Psychometric limits and critical evaporative coefficients for unacclimated men and women

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Kenney, W. Larry, and Michael J. Zeman. Psychometric limits and critical evaporative coefficients for unacclimated men and women. J Appl Physiol 92: 2256–2263, 2002.—Critical environmental limits, defined as those above which heat balance cannot be maintained for a given metabolic heat production, have not been determined for unacclimated subjects. To characterize critical environmental limits and to derive evaporative heat exchange coefficients ($K_e'$) for unacclimated young men ($n = 11$) and women ($n = 10$), subjects of average aerobic fitness walked at 30% maximal aerobic capacity in an environmental chamber. Critical environmental conditions were defined as the psychrometric loci of dry-bulb temperature and water vapor pressure at which core (esophageal) temperature was forced out of equilibrium (heat gain exceeded heat loss). Compared with the men in our study, the women had significantly higher core temperature; heat exchange chart; thermoregulation; heat balance; sweat evaporation; heat acclimation; sex differences; heat stress; psychrometric chart; i.e., an isotherm of free evaporative cooling. Because $E_{\text{max}} = K_e' \cdot v^{0.6}, (P_{\text{sk,sk}} - P_a)$, where $v$ is air velocity and $(P_{\text{sk,sk}} - P_a)$ is the vapor pressure gradient from fully wetted skin to air, $K_e'$ can be derived and used to model heat exchange with the environment and predict limits for prolonged work-heat exposures. Although some assumptions are required for this sequence of calculations, the resultant values are useful for continuing efforts to model human heat exchange with the environment.

The present study used two innovations of the Kamon and Avellini (13) protocol. In hot dry environments, critical limits are determined by individual sweating capacity as opposed to environmental limits (13), and these limits approach a vertical line on the psychrometric chart, i.e., an isotherm of free evaporation (17). To better predict the dry-bulb temperature ($T_{\text{db}}$) locus of this line, we held ambient water vapor pressure ($P_{\text{w}}$) constant and determined a critical $T_{\text{db}}$ at a given metabolic heat production have been determined for heat-acclimated men (3) and women (13, 14) but not for unacclimated subjects, in part because of perceived methodological concerns.

Belding and Kamon (3) originally used a time-intensive protocol to determine critical ambient vapor pressures at 36°C for a variety of exercise intensities and air movements. A shorter version of their original investigation was proposed (13) and then refined (16) to minimize the number and duration of tests necessary to determine these limits. However, these more time-efficient protocols require the ability to systematically change ambient temperature or water vapor pressure, i.e., with the use of a fairly sophisticated environmental chamber.

In addition to setting environmental limits, physiological responses can be used to determine the effective evaporative coefficient ($K_e'$) at each critical limit based on the assumption that, at those critical limits with high humidity, heat gain equals heat loss and the skin is fully wet. That is, $M_{\text{net}} \leq (R + C) = E_{\text{max}}$, where $M_{\text{net}}$ is the net metabolic heat production, $R + C$ is the combined dry heat gain or loss through radiation and convection, and $E_{\text{max}}$ is the maximal ambient capacity for evaporative cooling. Because $E_{\text{max}} = K_e' \cdot v^{0.6} \cdot (P_{\text{sk,sk}} - P_a)$, where $v$ is air velocity and $(P_{\text{sk,sk}} - P_a)$ is the vapor pressure gradient from fully wetted skin to air, $K_e'$ can be derived and used to model heat exchange with the environment and predict limits for prolonged work-heat exposures. Although some assumptions are required for this sequence of calculations, the resultant values are useful for continuing efforts to model human heat exchange with the environment.

