Aging and assessment of physiological strain during exercise-heat stress

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Moran, Daniel S., W. Larry Kenney, Jane M. Pierzga, and Kent B. Pandolf. Aging and assessment of physiological strain during exercise-heat stress. Am J Physiol Regulatory Integrative Comp Physiol 282: R1063–R1069, 2002; 10.1152/ajpregu.00364.2001.—The purpose of this study was to evaluate the physiological strain index (PSI) for different age groups during exercise-heat stress (EHS). PSI was applied to three different databases. First, from young and middle-age men (21 ± 2 and 46 ± 5 yr, respectively) matched (n = 9 each, P > 0.05) for maximal aerobic power. Subjects were heat acclimated by daily treadmill walking for two 50-min bouts separated by 10-min rest for 10 days in a hot-dry environment [49°C, 20% relative humidity (RH)]. The second database involved a group (n = 8) of young (YA) and a group (n = 7) of older (OA) men (26 ± 1 and 69 ± 1 yr, respectively) who underwent 16 wk of aerobic training and two control groups (n = 7 each) who were matched for age to YA and OA. These four groups performed EHS at 36°C, 40% RH on a cycle ergometer for 60 min at 60% maximal aerobic power before and after training. The third database was obtained from three groups of postmenopausal women and a group of 10 men. Two groups of women (n = 8 each) were undergoing hormone replacement therapy, estrogen or estrogen plus progesterone, and the third group (n = 9) received no hormone replacement. Subjects were over 50 yr and performed the same EHS: exercising at 36°C, 40% RH on a cycle ergometer for 60 min. PSI assessed the strain for all three databases and reported differences were significant at P < 0.05. This index rated the strain in rank order, whereas the postacclimation and postraining groups were assessed as having less strain than the preacclimation and pretraining groups. Furthermore, middle-aged women on estrogen replacement therapy had less strain than estrogen + progesterone and no hormone therapy. PSI evaluation was extended for men and women of different ages (50–70 yr) during acute EHS, heat acclimation, after aerobic training, and inclusive of women undergoing hormone replacement therapy.

esophageal temperature; heart rate; predictive indexes; rectal temperature

COLLECTIVELY, THE LITERATURE on heat tolerance for the general population suggests that middle-aged and older men and women are more exercise-heat intolerant, suffering more physiological strain during exposure to a hot environment than younger individuals (6, 27). Older men and women have been reported to have higher heart rates (HR), higher mean skin and core (Tc) temperatures, and lower sweat rates than younger men and women during exercise-heat stress (EHS). However, it is unclear from these studies whether the exercise-heat intolerance observed with aging was related to age per se or associated with other factors such as certain disease states, decreased physical activity, and/or lowered aerobic fitness (21).

In 1965, Robinson et al. (22) were the first to imply that “habitually active” middle-aged men displayed the same acute exercise-heat tolerance and acclimated to heat at about the same rate and degree as when they were younger. This was proved by the same four men in this study who were evaluated [40°C, 25% relative humidity (RH)] when they averaged 31 and 52 yr of age and showed that heat tolerance was approximately the same at both times of testing (22). More recently, studies emphasize the importance of aerobic fitness and physical characteristics such as body fat and body weight in maintaining work-heat tolerance with aging (21). In 1988, Kenney (10) compared the thermoregulatory responses of unacclimated older men and women to those of unacclimated younger men and women. These two age groups were matched for maximal aerobic power (V\text{O}_2\text{max}), surface area (A\text{D}), and A\text{D}-to-mass ratio, but they were different in average age by 35 yr. Evaluating Tc, mean skin temperature, and sweat rate during 75 min of light exercise at 37°C (60% RH) revealed the same level of physiological strain for the younger and older individuals. Also in 1988, Pandolf et al. (20) compared the acute heat tolerance on the first day of heat acclimation for young and middle-aged men who were matched for V\text{O}_2\text{max} and selected morphological factors. The middle-aged men’s tolerance time was half an hour longer than that of the younger men during the first day of acclimation (49°C, 20% RH). These middle-aged men were also at a thermo-
regulatory advantage during the few days of heat acclimation, but both groups acclimated to the same absolute degree. However, the middle-aged men were more chronically active than the younger men before heat acclimation. In 1990, Smolender et al. (24) did not find differences in tolerance time between young sedentary and moderately active middle-aged men during exposure to warm-humid (30°C, 80% RH) or hot-dry (40°C, 20% RH) environments. These studies (10, 20, 24) suggest that when middle-aged and younger individuals are matched for level of aerobic fitness and selected morphological factors (e.g., body mass, Ao, and percentage body fat), the resultant physiological strain between age groups during acute heat stress or heat acclimation is either the same or improved for middle-aged compared with younger individuals (9). In 1999, Thomas et al. (26) suggested that older men (61–78 yr) improved their skin blood flow response to EHS through the effect of aerobic training on the cutaneous vasodilator system.

