UTILITY OF PREDICTED HEAT STRAIN TO LIMIT SHORT-TERM HEAT STRESS EXPOSURES

Satoru Ueno[1], Ronald Long[2], Skai W. Schwartz[2], Candi D. Ashley[2], Shin-ichi Sawada[1], Thomas E. Bernard[2]

[1]Japan National Institute of Occupational Safety and Health, Kiyose, Tokyo, Japan and [2]University of South Florida, Tampa FL, USA

Contact person: uenos@h.jniosh.go.jp

INTRODUCTION

The Predicted Heat Strain (PHS) was proposed by Malchaire et al (2002) and validated against laboratory and field data (Machaire et al 2001) as part of the EU BIOMED II project. The result of the effort was an update to ISO7933 (2004). One useful purpose of PHS is to examine the pattern of heat strain that results from steady and time varying heat stress exposures. Alternative controls can be simulated on a desktop evaluation. A second use of the PHS is to limit acute heat stress exposures to the time it takes to reach a predicted physiological limit (either rectal temperature or dehydration).

Japan National Institute of Occupational Safety and Health and University of South Florida undertook several changes to PHS, mainly to account for clothing effects following the guidance of ISO9920 (2007). The purpose of this paper was to compare the predicted exposure limit from PHS and the modified PHS (called here PHSm) to observed data from trials designed to last from about 30 to 110 minutes (Bernard and Ashley 2009). From these comparisons, the ability of PHS and PHSm to limit acute exposures can be assessed.

METHODS

Twelve adults participated in the time-limited heat stress exposures. Prior to beginning the experimental trials to determine critical WBGT, they underwent a 5-day acclimatization to dry heat. Participants wore a base ensemble of shorts, tee-shirt (or sports bra for women), socks and shoes.

Three different clothing ensembles over the base ensemble were evaluated: work clothes (135 g m^{-2} cotton shirt and 270 g m^{-2} cotton pants), water-barrier, vapor-permeable ensemble (NexGen® LS 417), and vapor-barrier ensemble (Tychem QC®, polyethylene-coated Tyvek®). The limited-use coveralls had a zippered closure in the front and elastic cuffs at the arms and legs; and they did not include a hood.

Each participant walked on a treadmill at a moderate rate of work (190 W m^{-2}) at five levels of heat stress. The 15 combinations of clothing and heat stress level (see Table 1) were completed in random order. During trials, participants were allowed to drink at will. Core (rectal) temperature, heart rate and ambient conditions were monitored continuously and recorded every

5 minutes. The time at which T_{re} reached 38 °C (t@38) was noted. The safe exposure time (SET) was taken as the time at which the first of the following conditions was satisfied: (1) T_{re} reached 38.5 °C, (2) a sustained heart rate greater than 85% of the age-predicted maximum heart rate, or (3) participant wished to stop. Only trials in which t@38 was reached and trials that ended before 120 min were used to evaluate validity for t@38 and SET.

Table 1. Combinations of Clothing Ensemble and Target Levels of WBGT [°C] at 50% Relative Humidity

	Heat Stress Level				
Ensemble	HL1	HL2	HL3	HL4	HL5
Work Clothes	36	37	38	40	44
NexGen	33	34	36	38	41
Tychem QC	29	30	32	34	38

The experimental conditions for each trial were used as the heat stress conditions for the PHS and PHSm. These included dry bulb and radiant temperatures, ambient water vapor pressure, air speed, metabolic rate, walking speed, and intrinsic clothing insulation and estimated i_m from previous data as well as participant height and weight. The PHS and PHSm times were taken as the time at which predicted rectal temperature reached 38 °C. When walking speed was used, the wind direction was considered omni-directional. A second evaluation was performed in which the effective walking speed based on metabolic rate was used.

For comparison, t@38 and SET were compared to PHS and PHSm times. The outcomes were classified in three categories. On-Time (OT) was a condition in which the actual time (either t@38 or SET) occurred within a window that was plus or minus 10% of the predicted time (i.e., PHS or PHSm time). An early predicted time (E) was the outcome in which the predicted time plus 10% was earlier than the observed time. A late predicted time (L) occurred when the predicted time minus 10% was greater than the observed time.

RESULTS

There were 8 comparison groups based on observed time at two levels (t@38 and SET), predicted time by two methods (PHS and PHSm), and the use of walking speed at two levels (Yes and No). The experimental trials were not designed to have True Negatives, and thus sensitivity and specificity were not evaluated. The distribution of trials among Early, On-Time and Late was determined and provided in Table 2. If a broad view of protection including over-protection is taken, then protective accuracy can be computed as the ratio of the On-Time plus the Early over the total observations. These values were generally high but driven by the large number of Early observations.