Over a wide range of environments, body core temperature ($T_c$) equilibrates at levels proportional to metabolic rate and independent of ambient conditions (21, 26). Thermal environments above this designated “prescriptive zone” (18, 19) force $T_c$ out of equilibrium, resulting in a continuous rise in $T_c$. Critical conditions that define the upper limit of the prescriptive zone for...
three separate $P_a$ values. Second, in experiments in which $T_e$ did not achieve a true steady state (which occurs more commonly in unacclimated than in fully heat-acclimated subjects), we calculated the heat storage ($S$) associated with this “pseudo-steady state” and incorporated $S$ into the heat balance calculations, which led to the derivation of $K'_{e}$, i.e., $M_{net} \pm (R + C) \pm S = E_{max}$.

The purpose of the present investigation was to determine for the first time the critical environmental limits for unacclimated men and women. In addition, partial calorimetry was used to determine sex-specific values for $K'_{c}$. It was hypothesized that 1) critical environments for unacclimated men and women would be shifted downward [toward lower critical water vapor pressure ($P_{crit}$)] and leftward [toward lower critical temperature ($T_{crit}$)] on a psychrometric chart compared with heat-acclimated subjects because of lower sweating rates, altered sweat distribution, and lower evaporative efficiency; 2) these empirically determined psychrometric limits would fit standard biophysical models of heat exchange; and 3) the derived critical $K'_{c}$ would be lower for unacclimated subjects than previously published values (3, 13) for fully heat-acclimated subjects.

METHODS

Subjects. All experimental procedures were approved in advance by the Institutional Review Board at The Pennsylvania State University. After all aspects of the experiment were explained, oral and written informed consent was obtained. Each subject was subsequently approved for the experiment after each completed a medical screening examination. Twenty-one subjects were tested (11 men and 10 women). All subjects were healthy, normotensive, nonsmokers, and not taking any medications that might affect the physiological variables of interest in this study. None of the women was taking oral contraceptives, and no attempt was made to control for menstrual status. Subjects with a maximal aerobic capacity ($V_{O2max}$) in the upper or lower 20th percentile for their gender and age (1) were excluded. None of the subjects was physically active outdoors on a regular basis. $V_{O2max}$ was determined with the use of open-circuit spirometry during a maximal graded exercise test performed on a motor-driven treadmill. Subject characteristics are shown in Table 1. During the experiments, subjects wore thin, short-sleeved cotton tee-shirts, shorts, socks, and walking/running shoes. For consistency with previous studies that have used this minimal clothing ensemble, no clothing corrections were made for this “semi-nude” state (13).

Chamber characteristics. The environmental chamber used for this study utilized a three-mode controller (proportional, derivative, and integral) to optimize stability and response. Air is vertically discharged in an even pattern through the ceiling and returned through base molding on three sides. Because air returns behind the walls, wall temperature increases linearly with air temperature. The ceiling was mapped for optimal laminar flow. With no forced air movement in the chamber, velocity in the vicinity of the walking subjects was measured at 0.45 m/s. The same chamber was used in the studies by Kamon and colleagues (9, 13, 14), from which comparative data are presented later in this paper.

Testing procedures. Subjects were asked to refrain from vigorous exercise and alcohol consumption during the 24 h before each experiment and from caffeine on the day of the experiment. On arrival, each subject was weighed and donned a Polar heart rate (HR) monitor. The esophageal probe was inserted as the subject drank 5 ml of room temperature water per kilogram body weight. The subject then moved into the preconditioned environmental chamber for equilibration, and skin thermocouples were attached.

Two sets of protocols were used to determine either 1) the $P_{crit}$ for the upward inflection of esophageal temperature ($T_{es}$) at three distinct $T_a$ values (34, 36, and 38°C) or 2) the critical $T_{sb}$ ($T_{crit}$) at three distinct $P_a$ values (12, 16, and 20 Torr). The methods used to determine $P_{crit}$ and $T_{crit}$ have been previously described (13, 14, 16). Experiments were conducted year-round in randomized order to counterbalance any possible acclimation effects, and no attempt was made to heat acclimate subjects. Each subject participated in all six trials, with at least 2 days separating successive tests.

