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Short Communication

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Ability of Thermal Work Limit (TWL) to Assess Sustainable Heat Stress Exposures

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Abstract

Thermal Work Limit (TWL) recommends a maximum metabolic rate for a given environmental condition, clothing ensemble, and acclimatization state so that thermal equilibrium can be sustained at or below the limiting metabolic rate. The purpose of this paper was to assess the ability of TWL to recommend maximum sustainable levels of heat stress using an existing database of progressive heat stress trials using four levels of clothing (woven clothing, particle barrier, water barrier, and vapor barrier), three levels of relative humidity, and three levels of metabolic rate. Each trial had a compensable and an uncompensable observation plus and observation at the transition point from compensable to uncompensable. Each observation was classified as a case (steady increase in rectal temperature) or non-case (steady rectal temperature). The data were used to compare the difference between the observed metabolic rate (M_{obs}) and the limiting metabolic rate of TWL (i.e., $\Delta Limit_{TWL} = M_{obs} - TWL$), where $\Delta Limit_{TWL} > 0$ was above the TWL limit. The sensitivity and specificity for each of the four clothing ensembles were about 0.96 and about 0.20, respectively. Logistic regression for all the data found that $\Delta Limit_{TWL}$, clothing, metabolic rate, and water vapor pressure were significant predictors of outcome. The ln(odds) equations for each clothing ensemble predicted a probability of an uncompensable exposure. The probability of an uncompensable outcome (case) when $\Delta Limit_{TWL} = 0$ was 0.14 for work clothes and particle barrier, and 0.22 for water barrier and vapor barrier. The probability of a case at $\Delta Limit_{TWL} = 0$ was greater than the probability of a case for the wet bulb globe temperature-based exposure limits where the probability of a case was 0.01. That is, the TWL was less restrictive than WBGT but with higher risk.

Key words: clothing; exposure assessment; validity

What's Important About This Paper?

Heat stress exposure assessment includes consideration of the environmental conditions and metabolic demands, and most methods provide for the effects of clothing and acclimatization state. Thermal Work Limit (TWL) is a method to determine heat stress exposures based on a heat balance approach that considers more information than WBGT-based. This paper found that TWL has high specificity as method to prescribe an upper limit on metabolic rate while maintaining thermal equilibrium for a sustained exposure.

Introduction

Heat stress assessment considers the combination of metabolic rate, environment, and clothing as well as acclimatization state. Methods such as Predicted Heat Strain and the widely used wet bulb globe temperature (WBGT)-based limits (Malchaire *et al.*, 2001; ISO, 2004; NIOSH, 2016; ISO, 2017; ACGIH®, 2022) require knowledge of the environmental metrics and metabolic rate. The Thermal Work Limit (TWL) for heat stress assessment and management prescribes a limiting metabolic rate to describe the upper bound of a compensable heat stress exposure (Brake and Bates, 2002a). This method places less importance on knowing the actual metabolic rate than other methods mentioned above. Brake and Bates argued that workers naturally control the pace of work when they are allowed to do so (Brake and Bates, 2002).

Bates and Miller reasoned that alerting the workers to the TWL was sufficient control of the exposures to heat stress (Bates and Miller, 2002). Further, Miller, Bates, Schneider, and Thomsen evaluated TWL at construction sites in Abu Dhabi and Dubai (Miller *et al.*, 2011) and reported that self-regulation of work rate with educated workers tended to maintain heart rate in a sustainable range. Other investigators reported that TWL was a useful heat stress exposure metric in Iran (Farshad *et al.*, 2014) and in the Middle East (Ahmed *et al.*, 2020). The Australian Institute of Occupational Hygienists guide to managing heat stress (https://w2.aioh.org.au/resources/publications1/publications/a-guide-to-managing-heat-stress) lists TWL among assessment methods. Further, TWL is integrated into a commercial heat stress monitor (https://scarlet-tech.com/products/heat-stress-meter-twl-1s/). The wide use made TWL a good candidate for further examination.