Studies of middle-aged women and heat stress are usually involved with the influence of the hormonal system because of the menopause stage. The effects of different hormone replacement therapies for middle-aged women on the thermoregulatory system during rest and exercise in the heat have also been studied extensively during the last decade (3, 4, 8, 25). Analysis of circulating estrogen and progesterone during heat stress showed that an increased progesterone-to-estrogen ratio during the luteal phase was associated with an elevated Te (5). However, elevated circulating levels of unopposed estrogen in middle-aged women at rest and during EHS were associated with a lower regulated Tcl (25).

Recently, Moran et al. (19) introduced a physiological strain index (PSI) based on Tcl and HR, as representative of the combined strain reflected by the thermoregulatory and cardiovascular systems. This simple-to-use index scales the strain to a range of 0–10 and can be used on-line or during data analysis. PSI can be applied at any time, including rest or recovery periods whenever Tcl and HR are simultaneously measured, and has been validated for other species (16). Furthermore, this index successfully rates and correctly discriminates between different clothing ensembles, hydration levels, and climate conditions during EHS (17) and most recently for gender during various exercise-heat exposures (18). The purpose of this study was to extend PSI evaluation for men and women at different ages during EHS under different treatments.

MATERIAL AND METHODS

The material and methods for the original data are presented in greater detail elsewhere (3, 20, 26). The PSI was applied to three different databases contributed from the authors of previously published papers (3, 20, 26).

Protocol 1. Evaluation of PSI for young (Y, 21 ± 1 yr) and middle-aged (MA, 46 ± 2 yr) men during 10 days of heat acclimation was done using a database from Pandolf et al. (20). Two groups of nine men each, who were matched (P > 0.05) for VO$_{2}$max (52.9 ± 1.7 and 51.3 ± 3.1 ml·kg$^{-1}$·min$^{-1}$, Y and MA, respectively) and physical characteristics (body wt 76.3 ± 2.2 and 82.2 ± 3.2 kg, Ao 1.90 ± 0.03 and 2.01 ± 0.04 m$^2$ for Y and MA, respectively), participated in this study. All subjects were heat acclimated by treadmill walking (1.56 m/s, 5% grade) for two 50-min exercise bouts separated by a 10-min rest period for 10 consecutive days in a hot-dry (49°C, 20% RH) environment. The exercise intensity required ~45% VO$_{2}$max for both groups. Heat acclimation was preceded by an identical protocol in a comfortable environment (22°C, 50% RH) to collect baseline data. A number of experiments in protocol 1 were terminated before the scheduled exposure time during the first few days of acclimation, when a subject voluntarily withdrew, when a subject’s core temperature reached 39.5°C, or when HR exceeded 90% of HRmax for 3 consecutive min. However, in protocols 2 and 3 all the subjects completed all experimental exposures.

For protocol 1, rated perceived exertion (RPE) was evaluated by use of the Borg scale (2). This is a category rating scale from 6 to 20 with every odd number anchored by verbal expression ranging from “very, very light” at 7 to “very, very hard” at 20. Thermal sensation (TS) was evaluated using a category rating scale (28). This 17-point rating scale ranges from 0.0 to 8.0 in half-number increments with every whole number anchored by verbal expressions ranging from “unbearably cold” at 0.0 to “unbearably hot” at 8.0.