Each experiment was conducted in a programmable environmental chamber. $T_a$ and wet-bulb temperature ($T_{wb}$) were measured every 5 min with the use of precision mercury-in-glass thermometers (traceable standards provided by the National Institute of Standards and Technology) mounted in an ASHRAE box (American Society of Heating, Refrigeration, and Air-conditioning Engineers). $P_a$ was determined from $T_{es}$ and $T_{wb}$ with the use of a standard psychrometric chart.

During the three $T_{crit}$ experiments, $P_a$ was held constant and $T_{sb}$ was systematically increased ~1°C every 5 min after a 30-min equilibration period at 28°C. In the three $P_{crit}$ experiments, $T_{sb}$ was held constant while $P_a$ was increased ~1 Torr every 5 min after a 30-min equilibration period at 9 Torr.

During each test, the subjects walked continuously on a motor-driven treadmill for up to 2.5 h at a speed and grade that approximated 30% of their $V_{O2max}$. This exercise intensity was chosen for three reasons: 1) it reasonably simulates light-to-moderate daily workloads typical of a healthy, normally active population, 2) it is the intensity associated with an 8-h work day in industrial settings (5), and 3) it reflects the intensity for many self-paced activities. After the 30-min equilibration period, either the $T_{sb}$ ($T_{crit}$ tests) or the $P_a$ ($P_{crit}$ tests) in the chamber was increased in a step-wise fashion while chamber $T_{sb}$ and $T_{wb}$ and subject $T_{es}$, skin temperature ($T_{sk}$), and HR were monitored. To ensure that each subject was walking at the prescribed workload, oxygen uptake ($V_{O2}$) was determined after 30 min with a 3-min expired air sample collected in Douglas bags and analyzed for $CO_2$ concentration (Beckman LB-2, Fullerton, CA). $O_2$ concentration (S-3A

<table>
<thead>
<tr>
<th>Table 1. Subject characteristics by group</th>
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<tr>
<td><strong>Men</strong></td>
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<td>$n$</td>
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<td>Age, yr</td>
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<tr>
<td>Weight, kg</td>
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<tr>
<td>Height, cm</td>
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<tr>
<td>$A_o$, m²</td>
</tr>
<tr>
<td>$V_{O2max}$, ml·kg⁻¹·min⁻¹</td>
</tr>
<tr>
<td>Body fat, %</td>
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<tr>
<td>BMI, kg/m²</td>
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<tr>
<td>$A_o$/mass, m²/kg</td>
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Values are means ± SE. $A_o$, DuBois surface area; BMI, body mass index; $V_{O2max}$, maximal aerobic capacity. *Significantly different from men, $P < 0.05$.  

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oxygen analyzer, Applied Electrochemistry, Sunnyvale, CA), and volume (Parkinson-Cowan dry-gas meter, Cambridge, UK). Measurements. $T_e$ was measured with a probe made from a thermistor sealed in a pediatric feeding tube. The probe was inserted nasally and lowered in the esophagus to the level of the left atrium. $~0.25$ of the subject’s standing height, $T_{sk}$, was measured at four sites: leg ($T_{leg}$), thigh ($T_{th}$), arm ($T_{arm}$), and chest ($T_{ch}$) with copper-constantan thermocouples. A weighted mean $T_{sk}$ (in °C) was calculated (25) as

\[
T_{sk} = 0.3 \cdot T_{ch} + 0.3 \cdot T_{th} + 0.2 \cdot T_{arm} + 0.2 \cdot T_{leg}
\]

(1)

$T_{es}$ and $T_{sk}$ were continuously recorded, and HR was recorded at 5-min intervals on a dedicated computer.

Sweating rate was determined from the loss of nude weight, adjusted for water intake on a scale accurate to ±20 g. Respiratory losses were considered negligible. Fluid intake was prohibited between the initial nude weight and the final nude weight. The skin evaporative capacity ($E_{sk}$) for each test was calculated by multiplying the sweating rate by 0.68 W·h·g⁻¹, the specific heat of vaporization.

