

# A physiological strain index to evaluate heat stress

DANIEL S. MORAN,<sup>1,2</sup> AVRAHAM SHITZER,<sup>3</sup> AND KENT B. PANDOLF<sup>1</sup>

<sup>1</sup>United States Army Research Institute of Environmental Medicine, Natick, Massachusetts 01760-5007; <sup>2</sup>Heller Institute of Medical Research, Institute of Military Physiology, Sheba Medical Center, Tel Hashomer 52621; and <sup>3</sup>Department of Mechanical Engineering, Technion, Haifa 32000, Israel

**Moran, Daniel S., Avraham Shitzer, and Kent B. Pandolf.** A physiological strain index to evaluate heat stress. *Am. J. Physiol.* 275 (Regulatory Integrative Comp. Physiol. 44): R129–R134, 1998.—A physiological strain index (PSI), based on rectal temperature ( $T_{re}$ ) and heart rate (HR), capable of indicating heat strain online and analyzing existing databases, has been developed. The index rates the physiological strain on a universal scale of 0–10. It was assumed that the maximal  $T_{re}$  and HR rise during exposure to exercise heat stress from normothermia to hyperthermia was 3°C (36.5–39.5°C) and 120 beats/min (60–180 beats/min), respectively.  $T_{re}$  and HR were assigned the same weight functions as follows:  $PSI = 5(T_{ret} - T_{re0}) \cdot (39.5 - T_{re0})^{-1} + 5(HR_t - HR_0) \cdot (180 - HR_0)^{-1}$ , where  $T_{ret}$  and  $HR_t$  are simultaneous measurements taken at any time during the exposure and  $T_{re0}$  and  $HR_0$  are the initial measurements. PSI was applied to data obtained from 100 men performing exercise in the heat (40°C, 40% relative humidity; 1.34 m/s at a 2% grade) for 120 min. A separate database representing seven men wearing protective clothing and exercising in hot-dry and hot-wet environmental conditions was applied to test the validity of the present index. PSI differentiated significantly ( $P < 0.05$ ) between the two climates. This index has the potential to be widely accepted and to serve universally after extending its validity to women and other age groups.

heart rate; indexes; rectal temperature

THE PHYSIOLOGICAL CRITERION of heat strain was probably best defined in 1905 by Haldane (9) as the inability to maintain body core temperature at the level prescribed by the thermoregulatory center. This criterion has been adopted by many investigators, especially those who were concerned with safety limits for occupational exposure to heat (1).

During this century, attempts and efforts were made to combine environmental parameters and physiological variables in developing a unified heat stress index. Although over 20 heat strain indexes already exist, none are accepted as a universal physiological strain index. The main reason is probably related to the number and complexity of the interactions among the determining factors.

The existing indexes can be divided into two main categories: effective temperature (ET) scales, which are based on meteorological parameters only (e.g., ambient temperature, wet-bulb temperature, black-globe temperature), and rational heat scales, which include a combination of environmental and physiological parameters (e.g., radiative and convective heat transfer, evaporative capacity of the environment, and metabolic heat production). In 1923, Houghten and Yaglou (13) developed the ET index from which at least five additional

indexes were derived, among them the wet-bulb globe temperature (28). A modified version of ET was suggested in 1986 by Gagge et al. (5) that was based on more sophisticated heat exchange models (12). The ET indexes are widely applied to both assess and predict heat strain. However, they lack the capability to adjust for different levels of metabolic rate and different clothing, e.g., protective clothing (15, 24).

In 1937, Winslow et al. (27) developed the operative temperature index (TO), which considered the metabolic heat production ( $M$ ), heat transfer between the body and the environment ( $H_{r+c}$ ), and the evaporative capacity of the environment ( $E_{max}$ ). Based on the TO index, more than eight additional indexes have been developed (1). The best known of these is the heat strain index (HSI) suggested by Belding and Hatch (2). This index, which related  $M + H_{r+c}$  [total evaporation required ( $E_{req}$ )] to  $E_{max}$ , is widely accepted because it combines environmental variables and body activity. However, according to Belding there were situations in which heat strain was seriously underpredicted or overpredicted by this model, and corrections were developed for improving the prediction of the index for various exposures (1, 6, 11, 12, 17, 19).

