Evaluation of different levels of hydration using a new physiological strain index

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Moran, Daniel S., Scott J. Montain, and Kent B. Pandolf. Evaluation of different levels of hydration using a new physiological strain index. Am. J. Physiol. 275 (Regulatory Integrative Comp. Physiol. 44): R854–R860, 1998.—A physiological strain index (PSI), based on rectal temperature (Tre) and heart rate (HR), was recently suggested for evaluating heat stress. The purpose of this study was to evaluate the PSI for different combinations of hydration level and exercise intensity. This index was applied to two databases. The first database was obtained from eight endurance-trained men dehydrated to four different levels (1.1, 2.3, 3.4, and 4.2% of body weight) during 120 min of cycling at a power output of 62–67% maximum O2 consumption (Vo2max) in the heat (33°C and 50% relative humidity (RH)). The second database was obtained from nine men performing exercise in the heat (30°C and 50% RH) for 50 min. These subjects completed a matrix of nine trials of exercise on a treadmill at three exercise intensities (25, 45, and 65% Vo2max) and three hydration levels (euhydration and hypohydration at 3 and 5% of body wt). Tre, HR, esophageal temperature (Teo), and local sweating rate were measured. PSI (obtained from either Tre or Teo) significantly (P < 0.05) differentiated among all exposures in both databases categorized by exercise intensity and hydration level, and we assessed the strain on a scale ranging from 0 to 10. Therefore, PSI applicability was extended for heat strain associated with hypohydration and continues to provide the potential to be universally accepted.

Hypohydration increases physiological strain during exercise in the heat. A loss of only 1% water of body weight compared with euhydration causes an increase in core temperature during exercise in normothermic and warm environments (3). Hertzman and Ferguson (12) were the first to describe hypohydration during heat stress as a “failure of the thermoregulatory system.” The addition of hypohydration to the stress further reduces endurance and influences the thermoregulatory control systems, either through associated changes in blood volume (20) or through accompanying changes in plasma osmolality (11). The cardiovascular system is also affected by hypohydration during exercise in the heat. First, hypohydration results in an increase in heart rate (HR) to compensate for the fall in stroke volume. Second, hypohydration reduces cutaneous blood flow; thus the potential for dry heat exchange (by convection and radiation) between the body and the environment is lowered, impairing heat dissipation from the body (27). In 1979, Senay (28) suggested that the increased core temperature in hypohydrated individuals is necessarily the consequence of reduced heat transfer. In 1995, Sawka et al. (27) concluded that during exercise-induced heat stress, hypohydration compared with euhydration accelerates exhaustion from heat strain at a lower rectal temperature (Tre).

Hypohydration is usually associated with either a reduced or unchanged sweat rate (m˙sw) (27). When no change in m˙sw was reported during dehydration in a warm climate at a given metabolic rate, Tre was elevated, reflecting higher strain and delayed m˙sw threshold (26). Numerous investigators had attributed the higher core temperatures that accompany thermal hypohydration to either failure of the sweating response (3, 7) or to a redistribution of blood flow from the cutaneous regions. Some studies showed that different levels of hypohydration affected the sweating mechanism to different degrees (5, 25, 26). Montain et al. (17) found that the threshold temperature for sweating increased with hypohydration level, unlike sweating sensitivity, which decreased. In that study, the exercise intensity when combined with hypohydration increased sweating sensitivity but did not alter the sweating threshold temperature.

Heat strain indexes based on physiological parameters including m˙sw were suggested by a few researchers. McArdle et al. (15) developed the predicted 4-h sweat rate index (P4SR), which uses m˙sw as an indicator of heat strain and predicts m˙sw for 4 h of different combinations of metabolic rate and climatic condition. However, it was shown that sweat production by itself does not comprehensively represent heat strain (1, 9), and the P4SR was relevant only for fit-acclimatized men (14). Robinson et al. (23) suggested an index that relied on Tre, HR, m˙sw, and skin temperature. This index, based on an equal weighting of the four parameters with no relation to the metabolic rate, was developed on the basis of collected data involving heat-acclimatized subjects but was not validated for other conditions. Hall and Plote (8) suggested an index of physiological strain based on body heat storage which also used Tre, HR, and m˙sw. The complexity of calculating this index and the inability to assess the heat strain online were the main reasons that it has not been universally accepted.