Protocol 2. Fifteen young men (26 ± 1 yr) and 14 older men (69 ± 1 yr) participated in this study (26). The young (Y) and older (O) men were subdivided into two aerobic (A) training groups of eight (YA) and seven (OA) men, respectively, and two control (C) groups of seven men each (YC and OC, respectively). During the training program (16 wk), YA and OA exercised four times per week, achieving 60–80% of their maximal HR for 30–60 min per session. Training programs were reevaluated through examination of daily training records, and workloads were adjusted every 1–2 wk to ensure that subjects maintained their target HR while exercising. During workouts, subjects used treadmills, cycle ergometers, rowers, and stair climbers (Stairmaster, Kirkland, WA). The control groups (YC and OC) did not participate in any training regimen and were instructed to maintain their present level of daily activity throughout the 16-wk period. All subjects from these four groups performed an exercise heat-stress test before and after the 16-wk period. The exercise consisted of cycling on an ergometer for 60 min at 60% of each subject’s VO$_{2}$max in a hot environment (36°C, 40% RH). Core temperature was measured from a thermistor inserted in the esophagus to 25% of the subject’s height (23). The HR was measured by use of a Finapres blood pressure monitor (Ohmeda, Madison, WI).

Protocol 3. Twenty-five postmenopausal women, divided into three groups, participated in this study (3). Two groups of eight women each were on chronic hormone replacement therapy (≥2 yr) that consisted of estrogen only (E) or estrogen plus progesterone (E + P). The third group of nine women had no hormone replacement therapy (NO). All the women who participated were no longer experiencing symptoms (hot flashes, insomnia, etc.) normally associated with the perimenopausal period. The three groups, E, E + P, and NO, were matched (P > 0.05) for VO$_{2}$max (20.0 ± 1.7, 22.6 ± 1.9, and 24.4 ± 0.5 ml·kg$^{-1}$·min$^{-1}$, respectively) and age (54 ± 2, 58 ± 2, and 59 ± 2 yr, respectively). A group of eight men (M; VO$_{2}$max = 29.9 ± 1.4 ml·kg$^{-1}$·min$^{-1}$ and 52 ± 2 yr served as a control for the NO group to evaluate PSI. All four groups performed the same exercise in a hot environment (36°C, 40% RH). After a 10-min rest period, subjects exercised for 30 min at 40% VO$_{2}$max and then 30 min at 60% VO$_{2}$max. Core temperature was measured from a rectal thermistor inserted
10 cm past the anal sphincter. The HR was continuously monitored from a Finapres cuff attached to the middle finger of the right hand.

The PSI was calculated by either using esophageal temperature (T_{es}) or rectal temperature (T_{re}) as suggested by Moran et al. (19) as follows

\[
PSI = 5(T_{re} - T_{es}) \cdot (39.5 - T_{re})^{-1} + 5(HR - HR_{0}) \cdot (180 - HR_{0})^{-1}
\]

where T_{re} and HR_{0} are the initial T_{re} and HR taken before the exposure, and T_{es} and HR are simultaneous measurements taken at any time. The PSI categorized the strain from 0 to 10 as previously suggested (19).

Statistical analysis. Physiological responses for the different exposures (PSI, TS, and RPE) were modeled by a two-way analysis of variance. The model included the intrasubject variable day of acclimation, which was modeled by a repeated-measures analysis of variance model with contrasts T_{re} control day; the age group as a intersubject variable; and the interaction between day and age group.

All contrasts were considered significant at a P < 0.05 level of significance.

RESULTS

Protocol 1. Generally, final T_{es} and final HR were lowered in proportion to the duration of the acclimation. For Y, final T_{es} decreased (P < 0.01) from a mean value of 39.4 ± 0.1°C on day 1 to 38.9 ± 0.1°C on days 5–10. Final HR decreased (P < 0.01) from a mean value of 164 ± 5 beats/min on day 1 to 150 ± 5 beats/min on days 3–10. Similarly, for MA, final T_{es} and final HR progressively decreased with days of acclimation. Final T_{es} decreased from 39.0 ± 0.1°C on day 1 to 38.6 ± 0.1°C on days 4–10, and HR decreased from 148 ± 5 beats/min on day 1 to 132 ± 4 beats/min on days 4–10. Significant differences (P < 0.05) between Y and MA were found for final T_{es} on days 1–4 and for final HR on days 1, 2, 4, 5, and 7.