Heat strain indexes based on physiological parameters were also suggested. McArdle et al. (18) developed the predicted 4-h sweat rate index (P4SR), which uses sweat rate as an indicator of heat strain and predicts sweat rate for 4 h for different combinations of  $M$  and climatic conditions. However, it was shown that sweat production by itself does not comprehensively represent heat strain (1, 11). The P4SR was found relevant only for fit-acclimatized men (17). Robinson et al. (25) suggested an index of physiological effects that relied on rectal temperature ( $T_{re}$ ), heart rate (HR), skin temperature ( $T_{sk}$ ), and sweat rate ( $\dot{m}_{sw}$ ). The index, based on an equal weight for the four parameters with no relationship to the metabolic state, was developed on the basis of data collected involving acclimatized subjects, but was not validated for other conditions. Hall and Plote (10) suggested in 1960 an index of physiological strain based on body heat storage and also used  $T_{re}$ , HR, and  $\dot{m}_{sw}$ . The complexity of calculating this index and the inability to rate the strain online were the main reasons for it not being universally accepted.

In 1989, Hubac et al. (14) suggested a different method to evaluate heat strain. Their index was based on integration of HSI and data obtained from HR and  $\dot{m}_{sw}$  measurements. However, this index, which was developed for an 8-h work shift without rest, was limited and involved complex calculations.

In 1996, Frank et al. (4) introduced a cumulative heat strain index (CHSI) based on  $T_{re}$  and heart beats. The index was developed to facilitate an improved criterion for evaluating heat-intolerant subjects and was based on data from heat-intolerance tests. Recently, Gonzalez et al. (8) suggested, in a study that was conducted in three different laboratories and included a large number of subjects, that a protective clothing heat strain model should be based only on  $T_{re}$ . This proposed index, however, could be applied only to certain exposure conditions, e.g., protective clothing systems.

The purpose of this study was to develop a simple physiological strain index (PSI) to be used in hot environments. The index should be capable of indicating heat strain online, as well as being applicable to analyzing existing databases, and is expected to be sensitive enough to differentiate between similar exposures that differ in one variable (e.g., clothing, metabolic rate, climate).

## MATERIAL AND METHODS

Two database sets were used in this study. The first one served to develop the new index, whereas the second database, taken from an independent study (20), was used to validate the developed index.

**Subjects.** One hundred healthy young men at different levels of fitness and heat acclimation volunteered to participate in the study. The physical characteristics of the subjects were as follows (means  $\pm$  SE): age  $20 \pm 3$  yr; height  $178 \pm 10$  cm; weight  $74.6 \pm 10.5$  kg; and body surface area  $1.92 \pm 0.15$  m<sup>2</sup>. Ten subjects had a medical history of heat-related disorders. Before participation, each subject underwent a medical examination that included a complete medical history, electrocardiogram at rest, urine analysis, and blood screening biochemistry. Subjects were informed as to the nature of the study and potential risks of exposure to exercise in a hot climate. All subjects signed a consent form.

**Protocol.** The study was conducted in the climatic chamber at the Heller Institute of Medical Research, Sheba Medical Center, Tel Hashomer, Israel. Twenty-four hours before exposure, subjects were in good medical condition and had not taken any prescribed or unprescribed medication or alcohol. The subjects wore only shorts and sport shoes and performed exercise in a hot-dry climatic condition of 40°C, 40% relative humidity (RH) for 120 min. After 10 min of rest, the subjects began walking on a treadmill at a constant speed of 1.34 m/s at a 2% grade. A number of experiments were terminated before the scheduled 120 min time, when a subject voluntarily withdrew, when a subject's  $T_{re}$  reached 39°C, or when HR exceeded 180 beats/min for 3 consecutive minutes. Termination at any time was according to the attending physician's decision. The estimated rate of O<sub>2</sub> consumption ( $\dot{V}O_2$ ) for all subjects during exercise was 1 l/min [ $\sim 25$ –30% maximum  $\dot{V}O_2$  ( $\dot{V}O_{2max}$ )].