**Determination of $T_{es}$ and $P_{crit}$**. An example of the time course of $T_{es}$, $T_{sk}$, and environmental conditions for a typical $P_{crit}$ test is shown in Fig. 1. Typically, $T_{es}$ began to plateau by about minute 40 and remained at an elevated steady state as $P_a$ was increased 1 Torr per 5 min. The critical $T_{ch}$ or $P_a$ was defined by the subsequent upward inflection of $T_{es}$. The inflection point was selected graphically from the raw data (see Fig. 1). A line was drawn between the data points, starting at the 30th min. When the mean slope of the $T_{es}$ line began to deviate upward from the equilibrium phase slope, a second line was drawn from the point of departure of $T_{es}$ from the first line. The $T_{ch}$ or $P_a$ 1 min before the point at which the second line departed from the first was defined as the $T_{crit}$ or $P_{crit}$, respectively. To confirm graphical representation of the upward inflection of $T_{es}$, the slopes were redrawn with different time axes, including logarithmic scales. The upward rise in $T_{es}$ was typically preceded by an inflection point in the HR time course (13-15) and thus could be anticipated during the test.

In heat-acclimated subjects, $T_{es}$ typically equilibrates as a relatively horizontal line below the upward inflection forced by the changing environmental conditions (13-15). However, in the unacclimated subjects tested here, $T_{es}$ often increased gradually before its upward inflection. This occurred in 55 of the 126 experiments. Such a slow rise was considered a “pseudo-steady state” as long as a clear, definitive upward inflection eventually deviated from this slowly rising slope (13). The difference between the slope of this slow-rising $T_{es}$ and a zero-slope time course of $T_{es}$ constituted positive heat storage ($+S$). To be consistent, in the few (<10) subjects who displayed slightly negative sloping “steady states,” negative heat storage ($-S$) was calculated and $S$ was subsequently incorporated into heat balance calculations designed to determine $K_h$.

To test the reliability of the $T_{crit}$ and $P_{crit}$ data, four individual tests were repeated on a different day. These four repeat experiments were selected to cover the range of environments inherent in this study, i.e., they ranged from the driest to the most humid environment. Because the dependent variable in each case is an $x$, $y$ locus on a psychrometric chart, typical test-retest statistics would add a third dimension. For this reason, to calculate a test-retest correlation, the time points at which each critical point was achieved were compared. When inflection times were compared between the initial tests and the repeated tests, a correlation coefficient ($r$) of 0.97 resulted, with a slope of 1.02 and an intercept of -1.11.

**Calculation of critical $K_h$**. All calculations below were performed uniformly across subjects. Metabolic rate ($M$; W/m²) was derived from the $V_{O2}$ (l/min) and respiratory exchange ratio (RER; unitless) as

\[
M = 352 \cdot (0.23 \cdot \text{RER} + 0.77) \cdot V_{O2}/A_d
\]

(2)

where $A_d$ is Dubois surface area (m²). External work ($W$; W/m²) was calculated as

\[
W = 0.163 \cdot m_b \cdot v_w \cdot f_6/A_d
\]

(3)

where $m_b$ is body mass (kg), $v_w$ is walking velocity (m/min), and $f_6$ is fractional grade of the treadmill. $M_{net}$ was then calculated as $M - W$.

Dry heat exchange via radiation and convection (W/m²) was determined as

\[
(R + C) = h_{r+c} \cdot (T_{ch} - T_{sk})
\]

(4)

where $h_{r+c}$ (W·m⁻²·°C⁻¹) is the combined radiative and convective heat transfer coefficient and $T_{ch} - T_{sk}$ represents the temperature gradient between the ambient air and the skin. In this study, $h_{r+c}$ was determined for each subject by using the formula

\[
h_{r+c} = 6.5 \cdot (\text{treadmill speed; m/s})^{0.39} + 4.7
\]