In 1980, Lee (14) summarized his review of 75 years of searching for a universal heat stress index as follows: “any reader who was hoping for the evolution of a single heat index applicable to all aspects of human endeavor...”
must by now be sadly disappointed." Although more inclusive and advanced indexes have been developed in the last 20 years, these indexes were unfortunately found to be complicated and difficult to apply (4, 6, 13, 22).

Recently, Moran et al. (19) introduced a physiological strain index (PSI) based on Tre and HR as representative of the combined strain reflected by the thermoregulatory and cardiovascular systems. This simple-to-use index scaled the strain to a range of 0–10 and can be used online or during data analysis. It was shown that the PSI can be applied at any time, including rest or recovery periods, whenever Tre and HR are measured (19). Furthermore, this index successfully rated and correctly discriminated between different clothing ensembles and climate conditions during heat stress.

The purpose of this study was to examine the ability of the PSI to assess and categorize heat strain at different combinations of hypohydration level and exercise intensity. In addition, we aimed to evaluate the interaction between PSI and m˙sw for these experimental conditions.

MATERIAL AND METHODS

The PSI was applied to two databases (16, 17). The first produced different levels of dehydration by having volunteers drink different volumes of fluid during prolonged exercise in the heat (16). The second database, taken from an independent study, examined the HR, core temperature, and sweating response to different combinations of hypohydration level and exercise intensity (17).

Protocol 1. Evaluation of PSI for different levels of dehydration during prolonged exercise was done using a database from Montain and Coyle (16) and was within the range of 53–175 beats/min for HR, 36.8–39.7°C for Tre, and 36.4–39.2°C for Te. Eight endurance-trained male cyclists [age 23 ± 3 yr, body wt 72.2 ± 11.6 kg, and maximum O2 consumption (VO2max) 66.2 ± 7.6 ml·kg⁻¹·min⁻¹] cycled at a power output eliciting 62–67% VO2max for 120 min in a warm environment (33°C and 50% relative humidity (RH)). Each subject completed four experimental exposures while ingesting different volumes of fluid during exercise: no fluid or a fluid volume sufficient to replace the sweat losses during the 50-min exposure time during the 65% VO2max trials when a subject voluntarily withdrew, when a subject's esophageal temperature (Te) reached 39.5°C, or when HR exceeded 90% of maximum HR for 3 consecutive minutes.

In both protocols, Te was measured from a thermistor (model YSI 401, Yellow Springs Instruments, Yellow Springs, OH) inserted 10 cm past the anal sphincter. Te was measured by a thermodilution catheter placed in the left ventricle and recorded at 10-min intervals with a telemetry system. In addition, in the second protocol, local m˙sw of the upper arm was calculated from a continuously ventilated dew point sensor within a 15.9-cm² capsule (16).

Calculations. The PSI was calculated using either Te or Tre as suggested by Moran et al. (19) as follows

\[
PSI = 5(T_{re} - T_{r0}) \cdot (39.5 - T_{r0})^{-1} + 5(HR_r - HR_0) \\
\cdot (180 - HR_0)^{-1}
\]

where T_{r0} and HR_0 are the initial Te and HR, respectively, and T_{re} and HR_r are simultaneous measurements taken at any time.

The PSI was categorized (Table 1) as previously suggested (19).

Sweating sensitivity was calculated as the slope of the regression line representing minute m˙sw and Te values obtained during the linear phase of the exercise transient (<20 min of exercise). The threshold for active thermoregulatory sweating was defined as the Te when m˙sw exceeded 0.06 mg·(cm²)⁻¹·min⁻¹ and began to progressively increase sweating above resting values (16).

Statistical analysis. Physiological responses at the different levels of hydration and the interaction of exercise intensity and hydration level on sweating were analyzed by two-way ANOVA for repeated measures. All statistical contrasts were accepted at the P < 0.05 level of significance. All experimental data are presented as means ± SE. The material and methods are presented in greater detail elsewhere (16, 17).

RESULTS

Database 1. Generally, Te and Tre were elevated in proportion to the magnitude of the hypohydration levels, and the four trials were significantly different from each other (P < 0.05), with the exception of the 3.4 and 4.2% BWL exposures (Fig. 1). Similarly, HR increased progressively during exercise at the different levels of hypohydration. However, at 120 min of exercise, HR was not significantly different between the exposures of 1.1 and 2.3% BWL and the 3.4 and 4.2% BWL (Fig. 1).