**Measurements.** During the exposures, HR and  $T_{re}$  were continuously monitored and recorded at 1-min intervals.  $T_{re}$  was measured by a thermistor probe inserted 10 cm beyond the anal sphincter (Yellow Spring Instruments series 401). Heart beats and HR were monitored and recorded online through bipolar chest leads using Polar belt electrodes (Polar CIC). Sweat rate was calculated from changes in body weight before and after the exercise (Shinko Denski  $\pm 5$  g) corrected for water intake and urine. The subjects were encouraged to drink cold tap water ad libitum.

**Calculations.** Heat strain indexes (HSI and CHSI) were calculated as suggested by Belding and Hatch (2) and Frank et al. (4), respectively.  $E_{max}$  and  $E_{req}$  used in the HSI were calculated according to Givoni and Goldman's (7) original equations, with algorithm modifications published by Pandolf et al. (23). All calculations of the normalized areas under the  $T_{re}$  curve at any time ( $AUC_{T_{re}}$ ), normalized by initial data point, were calculated according to the trapezoidal rule as follows (3)

$$AUC_{T_{re}} = \Delta t \quad (1)$$

$$(0.5T_{re0} + T_{re1} + T_{re2} \dots + T_{re n-1} + 0.5T_{re n}) \cdot T_{re0}^{-1}$$

where  $\Delta t$  is the time interval for measuring  $T_{re}$  and  $T_{re0}$  is the initial  $T_{re}$ .

Similarly, the area under the HR curve at any time point ( $AUC_{HR}$ ), normalized by the initial data point, was calculated as follows

$$AUC_{HR} = \Delta t \quad (2)$$

$$(0.5HR_0 + HR_1 + HR_2 \dots + HR_{n-1} + 0.5HR_n) \cdot HR_0^{-1}$$

where  $HR_0$  is the initial HR.

Validation of the developed index was done with a database from Montain et al. (20), within the range of HR = 68–171 beats/min and  $T_{re} = 36.4$ –39.4°C. Seven healthy male subjects [age  $21 \pm 1$  yr, body weight  $80.1 \pm 4.0$  kg, body surface area  $2.0 \pm 0.08$  m<sup>2</sup>, and  $\dot{V}O_{2max}$   $52 \pm 2$  ml  $\cdot$  kg<sup>-1</sup>  $\cdot$  min<sup>-1</sup>] walked on a treadmill ( $\dot{V}O_2 \sim 1.5$  l/min) for 180 min while wearing partial protective clothing ensembles consisting of pants and coat (insulation coefficient = 1.3 and evaporative potential of garment = 0.55 at wind speed 2.2 m/s) in both hot-dry (43°C, 20% RH) and hot-wet (35°C, 50% RH) climatic conditions. In addition, we used this database to compare other heat strain indexes (HSI, CHSI) to the newly developed index.

**Statistical analysis.** Physiological responses in hot-dry vs. hot-wet climatic conditions were analyzed by two-way analysis of variance. All statistical contrasts were accepted at the  $P < 0.05$  level of significance. Data are presented in this study as means  $\pm$  SE.

