# Physiological and biophysical limits to work in the heat for clothed men and women

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KAMON, ELIEZER, BARBARA AVELLINI, AND JANET KRAJEWSKI. *Physiological and biophysical limits to work in the heat for clothed men and women.* J. Appl. Physiol.: Respirat. Environ. Exercise Physiol. 44(6): 918-925, 1978.—Heat-acclimated, lightly clothed men and women (four of each) walked on a treadmill at 25% and 43% $\dot{V}O_2$ max, respectively, (M = 194 $W \cdot m^{-2}$), under seven air temperatures ($T_a$) ranging from 36 to 52°C. Each experiment involved 1 h of fixed and a 2nd h of progressively increasing ambient vapor pressure ($P_a$). The relative steady state of rectal temperature ($T_{re}$), mean skin temperature ($\bar{T}_{sk}$), and heart rate (HR) reached in the 1st h were forced upward during the 2nd h by the rising $P_a$. The critical air vapor pressure ($P_{crit}$) was identified by the $T_{re}$ point of inflection for each $T_a$. One man did not fully reach steady state, but inflection could be determined for his physiological responses. The mean values of all points of inflection were calculated for $T_{re}$, $\bar{T}_{sk}$, and HR. Significant sex difference in HR was found only by excluding the results of the one man. $T_{re}$ and $\bar{T}_{sk}$ showed no significant difference between men and women. The coefficient for evaporative heat transfer ($h_e$), which could be derived using the $P_{crit}$ for the low $T_a$ range, was 14.5 ± 2.2 $W \cdot m^{-1} \cdot Torr^{-1}$.

thermoregulatory limits; rectal temperature; evaporative heat transfer coefficient

WHEN MEN AND WOMEN are newly exposed to heat they show a pronounced sex difference in thermoregulation (3, 5). This sex difference tends to diminish during heat acclimatization (8, 19) and in the nonacclimatized state the core temperature ($T_c$), mean skin temperature ($\bar{T}_{sk}$), and heart rates (HR) are markedly higher and sweat rate lower in the women than in the men. After acclimatization either no difference is observed, or the women show a slightly higher $T_c$ and $\bar{T}_{sk}$. If sweating is considered alone, the foregoing studies as well as the study by Morimoto et al. (14) show that although the sex difference in sweating becomes smaller it is still markedly lower in the women.

Under high ambient air temperatures ($T_a$), where the gradient $T_a$ to $\bar{T}_{sk}$ adds to the metabolic heat ($M$) by radiation and convection ($R + C$), the limit of exposure is defined by the sweating capacity. Therefore, women's high $T_a$ limits should be lower than men's, provided they work at equal metabolic rates. Under low $T_a$, where dry heat gain is small and the total heat load ($M + R + C$) is less than the cooling capacity of the total available sweat, the limit of exposure is defined by the ambient vapor pressure ($P_a$). Under these conditions men's higher sweating rate is not beneficial. Therefore, the limits of $P_a$ should be the same for men and women.

The most widely accepted criterion for heat strain is the rise in core body temperature ($T_c$) above an expected work specific level. The criterion was chosen because of the observation that over a wide range of environments, $T_c$ equilibrates at levels proportional to the metabolic rate (15, 18). Indeed, several experiments were conducted in search for the ambient conditions of equal physiological strain (17), the "prescriptive zone" for heat exposure (12) and the limits set by the ambient evaporative capacity (1). These studies used as the main criterion the attainment of, or deviation from, the expected equilibrium in $T_c$. Although other physiological criteria were also used in these studies, a recent attempt to search for the evaporative limits set by the $P_a$ was based on the deviation from equilibrium of $\bar{T}_{sk}$, HR, rate of weight loss, sensation of sweating, and thermal discomfort, rather than the deviation of $T_c$ (2).

However, because in the past the empirical approach to the definition of these limits to prolonged work under hot ambient conditions was found tedious and time consuming, it was not fully explored. Instead, the information gathered from experiments under a limited number of ambient conditions were used to develop a theoretical basis for the extension of the limits to a wider range of ambient conditions. These limits were mostly described graphically on a psychrometric chart as isotherms (6), lines of expected skin wettedness (16), and isohids (11). Because these environmental limits were based on the balance between ($M + R + C$) and the ambient evaporative capacity ($E_{max}$), the use of the absolute value of $M$ applied equally to all individuals. However, since $M$ as a fraction of the maximal oxygen uptake ($\dot{V}O_{2\,max}$) determines the physiological, mostly cardiovascular, strain, working at the same $M$ does not apply equally to all individuals. This constraint particularly applies to men and women whose $\dot{V}O_{2\,max}$ is significantly different.

The present study undertook two comparisons: *1*) the physiological responses of acclimated and clothed men and women to exposure to similar ambient conditions and $M$ levels; and *2*) the psychrometric limits of exposure for the men and women. This undertaking was possible because of the use of the relatively quick technique of multiple exposures with stepwise increase in $P_a$ at each $T_a$ defining the limits at the point of the inflection upward of $T_c$ (1). Although the upward inflections seen in the physiological responses during the stepwise increase in $P_a$ were previously described by us (1, 9) and by others who adopted this method (2), we found it worthwhile to provide the results of this study in some detail because of the following reason. Since the expected sex differences in the physiological responses were not clearly seen in this study, there was reason to question the method of the identification of the rectal temperature ($T_{re}$) inflection and thus the definition of the $P_a$ limits.

## METHODS

The physical characteristics of the participants who were paid volunteers are given in Table 1. The nature of the experiment was explained to them and their consent to participate was obtained. They were subsequently accepted for the experiments by a physician whose qualifying examination included exercise stress test to exhaustion. They were then subjected to a thorough heat acclimatization regimen.