The purpose of this study was to evaluate the ability of the TWL to distinguish between compensable (i.e., able to maintain thermal equilibrium) and uncompensable (i.e., marked by increasing heat storage) heat stress exposures.

Methods

Previously collected data at University of South Florida (USF) (Bernard *et al.*, 2005; Bernard *et al.*, 2008) were used for this paper. The heat stress protocols were approved by the USF institutional review board. The studies included five clothing ensembles: work clothes (140 g m^{-2} cotton shirt and 270 g m^{-2} cotton pants; I_{clo} = 0.61 clo, i_m = 0.38) and cotton coveralls (310 g m^{-2}, 0.61 clo, 0.38) plus three nonwoven coveralls without head covering: (i) particle-barrier (Tyvek 1424 and 1427, 0.69 clo, 0.37); (ii) water-barrier, vapor permeable (NexGen LS, 0.68 clo, 0.31), and (iii) vapor-barrier (Tychem QC, 0.65 clo, 0.17). One study (Bernard *et al.*, 2005) targeted a metabolic rate of 160 Wm^{-2} at three levels of relative humidity (RH) (20%, 50%, and 70%). (Note: The mention of trade names is to provide technical information and not an endorsement.) The other study (Bernard *et al.*, 2008) targeted three levels of metabolic rate (low, moderate, high) at 115, 175, and 250 Wm^{-2} at RH = 50%. In both studies, each participant wore each of the five clothing ensembles. All participants (20 men and 9 women) were acclimatized for 1 week at 50°C and 20% RH at 300 W. Because there were no differences in outcomes between work clothes and cotton coveralls, the two ensembles were combined as one ensemble called woven clothing (Bernard *et al.*, 2005; Caravello *et al.*, 2008). There were 176 trials for woven clothing, 119 for particle barrier, 91 for water barrier, and 94 for vapor barrier.

The progressive heat stress protocols were described elsewhere (Bernard *et al.*, 2005; Bernard *et al.*, 2008; Garzón-Villalba *et al.*, 2017). The progressive protocol identified a transition environment that marks the transition from compensable (maintenance of thermal equilibrium with stable core temperature) to uncompensable (loss of thermal equilibrium with increasing core temperature) heat stress. To provide clear observations of compensable and uncompensable heat stress for the validation of exposure limits, the observations at 15 min prior to and after the transition point were used for this dataset and classified as a case (uncompensable) or a non-case (compensable) (Garzón-Villalba *et al.*, 2017).

The transition point was also classified as a non-case or case depending on the value of rectal temperature (case if >38°C) or a case if it showed a gradual increase greater than 0.1°C in the preceding 20 min (Garzón-Villalba *et al.*, 2017).

For each observation, TWL was computed based on the environmental conditions at that time in the progressive heat stress protocol. The dependent variable ($\Delta Limit_{TWL}$) was the difference between the observed metabolic rate (M_{obs}) in the trial and the TWL for each observation (3 observations per trial) expressed as metabolic rate; $\Delta Limit_{TWL} = M_{obs} - TWL$. A positive value of $\Delta Limit_{TWL}$ represented an over-exposure. Each observation was classified as above or at/below the TWL limit.

All statistical analyses were performed using JMP v16 (SAS, Cary NC). For each clothing ensemble, 2 × 2 tables were tabulated (case status x TWL status). First, an overall logistic regression model was run. The model was $\ln(odds) = \alpha + \beta_1\ \Delta Limit_{TWL} + \beta_2\ Clothing + \beta_3\ M + \beta_4\ P_v + \varepsilon$, where M is metabolic rate in watts and P_v was ambient water vapor pressure in kPa. Clothing (4 levels) was categorical and $\Delta Limit_{TWL}$, M and P_v were continuous variables. Then logistic regression was used to examine the principal relationship of $\ln(odds) = \alpha + \beta\ \Delta Limit_{TWL} + \varepsilon$ for each clothing ensemble. The area under the ROC curve (AUC) was also noted.