The PSI correctly discriminated between combinations of exercise intensity and hypohydration level for these trials. A comparison of PSI at the four levels of
dehydration induced by ingesting different volumes of fluid during exercise is depicted in Fig. 2 and Table 2. Significantly higher values of PSI were observed with increasing hypohydration level ($P < 0.01$). As a consequence of the significantly higher values of $T_{re}$ compared with $T_{es}$ ($P < 0.01$), there were also significantly higher values of PSI for $T_{re}$ than for $T_{es}$.

PSI rated the strain in rank order according to the hypohydration level (from 6.5 to 8.7 for 1.1 to 4.2% BWL, respectively). Categorization of the strain was done according to a previous study (19). However, the Borg scale (2) for subjective rating of perceived exertion (RPE) revealed a similar strain categorization as with PSI (Table 2). The RPE increased with hypohydration level during the 120-min exposures and was significantly different across all trials ($P < 0.05$), with the exception of 1.1 and 2.3% BWL exposure. The mean RPE categorized the four levels of hypohydration as “somewhat hard” to “very hard,” ranging from 13.4 to 17.6 for 1.1 to 4.2% BWL, respectively.

Database 2. HR, $T_{re}$, and $T_{es}$ dynamics during these experimental exposures are presented in Figs. 3 and 4. Generally, at the same exercise intensity HR, $T_{re}$ and $T_{es}$ values were higher with increasing levels of hypohydration. At the low exercise intensity (25% $V_{O_2\max}$), HR values were significantly less than for the other two

Fig. 1. Physiological strain index (PSI), calculated from rectal temperature ($T_{re}$) and heart rate (HR), applied to mean values obtained from 8 subjects exposed to heat stress [33°C, 50% relative humidity and 65% maximum O$_2$ consumption ($V_{O_2\max}$)] at 4 different levels of hypohydration [1.1, 2.3, 3.4, and 4.2% body weight loss (BWL)]. bpm, Beats/min.

Fig. 2. PSI calculated from $T_{re}$ (A) and esophageal temperature ($T_{es}$, B) on database of Montain and Coyle (16). Values obtained from 8 subjects exposed to 4 different levels of hypohydration (1.1, 2.3, 3.4, and 4.2% of BWL) during exercise.
Table 2. Evaluation and categorization of different strains by PSI and RPE

<table>
<thead>
<tr>
<th>Hydration, %BW</th>
<th>PSI Units</th>
<th>Strain</th>
<th>RPE Units</th>
<th>Strain</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1</td>
<td>6.5 ± 0.8</td>
<td>Moderate</td>
<td>13.4 ± 0.5</td>
<td>Somewhat hard</td>
</tr>
<tr>
<td>2.3</td>
<td>7.4 ± 0.3</td>
<td>High</td>
<td>14.1 ± 0.6</td>
<td>Somewhat hard to hard</td>
</tr>
<tr>
<td>3.4</td>
<td>8.1 ± 0.4</td>
<td>High</td>
<td>15.6 ± 0.8</td>
<td>Hard</td>
</tr>
<tr>
<td>4.2</td>
<td>8.7 ± 0.3</td>
<td>Very high</td>
<td>17.6 ± 0.3</td>
<td>Very hard</td>
</tr>
</tbody>
</table>

Unit values are means ± SE. Eight subjects were evaluated after 120 min of exposure to heat stress [30°C, 50% relative humidity (RH), and 65% maximum O2 consumption (VO2max)] at different hydration levels. RPE, rating of perceived exertion; BWL, body weight loss.

The intensities (45 and 65% VO2max) across all hydration levels (P < 0.05). Similarly, HR values at 3 and 5% BWL for the moderate intensity were not significantly different from the euhydration values at the high exercise intensity (Fig. 3). Compared with simultaneous measurements of Te and T es, all Te values were significantly higher (−0.1–0.4°C, P < 0.01). Analysis of the Te and T es dynamics during all the exposures revealed a pattern in which the low exercise intensity at 5% BWL overlapped with the high intensity during euhydration (Fig. 4).

In Fig. 5, PSI was applied to HR and Tre (Fig. 5A) and HR and T es (Fig. 5B) collected from the nine subjects performing the nine experimental combinations (17). PSI was found to be correlated (r = 0.99) with exercise intensity and with hypohydration level using either Tre or T es. PSI succeeded in clearly differentiating among all the exposures on a scale within the 0–10 range. There were no significant differences between PSI calculated using Tre or T es at 25 and 45% VO2max. However, PSI obtained at 65% VO2max from Tre was significantly higher than the PSI obtained from T es (P < 0.01).