Generally, the three indexes (RPE, TS, and PSI) used to assess heat strain during the acclimation procedure were higher for MA than for young strain than for MA for all 10 acclimation days (Fig. 1). Significant differences (P < 0.05) for final RPE were found on all acclimation days except on day 7 and the control day, whereas for final TS significant differences were noted only on day 1. However, final PSI was significantly higher (P < 0.05) for Y on the control day and on days 1–9. Analysis of final RPE and TS between the acclimation days revealed an increase of final RPE for Y and MA on day 2, and for Y also on day 3, and it then decreased on days 4–10. Both final RPE and final TS did not differ (P > 0.05) between the 10 acclimation days for either the Y or MA. However, final RPE decreased (P < 0.05) for Y from 12.8 ± 0.52 U on day 1 to 11.8 ± 0.49 U on days 8–10 (Fig. 1, top), and final TS decreased (P < 0.05) from 6.2 ± 0.19 U on day 1 to 5.6 ± 0.31 U on days 5 and 7–10 (Fig. 1, middle). For MA, there were no significant differences for final RPE or final TS between the 10 acclimation days. Concomitantly, final PSI decreased significantly (P < 0.05) for Y from day 1 to days 2–10 (from 9.2 ± 0.28 U to 8.5 ± 0.30 U, respectively) and for MA from day 1 to days 3–10 (from 7.5 ± 0.27 U to 6.7 ± 0.35 U, respectively) (Fig. 1, bottom).

Protocol 2. T_{es}, HR, and PSI dynamics for the different groups during the EHS before and after 16 wk of training are presented in Fig. 2. Generally for both young and older aerobic training groups (YA and OA, respectively), T_{es}, HR, and PSI values during the first EHS were higher than values obtained during the second EHS. In contrast, these physiological values and PSI were higher for the control groups (YC and OC) during the second EHS, which were executed after 16 wk.

The T_{es} values for YA and OA across time were higher during the first EHS, performed before aerobic training, than T_{es} values observed during the second EHS performed after the training (Fig. 2, top). However, values across time were significantly (P < 0.05)
lower during the second EHS only for OA when compared with the first EHS. HR dynamics were clearer, and values across time during the second EHS were significantly ($P < 0.05$) lower than during the first EHS for YA and OA (Fig. 2, middle). Assessment of the four exposures by PSI is depicted in Fig. 2 (bottom). Generally, higher ($P < 0.05$) strain was observed for YA and categorized as high strain at the end of both exposures than for OA, which was categorized as moderate in the first EHS and as low strain at the end of the second EHS. The latter was the consequence of the higher physiological ($T_{es}$ and HR) values measured for YA than for OA. YA and OA were assessed across time with lower ($P < 0.05$) strain during the second EHS compared with the first EHS. However, significant ($P < 0.05$) differences between the first and the second EHS were observed for YA only from the 18 min of the EHS through the 40 min of the exposure.

The two control groups (YC and OC) were instructed to maintain their level of daily activity during the 16 wk of training for the aerobic groups. However, higher HR and $T_{es}$ values were measured for YC than OC in the both EHS (before and after the 16-wk period). Analysis of the two EHS across time resulted in higher $T_{es}$, HR, and PSI for the second EHS (Fig. 3). However, no significant ($P > 0.05$) differences in $T_{es}$, HR, and PSI were found between the two EHS for YA or for OC. In general, PSI categorized YC with high strain and OC with moderate strain at the end of both EHS. Protocol 3. A comparison of $T_{re}$, HR, and PSI for the four groups (E, E + P, NO, and M) during the same EHS is depicted in Fig. 4. The lowest ($P < 0.05$) $T_{re}$ values across time were observed for E (Fig. 4, top); however, these values were not significantly different from those for M. For E + P and NO, higher ($P < 0.05$) $T_{re}$ values of
DISCUSSION

The PSI for the three different databases under investigation described the heat strain of young, middle-aged, and older men and/or women. The PSI succeeded to rate each one of these exposures on its universal scale of 0–10. This index, which is based on only two physiological variables, HR and $T_c$ ($T_{re}$ or $T_{es}$ in this study), categorized every exposure. The focus of this paper was to extend PSI evaluation for men and women of different ages receiving different treatments during EHS (Figs. 3–4).

