

MODIFICATIONS TO PREDICTED HEAT STRAIN (PHS) (ISO7933)

Satoru Ueno¹, Shin-ichi Sawada¹, Thomas E. Bernard²

¹Japan National Institute of Occupational Safety and Health, Kiyose, Tokyo, Japan

²University of South Florida, Tampa FL, USA

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

INTRODUCTION

The Predicted Heat Strain (PHS) is a rational model for heat stress exposure assessment. It was proposed by Malchaire et al. (2001) and was adopted by the International Organization for Standardization (ISO) as ISO7933 in 2004. The key predictions of the PHS are rectal temperature (T_{re}) and sweat rate. These predictions were validated for laboratory and field trials as part of the BIOMED II project (Malchaire et al 2002). A time limit for an exposure is provided based on T_{re} reaching 38 °C or a cumulative sweat loss limit that is based on acclimation state and percent of population.

Important factors in the determination of the time limit include environmental conditions, metabolic demands, and clothing. Since the publication of PHS and ISO7933, the ISO has published a standard for clothing that includes adjustments for insulation and evaporative resistance based on wind speed, walking speed, and walking direction (ISO9920-2007). These adjustments differ from those used in ISO7933. One purpose of the effort reported in this paper was to include the clothing adjustments (called resultant insulation and evaporative resistance in ISO9920) in the PHS model.

A further change in the model was added to better account for recovery. Specifically, there were conditions under which T_{re} would not return to an appropriate baseline. That is, it would remain elevated above the metabolically-driven equilibrium temperature when the environment would allow it to return to the expected baseline. In addition, there were some circumstances in which the T_{re} would find a level below the metabolic equilibrium temperature.

This paper describes two major and one minor modifications to the PHS model and discusses some of the implications of the changes.

METHODS

The first step was to change the PHS methods for estimating the dynamic insulation and evaporative resistance, called resultant values in ISO9920. The methods differed in the way a correction factor was computed to adjust the static value to a dynamic (resultant) value. In ISO7933, the correction factor for evaporative resistance (CF_{re}) was calculated by using the correction factor for total insulation (CF_i) divided by the correction factor for clothing permeability index. In ISO9920, the CF_{re} is based on either the CF_i or a function of wind and walking speeds. For this paper, the CF_{re} was based on CF_i .

We compared the CF_i and CF_{re} estimated by ISO7933 and ISO9920. Because both air velocity and walking velocity were included in the formula for CF_i , we calculated the independent effects of air velocity and walking velocity to the CF_i and CF_{re} . Because the formula for CF_i changes for clothing less than 0.6 clo, CF_i and CF_{re} were compared at 0.3 clo and 1.0 clo.

There were times when the core temperature did not return to the equilibrium level associated with the metabolic rate. While the amount of heat loss needed to reduce the core temperature was computed and factored into the model, this was not sufficient to bring the core temperature all the way down (and sometimes it was too much and the core temperature was reduced below the equilibrium value for the metabolic rate). To account for this discrepancy, two steps were taken. The first was to assess the elevation of the current core temperature above the equilibrium value. If E_{req} was less than zero and there was still a core temperature elevation, the required sweat rate (SW_{req}) was adjusted proportionately to the difference. To fine tune the outcome, E_p and SW_p were set to zero when the equilibrium core temperature was reached.

Finally, as a minor modification, posture adjustments to the available surface area for convection and maximum evaporative cooling were instituted for sitting (0.7) and squatting (0.9). It was assumed that there was no conduction across the surfaces in contact with the body during sitting.

After changing the PHS code to compute CF_i and CF_{re} by either method, the code was verified using the standard test conditions in ISO7933. Values for final T_{re} , water loss, $D_{lim\ tre}$, $D_{limloss50}$, $D_{limloss95}$ by PHS model (ISO7933) and PHS_m (PHS with the changes). We also calculated $D_{lim\ tre}$ by PHS model and PHS_m using trial conditions used for high heat stress exposure conditions (safe exposure times less than 120 min) for 142 trials (Bernard and Ashley 2009).

An Excel workbook with a VBA macro was used to compute PHS and PHS_m .

RESULTS

The first step in the PHS modification process was to examine the differences between CF_i and CF_{re} as specified by ISO7933 and ISO9920 as a function of air speed, walking speed, and clothing level. Fig. 1 illustrates the comparison.

CF_i was not substantially different for either method, and decreased with air and walking speed. CF_{re} by ISO9920 was larger than ISO7933, and the difference increased with either air or walking speed. As a note, the difference in methods for estimating CF_{re} in ISO9920 was less than 5% over the same conditions.

The outcomes by PHS and PHS_m were compared using the standard test conditions in ISO7933 (Table 1). The calculation time limit was 480min. PHS_m showed higher Final T_{re} than PHS. The temperature difference between PHS and PHS_m increased when the final T_{re} increased. Maximum allowable exposure time for heat storage ($D_{lim\ tre}$) was shorter in PHS_m than PHS. In example 3 and 7, PHS did not have limitation but PHS_m had limitation time of 117 min and 196 min respectively.