(5)

where 6.5·(treadmill speed; m/s)⁰.₃⁹ is the convective coefficient for treadmill walking directly determined by Nishi and
Gagge (22) and 4.7 is the radiative coefficient for indoor environments. Where appropriate, $S$ (W/m²) was calculated as

$$S = AT_b \cdot \frac{(0.97 \text{ W} \cdot \text{h} \cdot \text{kg}^{-1} \cdot \text{°C}^{-1}) \cdot (m/A_p)}{6}$$

where 0.97 W·h·kg⁻¹·°C⁻¹ is the specific heat of the body and $AT_b$ represents the change in mean body temperature measured over the time period ($AT$, h) between 30 min and the time at which the critical T assessing inflection point was observed. The equation for $AT_b$ (°C), which is a function of the change in both $T_{sk}$ and $T_{wb}$ was

$$AT_b = (0.9 \cdot T_{wb} + 0.1 \cdot T_{sk}) \text{ at critical point}$$

$$-(0.9 \cdot T_{wb} + 0.1 \cdot T_{sk}) \text{ at minute 30}$$

Maximal evaporative capacity of the environment ($E_{max}$; W/m²) was calculated as

$$E_{max} = K' \cdot v^{0.6} \cdot (P_{sk} - P_a)$$

where $v$ (m·s⁻¹) was equal to 0.45 for this study. At each critical environmental condition, the evaporative cooling required to maintain thermal balance ($E_{req}$) equals $E_{max}$, i.e.,

$$M_{net} = (R + C) \cdot S = E_{max}$$

and the heat balance equation can be solved for $K'$. This solution assumes a fully wetted skin surface, a requirement that, as expected, was met only in the $P_{crit}$ tests (see Discussion).

Isothermal lines were constructed on a psychrometric chart from mean group data following the procedures described by Kerslake (17) and Hatch (11) and with the $T_{sk}$ and the mean $K' \cdot v^{0.6}$ values determined in the present study. The portion of the isotherm for fully wet skin was constructed by using a psychrometric anchor point with locus $T_{sk} = T_{sk} - (E_{sk}/M_{net})$, $P_a = P_{sk}$. The slope of the line ($\psi$) was $h_r + J(K' \cdot v^{0.6})$. The curved portion of the isotherm at higher $T_{db}$ values and lower $P_a$ values was constructed by calculating the $T_{db}$ for free evaporation (using the highest mean evaporative rate for each group) and constructing a curve according to Kerslake (17), where the $T_{db}$ for free evaporation = $T_{db} + (E_{sk} - M_{net})/h_r$. In each case, this assumed that the mean sweating rate for the full exposure time represented the sweating rate at the critical $T_c$ inflection. As shown subsequently by the data collected, this was not the case, especially for the women.

**Statistical analysis.** Variables that changed throughout conditions were analyzed with an analysis of covariance with repeated measures. A SAS program was written by using the PROC MIXED statement, with independent variables of sex and the fixed critical condition; the dependent variable was the unknown critical environmental parameter. A one-way analysis of variance was used to compare subject characteristics and variables calculated once per trial, e.g., $M_{net}$, ($R + C$), sweating rate, $K'$, and so forth. Where significant $F$ values were found, Tukey’s follow-up tests were performed. Differences were considered significant at the 0.05 level.

**RESULTS**

Subjects for this study were recruited to be representative of the population with respect to body size, adiposity, and aerobic fitness. Thus the women were shorter, weighed less, and had a higher percent body fat and a lower body surface area than the men (all at $P < 0.05$; Table 1). Body fatness ranged from 11 to 26% for the men and from 16 to 29% for the women. With respect to body mass index, the men ranged from the 18th to the 71st percentile for their age group, whereas the women ranged from the 24th to the 87th percentile (1). The women also had a 13–14% lower $V_{O2,max}$, which translated to a significantly lower $M$, $M_{net}$ (139 ± 3 vs. 191 ± 6 W/m², $P < 0.001$) and $E_{req}$ during exercise of $30\% V_{O2,max}$ (Table 2) in each critical environment. The measured exercise intensity ranged from 29.9 ± 1.1 to 32.3 ± 1.0% $V_{O2,max}$ for the men and from 28.3 ± 0.9 to 30.0 ± 1.0% $V_{O2,max}$ for the women across trials ($P > 0.05$). Mean sweating rate was consistently and significantly ($P < 0.05$) lower in the women, as was the $E_{sk}$ of the sweat produced (Table 2).

