clothed, however, is that encapsulat-

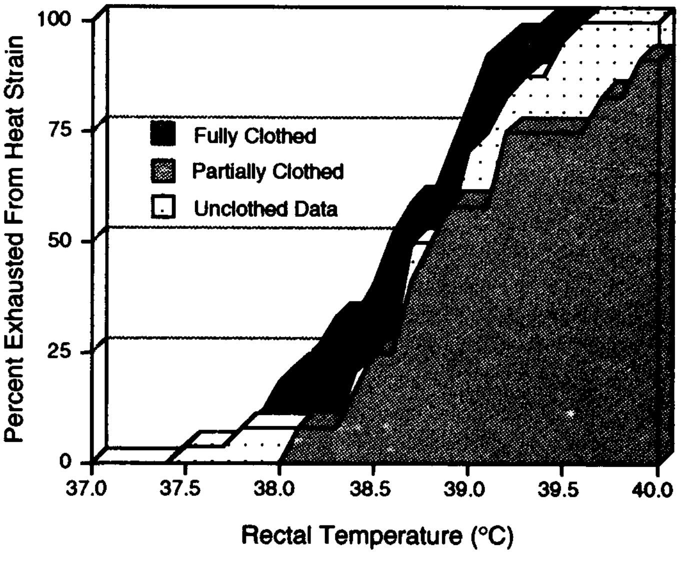

FIG. 3. Comparison of incidence of exhaustion from heat strain relative to rectal temperature at exhaustion when subjects were wearing full (n = 28 trials) and partial clothing (n = 12 trials) during high-intensity exercise (~600 W) and when they were unclothed during uncompensable heat stress (n = 28 subjects). Unclothed curve (n = 28 subjects) is combined data from 2 published data bases (7, 23).

ing the head with the face mask and hood subjectively increased discomfort. Whether exposure of other regions of the body would have the same impact on physiological tolerance as removal of the face mask and hood, gloves, and overboots remains to be determined.

The finding that full clothing reduces physiological tolerance to heat strain and that partial clothing can return tolerance to similar levels as when unclothed has important implications for occupational medicine. First, our data confirm that there is a cumulative incidence of exhaustion over a broad range of T_{re} rather than an abrupt increase in casualties at a specific core temperature (7, 23). Equations currently available (20) to predict the incidence of exhaustion are based on a threshold core temperature of 38.9°C. Second, the reduced physiological tolerance of subjects to heat strain while fully clothed means that the incidence of exhaustion will be greater at a given core temperature. However, the incidence of exhaustion can be reduced by removing only a portion of the protective clothing. Third, our results have implications for the microclimate cooling systems developed to improve heat loss of persons wearing protective clothing in hot environments (27). Previous microclimate cooling research has examined cooling different body regions to maximize heat loss (19, 28); future research should consider the efficacy of regional microclimate cooling and its effects on physiological tolerance to heat strain.

Additional findings of this study were that neither exercise intensity nor climate altered physiological tolerance to heat strain. T_{re} at exhaustion was similar regardless of whether subjects were performing moderate- or high-intensity exercise in full clothing. This was surprising as we anticipated that the smaller cardiac reserve and greater heat strain index during high-intensity exercise would reduce physiological tolerance to heat strain. Although high-intensity exercise did result in higher heart rate at exhaustion and shorter exercise time, T_{re} at exhaustion was not different than it was during moderate-intensity exercise. Therefore, it appears that metabolic rates between 400 and 600 W have little affect on physiological tolerance to heat strain. The tropical and desert climates also resulted in similar T_{re} at exhaustion. Thus, altering the maximum evaporative capacity was insufficient to alter physiological tolerance to heat strain when the climates were matched for WBGT. These results agree with the findings of Shvartz and Benor (25), who found similar T_{re} at exhaustion when subjects exercised in vapor barrier suits in ambient temperatures ranging from 30 to 50°C. Whether more hot and humid environmental conditions that mimic the evaporative capacity of full clothing reduce tolerance to heat strain remains to be determined.

Even though it is possible that the lower T_{re} at exhaustion when subjects were in full clothing was due to the slow response time of T_{re} during the initial minutes of exercise and the shorter exercise time compared with that when subjects were only partially clothed, two findings argue against this possibility. First, moderate-intensity exercise resulted in a 20- to 40-min longer exercise time compared with high-intensity exercise but had no effect on T_{re} at exhaustion. Furthermore, because exercise time lasted 46 min during the full clothing trials, T_{re} probably reflected core temperature, as Kraning and Gonzalez (13) reported that T_{re} and esophageal temperature were nearly identical after ~30 min of exercise during similar uncompensable heat stress conditions.

In summary, this investigation examined the impact of exercise intensity, clothing level, and climate on physiological tolerance to heat strain. The study's new findings concerning exhaustion from heat strain are as follows: *1*) full encapsulation of subjects in protective clothing reduces physiological tolerance, *2*) partial encapsulation of subjects results in physiological tolerance similar to that reported for unclothed persons, *3*) increasing the metabolic rate from 400 to 600 W when subjects are dressed in full clothing does not alter physiological tolerance, and *4*) physiological tolerance is similar when subjects are wearing protective clothing in desert and tropical climates having the same WBGT. These findings can be used to improve occupational safety guidelines for human heat exposure as they provide further evidence that the incidence of exhaustion from heat strain can be predicted from core temperature.

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