The probability of an uncompensable exposure (case) was estimated from the logistic regression when $\Delta Limit_{TWL} = 0$. Finally, the value of $\Delta Limit_{TWL}$ was estimated when probability of an unsustainable exposure was 0.05 [odds = 0.053 and ln(0.053) = −2.94].

Table 1. 2 × 2 tables for four clothing ensembles that show the distribution of cases (Yes v. No) at the decision levels (Above v At/Below TWL) with the associated sensitivity and specificity

Woven clothing	Yes	No
Above TWL	248	220
At/below TWL	7	53
Sensitivity/specificity	0.97	0.19
Particle barrier	Yes	No
Above TWL	165	157
At/below TWL	8	27
Sensitivity/specificity	0.95	0.15
Water barrier	Yes	No
Above TWL	138	107
At/below TWL	4	24
Sensitivity/specificity	0.97	0.18
Vapor barrier	Yes	No
Above TWL	138	109
At/below TWL	4	31
Sensitivity/specificity	0.97	0.22

Results

A table summarizing the trial data (mean ± standard deviation) of metabolic rate (M in Watts), air temperature (T_{db} in °C), water vapor pressure (P_v in kPa), WBGT (°C), TWL (Wm^{-2}), and $\Delta Limit_{TWL}$ (Wm^{-2}) by clothing, relative humidity level, and metabolic rate level is included as Supplementary data (available at Annals of Occupational Hygiene online).

Table 1 provides the 2 × 2 tables (case status x TWL status) for each clothing ensemble. For clothing, the sensitivity of TWL to identify an uncompensable exposure was 0.95 for particle barrier and 0.97 for woven clothing, water barrier, and vapor barrier. The specificity for the four ensembles was between 0.15 and 0.22.

When the full model [$\ln(odds) = \alpha + \beta_1\ \Delta Limit_{TWL} + \beta_2\ Clothing + \beta_3\ M + \beta_4\ P_v + \varepsilon$] was run, $\Delta Limit_{TWL}$, Clothing, M, and P_v were statistically significant. The results from running the principal model [$\ln(odds) = \alpha + \beta\ \Delta Limit_{TWL}$] are reported in Table 2. In addition to the model are the area under the ROC curve (AUC), the predicted probability of an uncompensable exposure at $\Delta Limit_{TWL} = 0$, and the value of $\Delta Limit_{TWL}$ when the predicted probability of an uncompensable exposure was 0.05.

Table 2. Results of the logistic regression [ln(odds)] for each clothing ensemble with the associated area under the ROC curve (AUC), the probability of an uncompensable exposure at the TWL ($\Delta Limit_{TWL} = 0$), and the value of $\Delta Limit_{TWL}$ for a probability of uncompensable at 0.05

Ensemble	ln(odds)	AUC	p at $\Delta Limit_{TWL} = 0$	$\Delta Limit_{TWL}$ at p=0.05
Woven clothing	$-1.78 + 0.026\ \Delta Limit_{TWL}$	0.81	0.14	−45
Particle barrier	$-1.89 + 0.027\ \Delta Limit_{TWL}$	0.82	0.13	−39
Water barrier	$-1.28 + 0.023\ \Delta Limit_{TWL}$	0.76	0.22	−72
Vapor barrier	$-1.28 + 0.026\ \Delta Limit_{TWL}$	0.77	0.22	−64

Discussion

TWL was designed to provide an upper limit on metabolic rate so that thermal equilibrium could just be maintained. Thus, the data from the progressive heat stress protocol were particularly well-suited to examine the ability of TWL to specify an upper limit. The environmental conditions at the transition and 15 min prior to and after the transition provide data for classifications of non-cases and cases to better evaluate the performance of TWL.