## RESULTS

It is assumed that the maximal acceptable rise of  $T_{re}$  during exposure to heat stress from normothermia to hyperthermia is 3°C (based on maximal change from 36.5 to 39.5°C). Similarly, the maximal allowable elevation of HR is assumed to be 120 (based on maximal change from 60 to 180 beats/min). On the basis of these values, an integral stress index (ISI) may be fitted as follows

$$ISI = 10(AUC_{T_{re}} \cdot T_{re0}/3 + AUC_{HR} \cdot HR_0/120)t^{-1} \quad (3)$$

where 10 is an arbitrary constant introduced to increase the numerical values predicted by the model and  $t$  is the total exposure time (min).

The response of the ISI curve was similar for  $T_{re}$  and HR dynamics, unlike the CHSI curve, which represented a mirror image pattern to  $T_{re}$  and HR dynamics as depicted in Fig. 1. The ISI described the strain online on a scale of 0–15, whereas the CHSI rated the strain from 0 to a few hundreds or thousands, depending on the length of the exposure time. However, it can be seen that both indexes, after 120 min, i.e., during the

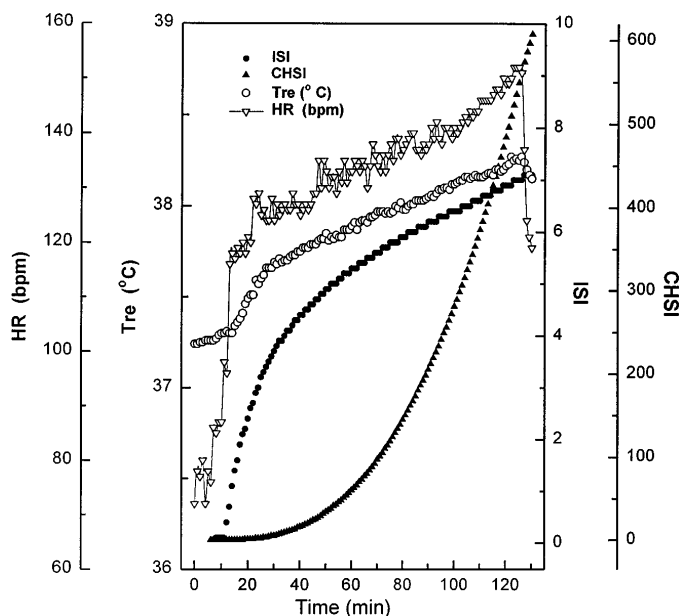


Fig. 1. Integral Stress Index (ISI) and Cumulative Heat Stress Index (CHSI) applied by rectal temperature ( $T_{re}$ ) and heart rate (HR) data obtained from 1 subject. Notice that, after 120 min, although HR and  $T_{re}$  decrease, CHSI and ISI continue to rise. bpm, Beats/min.

recovery period, continued to rise while  $T_{re}$  and HR decreased (Fig. 1).

To evaluate heat stress on a universal scale of 0–10 and to overcome the limitations of continually getting higher values during rest or recovery periods, we constructed an index that enabled us to calculate the physiological strain online at any time. The index was based on the same maximal rise values for  $T_{re}$  and HR as described above for the ISI (according to the Human Use Review Committee Limits). Thus the following normalized physiological stress index (PSI) is suggested

$$PSI = 5(T_{ret} - T_{re0}) \cdot (39.5 - T_{re0})^{-1} + 5(HR_t - HR_0) \cdot (180 - HR_0)^{-1} \quad (4)$$

where  $T_{ret}$  and  $HR_t$  are simultaneous measurements taken at any time.  $T_{re}$  and HR, which depict the combined load of the cardiovascular and the thermoregulatory systems, were assigned with the same weight by using a constant of 5. Thus the index was scaled to a range of 0–10 within the limits of the following values:  $36.5 \leq T_{re} \leq 39.5^\circ\text{C}$  and  $60 \leq HR \leq 180$  beats/min.