Acclimatization involved daily treadmill walks up to 2 h at 30% $\dot{V}o_{2\,max}$ under the following ambient conditions: *1*) dry, 50°C dry bulb (db); 25°C wet bulb (wb) for the first 5 days; *2*) humid, 45°C (db); 31°C (wb) for 2 days; *3*) finally 2–4 days under the same conditions of the first 5 days. The exposure to high humidity was aimed at stimulating excessive sweating rates. Acclimatization was determined by the leveling off of rectal temperature and heart rate, observed on all the subjects during the last 3 days, except for *man 4* whose responses did not level off. Since his subjective feeling was good he was included in the experiments after an additional week of acclimatization.

During the experiments, the men walked on a level treadmill at 1.56 $m \cdot s^{-1}$, a speed used in previous studies in this and other laboratories. The women could not sustain such a speed comfortably. Therefore, they walked 1.34–1.45 $m \cdot s^{-1}$, but to obtain metabolic heat production similar to that obtained with the men the treadmill was upgraded 2–4%.

Heart rates were recorded by use of chest-skin electrodes and two leads connected to a cardiograph, once every 10 min during the 1st h, and every 5 min during the 2nd h. Yellow Spring thermistors, inserted 10 cm beyond the sphincter, were used to measure $T_{re}$. Skin temperature was measured with thermocouples attached to the skin, but not covered, on the following six sites: forehead, back (scapula), chest, forearm, and two thighs. $T_{re}$ and the temperatures for six sites on the skin were continuously recorded (5-s cycles between readings) on a strip chart (Esterline-Angus). $\bar{T}_{sk}$ was derived by averaging the temperatures recorded for the six sites.

Oxygen consumption was determined by the open-circuit method. A 2-min sample of expired air was collected in a Douglas bag during the 40th min of each experiment. Air volume and $O_2$ concentrations were measured using a Cowan-Parkinson dry spirometer and E-2 Beckman analyzer, respectively.

Sweating was determined by loss of weight, adjusting for water intake. The scale was accurate to ±20 g. Respiratory weight and evaporative losses were considered negligible and were not taken into account. Drinking was encouraged. Water was at temperature range of 24–30°C.

The women were dressed in halter tops, long-sleeve shirts, underpants, trousers, cotton socks, and gym shoes. To match this clothing, the men wore only long-sleeve shirts, trousers, underpants, socks, and gym shoes. The shirts and trousers were military-type khaki cotton twill. Neither the men nor the women wore T-shirts; the clothes were worn loose fit.

Air movement (v) was at 1 $m \cdot s^{-1}$.

The experiments sought the critical air vapor pressure ($P_{crit}$) for the upward inflection of the measured $T_{re}$ for each of the following $T_a$: 36, 38, 40, 44, 46, 48, and 52°C. Each experiment started at a fixed $T_a$ and at $P_a$ thought to be subcritical by 3 Torr. After 60 min when HR and $T_{re}$ were either at equilibrium, or at relative steady state, the $P_a$ was increased by 1–1.5 Torr every 10 min. This was described in detail elsewhere (1, 10).

Metabolic rate (*M* in watts) was derived from the measured $O_2$ uptake as; $M = 341\ \dot{V}o_2$. External work (*W*) was subtracted for the uphill walking. Thus, heat

TABLE 1. *Anthropometric measurements, maximal oxygen consumption, oxygen cost of walking, and metabolic heat production (less external work) for subjects*

| Subj No. | Age, yr | Wt, kg | Ht, cm | Surface Area, $m^2$ | $\dot{V}o_{2\,max}$, $l \cdot min^{-1}$ | Cost of Walking | | $(M - W)$, $W \cdot m^{-2}$ |
|---|---|---|---|---|---|---|---|---|
| | | | | | | $\dot{V}o_2$ $l \cdot min^{-1}$ | $\% \dot{V}o_{2\,max}$ | |
| *Men* | | | | | | | | |
| 1 | 24 | 72.7 | 179.7 | 1.92 | 4.64 | 1.04 | 22 | 185 |
| 2 | 24 | 61.5 | 174.0 | 1.75 | 3.67 | 0.91 | 25 | 180 |
| 3 | 20 | 65.0 | 180.3 | 1.83 | 3.69 | 1.05 | 28 | 200 |
| 4 | 25 | 67.3 | 175.3 | 1.81 | 4.42 | 1.10 | 25 | 211 |
| Mean ± SD | 23.3 ± 2.2 | 66.6 ± 4.7 | 177.3 ± 3.1 | 1.83 ± 0.10 | 4.11 ± 0.50 | 1.03 ± 0.08 | 25 ± 2.5 | 194 ± 15 |
| *Women* | | | | | | | | |
| 1 | 21 | 82.5 | 163.8 | 1.86 | 3.02 | 1.09 | 36 | 182 |
| 2 | 20 | 55.5 | 158.7 | 1.55 | 2.63 | 1.06 | 40 | 215 |
| 3 | 26 | 51.1 | 161.3 | 1.53 | 1.86 | 0.96 | 52 | 188 |
| 4 | 22 | 52.5 | 163.8 | 1.51 | 2.12 | 0.97 | 46 | 190 |
| Mean ± SD | 22.3 ± 2.6 | 60.4 ± 14.8 | 161.9 ± 2.4 | 1.61 ± 0.20 | 2.41 ± 0.52 | 1.02 ± 0.06 | 43.5 ± 7.0 | 194 ± 20 |

exchange was calculated using $(M - W)$ for metabolic heat production. Total sweat loss was derived from the nude weight difference before and immediately after each experiment. Heat equivalence of sweat was calculated using 0.67 $W \cdot h \cdot g^{-1}$ as latent heat.

The effective evaporative heat transfer coefficient $h_e'$ was derived, similar to the previously described methods (1, 10) from the equation

$$h_e' = \frac{(M - W) + R + C}{P_s - P_{crit}} \qquad [W \cdot m^{-2}\ Torr^{-1}]$$

$h_e'$ is for $v = 1\ m \cdot s^{-1}$, $P_s$ is saturated vapor pressure at the measured $\bar{T}_{sk}$, and $P_{crit}$ is the critical ambient vapor pressure, derived from $T_{db}$ and $T_{wb}$ at the $T_{re}$ inflection.