Table 3 presents the $T_{db}$ and $P_a$ psychrometric locus values for each critical environment as well as the mean $P_{sk} - P_a$. In the tests conducted at $T_{db}$ = 34, 36, and 38°C (coinciding with the more humid environments), each respective $P_{crit}$ was significantly higher and each $P_{sk} - P_a$ was significantly lower for the women ($P < 0.05$). No significant sex differences were seen in the critical $P_{sk} - P_a$ for the tests at fixed low ambient vapor pressures. These critical environmental loci are plotted on a standard psychrometric chart in Fig. 2.

Also shown in Fig. 2 are calculated isothermal lines from previously published biophysical models of heat

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**Table 2. Sweating rate and calculated heat balance variables for unacclimated men and women in each critical environment**

<table>
<thead>
<tr>
<th>Temperature</th>
<th>Sweating Rate, ml·m⁻²·h⁻¹</th>
<th>$M_{net}$, W/m²</th>
<th>$E_{sk}$, W/m²</th>
<th>$E_{req}$, W/m²</th>
<th>$K'$, W·m⁻²·Torr⁻¹</th>
<th>$w$, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>34°C</td>
<td>306 ± 10</td>
<td>262 ± 38</td>
<td>189 ± 6</td>
<td>158 ± 7</td>
<td>17.4 ± 0.6</td>
<td>1.30</td>
</tr>
<tr>
<td>36°C</td>
<td>357 ± 16</td>
<td>257 ± 27</td>
<td>191 ± 6</td>
<td>175 ± 6</td>
<td>15.5 ± 0.6</td>
<td>1.34</td>
</tr>
<tr>
<td>38°C</td>
<td>394 ± 14</td>
<td>278 ± 14</td>
<td>191 ± 6</td>
<td>195 ± 6</td>
<td>14.2 ± 0.3</td>
<td>1.36</td>
</tr>
<tr>
<td>12 Torr</td>
<td>318 ± 16</td>
<td>250 ± 14</td>
<td>190 ± 6</td>
<td>235 ± 13</td>
<td>189 ± 10</td>
<td>0.92</td>
</tr>
<tr>
<td>16 Torr</td>
<td>279 ± 19</td>
<td>243 ± 13</td>
<td>190 ± 6</td>
<td>256 ± 10</td>
<td>201 ± 6</td>
<td>0.73</td>
</tr>
<tr>
<td>20 Torr</td>
<td>354 ± 24</td>
<td>248 ± 20</td>
<td>191 ± 6</td>
<td>286 ± 12</td>
<td>232 ± 4</td>
<td>0.91</td>
</tr>
</tbody>
</table>

Values are means ± SE for 11 men and 10 women. $M_{net}$, metabolic heat production; $E_{sk}$, evaporative cooling from the skin; $E_{req}$, required evaporation to maintain heat balance, i.e., $M_{net} = (R + C)$ where $R + C$ is combined dry heat gain or loss through radiation and convection; $K'$, derived critical evaporative coefficient; $w$, %skin wettedness, calculated as $E_{req}/E_{max}$, using each derived $K'$ to calculate $E_{max}$. *Significant sex difference at $P < 0.05$. 