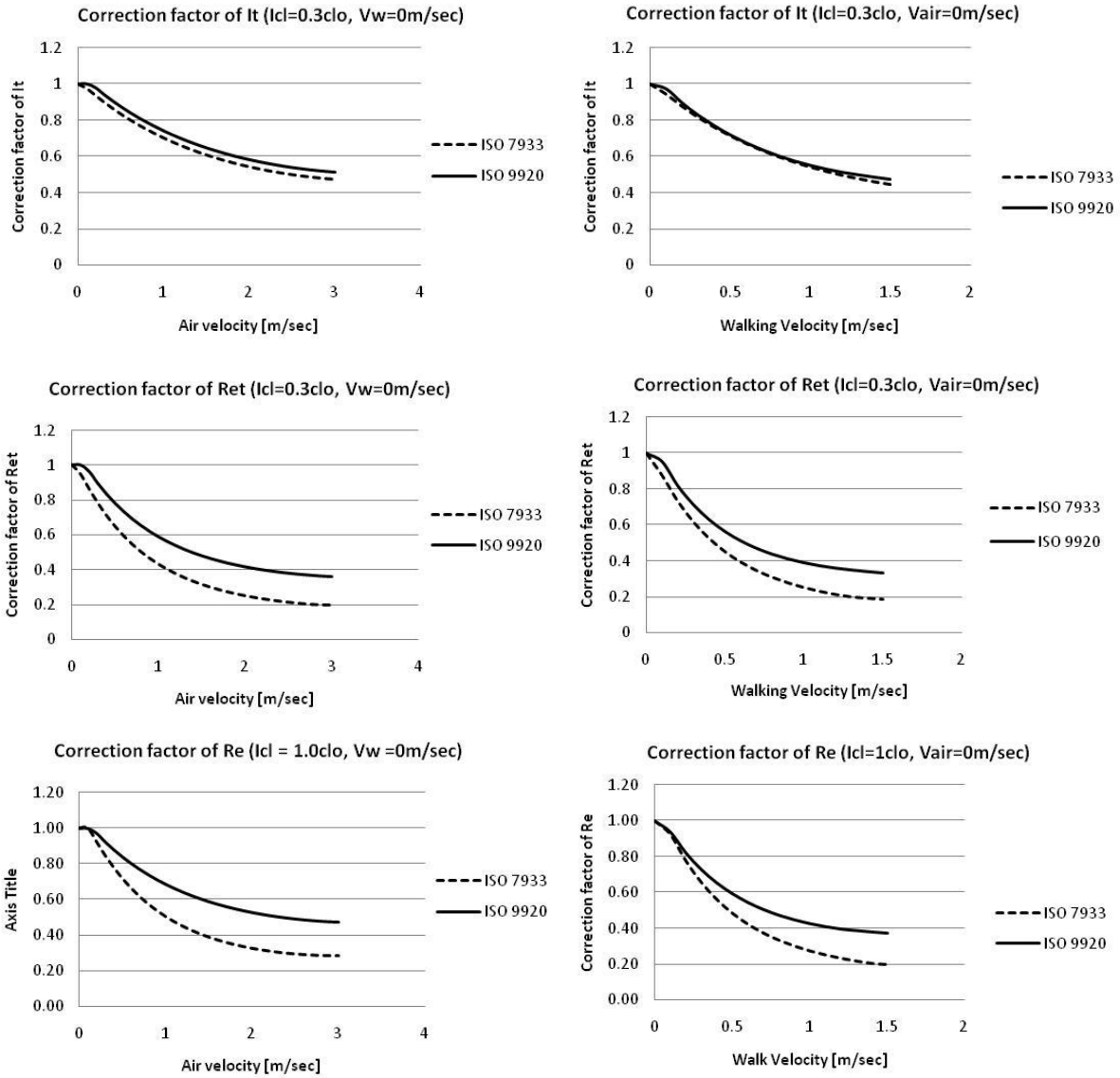


Fig. 1. Correction factors for I_{cl} and R_{et} calculated by ISO7933 and ISO9920.