Dry heat exchange $(R + C)$ was calculated in terms of the operative temperature $(T_o)$

$$(R + C) = h_o(T_o - \bar{T}_{sk}) \qquad [W \cdot m^{-2}]$$

Actually, $T_o = T_a$, since no radiant heat existed. The measured $T_g$ was within 0.5°C of $T_a$.

In search for $h_e'$ we first used $h_o = 12.5$ for seminude men (11, 13), but corrected for clothing by a factor of 0.65 (7). Thus $h_o = 8.8$. Later on, consideration had to be given to the clothing used in this study. This required a slight change in the $h_o$ value for the construction of the isotherm which is explained in the results.

Isotherms were constructed on a psychrometric chart according to Hatch (6) and Kerslake (11), but on the basis of the $\bar{T}_{sk}$ found in and the $h_e'$ derived from this study. The portion of the straight line for fully wet skin was constructed using the anchor point of $P_s$ at $\bar{T}_{sk}$, and $T_a = \bar{T}_{sk} - M/h_o$. The slope of the line was $-\psi = h_o/h_e$. The portion of the curved line was constructed according to Kerslake (11, p. 92). The $T_a$ for free evaporation was $T_a = T_{sk} + (S - M)/h_o$, where $S$ = heat equivalence for sweat loss; the mean values for the highest $S$ measured were used separately for the men and the women. Sweat loss was assumed a fair representative of sweating rate.

All comparisons between men and women were carried out using noncorrelated $t$ tests. The regression of $T_{re}$ on time was computed by the least-squares method for the temperatures which, in this case, were taken every 5 min, from the 50th min on. The slopes of the regressions were compared by analysis of covariance. The $h_e'$ values for the different $T_a$'s were treated using one factor analysis of variance with repeated measures and a Tukey post-hoc test to compare mean differences.

*Procedures*. Each subject was tested daily. If a subject could not be tested for 2 or 3 days, the first reexposure was used for reacclimatization under 50°C db, 25° wb. The women were acclimatized and were tested throughout their menstrual cycles. None of them required special resting days because of menstrual difficulties. On arrival at the laboratory the subject rested 20–30 min and was then prepared for the test by determination of his nude weight and placement of the rectal probe, chest electrodes, and skin thermocouples. Thereafter, the dry clothing was weighed; the subject dressed and entered the heat chamber. Connections to the instrument and weighing lasted 5–10 min, after which the treadmill walking started. At the end of the experiment, the subjects stepped on the scale for weighing and then walked to an adjacent room to undress quickly for nude weighing and weighing of the wet clothes.

## RESULTS

*Physiological responses*. The oxygen consumption and the metabolic heat production are given in Table 1. The treadmill speed and the grade were adjusted to the subjective comfort of each woman, but with a yield of metabolic heat $(M - W)$ similar to that of the men. Consequently, the $O_2$ consumption relative to body weight and as percent of $\dot{V}o_{2\,max}$ was higher for the women than for the men.

Two typical examples of the time course of $T_{re}$ are shown in Fig. 1*A*. It can be seen that, from about the 50th min, $T_{re}$ started to level off. This trend to level off continued into the 2nd h at which time the $P_a$ was increased. The 10-min step increase in $P_a$ resulted in a departure of $T_{re}$ from the steady state reached during the end of the 1st h. In most cases $T_{re}$ completely equilibrated prior to the upward inflection, as shown for *woman 4* in Fig. 1*A*. In few cases $T_{re}$ revealed a very slow rise prior to the upward inflection as shown for *man 1* in Fig. 1*A*. Such a slow rise was considered "steady state." An exception to these typical $T_{re}$ responses was observed in *man* 4, whose $T_{re}$ revealed a consistent rise with no clearly defined steady state (Fig. 1*B*). However, since a departure from this rise in $T_{re}$ was noticed during the 2nd h and an upward inflection of $T_{re}$ could be detected, the data obtained from *man 4* were included in the description of the results. The treatment of the data prior and after the inflection point is described below under the definition of the $P_{crit}$.

The mean values of $T_{re}$ observed at the point of inflection were taken as the representatives of the steady-state values. These values are summarized in Table 2. Since no correlation was found between the steady-state $T_{re}$ and $T_a$, the results of all seven exposures were averaged for each individual. There was no significant difference between the men and the women in the $T_{re}$ value at the inflection point even when *man 4* was excluded from the statistical analysis.

Similar to $T_{re}$, HR, and $\bar{T}_{sk}$ reached equilibrium, or relative steady state, during the 1st h. Unlike $T_{re}$, these two physiological responses tended to level off early in the 1st h (Fig. 1*A*). The typical steady-state responses continued into the 2nd h, but eventually revealed an upward inflection as a result of the step increase in the $P_a$. The upward inflection of HR and $\bar{T}_{sk}$ did not always coincide with the inflection of $T_{re}$ (Fig. 1*A*). *Man 4* was exceptional in that leveling off of his HR and $\bar{T}_{sk}$ was not apparent during the 1st h, although an upward inflection could be defined during the 2nd h (Fig. 1*B*).