During the last century, more than 20 heat strain indexes have been proposed (1, 7, 14). However, none has been accepted as a universally valid index for rating heat strain. This is mainly attributed to the number and complexity of the interactions among the determining factors (1). In a previous study (19), it was shown that both the heat strain index (HSI) and the cumulative heat strain index (CHSI) were limited in their physiological strain assessments. The HSI was not able to assess strain on-line and was limited in its ability to rate strain while subjects were wearing protective garments. In addition, HSI is based on components and calculations of more than 15 variables, which could be a source for errors. Thus HSI failed to rate the exposures in hot, dry climate conditions with higher strain than hot, wet conditions because protective clothing was worn, whereas PSI did correctly rate the strain. The CHSI, which is based on multiplication of heart beats and $T_{re}$, was found to be limited to exposures with no rest or recovery periods. Furthermore, because CHSI is based on heart beats, which are not common to measure, difficulties are imposed in using this index. The performance of EHS by middle-aged and older people is expected to cause even more difficulties in evaluating the resultant physiological strain. The combinations of different age groups, gender, heat stress, exercise intensities, drug treatments, and study duration provided by our three unique databases further challenged the ability of PSI to discriminate the relative strain of exercise in the heat because of the many mechanisms and parameters involved.

We expected that $T_c$ and HR could be used for physiological strain assessment. $T_c$ reflects the body heat storage and is elevated during exercise proportional to exercise intensity, whereas HR rapidly responds to changes in metabolic demands and environmental conditions (15). Although final PSI followed the patterns of final HR and $T_{re}$ across days of acclimation (20), differences in final PSI between the young and middle-aged groups were far greater for the control day, days 8–10, and when compared within the same group between day 1 and day 10 (Fig. 1). On the other hand, applying PSI to the same database containing $T_{re}$ or $T_{es}$ and HR measurements more clearly evaluated the relative strain. In fact, PSI effectively described the physiological strain for the first two protocols, according to basic principles of environmental physiology: 1) physiological strain gradually decreased during 10 days of heat
acclimation (Fig. 1), and 2) generally, physiological strain decreased during EHS after 16 wk of aerobic training, although no differences were found for the YA group at the end of the exposures (Fig. 2).

Aging is well documented to be associated with some biological and physiological changes. The loss of skeletal muscle mass, changes in body size and composition, decrease in active vasodilator sensitivity to increasing core temperature (13), and decrease in maximal HR are all known to impact the thermoregulatory and/or the cardiovascular systems (12). The latter is expected to be more pronounced during EHS, in which a larger increase in cardiac output is necessary to perfuse both skin and active muscle vascular beds (12). The commonly used calculation for maximal HR is HR_{max} = 220 – age. The value of 180 used in PSI was derived from the Human Use Committee restriction, which does not allow humans to continue to perform experiments when HR > 180 beats/min. Consequently, for older people HR_{max} is lower (e.g., for 60 yr we expect HR_{max} of 160 beats/min), and therefore it might be legitimate to consider adjustment of the 180 PSI value. However, we did not adjust PSI for two main reasons. First, the value of 180 represents HR_{max} for a 40-yr-old individual; therefore, the expected change in PSI would be minor for our age groups (e.g., for Tr_e = 38°C and HR = 120 beats/min, when you compare HR_{max} of 180 beats/min and 160 beats/min, PSI will be 5 and 4.5, respectively). Second, most of the other heat strain indexes have not been extensively used because of the many adjustments needed for different conditions and the complicated calculations required (1, 14). Although we value the simplicity of PSI, it might be suggested that further studies be carried out to consider a different interpretation of PSI values for individuals of >50 yr of age.

However, the three databases used generally support the notion that chronological age per se, unadjusted for VO_{2 max}, is not always a sufficient determinant of physiological strain in the heat. It appears that VO_{2 max} for men and women is more important than age in predicting physiological strain during exercise in the heat (9). Furthermore, middle-aged men matched to young men for VO_{2 max} were found to acclimate to heat better than the young men (Fig. 1). In addition, comparison between young and older (69 ± 1 yr) men who were aerobically trained for 16 wk showed that the older men had significantly lower strain than the young men (Fig. 2). Therefore, we believe that evaluation of physiological strain and aging must be first related to physical fitness, lifestyle, health, and morphological characteristics.