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Figure 2. A standard psychrometric chart showing the mean Pcrit and values determined empirically for 11 unacclimated men (○) and 10 unacclimated women (○). Pcrit values were significantly higher for the women in the humid conditions because of their lower absolute heat production at 30% maximal aerobic capacity (VO2max), whereas no differences were seen in drier environments (see text for full explanation). The dotted arrowheads point to separate biophysical anchor points with coordinates \( T_{db} = T_{sk} - (E_{sk}/M_{net}) \), \( P_{a} = P_{sk} \), and have a calculated slope \(-\psi = h_{r-e}/K_{e'}^{v^{0.6}}\), where \( E_{sk} \) is skin evaporative capacity, \( M_{net} \) is net metabolic heat production, \( P_{sk} \) is vapor pressure gradient, \( h_{r-e} \) is the combined radiative and convective heat transfer coefficient, \( K_{e'} \) is the critical evaporative coefficient, and \( v \) is air velocity. Data fit the calculated relation for both the men and the women. On the other hand, the dotted isotherms curving toward a limit for free evaporation at \( T_{db} \) values above 40°C were significantly lower than the experimental data. These curves transition from full wettedness \((w = 1)\) to free evaporation \((w = 0)\) and are a function of \( T_{sk} \) and \( E_{sk} \).
DISCUSSION

The objective of the present study was to determine, for unacclimated subjects, the range of hot ambient environments beyond which $T_c$ would not equilibrate at a level set by exercise intensity. The protocol used was a modification of that developed by Belding and Kamon (3) and refined by Kamon and Avellini (13) and then again refined by Kenney (15, 16). The underlying basis was to empirically determine a family of ambient conditions under which $M_{net}$. At full skin wettedness, $E_{max}$ can be derived by solving the heat balance equations involved. Before this investigation, this approach had only been used for fully heat-acclimatized men and women (3, 13, 14).

Potential limitations. The approach utilized in the present paper is built on heat balance calculations that, although theoretically sound, are based on numerous previous investigations, each of which made unique assumptions. Coefficients and calculations chosen for this investigation in some cases followed the previous studies of Kamon and colleagues (3, 13) so that comparisons could be made more directly between the studies. Some coefficients were directly determined, i.e., by naphthalene sublimation (22), whereas others were based on indirect calculations from empirical data. With the exception of Kamon and colleagues (13, 14), subjects in those previous studies were predominantly men.

Psychrometric limits. When $T_{db}$ is close to $T_{sk}$, dry heat transfer is minimal and heat exposure at a given metabolic rate is limited by the vapor pressure gradient, $P_{sk} - P_a$. In such environments, one would predict that higher sweating rates typically exhibited by men (2, 4, 6–8, 10, 12, 20, 24) would not be beneficial and that critical limits would be similar between unmatched men and women. Under hotter, drier ambient environments where $(R + C)$ is positive and $E_{max}$ is high, the limit to prolonged exposure is defined by sweating capacity; men, who typically have higher maximal sweating rates, should have an advantage in these environments. However, such was not the case in this experiment.

As shown in Fig. 2, separate limit lines were observed for the men and women at $T_{db} = 34–38^{\circ}C$, with the women's limits occurring at higher ambient vapor pressures. This was solely due to the women's lower exercise intensity (18, 19) and corresponding metabolic heat production, as opposed to a true sex difference. We chose a relative exercise intensity of 30% $V_{O2 max}$ because 1) it reasonably simulates light-to-moderate daily workloads typical of a healthy, normally active population, 2) it is the intensity associated with an 8-h work day in industrial settings (5), and 3) it reflects the intensity for many self-paced activities. Furthermore, physiological strain during exercise in the heat is primarily a function of relative intensity. For these reasons, such a choice made sense to satisfy the practical
aspects of the study. However, because average (e.g., 50th percentile) men and women differ in $V_{O_2\text{max}}$, our subjects exercised at different absolute intensities that resulted in differing $M_{\text{net}}$ values.