The HR and $\bar{T}_{sk}$ values for the time of inflection of the $T_{re}$ were averaged for each subject (Table 2). There was no significant difference between the men and the women in the mean HR and $\bar{T}_{sk}$. However, since *man 4* differed from the other men in the rate of rise of these responses prior to the upward inflection, sex differences were sought by excluding him from the statistical analysis. Indeed, the mean ± SD of the HR for the three men was 111 ± 10. Thus, without *man 4* there was a

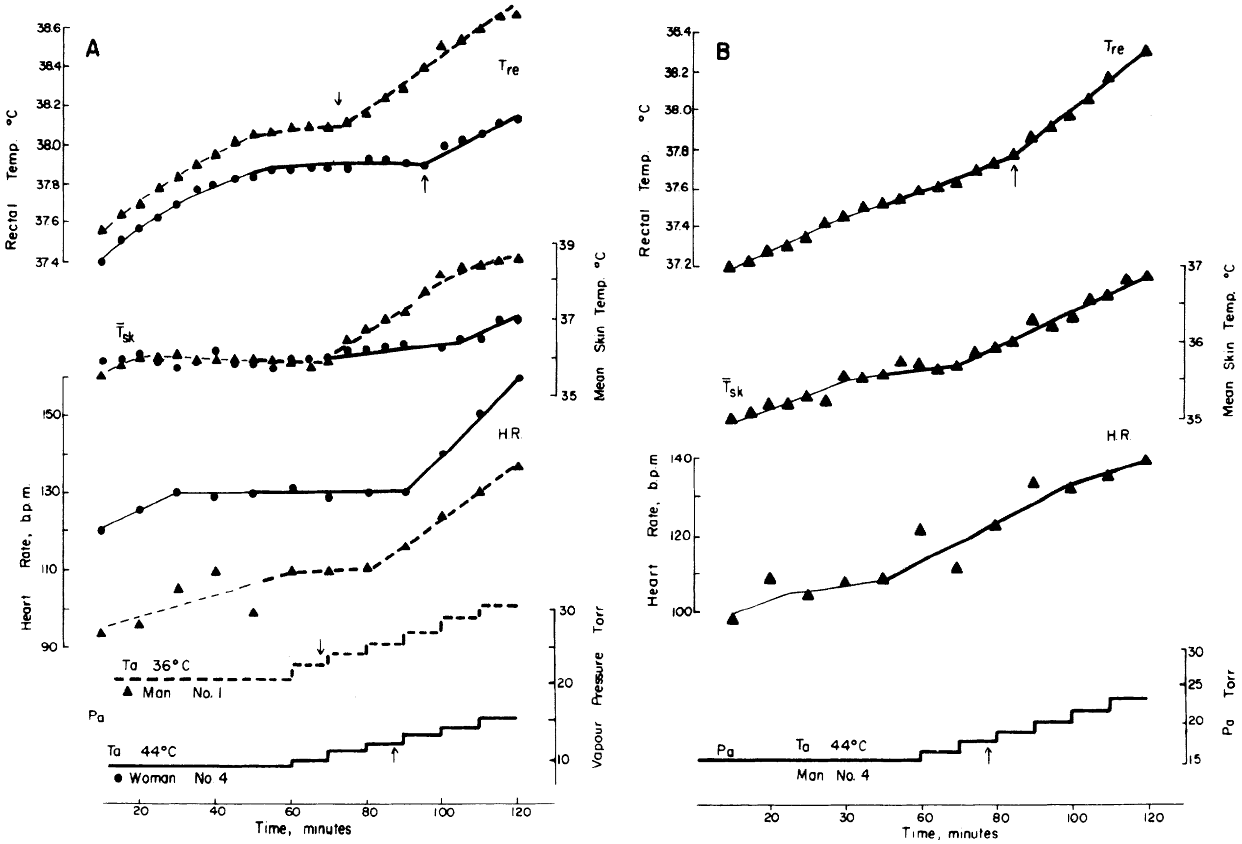


FIG. 1. *A*: typical example of the time course for rectal temperature, mean skin temperature, and heart rate and step increase in ambient water vapor pressure. *Thick lines* represent use of slopes to identify points of inflection; *arrows* indicate point of inflection of $T_{re}$ and identification of critical $P_a$. *B*: example of time course of rectal temperature, mean skin temperature, and heart rate for *man 4*. *Lines* and *arrow* are as in 1*A*.

significant difference in the HR ($P < 0.05$) between the men and the women (Table 2). However, even after excluding *man 4*, there was no significant difference in $\bar{T}_{sk}$ or in $T_{re}$.

The sweat loss was consistently higher for the men as compared to the women (Table 4). The differences were statistically insignificant for the $T_a$ range of 36–44°C but the highest mean sweat loss was observed at 52°C and was equivalent to 380 and 450 $W \cdot m^{-2}$ for the women and men, respectively.

*Definition of critical vapor pressure*. The $P_{crit}$ was defined by the upward inflection of the measured $T_{re}$. This was done graphically using the raw data from the recorder's strip chart. It should be noted that $T_{re}$ was recorded once every 25 s. On the assumption that steady state was reached after the 50th min, a line was drawn between the data points, starting at the 50th min. A second line was drawn from the point of the departure of $T_{re}$ from the first line. The lines were similar to those described in Fig. 1, *A* and *B*. The first line, describing the $T_{re}$ rise between the 50th min and the point of the upward inflection, was straight. The second line was either straight, or it curved toward the end. The $P_a$ one step prior to the point at which the second line departed from the first line (upward inflection of $T_{re}$) was defined as the $P_{crit}$. This procedure was assumed to make allowance for the 5- to 10-min lag in the $T_{re}$ change-over time. To confirm the graphical identification of the upward inflection of $T_{re}$, the slopes of the two lines were compared using an analysis of covariance. The analysis was conducted separately for each exposure of each subject. The slopes of the two lines were significantly different for the majority of the exposures. The few insignificant differences between the two slopes were found in one exposure only, for each of *women 2* and *4* and *men 1* and *3*. Again *man 4* was exceptional in that insignificant difference between the two slopes was found in three of his exposures. These statistical results