PSI categorized the heat strain in rank order according to the combined exercise intensity and hydration level (Table 3). In general, the euhydration exposures were ranked as little or low strain with values of 1.6 ± 0.2 to 3.1 ± 0.3. The 3% BWL exposures were ranked as moderate strain and ranged from 4.3 ± 0.2 to 6.4 ± 0.4, and the 5% BWL exposures were categorized with high and very high strains, ranging from 7.4 ± 0.3 to 10.0 ± 0.9.

The m˙sw at 20 min of exercise and the comparative PSI values are presented in Figs. 6 and 7. The m˙sw and PSI values at the three exercise intensities and across the three hydration levels are presented in Fig. 6. Figure 6 shows that m˙sw increased with exercise intensity and correlated well (r = 0.99) with PSI. The m˙sw at the three different hydration levels, across all exercise intensities, is presented along with the evaluation of the strain by PSI in Fig. 7. An inverse correlation is depicted between PSI and m˙sw (r = −0.99). At higher hypohydration levels, the m˙sw decreased and PSI values increased.

**DISCUSSION**

The PSI for the two different databases under investigation accurately described the heat strain of men dehydrated to four different levels during 120 min of cycling and the strain accompanying a matrix of three exercise intensities and three hypohydration levels. Our index succeeded in rating each one of these exposures on its universal scale of 0–10. The index, which is based on only two physiological parameters, HR and core temperature (Tre or T es in this study), categorized every exposure in the proper and expected order, whereas HR, Tre, and T es during the different exposures were limited in their individual ability to categorize each exercise intensity-hyphydration level combination separately (Figs. 1, 3, and 4).

During the last century, more than twenty heat strain indexes have been proposed (1, 14). However, none has been accepted as a universally valid index for rating heat stress. This is mainly attributable to the number and complexity of the interactions among the determining factors (1, 19). The ability to sustain exercise in the heat depends mainly on the effective heat transfer from the contracting muscles to the skin and from the skin to the environment. Dehydration compromises blood flow to the skin, resulting in greater thermal and cardiovascular strain. Thus, when hypohydration accompanies heat stress, it causes even more difficulties in evaluating the resultant physiological strain. The combination of many different levels of hypohydration and different exercise intensities pro-

![Fig. 3. HR dynamics (means ± SE) of all subjects who participated in 9 experimental exposures consisting of 3 exercise intensities (25, 45, and 65% VO2max) and 3 hydration levels (euhydration and hypohydration at 3 and 5% of body wt). * Drop due to subject attrition.](image-url)
vided by our two unique databases challenged the ability of the PSI to discriminate the relative strain of exercise in the heat.

It is well known that $T_{es}$ values are generally lower than simultaneous $T_{re}$ measurements (21, 24). $T_{es}$ responds rapidly and quantitatively to changes in blood temperature with a time constant of $\sim 1$ min, whereas $T_{re}$ responds more slowly with a time constant of $\sim 12$ min (e.g., during exercise) (27). To further the appreciation of the versatility of the PSI, we examined the physiological strain using both $T_{re}$ ($PSI_{re}$) and $T_{es}$ ($PSI_{es}$) measurements.

The simultaneous measurement of $T_{re}$ and $T_{es}$ in both database sets revealed higher $T_{re}$ ($P < 0.01$) (Figs. 2 and 4). Therefore, it was expected that $PSI_{re}$ would result in higher values than $PSI_{es}$. This was true for the first database, because $PSI_{re}$ was significantly higher than $PSI_{es}$ by $\sim 0.5–1.0$ unit ($P < 0.01$). However, in the second database, $PSI_{re}$ was not significantly higher than $PSI_{es}$ during exercise at 25 and 45% of $V_{\dot{O}_2 max}$. $PSI_{re}$ was highest during the higher exercise intensity (65% of $V_{\dot{O}_2 max}$) (Fig. 4). These minor differences between $PSI_{re}$ and $PSI_{es}$ are attributed to the PSI construction, which normalized each physiological
parameter (HR and T<sub>re</sub> or T<sub>es</sub>) to its initial value. Regardless, it can be concluded that PSI<sub>T</sub> and the original PSI (PSIT<sub>re</sub>) are both able to provide meaningful values for estimating different levels of hypohydration during exercise heat stress, including severe conditions in which body heat balance is violated.