Table 1. Differences in outcomes for standard test conditions

Parameters	1		2		3		4		5		6		7		8	
Acclimatized	Yes		Yes		Yes		No		No		No		Yes		Yes	
Posture	Standing		Standing		Standing		Standing		Standing		Standing		Standing		Standing	
t_a (° C)	40		35		30		28		35		34		40		40	
Pa(kPa)	2.5		4.0		3.0		3.0		3.0		3.0		3.0		3.0	
t_r (° C)	40		35		50		58		35		34		40		40	
v_a (m/s)	0.3		0.3		0.3		0.3		0.3		0.3		0.3		0.3	
M(W/m ²)	150		150		150		150		206		150		150		150	
I_{cl} (clo)	0.5		0.5		0.5		0.5		0.5		1.0		0.4		0.4	
θ (degree)	0		0		0		0		0		0		0		90	
Walk speed (m/s)	0		0		0		0		0		0		0		1	
Output	PHS	PHSm	PHS	PHSm	PHS	PHSm	PHS	PHSm	PHS	PHSm	PHS	PHSm	PHS	PHSm	PHS	PHSm
Final t_{re} (° C)	37.5	37.7	39.8	41	37.7	39	41.2	42.5	39.2	41.3	41	42.5	37.5	38.4	37.6	37.6
Water loss (g)	6174	7209	6938	6973	7167	7206	5807	5807	7252	7371	5551	5642	6691	7215	5386	5541
$D_{lim\ tre}$ (min)	480	480	74	56	480	117	57	44	69	45	67	54	480	196	480	480
$D_{limloss\ 50}$ (min)	439	378	385	382	380	377	466	466	371	360	480	479	406	377	480	480
$D_{limloss\ 95}$ (min)	297	257	256	256	258	255	314	314	246	237	317	314	275	255	339	329

To compare the differences of $D_{lim\ tre}$ calculated by PHS and PHS_m, 142 experimental conditions from a previous study were used. $D_{lim\ tre}$ was longer in PHS than in PHS_m (Fig. 2). When the $D_{lim\ tre}$ was below 20 min, PHS and PHS_m were about the same value. As $D_{lim\ tre}$ increased, the difference became larger.

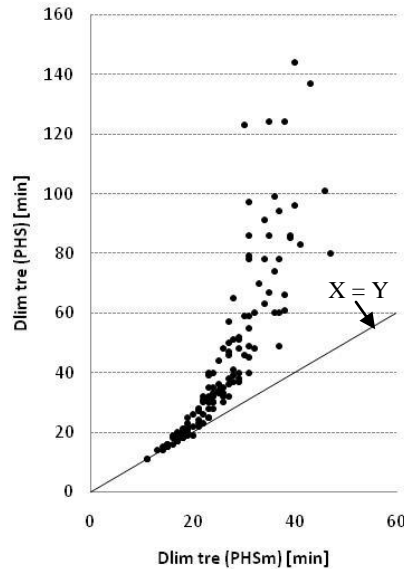


Fig. 2. Differences in predicted time limit by PHS and PHS_m based on experimental trials for short term exposures.

To illustrate the code changes for recovery to the equilibrium core temperature, T_{re} time course for an exposure and recovery by PHS, PHS_m, PHS_{ce} (core equilibrium included in PHS), PHS_{mce} (core equilibrium included in PHS_m) (see Fig. 3). The faster rate of rise was expected for PHS_m. The recovery to different levels from the different levels of rectal temperature without the code adjustment was also expected.

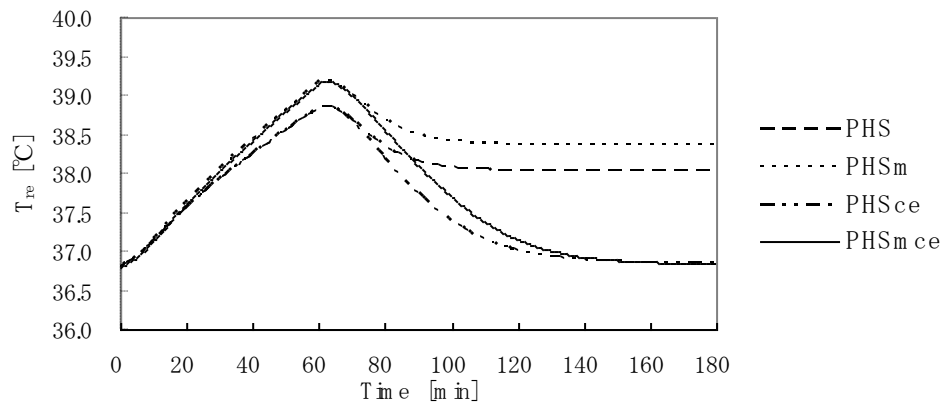


Fig. 3. Recovery of T_{re} calculated by four variations of the PHS model.

CONCLUSIONS

By introducing the dynamic correction factor of clothing insulation and evaporative resistance of ISO9920 (PHS_m) into ISO7933 (PHS), there was little change in the total dynamic (resultant) insulation, but the total dynamic evaporative resistance was higher for PHS_m. Thus the predicted heat strain was greater in PHS_m than PHS. This trend was seen both in the test scenarios published in ISO7933 and from a set of experimental data.

After the elevation of current core temperature above equilibrium temperature was used to adjust predicted sweat rate, T_{re} returned to the equilibrium temperature as intended.

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