TABLE 2. *Heart rate, rectal temperature, and mean skin temperature averaged for each subject at point of $T_{re}$ inflection*

| Subj No. | *n* | Heart Rate, beats·min⁻¹ | $T_{re}$, °C | $\bar{T}_{sk}$, °C |
|---|---|---|---|---|
| *Men* | | | | |
| 1 | 7 | 106 ± 4 | 38.12 ± 0.14 | 36.30 ± 0.37 |
| 2 | 7 | 123 ± 10 | 37.99 ± 0.38 | 36.16 ± 0.36 |
| 3 | 7 | 105 ± 6 | 37.59 ± 0.07 | 35.80 ± 0.46 |
| 4 | 7 | 133 ± 11 | 38.11 ± 0.29 | 36.40 ± 0.32 |
| Mean ± SD | 28 | 117 ± 13 | 37.94 ± 0.32 | 36.18 ± 0.43 |
| *Women* | | | | |
| 1 | 7 | 123 ± 5 | 38.20 ± 0.16 | 35.70 ± 0.46 |
| 2 | 7 | 145 ± 9 | 38.14 ± 0.17 | 36.26 ± 0.56 |
| 3 | 7 | 142 ± 8 | 37.96 ± 0.04 | 36.18 ± 0.67 |
| 4 | 7 | 130 ± 5 | 37.78 ± 0.12 | 35.95 ± 0.46 |
| Mean ± SD | 28 | 135 ± 10 | 38.02 ± 0.21 | 36.03 ± 0.56 |

were considered a reasonable validation of the graphical identification of the point of inflection of $T_{re}$, and thus the selection of $P_{crit}$.

*Biophysical observations*. The $P_{crit}$ decreased with the increase in $T_a$ for each individual. The mean values of the $P_{crit}$ at each $T_a$ were summarized in Table 3 and shown in Fig. 2, separately for each sex. Though the regression of $P_a$ on $T_a$ could be fitted by one straight line for the women, it could be fitted by two straight lines for the men: one line for $T_a$ between 36 and 40°C and a second steeper line for $T_a$ range of 40–52°C. The two lines for the men resulted from the higher $P_{crit}$ observed in men as compared to women. Although most of the $P_{crit}$ values obtained were somewhat higher for the men than for the women, statistically the mean value for the men was significantly higher ($P < 0.05$) than for the women, for $T_a$ of 40°C only. Excluding *man 4*, significant difference was found also at 44°C.

*Effective coefficient of evaporative heat transfer*. The $h_e'$ values were calculated for each subject at each $T_a$ (see METHODS). The mean $h_e'$ values at each $T_a$ were summarized in Table 3. A distinct difference in the $h_e'$ values could be seen as follows: at the $T_a$ range of 36–40°C for men and 36–38°C for the women, the values were not significantly different in both sexes and for all temperatures. At the higher $T_a$ (44–52°C for the men and 40–52°C for the women), the $h_e'$ values were not significantly different within these temperature ranges, but they all were significantly smaller ($P < 0.05$) than at the lower $T_a$ range.

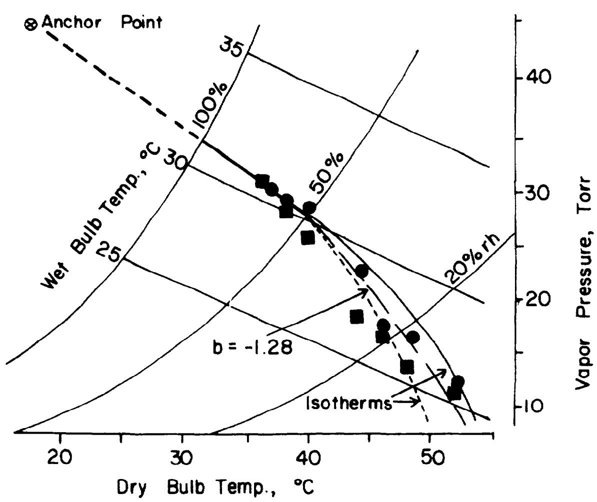


FIG. 2. Critical vapor pressure for men (●) and women (■), and computed limit lines: (——) common isotherm for men and women; (——) isotherm for men; (-----) isotherm for women; (- - -) regression of critical $P_a$ on $T_a$ for $T_a > 38$°C, calculated for both sexes; $b$ = slope of critical $P_a$ ($P_{crit}$) on $T_a$.

TABLE 3. *Critical vapor pressure and calculated evaporative heat transfer coefficient*

| | | $T_a$, °C | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | 36 | 38 | 40 | 44 | 46 | 48 | 52 |
| $P_{crit}$, Torr | Men | 30.6 ±1.4 | 29.6 ±1.1 | 28.9* ±1.3 | 22.9 ±2.6 | 18.0 ±2.0 | 17.0 ±2.5 | 12.5 ±1.3 |
| | Women | 31.0 ±2.5 | 28.5 ±2.5 | 26.0 ±1.2 | 19.1 ±1.8 | 17.2 ±1.9 | 14.0 ±0.8 | 11.8 ±3.4 |
| $h_e$, $W \cdot m^{-2}$ $Torr^{-1}$ | Men | 14.1 ±0.9 | 13.5 ±0.5 | 15.1 ±2.8 | 11.7 ±0.9 | 10.6 ±0.8 | 10.8 ±1.1 | 9.4 ±1.7 |
| | Women | 16.0 ±3.0 | 14.0 ±2.0 | 10.9 ±0.8 | 10.0 ±1.1 | 9.8 ±0.9 | 9.8 ±0.3 | 9.9 ±0.2 |

Values are means ± SD calculated for each subject (see METHODS). * $P < 0.05$ vs. women.

The total mean and standard deviation for the higher $h_e'$ values (men ≤ 40°C, women ≤ 38°C) was 14.5 ± 2.2 $W \cdot m^{-2} \cdot Torr^{-1}$. Since at the higher $T_a$ range (>40°C for men, >38°C for women) the balance $(M - W + R + C) = E_{max}$ was most likely not satisfied, the derived $h_e'$ values were not meaningful. This is further demonstrated in the next section, and will be dealt with in the DISCUSSION.