The two databases used supported earlier observations that hypohydration increased T<sub>re</sub> and HR during exercise in the heat (25–27). Furthermore, as the severity of hypohydration increases during exercise in the heat, there is an associated increment in the elevation of T<sub>re</sub> and HR. The incrementally increased T<sub>re</sub> had been associated with a decreased m<sub>sw</sub>. Correspondingly, it was expected that T<sub>re</sub>, T<sub>es</sub>, and HR could be used for physiological strain assessment. T<sub>re</sub> and T<sub>es</sub> reflect the body heat storage and are elevated proportionally to exercise intensity during exercise. HR reflects the demands of the circulatory system. Unlike T<sub>re</sub>, HR rapidly responds to changes in metabolic demands and environmental conditions (18). However, as depicted in Figs. 1, 3, and 4, T<sub>re</sub>, T<sub>es</sub>, and HR were limited in their ability to individually quantify and categorize the different experimental exposures. On the other hand, applying PSI to the same database containing T<sub>re</sub> or T<sub>es</sub> and HR measurements clearly evaluated the relative strain with a simple scale ranging from 0 to 10 (Fig. 5). In fact, the PSI described well the physiological strain at the different exercise intensities and hypohydration levels according to classic physiology: 1) exercise intensity correlated with the physiological stress and with m<sub>sw</sub> (Fig. 6) and 2) hypohydration level correlated with the physiological stress and inversely correlated with m<sub>sw</sub> (Fig. 7). The commonly used RPE scale was also correlated with hypohydration levels. However, although RPE correlated with PSI and discriminated among the different hypohydration levels, it was limited in significantly differentiating between two exposures (1.1 and 2.3% BWL), unlike the PSI.

The PSI, unlike other heat strain indexes, depicts the combined strain reflected by the cardiovascular and thermoregulatory systems. This enables the PSI to make comparisons between different studies. The first database analyzed in this study was collected for 120 min, whereas the second database was obtained for 50 min. However, a comparison of PSI between the two databases for similar exposures (65% V<sub>O2max</sub>, and 3% BWL) after 50 min of exercise revealed the same moderate strain category values of 6.0 and 6.4 (for the first and the second databases, respectively). In a previous study, the PSI showed the ability to assess heat strain at different combinations of metabolic rate, climate condition, and clothing (19). In this study, we were able to extend its evaluation to different combinations of hypohydration levels and exercise intensities in the heat using either T<sub>re</sub> or T<sub>es</sub> and RPE.

In summary, the PSI successfully evaluated the heat stress in subjects who exercised in a warm environment at different exercise intensities combined with different levels of hypohydration. This index overcame the individual limits of the physiological parameters (T<sub>re</sub>, T<sub>es</sub>, and HR) in assessing heat stress for this study and continues to provide the potential to be accepted universally.

This work was conducted at the United States Army Research Institute of Environmental Medicine (Natick, MA) while the first author was a National Research Council Postdoctoral Associate.

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

### Table 3. Calculated PSI from measured HR and T<sub>re</sub>

<table>
<thead>
<tr>
<th>Work Intensity, %V&lt;sub&gt;O2max&lt;/sub&gt;</th>
<th>Hydration, %BWL</th>
<th>PSI Units</th>
<th>Strain</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>0</td>
<td>1.6±0.2</td>
<td>Little</td>
</tr>
<tr>
<td>45</td>
<td>3</td>
<td>2.2±0.3</td>
<td>Little</td>
</tr>
<tr>
<td>65</td>
<td>5</td>
<td>3.1±0.3</td>
<td>Low</td>
</tr>
<tr>
<td></td>
<td>0</td>
<td>4.3±0.2</td>
<td>Low</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>5.5±0.4</td>
<td>Moderate</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>6.4±0.4</td>
<td>Moderate</td>
</tr>
<tr>
<td></td>
<td>0</td>
<td>7.4±0.3</td>
<td>High</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>9.1±0.9</td>
<td>Very high</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>10.0±0.9</td>
<td>Very high</td>
</tr>
</tbody>
</table>

Unit values are means ± SE. Nine subjects were evaluated during exercise in the heat (36°C and 50% RH) after 50 min at different exercise intensities (25, 45, and 65% V<sub>O2max</sub>) and different hydration levels (euhydration and hypohydration at 3 and 5% body wt).
REFERENCES