The commonly used Borg scale (2) for subjective RPE and the TS (28) scale were used in the first protocol to assess the subjective strain during heat acclimation. These indexes revealed similar strain categorization compared with PSI (Table 1) and assessed the middle-aged men with less strain than those younger men throughout the 10 days of heat acclimation. However, RPE and TS were found to be limited in significantly differentiating between the strain assessment for the first day of acclimation and the other 9 acclimation days. Both PSI and TS showed similar trends during acclimation, but PSI better represented the decline in the strain for the young and the middle-aged men and was also significantly different between these two groups on the control day and days 1–9 of acclimation.

It is well documented (3, 11, 25) that hormone replacement therapy in postmenopausal women acutely affects temperature regulation and control of body fluids. However, the chronic effects of hormone replacement therapy on thermoregulation during exercise and environmental stresses are not known. In this study, we were able to use PSI as a useful tool to discriminate between the strain during two exercise intensities in the heat for women under different types of hormone replacement therapy. PSI across all four groups in protocol 3 followed more closely the pattern of HR than Tr_e (Fig. 4). However, this index better represented the strain than either HR or Tr_e independently in assessing the group of women using estrogen replacement therapy with less strain than the female control group or the women using E + P replacement therapy. Furthermore, we were able to evaluate the strain for middle-aged men and women that were not under any treatment and served as control groups. No gender differences in strain during EHS were found between these two control groups.

PSI, unlike other heat strain indexes, depicts the combined strain reflected by the cardiovascular and thermoregulatory systems. This enables the use of PSI to compare between different studies during different exposures and to overcome the limitations of other strain indexes, including HSI, which is based on more than 15 variables; CHSI, which is based on heart beats and Tr_e; and predicted 4-h sweat rate index (P4SR), which uses only sweat rate as an indicator for heat strain. The first database analyzed in our study was

### Table 1. Evaluation and categorization of different heat strains by PSI, TS, and RPE

<table>
<thead>
<tr>
<th>Acclimation</th>
<th>Day</th>
<th>PSI</th>
<th>TS</th>
<th>RPE</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Y</td>
<td>MA</td>
<td>Y</td>
</tr>
<tr>
<td>Control</td>
<td></td>
<td>Moderate</td>
<td>Low</td>
<td>Comfortable</td>
</tr>
<tr>
<td>Day 1</td>
<td></td>
<td>Very high</td>
<td>High</td>
<td>Hot</td>
</tr>
<tr>
<td>Day 10</td>
<td></td>
<td>High</td>
<td>Moderate</td>
<td>Warm</td>
</tr>
</tbody>
</table>

Young (Y) and middle-aged (MA) subjects (n = 9 each) evaluated heat strain after 120-min exposure to heat stress (49°C, 20% relative humidity, 45% maximal aerobic power) during control, day 1, and day 10 of heat acclimation. PSI, physiological strain index; TS, thermal sensation; RPE, rate of perceived exertion.
collected from young and middle-aged men for 10 days of heat acclimation, whereas the second database was obtained from young and older men during EHS before and after 16 wk of aerobic training, and the third database was obtained from middle-aged women who used different hormone replacement therapies during EHS.

In summary, in this study, we were able to extend PSI evaluation for men and women in different age groups (<70 yr) during heat acclimation, during acute EHS after aerobic training, and in women undergoing hormone replacement therapy. PSI rated the strain in rank order according to basic environmental physiology principles, whereas the postraining and the post-acclimation groups were assessed with less strain than the pretraining and the preacclimation groups. The latter is in accordance with previous results in which PSI successfully evaluated the heat strain in five different studies (17–19) for subjects who exercised at different conditions and protocols for climate, exercise intensity, level of hydration, and type of clothing, and for gender. In these studies, PSI was also found to be in high correlation with other heat strain indexes (e.g., HSI, CHSI). This index overcomes the individual limitations of the individual physiological parameters (T_{es}, T_{a}, and HR) in assessing heat strain for these databases and continues to provide the potential to be widely accepted.

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