*Isotherms*. Isotherms were constructed by fixing the anchor point $P_a = P_s$ and $T_a = \bar{T}_{sk} - M/h_o$ (Fig. 2), and using $h_e' = 14.5\ W \cdot m^{-2} \cdot Torr^{-1}$, $h_o/h_e = -\psi = 0.71$ (see METHODS), sweating capacity $S$ equivalent to 450 $W \cdot m^{-2}$ for men and 380 $W \cdot m^{-2}$ for women, which were the respective mean values for the highest sweat loss ($T_a$ 52°C, Table 4), M = 194 $W \cdot m^{-2}$, and $\bar{T}_{sk}$ = 36.14°C. The last two values were the means for the data, pooled together for the men and the women. The highest sweat loss values were used as best approximation for the highest sweating rates.

A slight correction was made for the coefficient for radiant heat transport $h_r$. In our previous observations on seminude men and women (1, 10), we found $h_e$ = 18.4 $W \cdot m^{-2} \cdot Torr^{-1}$. Therefore, the ratio of clothed subjects in this study to seminude from the previous studies was 0.79 (14.5 ÷ 18.4). This ratio was somewhat higher than the 0.65 which was suggested previously (1, 7). Although not analogous it was thought that the correction of $h_r$ according to the $h_e$ ratio of 0.79 was nearest to the expected $h_r$ value. For seminude $h_r$ = 4.7 (11). Thus $h_r = 4.7 \cdot 0.79 = 3.7\ W \cdot m^{-2} {}^{\circ}C^{-1}$; $h_c = h_e \div 2.2 = 14.5 \div 2.2 = 6.6$. Thus $h_o = h_r + h_c = 10.3$ was used in the construction of the isotherms.

The isotherms described in Fig. 2 started at the lower $T_a$ range with a common straight line for the men and the women. As was expected from the higher $S$, the curved portion of the isotherm started at higher $T_a$ for the men (43°C) as compared to that for the women (39°C). The isotherms agreed reasonably well with the $P_{crit}$ values for each sex. However, a straight line also seemed to fit the relationship between the $P_{crit}$ and the high $T_a$ values for work at the $M$ level employed. A regression of the $P_{crit}$ on $T_a$ between 40 and 52°C, calculated by the least-squares method for the combined data on the men and the women was described (Fig. 2). The regression obtained was: $P_{crit} = 77.8 - 1.28\ T_a$(°C).

## DISCUSSION

*Physiological responses*. The results of this study were somewhat unexpected in that the average values of the HR and $T_{re}$, at equilibrium or relative steady state, were not different for the men and the women and that in spite of the difference in the sweating rate, the limits based on the $P_{crit}$ were practically the same for the two groups. The similarity in $P_{crit}$ was also taken to indicate that the time constant of the change in $T_{re}$ was the same for both sexes.

This study was designed to separate, in part, the responses to ambient stress from the responses to the stress of work. During the 1st h, the ambient conditions were set at subcritical $P_a$, allowing $T_{re}$ and HR to equilibrate at the work specific levels. Subsequently, to obtain a rise in these responses, the heat stress was increased by the stepwise increase in $P_a$. Assuming no sex difference in the time constant of $T_{re}$ changes, this procedure was expected to reveal differences between the men and the women, primarily because of the difference in the relative work load. The failure to show such sex differences could be attributed to *man 4* whose responses did not approach a steady state during the exposures to the subcritical $P_a$. Thus, $T_{re}$ and HR at the point of the $T_{re}$ inflection were quite higher for him than for the other men. Excluding *man 4* from the comparison between the men and the women revealed a significant difference in HR only; the women's higher HR was proportional to their higher $\%\dot{V}o_{2\,max}$. Similar proportional difference in HR was reported by Hertig and Sargent (8) for acclimated men and women working under two relatively dry-hot ambient conditions. However, Wyndham et al. (19) found no difference in HR for acclimatized men and women at levels requiring 1 liter $O_2 \cdot min^{-1}$ (the same as in this study), and under very humid ambient conditions. These conflicting results and the difference that *man 4* made in this study seemed to indicate that the individual HR responses to heat could vary to such an extent that the expected differences due to relative work load were masked.

The $T_{re}$ was expected to be higher in the women than in the men for two reasons. *1*) As in the case of HR, under nonstressing ambient conditions, $T_{re}$ equilibrated in proportion to $\%\dot{V}o_{2\,max}$ (18). *2*) With exposure to heat, the onset of sweating is delayed in women; thus their body temperature showed a greater increase as compared to men (3).

The expected difference in $T_{re}$ was not apparent in the present study, even when *man 4* was excluded from the comparison. Sex differences in $T_{re}$ could neither be found by Wyndham et al. (19), nor could they be concluded from the study of Hertig and Sargent (8). The $T_{re}$ difference, due to the relative work load employed in these studies and in our experiments, was expected to be about 0.5°C (9; 11, p. 132). However, the evidence here and in the literature seemed to indicate that under stressing ambient conditions, $T_{re}$ equilibrium was related to the absolute rather than to the relative metabolism. It should be noted that since drinking was encouraged, water deficit was negligible and was similar for the men and the women: 106 $g \cdot m^{-2} \cdot h^{-1}$ (mean).

$\bar{T}_{sk}$ at the point of inflection was practically the same for all the seven exposures and it was not different in men than in women. Such a contrast value of $\bar{T}_{sk}$ for all the $T_a$ is in agreement with the accepted notion that acclimated men maintained constant $\bar{T}_{sk}$ under stressing ambient conditions, as long as their heat balance was not impaired (1, 6, 17). The average $\bar{T}_{sk}$ of 36°C was higher than the previously established 35°C for men (1) but was the same as that for women (10). The similarity of $\bar{T}_{sk}$ in both sexes under all $T_a$ exposures justified the identification of the limit line along the $P_{crit}$ as the isotherm.

The similarity in $T_{re}$ and $\bar{T}_{sk}$ meant that the core-to-surface temperature gradient was the same in both sexes, which, in terms of heat dissipation, was a disadvantage for the women. Since the women's total surface area was smaller, they had to transport more heat per their total area and were under more cardiovascular strain, compared to the men.