This index was applied to the data obtained from the 100 subjects performing exercise in the heat; concomitantly, a new scale to evaluate physiological heat stress was suggested (Table 1). Because the subjects were not a homogeneous group and varied in their physical fitness, acclimation status, and tolerance to heat, data analysis was applied individually. Figure 2 depicts data obtained from three different subjects exposed to the same climatic conditions ( $40^\circ\text{C}$ , 40% RH), but at different strain levels during the heat exposure. Mild physiological strain, rated as 3–4, was observed for the first subject (Fig. 2, *left*), moderate strain marked as 4–6 is presented for the second subject (Fig. 2, *middle*), and

heavy physiological strain, which linearly increased with exposure time and rated as 8.5 after 120 min, is seen for the third subject (Fig. 2, *right*).

A separate database was applied to test the validity of the present index. This database was compiled from results obtained during 180-min exposure under two combinations of clothing ensembles and two different climatic conditions (hot-dry and hot-wet) at various work loads (20). A comparison of  $T_{re}$  and HR data obtained at moderate work between hot-dry and hot-wet climatic conditions is depicted in Fig. 3. Significantly higher values of  $T_{re}$  and HR were observed in the hot-dry climatic condition ( $P < 0.05$ ).

Three indexes (HSI, CHSI, and PSI) were applied to the same  $T_{re}$  and HR database presented in Fig. 3. The CHSI and PSI rated the exposures in the hot-dry climate at higher physiological strain for the subjects (Fig. 4). In contradiction, the HSI, used in the Montain et al. study (20), rated the exposures in the hot-wet climate with higher values than the hot-dry climate ( $HSI = 105 \pm 3.1$  and  $95 \pm 1.8$ , respectively).

## DISCUSSION

The present index to evaluate heat strain describes well the physiological strain on a universal scale of 0–10. This index is based on only two physiological parameters, HR and  $T_{re}$ , which adequately depict the combined strain reflected by the cardiovascular and thermoregulatory systems. Both systems are assumed to contribute equally to the strain by assigning the same weight function to either one. However, this simply constructed index enables separate analysis of each one of the two systems contributing to the strain (Eq. 4).

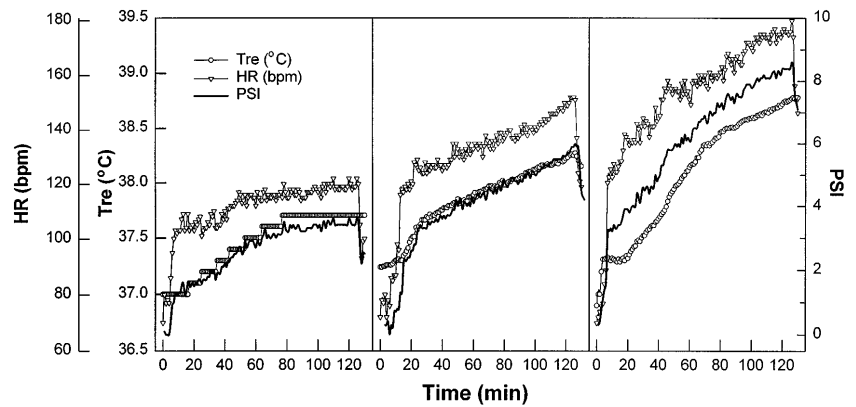
PSI differs from other indexes that have been suggested in the past. The CHSI (4), which was also based on  $T_{re}$  and HR, was found to be a valid model in estimating heat tolerance, but it is limited in its use for three major reasons. First, the index could only compare subjects exposed for the same duration. The values predicted by this index were very large ( $\sim 0$ –4,000), and completely different values could be obtained at varying durations, which did not necessarily

Table 1. Calculated PSI from measured HR and  $T_{re}$  obtained from 100 subjects exposed to 120 min heat stress