For each factor in Table 2, there were trends worth noting. Using the actual walking speed to one estimated from metabolic rate led to fewer Early classifications within each of the four combinations of observed and predicted time. For t@38 and PHS with actual walking speed, the distribution was somewhat balanced; and it shifted to Early for PHSm and for estimated walking speed. For SET, there was a general movement to Early regardless of the predicted time or walking speed method.

Table 2. Classification of outcomes for the eight comparison groups.

	Early	On-Time	Late	Total
		Actual V_{walk}		
t@38 v. PHS	55	28	71	154
t@38 v. PHSm	123	17	14	154
SET v. PHS	92	23	53	168
SET v. PHSm	157	8	3	168
		Estimated V_{walk}		
t@38 v. PHS	121	22	11	154
t@38 v. PHSm	134	15	5	154
SET v. PHS	158	8	2	168
SET v. PHSm	164	3	1	168

Figures 1 and 2 illustrate the relationships between individually observed safe exposure times (SETs) and individually determined predicted times when walking speed was used. As expected from Table 2, there was a trend for the predicted times to be less than the observed times (to the right and below of the identity line). This effect was greater for PHSm than PHS. The trial protocol called for stopping at 120 min and represented greater than 120 min.

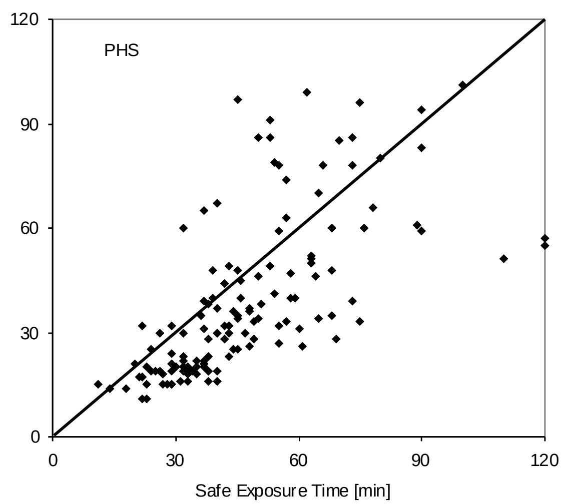

Figure 1. Predicted time from PHS compared to the observed safe exposure time.

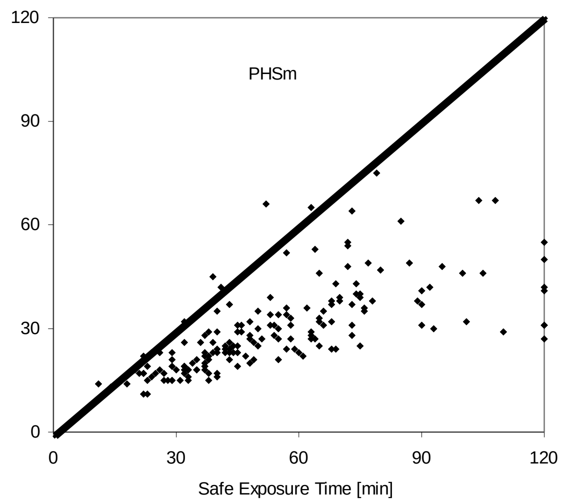

Figure 2. Predicted time from PHSm compared to the observed safe exposure time.

CONCLUSIONS

Comparing t@38 with PHS including walking speed was the approach most in line with the original intent of PHS. That is, (1) PHS used walking speed to adjust for the dynamic effects of work on clothing factors and the metabolic estimation was offered as an alternative and (2) it was validated in its ability to predict a mean rectal temperature response (Malchaire et al 2001). This comparison supported the original validation with a roughly balanced set of outcomes among Early, On-Time and Late.

The validity study also showed that the 95% confidence interval included 38.5 °C; and was up to 38.7 °C (see Fig 2 and 4 of Malchaire et al 2001). This fact means that most rectal temperatures will be less than 38.7 °C when the model predicts 38 °C. For this reason, a comparison to the observed safe exposure time at 38.5 °C (or elevated heart rate or fatigue) was appropriate. While PHS was indicative of the mean response, it was not protective when used as a method to limit heat stress exposures in a prescriptive fashion. When using the SET value, there were a large number of Late outcomes (53 of 168 or 32%).

The lower predicted times of PHSm were not intended but an outcome of updating the methods to adjust static values of insulation and evaporative resistance to dynamic (resultant) values. The result was fewer Late outcomes (3 of 168 or 2%) but more Early ones (157 of 168 or 93%). The protective accuracy was generally high for PHSm, but this was driven by a high number of Early trials. That means that PHSm was overly protective in 93% of the trials.

Overall, the use of PHS or PHSm for prescribing acute exposures appeared to be limited. Where PHS had significant risk of Late outcomes pointing out the risk for over-exposures, PHSm was characterized by a large number of Early outcomes, which may reduce the utility for exposure planning.

It was clear from the data that substituting a metabolic rate for actual walking speed led to a systematic lowering of the predicted times. This may be an area for further investigation.

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