The maximal sweat loss obtained in this study was slightly higher, but in reasonably good agreement with the previously obtained values for women (10) and those obtained by others for men and women (4, 8). The men's consistently higher sweating rates were significant for the high $T_a$ of 46–52°C only. Judged by the insignificant difference in the $P_{crit}$ at this $T_a$ range, the additional sweating did not improve the men's exposure limits over the women's, in spite of being exposed to similar $P_a$ range as the women. These irreconcilable results could be explained by the critical skin wettedness that, as will be shown later, was nearly constant (at about 70%) for the high $T_a$ range and was practically the same for both sexes. This similarity in wettedness of the skin at the $P_{crit}$ equally restricted evaporation for both sexes.

The sweat loss of *man 4* was the highest in his group; yet he had difficulties with thermoregulation, judged from his inability to reach steady-state HR and $T_{re}$. His difficulties were also apparent in the limits of exposure, in that the $P_{crit}$ values for him were lower than the other men and were actually in the range of the values obtained for the women. This seemed to indicate that *man 4* was an example of difficulties of thermoregulation which resulted from circulatory rather than sweating insufficiencies (20). This was so despite the fact that he was active in sports and maintained a high level of physical fitness (Table 1).

*Biophysical considerations*. The results of this study confirm our previous observation (10) that the same evaporative heat transfer coefficient applies to men and women. The derivation of the coefficient $h_e'$ was based on the assumption that at the $P_{crit}$ *a*) the body was in thermal steady state, and *b*) the skin was saturated. In thermal equilibrium the total heat load $(M - W + R + C)$ equaled evaporative heat loss $E$, which also meant that $E = E_{max}$. At the $P_{crit}$, $(M - W + R + C) = E_{max}$, or $E/E_{max} = 1$. The ratio $E/E_{max}$ also reflected a fully wet skin w = 1. If the balance between $E$ and $E_{max}$ was not satisfied, with w < 1, the $P_s$ assumed for the prevailing $\bar{T}_{sk}$ would be too high and the calculated $h_e'$ would be low. This, indeed, was shown in Table 3; the $h_e'$ values for $T_a > 40$°C in the men and the $T_a > 38$°C in the women were significantly lower compared to the respective $h_e'$ values for $T_a < 40$°C and < 38°C.

Similar to the approach taken previously (10) the $E$ value averages for the 2 h and the calculated $E_{max}$ for $P_{crit}$ were used to estimate the $E/E_{max}$ ratio for $P_{crit}$. These values were summarized in Table 4 for each $T_a$. It can be seen that, although $E/E_{max} < 1$ was obtained for $T_a > 40$°C and > 38°C for the men and women, respectively, $E/E_{max}$ of about 1 was obtained for the lower $T_a$'s. It should be noted that because the method

TABLE 4. *Evaporation rate, ratio between evaporation and ambient maximal evaporative capacity, and sweat rates at each air temperature*

| | | $T_a$, °C | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | 36 | 38 | 40 | 44 | 46 | 48 | 52 |
| $E$,* $W \cdot m^{-2}$ | Men | 207 ±32 | 216 ±24 | 222 ±55 | 246 ±38 | 346 ±52 | 356 ±56 | 366 ±60 |
| | Women | 203 ±8 | 266 ±66 | 260 ±48 | 322 ±53 | 301 ±39 | 300 ±43 | 338 ±22 |
| $E/E_{max}$† | Men | 1.00 | 0.95 | 0.95 | 0.77 | 0.91 | 0.89 | 0.71 |
| | Women | 1.00 | 1.17 | 0.87 | 0.86 | 0.75 | 0.68 | 0.70 |
| $S$,* $W \cdot m^{-2}$ | Men | 355 ±84 | 389 ±35 | 359 ±27 | 353 ±27 | 448‡ ±25 | 447‡ ±70 | 449‡ ±19 |
| | Women | 298 ±43 | 364 ±85 | 304 ±53 | 349 ±44 | 335 ±53 | 331 ±51 | 379 ±17 |

* Values are means ± SD. † $E_{max} = h_e (P_{sk} - P_a)$, where, $h_e = 14.5\ W \cdot m^{-2} \cdot Torr^{-1}$ averaged from the individual $h_e$ obtained for men at Ta 36–40°C and women at Ta 36–38°C (Table 3), $P_{sk}$ for $\bar{T}_{sk}$ at $P_{crit}$ (Table 2). ‡ $P < 0.05$ vs. women.

called for a step increase in $P_a$ during the 2nd h, the $P_{crit}$, used to compute $E_{max}$, was obtained at the temporary point of inflection of $T_{re}$. $E$ was averaged for the 2 h of exposure (the search for the $T_{re}$ inflection prevented disruption of the test for weighing). Consequently, the calculated ratio $E/E_{max}$ could only be an approximation of the ratio expected at the $P_{crit}$. The fact that values close to 1 were obtained for the $T_a$ range at which the $h_e'$ values were similar, and a ratio of less than one was obtained for the rest of the $T_a$ tested, was explained as follows. During the 1st h of exposure (at subcritical $P_a$), sweating lagged behind the required $E$ for about 30–40 min, until the rising $T_{re}$ equilibrated. During the 2nd h, two conditions prevailed. *a*) Under the low $T_a$, as the $P_{crit}$ was approached and then surpassed, the progressive restriction of evaporation resulted in oversweating; the 2nd h sweat run-off, which was taken as $E$ (weight loss), compensated for the insufficient sweating of the 1st h, to yield an average $E$ close to that expected for the $P_{crit}$. *b*) Under the high $T_a$, evaporation could be achieved more readily, but sweating rate was insufficient. Consequently, the averaged $E$ was lower than expected and, in addition, the $P_a$ for the true $E_{max}$ was not reached, which resulted in a low $E/E_{max}$ ratio. This difference between low and high $T_a$ was also noticed by observation. During the period of the rise in $T_{re}$ (2nd h), the subjects were wet from head to toe with sweat dripping when under the low $T_a$, but seemed much less wet with no apparent dripping sweat when exposed to the high $T_a$.