To evaluate the TWL in a controlled environment, Miller and Bates (Miller and Bates, 2007) used 12 participants apparently wearing street clothes in a fixed environment (TWL = 160 Wm^{-2}, WBGT = 31°C). During the trials, the metabolic rate was adjusted up (or down) at the beginning of 30-min periods among rates of 115, 130, and 145 Wm^{-2} to find the highest metabolic rate that allowed a physiological steady state. All of the trials were below the TWL with 22 non-cases (compensable exposures) and 2 cases (uncompensable exposures). (Note: We reclassified 3 exposures from uncompensable to compensable because the core temperature may have reached a steady level at 38.2°C. This change in case status improved the apparent performance of TWL. One observation was dropped as the authors noted the possibility of heavier clothing than usual.) These data provided limited insight into how well TWL met the goal of limiting exposures to sustainable levels because the range of exposures did not include exposures above the TWL and span a range of humidity and metabolic rates. The data reported in this paper for woven clothing included 468 observations above the TWL and 60 at or below the TWL.

Looking at the results of the overall model [$\ln(\text{odds}) = \alpha + \beta_1\,\Delta\text{Limit}_{TWL} + \beta_2\,\text{Clothing} + \beta_3\,M + \beta_4\,P_v$], there were significant findings for all the independent variables. While Clothing, M and P_v were included in TWL as part of the underlying rational model, the variance attributable to Clothing, M, Pv, and random error suggested that there is some potential for future improvements in the implementation of TWL.

Because there were significant differences among the four clothing ensembles, TWL was examined for each ensemble using the 2 × 2 tables reported in Table 1 and the logistic regression analyses reported in Table 2. Separate evaluations avoided any bias in the overall results due to the prevalence of one ensemble over others in actual workplaces.

As reported in Table 1, specificity was about 0.96 for each of the ensembles suggesting confidence that uncompensable exposures were correctly identified, but the low specificities between 0.15 and 0.22 reflected the prevalence of false positives among the observations. There were few false negatives among the data.

Table 2 reports the results of the logistic regressions. A weak ability to discriminate compensable and uncompensable was expected from the sensitivity and specificity data of Table 1. The area under the ROC curves was about 0.8 for each clothing ensemble. A remarkable finding was the probability of uncompensable at the TWL limit. As a working population approaches the TWL, the probability of an uncompensable exposure increases toward 0.13 for woven clothing and particle barrier and 0.22 for water barrier and vapor barrier. To bring the probability down to 0.05, the TWL would have to be reduced by 40 Wm^{-2} for woven and participle barrier and by about 70 Wm^{-2} for water barrier and vapor barrier. These are substantial reductions when compared with the TWL of 160 Wm^{-2} used in the validation study of Miller and Bates (Miller and Bates, 2007).

In addition to changing the basis for the limit for heat stress exposures from environment to metabolic rate, TWL was promoted as a less restrictive exposure limit to heat stress than the ACGIH TLV for heat stress and strain (ACGIH®, 2022; Miller and Bates, 2007). For TWL, the area under the ROC curve for woven clothing was 0.81, and the sensitivity and specificity at $\Delta\text{Limit}_{TWL} = 0$ were 0.97 and 0.19 (see Table 2). For comparison, the WBGT-based limits for woven clothing had 0.85 for the AUC, sensitivity of 1.0, and specificity of 0.01 (Garzón-Villalba *et al.*, 2017). That is, the WBGT could be slightly better at discrimination. At the occupational exposure limit (e.g., ΔTLV = 0), the WBGT-based exposure limits were more protective with a lower probability of uncompensable decisions (sensitivity = 1.0) (Garzón-Villalba *et al.*, 2017). Changing the perspective, the question might be how much higher would the WBGT limit be to have a similar probability of uncompensable (say, $P = 0.15$). For woven clothing, the increase would be about 4°C-WBGT (see figure 3, Garzón-Villalba *et al.*, 2017). In summary, the relaxed restriction of TWL over WBGT-based limits comes with an increased level of risk acceptance and not a fundamentally better approach.