Strain	PSI	HR, beats/min	$T_{re}$ , $^\circ\text{C}$	$n$
	0	$71 \pm 1.0$	$37.12 \pm 0.03$	100
No/little	1	$90 \pm 1.1$	$37.15 \pm 0.04$	47
	2	$103 \pm 1.1$	$37.35 \pm 0.03$	81
Low	3	$115 \pm 1.3$	$37.61 \pm 0.03$	80
	4	$125 \pm 1.4$	$37.77 \pm 0.04$	61
Moderate	5	$140 \pm 1.9$	$37.99 \pm 0.05$	28
	6	$145 \pm 5.3$	$38.27 \pm 0.07$	13
High	7	$159 \pm 1.3$	$38.60 \pm 0.04$	5
	8	175	38.7	1
Very high	9			0
	10			0

Values are means  $\pm$  SE ( $n$  is no. of subjects). Heat stress,  $40^\circ\text{C}$ , 40% relative humidity, 1.34 m/s at 2% grade; PSI, physiological stress index; HR, heart rate. No data available for very high strain.

Fig. 2. Physiological Strain Index (PSI) (solid line), calculated from  $T_{re}$  (○) and HR (▽) applied to 3 subjects exposed to the same heat stress [40°C, 40% relative humidity (RH), 1.34 m/s at a 2% grade].



relate directly to the strain (4). In addition, the CHSI (a multiplication of HR and  $T_{re}$ ) depicted a hyperbolic curve pattern, with almost no strain during the first hour of exercise (see Figs. 1 and 4). The hyperbola is a contradiction to the dynamics of the physiological parameters (HR and  $T_{re}$ ) and might be misleading in analyzing the strain when evaluating the index curve. Second, the CHSI continued to rise during a steady-state or recovery period, although  $T_{re}$  and HR decreased (Fig. 1). As a consequence, the validity of CHSI has been limited to exposures with no rest or recovery periods. Furthermore, this index, which is based from online measurements and calculations, would be lim-

ited to online use only. Third, CHSI was based on heart beats rather than on heart rate. This posed some difficulties in using the index as it is not common to measure heart beats. The implications of CHSI with HR at different time intervals could affect its accuracy.

These limitations categorized the CHSI, like most heat strain indexes, as an index that applied to a particular type of exposure. However, when we compared the strain between hot-dry and hot-wet in a study by Montain et al. (20), the CHSI and the PSI succeeded in rating the hot-dry climate conditions with a higher strain, unlike HSI, which rated the hot-wet with a higher strain (Fig. 4).

The HSI uses the approach that the ratio of  $E_{req}/E_{max}$  provides a meaningful index but was presently found to

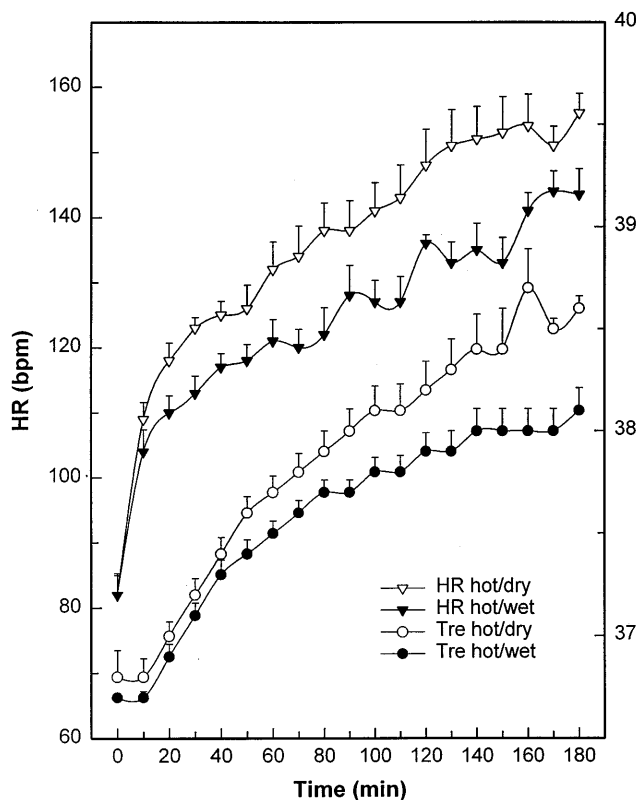


Fig. 3. Comparison between  $T_{re}$  dynamics in hot-dry (○) and hot-wet (●) climates and between HR dynamics in hot-dry (▽) and hot-wet (▼) climates. Values (means ± SE) obtained from 7 subjects exposed to moderate exercise (425 W) wearing mission-oriented protective posture gear (from Ref. 20).