$S$ was expected to exceed $E$ by about 50% for conditions where $w = 1$ (11). To confirm the approximated values suggested from this study for the $P_{crit}$ (Table 4), few additional tests were conducted. One woman and two men were each exposed for 2 h to temperatures of 38, 40, 44, and 52°C. The $P_{crit}$ was fixed at the level found at each of these temperatures for each subject. During each test, HR, $T_{re}$, and $\bar{T}_{sk}$ leveled off as expected. The average hourly values of $S$ and $E$ yielded the following mean $S/E$ ratios: 1.51 for the women at 38°C and the men at 38 and 40°C; 1.29 for the women at 40 and 44°C and the men at 44°C; and 1.19 at 52°C for the men and women. Put differently, these tests showed that under the air temperatures at which $w = 1$ was approximated for the $P_{crit}$, sweat exceeded evaporation by 51%; but under air temperatures at which the approximation for w was less than 1, sweat exceeded evaporation by 20–30% only.

Additional support to the partially wet skin ($w < 1$) for the high $T_a$ range (>38°C) for women, >40°C for men) was found in the isotherms.

The upper part of the isotherm confirmed the assumption of a fully wet skin at the low $T_a$ range ($T_a < 38$°C for women and $T_a < 40$°C for men) for the following reason. This upper part of the isotherm was a straight line passing through the $P_{crit}$ points, at the low $T_a$ range, and through the anchor point at $P_s$ for the saturated measured $\bar{T}_{sk}$, and $T_a = T_{sk} - M/h_o$ (see METHODS and Fig. 2). Therefore, $h_e' = h_e$, where $h_e$ is the evaporative heat transfer coefficient.

The lower part of the isotherm (the curved portion) represented the conditions of $w < 1$. The deviation of this portion of the isotherm from the straight upper part of the isotherm was limited by the sweating capacity and was in a very good agreement with the $P_{crit}$ values for the high $T_a$ range. Furthermore, the onset of the curved line at 39°C for the women and 43°C for the men agreed with the sex difference in the $P_{crit}$, found at $T_a$ 40°C and also at $T_a$ 44°C when *man 4* was excluded.

The sex differences in the $P_{crit}$ and in the $S$ implied that the wettedness should also differ. Judged by the magnitude of the observed higher $S$ and $P_{crit}$ in the men as compared to the women (Tables 3 and 4), the difference in w was most likely very small. A test specifically designed to measure w at each $P_{crit}$, using a large sample, is needed to establish the significance of the sex differences. Such a test was beyond the scope of this study.

The lower $h_e'$ for the high $T_a$ range could be taken to mean that $h_e' = w \cdot h_e$ and w could be derived for the high $T_a$ range by the following reasoning. With the decrease in $P_{crit}$ as $T_a$ increased, $h_e'$ also decreased. However, the $h_e'$ values within the range of the high $T_a$ (>38°C for women, >40°C for men) were not significantly different either between the sexes or for each sex within this $T_a$ range. The mean ± SD of $h_e'$ was 10.3 ± 0.71 $W \cdot m^{-2} \cdot Torr^{-1}$. For $h_e' = 10.3$ and $h_e$ 14.5, $w = 0.71$. This w value applied to all the $P_{crit}$ within the high $T_a$ range. This could be considered the critical w ($w_{crit}$) for the high $T_a$. The similarity in the $P_{crit}$ for the men and the women and the linear regression which could be fitted to the data suggested that, for all practical purposes, starting from $T_a = 40$°C, a regression with a slope of −1.28 applied quite well for both the men and the women. Such a straight line representing $w = 0.71$ could make simpler the psychrometrically defined limit of exposure for an $M$ of about 200 $W \cdot m^{-2}$. The line most likely could intercept the vertical line for $w = 0$. Unfortunately a search for the $T_a$ at which $w = 0$ was not possible because of technical difficulties in maintaining the low $P_a$ needed at the high $T_a$ range at which $w = 0$.

A similar regression of $P_{crit}$ on $T_a$ and $w = 0.6$ was established for seminude women exposed to the high $T_a$

range (10). This close agreement between the decreased $P_{crit}$ and the applicability of $w_{crit}$ for unclothed as well as clothed individuals supports the observation made by Berglund and Gonzalez (2) that the estimated $w_{crit}$ for clothed and unclothed individuals is almost identical at the same air velocity.

This method of seeking the $P_{crit}$ at which the rise in $T_{re}$ occurred was originally developed by Belding and Kamon (1) explicitly for the purpose of obtaining a physiologically based coefficient descriptive of evaporative cooling, with an emphasis on establishing a correction for clothing. In that study, the coefficient applicable to seminude men was 18.4 $W \cdot m^{-2} \cdot Torr^{-1}$, in agreement with the values reported by others for men (13, 16) and in our previous observation on women (10). A correction of 0.65 was established for clothing, including T-shirt, cotton khaki long-sleeve shirt, trousers, socks, and gym shoes (1, 7). The coefficient ($h_e{}' = 14.5\ W \cdot m^{-2} \cdot Torr^{-1}$) suggested in this study implies a correction of 0.79 over seminude (18.4 ÷ 14.5), which was smaller than the previously established 0.65 value and the recently suggested correction for sedentary men similarly clothed (2). This difference was not unexpected because in this study the clothing did not include T-shirts and the shirts were worn loose at the sleeves and open halfway down the chest. This substantially reduced the insulative clothing value as compared to that for the clothing used in the previous study.

The sensitivity of this method to the changes in clothing demonstrated the merits of using a step increase in $P_a$ *a*) to establish physiologically based limits of exposure to heat, and *b*) to measure directly the evaporative heat transfer properties of different types of clothing.

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