In conclusion, the TWL provides a novel approach to control heat stress exposures in workplaces that allow self-pacing for workers who are sufficiently trained. TWL follows the public health approach with high sensitivity at the cost of low specificity. TWL does provide similar ability to safely limit heat stress exposures among the four clothing ensembles. For woven clothing, there is no reason to believe that it is fundamentally better than WBGT-based approaches. While the TWL is less restrictive than the traditional WGBT occupational exposure limits, TWL requires a higher level of risk acceptance than the WBGT method.

Supplementary data

Supplementary data are available at *Annals of Work Exposures and Health* online.

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Conflict of interest

The authors declare no conflict of interest relating to the material presented in this article. One of the authors [Bernard] has acted as an expert witness for both private companies and OSHA in litigation concerning heat stress exposures and may in future serve as an expert witness in court proceedings related to heat stress. The contents, including any opinions and/or conclusions, are solely those of the authors.

References

ACGIH®. (2022). *Heat stress and strain. Threshold limit values and biological exposure indices for chemical substances and physical agents*. Cincinnati, OH: ACGIH®.

Ahmed HO, Bindekhain JA, Alshuweihi MI *et al*. (2020) Assessment of thermal exposure level among construction workers in UAE using WBGT, HSI and TWL indices. *Industrial Health*; **58**: 170–81.

Bates GP, Miller V. (2002). Empirical validation of a new heat stress index. *J Occup Heal Saf*; **18**:145–52.

Bernard TE, Caravello V, Schwartz SW *et al*. (2008). WBGT clothing adjustment factors for four clothing ensembles and the effects of metabolic demands. *J Occup Environ Hyg*; **5**:1–5.

Bernard TE, Luecke CL, Schwartz SW *et al*. (2005). WBGT clothing adjustments for four clothing ensembles under three relative humidity levels. *J Occup Environ Hyg*; **2**:251–6.

Brake DJ, Bates GP. (2002) A valid method for comparing rational and empirical heat stress indices. *Ann Occup Hyg*; **46**: 165–74.

Caravello V, McCullough EA, Ashley CD, Bernard TE. (2008). Apparent evaporative resistance at critical conditions for five clothing ensembles. *Eur J Appl Physiol*. **104**:361–7.

Farshad A, Montazer S, Monazzam MR *et al*. (2014). Heat stress level among construction workers. *Iran J Public Health*; **43**:492–8.

Garzón-Villalba XP, Wu Y, Ashley CD *et al*. (2017). Ability to discriminate between sustainable and unsustainable heat stress exposures-part 1: WBGT exposure limits. *Ann Work Expo Health*; **61**:611–20.

Malchaire J, Piette A, Kampmann B *et al*. (2001) Development and validation of the predicted heat strain model. *Ann Occup Hyg*; **45**: 123–35.

Miller V, Bates G. (2007) The thermal work limit is a simple reliable heat index for the protection of workers in thermally stressful environments. *Ann Occup Hyg*; **51**: 553–61.

Miller V, Bates G, Schneider JD *et al*. (2011) Self-pacing as a protective mechanism against the effects of heat stress. *Ann Occup Hyg*; **55**: 548–55.

ISO. (2004). *ISO 7933: Ergonomics of the thermal environment—analytical determination and interpretation of heat stress using calculation of the predicted heat strain*. Geneva: ISO.

ISO. (2017). *ISO7243: Ergonomics of the thermal environment—assessment of heat stress using the WBGT (wet bulb globe temperature) index*. Geneva: ISO.

NIOSH. (2016). NIOSH criteria for a recommended standard: occupational exposure to heat and hot environments. In Jacklitsch B, Williams WJ, Musolin K, Coca A, Kim J-H, Turner N, editors. Cincinnati, OH: Department of Health and Human Services, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health [DHHS (NIOSH) Publication No. 2016-106].