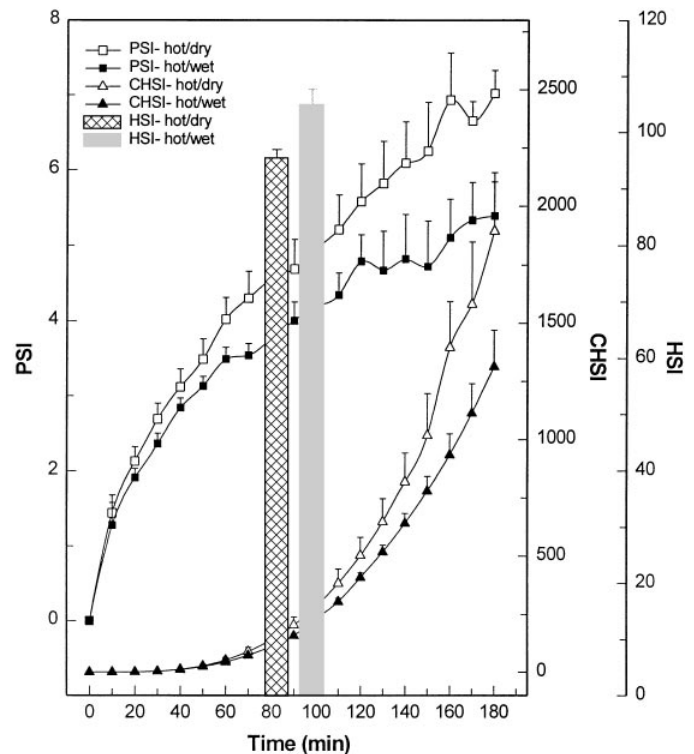


Fig. 4. Comparison between Heat Stress Index (HSI), CHSI, and PSI applied on Montain et al. (20) database. Note that HSI rated the hot-wet climate as the higher strain, in contradiction to CHSI and PSI, which rated the hot-dry climate as the higher strain.

be limited (1). This index was based on many components and calculations and involved more than 15 variables (e.g., ambient temperature, barometric pressure, wind velocity, ambient water vapor pressure, skin temperature, skin water vapor pressure, clothing insulation coefficient, water vapor permeability of clothing coefficient, body surface area, metabolic rate, external work load, and heat exchange by radiation and convection), which made it inconvenient to use and also could be a source for errors. There were conditions in which HSI was limited in its ability to rate heat stress, i.e., while wearing light clothing, which causes  $E_{\text{req}} = E_{\text{max}}$ , or while wearing protective garments, which create a microclimate different from the environment (12, 16). These limitations necessitated the development of additional criteria, restrictions, and corrections for improving the prediction of HSI. It can be concluded from the Montain et al. study (20) that HSI failed to rate the exposures in hot-dry climate conditions with higher strain, because subjects were dressed in protective clothing (Fig. 4).

Among the possible criteria to construct a new physiological strain index, we considered  $T_{\text{re}}$ , HR,  $\dot{m}_{\text{sw}}$ , and  $T_{\text{sk}}$ . It was deemed essential to include  $T_{\text{re}}$  and HR.  $T_{\text{re}}$  reflects the body heat storage and is elevated during exercise because of the partial accumulation of heat produced as a by-product of skeletal muscle contraction. HR reflects the demands of the circulatory system. It is an immediate effector of the vasomotor response to metabolic and environmental conditions (21).