Within each group, the empirically derived limits in this temperature range fit well with biophysical models published by others (11, 17, 23). In Fig. 2, the depicted dotted arrows point to biophysical anchor points with coordinates $[T_{\text{db}} = T_{sk} - (E_{sk}/M_{\text{net}}), P_a = P_{s,sk}]$ and have a calculated slope of $-\psi = h_{sc}/K_e' \cdot e^{0.6}$. Data fit the calculated relationship for both the men and the women, supporting the fact that the skin was fully wet and adding credibility to the psychrometric limits. On the other hand, the limit lines calculated for free evaporation at $T_{\text{db}}$ values above 40°C were significantly lower than the experimental data. These curves (shown in Fig. 2) show a gradual curvilinear transition from full wetness (w ≥ 1) to free evaporation (w = 0) and are a function of $T_{sk}$ and $E_{sk}$. In reality, different individuals would have different limits for free evaporation and thus different vertical limit lines, extending to the right as far as the individual sweat capacity will allow it to go until wettedness drops below 1. The single line drawn in Fig. 2 reflects the highest mean sweating rate for each group.

As argued by Kamon and Avellini (13), the most obvious explanation for the lack of fit of the empirically derived data in hot, dry environments is our use of total sweating rate for the full 1.5- to 2.5-h exposures as representative of the sweating rate at each $T_{\text{crit}}$. The experimental protocol prohibits measurement of the true sweating rate at the time each critical environment is reached. Our calculated sweating rate, an average over a long time period (including time spent in less stressful environments early in the exposures and during the transients), likely underpredicts the true sweating rate in the critical environment. If so, the relatively larger overestimate in the unacclimated women might be expected on the basis of the known sluggish onset of sweating (4, 6, 7, 10) and lower sweating rates (2, 4, 6–8, 10, 12, 20, 24) of unacclimated women. It is important to note that such sweating differences are minimized or disappear altogether when women are acclimated and appropriately matched with their male counterparts (e.g., Ref. 9).

As explained in RESULTS, we were able to compare our data with data collected from a group of fully heat-acclimated women tested ~25 yr ago in the same laboratory. The comparison, shown in Fig. 3, clearly elucidates the thermoregulatory advantage imparted by heat acclimation in terms of thermal tolerance. A key adaptation of heat acclimation is a higher sweating rate for any given exercise intensity. Such an increase in sweating would only be advantageous in environments in which ambient $P_a$ is low enough to permit high evaporative rates. In addition, heat-acclimated subjects have a more uniform sweat distribution over the skin surface, which increases evaporative efficiency. These advantages are shown by the flatter slope and higher values of the psychrometric limit line at $T_{\text{db}}$ values above 40°C in heat-acclimated subjects, delimiting a larger range of environments comprising the prescriptive zone.

**Evaporative coefficients.** As shown in Table 2, $K_e'$ values at $T_{\text{db}} = 34–38^\circ\text{C}$ were not significantly different between men and women. Calculation of $K_e'$ requires conditions of fully wet skin, and thus only the $K_e'$ values calculated in the more humid environments are meaningful. In the dry environments, the use of $P_{s,sk}$ when the skin was not fully saturated would result in an overestimate of $E_{\text{max}}$ and an artificially low $K_e'$. As in previous studies, $K_e'$ decreases slightly with increasing $T_{\text{db}}$ and decreasing $P_a$ within this temperature range. The values of $K_e'$ for unacclimated men (17.4, 15.5, and 14.2 W · m$^{-2}$ · Torr$^{-1}$) and women (16.8, 15.5, and 14.2 W · m$^{-2}$ · Torr$^{-1}$) at 34, 36, or 38°C, respectively, were lower than those previously published for fully heat-acclimated men (18.4 W · m$^{-2}$ · Torr$^{-1}$ at 36°C) (3) and women (17.7 W · m$^{-2}$ · Torr$^{-1}$ at 36°C and 15.5 W · m$^{-2}$ · Torr$^{-1}$ at 38°C) (13). These values are more appropriate for future models of heat transfer between humans and the environment when heat acclimation is absent.

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