After McArdle (18) developed the P4SR index to describe heat strain, it was debatable whether  $\dot{m}_{\text{sw}}$  by itself could be a valid measure of strain. Hatch (11) and Belding (1) argued that  $\dot{m}_{\text{sw}}$  does not reflect only the physiological heat strain, but it can also be affected by dehydration. We believed that  $\dot{m}_{\text{sw}}$  was a valid criteria when combined with HR and  $T_{\text{re}}$ . However, because we decided to develop an online index,  $\dot{m}_{\text{sw}}$  was not included because of the difficulty in measuring it online.  $T_{\text{sk}}$  is also a well-known criterion of heat strain. While  $T_{\text{sk}}$  is higher in warm environments,  $T_{\text{re}}$  is relatively unaffected by ambient temperature over a wide range (26). As a response to higher  $T_{\text{sk}}$ , skin blood flow increases to achieve core-to-skin heat transfer for thermal equilibrium. Elevated  $T_{\text{sk}}$  is associated with reduced cardiac filling and stroke volume; therefore, the way to maintain cardiac output is by increasing HR (26). Thus we concluded that physiological strain could be adequately represented by the stress factors of HR and  $T_{\text{re}}$  only.

Our first attempt was to develop a new integral stress index (ISI). This index assumed that the maximum values of HR and  $T_{\text{re}}$  during heat stress were 180 beats/min and 39.5°C, respectively (Eq. 3). It rated the stress on a scale of 0–15 in the same curve pattern as HR and  $T_{\text{re}}$  were depicted. However, during the recovery or rest period, ISI continued to rise, producing limitation in its applicability.

The new PSI is designed for both the layman and the scientist. This index is simple to use, scaled to a range of 0–10, where 0 presents no strain and 10 very

strenuous physiological conditions. It is based from online calculations at different time intervals. Thus, unlike the HSI and other models, PSI is computed while the subject is exposed to stress with no need to wait until the end of the exposure to analyze the strain. Because it is calculated by HR and  $T_{\text{re}}$  measurements, it can be applied at any time, including rest or recovery periods, whenever these parameters are measured. This characteristic cannot be achieved by any other existing heat strain index. Furthermore, unlike most heat strain indexes that involve many variables and parameters, PSI calculations involve only two parameters, which helps decrease the source of error. Moreover, the principle behind PSI is evaluation of the physiological strain resulting from the cardiovascular and the thermoregulatory systems. Therefore, the strength of this index is its ability to rate and to compare the strain between any combination of climate and clothing. It is believed that the PSI suggested in this study is unique, in that it yields a quantitatively descriptive figure of heat strain at any time point.

It is well known that the physiological heat strain for middle-aged men and women during physical work in the heat is greater than that observed for younger individuals (22). The greater physiological strain is indicated mainly by higher  $T_{\text{re}}$  and HR values. Due to the fact that the subjects participating in the present study were young men, we assumed that 3°C and 120 beats/min were the maximal rise (for  $T_{\text{re}}$  and HR, respectively) from normothermia to hyperthermia during exposure to heat stress. However, several investigators showed that tolerance to heat stress for the general population of middle-aged men and women is less than for those younger (22). To apply PSI to women and different age groups, more studies should be done for proper validation.

In conclusion, although there are many heat strain indexes, we found that they were valid only under certain specific conditions. The present study suggests a simple valid physiological strain index to evaluate heat stress either online or when data analysis is applied. This simple index should be easier to interpret and to use than other indexes available and includes the ability to depict rest and recovery periods. PSI is capable of overcoming the limits of previous indexes, while providing the potential to be widely accepted and used universally. However, further investigation is required to possibly adjust this index for women and different age groups.

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

Address for reprint requests: D. S. Moran, USARIEM, 42 Kansas St., Natick, MA 01760–5007.

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