Validation of the Thermal Work Limit (TWL)
Against Known Sustainable Heat Stress Exposures

by

Danielle L. Kapanowski

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Department of Environmental and Occupational Health
College of Public Health
University of South Florida

Major Professor: Thomas E. Bernard Ph.D.
René Salazar, Ph.D.
Candi D. Ashley, Ph.D.

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DEDICATION

This thesis is dedicated to my husband Ryan Bontrager who has been my rock of support throughout my graduate studies. Thank you for always believing that I could do this, even when I was positive that I could not. I could have never gotten this far in life without your love and guidance.

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ABSTRACT

Workers are exposed to stressful thermal work environments in multiple industries every day. Methods for assessing heat stress often struggle to balance productivity without compromising the health of the workers. The Thermal Work Limit (TWL) is a method that has been adopted in areas outside of the United States as a viable method for heat assessment that combines health with productivity. TWL recommends a maximum metabolic rate for a given set of environmental conditions, clothing ensemble and acclimatization state. The purpose of this paper was to evaluate the validity of the TWL against a set of heat stress data known to be at the maximum sustainable level.

A range of conditions were combined through environmental (20%, 50% and 70% relative humidity), clothing (woven clothing, WC; particle barrier coveralls, PB; water barrier coveralls, WB; and vapor barrier coveralls, VB), and workload factors (metabolic rates at low, L; moderate, M; and high, H) at the transition from sustainable to unsustainable exposure to ensure that the TWL method is thoroughly explored. Data from previous heat stress studies were used to compare the difference in predicted TWL with a calculated value.

An analysis of variance (ANOVA) demonstrated that there were significant effects of the TWL due to clothing, metabolic rate level and relative humidity level. TWL provided similar results for WC, PB and WB, but had systematically lower values for VB.

This suggested a more protective recommendation with high evaporative resistance. As the metabolic rate increased, the recommended limiting TWL also went up out of proportion to the metabolic rate, which provided greater protection at increasing metabolic rates. Under drier conditions (20% relative humidity), the TWL was systematically lower than for 50% and 70% relative humidity.

While there were significant differences due to the main effects, the TWL was designed to be used without defined limits on environmental conditions, metabolic rate or clothing. Therefore, all of the conditions represented a comprehensive test of the TWL. Overall, the TWL was less protective than the current methods used by ACGIH Threshold Limit Values (TLV) and National Institute for Occupational Safety and Health (NIOSH) Recommended Exposure Limit (REL). At the threshold, the TWL had a 7% probability of being unsustainable compared to the threshold probability of 1% for the TLV and REL.

INTRODUCTION

Heat stress has long been identified as an occupational health hazard and its assessment continues to be a topic of interest for health and safety professionals. Heat stress is influenced by the combination of metabolic rate, environmental conditions, and clothing. These three factors together can be used in different heat stress models to predict the intensity of heat stress.

The metabolic rate is the amount of internal heat generation that must be dissipated from the body to maintain thermal equilibrium. Maintaining a state of equilibrium where the heat produced by the body is equal to the amount of heat given off is the ideal situation for a worker. Metabolic rates vary based on the type and rate of effort required to perform the work.

Environmental factors often used to evaluate heat stress include air temperature, humidity, air speed, and the average temperature of the solid surroundings. Different assessment methods evaluate these factors in different combinations, depending on the parameters of the index chosen for heat stress assessment.

Clothing has three characteristics that affect thermal balance. The characteristics of insulation, permeability and ventilation of clothing can all impact thermal balance. Insulation has a direct effect on radiation, convection, and conduction. Higher insulation will result in a lower rate of heat flow from warmer to cooler. Permeability is the measurement of the diffusion of water vapor through clothing. This directly influences evaporative cooling. The higher the diffusion rate, the greater the cooling effect. Ventilation is the measure of the air movement through the fabric and around openings which can enhance heat transfer through evaporative and convection modes.

Empirical and rational methods have been developed over time to assess heat stress. Empirical methods relate the heat stress index to an outcome such as a sustainable level of heat stress. The American Conference of Governmental Industrial Hygienists (ACGIH) Threshold Limit Values (TLVs) and the National Institute for Occupational Safety and Health (NIOSH) Recommended Exposure Limit (RELs) are empirical methods based on wet bulb globe temperature (WBGT). WBGT is an index that combines effects of natural wet bulb temperature (humidity and air movement) with globe temperature (heat and air temperature) and dry bulb temperature (air temperature). The WBGT can be adjusted to address indoor or outdoor conditions as required. WBGT has continued to be widely used due to ease of use and heat stress interpretation (ACGIH, 2017; Jacklitsch et al., 2016).

In contrast to empirical methods that are based on observed relationships between stress and effects, rational methods are based on biophysical models of heat exchange. Rational models start with a heat balance equation that looks at a hypothetical person and the environment. A basic heat balance equation is:

$$\Delta \quad = (M - W) \pm C \pm R \pm K - E$$

where

ΔS=change in body heat

(M-W) = total metabolism minus external work performed

C = convective heat exchange

R = radiative heat exchange

K = conductive heat exchange

E = evaporative heat loss

Radiation, convection, conduction, and evaporation are the major avenues of human heat exchange.

Rational indices attempt to predict sweat rate, core temperature or core temperature increase, heart rate or a combination of these physiological parameters. Rational indices measure conditions of the environmental conditions to predict population thermal strain.

Agencies such as the ACGIH and NIOSH provide guidance for hazard control through assessment by providing TLVs and RELs in the form of graphs and tables that identify upper limits. The ACGIH provides a table for clothing adjustment values that can be considered in the heat stress evaluation. Heat stress indices are explicitly or implicitly based on heat balance. While most often the heat stress limit is expressed as environmental conditions at a given metabolic rate, it is equally fair to prescribe an upper limit of metabolic rate under given environmental conditions. In a sense, that approach is taken in work and recovery tables. Bates and Brake posit this approach using a rational model of heat stress exposure (R. Brake & Bates, 2001).

LITERATURE REVIEW

The Thermal Work Limit (TWL) was developed by Brake and Bates with the goal of describing a work load limit, specifically a metabolic rate limit that depends on environmental conditions, clothing and acclimatization state. They used an underlying rational model of heat stress that considered the avenues of heat exchange between a person and the environment. In principal, the difference between the TWL approach and typical empirical or rational methods of heat stress assessment was that in TWL the dependent variable was metabolic rate rather than environmental conditions or time They argue that workers naturally control the pace of work when they are allowed to do so (R. Brake & Bates, 2001). TWL was adopted by Australian industries based on the premise that the TWL is a more relaxed exposure limit to heat stress than the WBGT-based methods, yet sufficiently protective (Miller & Bates, 2007). Based on its success in Australia, TWL was adopted in the Middle East (G. P. Bates & Schneider, 2008).

Bates and Miller conducted a small study in 2002 (G. Bates & Miller, 2002). They concluded that there is no need to constantly determine the metabolic rate and while the environmental conditions need to be measured, there is less emphasis on specific components when the workers are educated on self-pacing. Brake and Bates concluded that the TWL method works for self-paced workers and management who are educated about working in heat and are well hydrated (D. J. Brake & Bates, 2002).

Miller, Bates, Schneider, and Thomsen published a study on the TWL method that evaluated heat stress at construction sites in Abu Dhabi and Dubai (Miller, Bates, Schneider, & Thomsen, 2011). Three locations with differing workloads were evaluated to address the practice of self-pacing against heat stress. Each group was monitored by tympanic temperatures and external heart rate monitors. Field test 1 was performed in August 2007 on workers mainly performing manual labor with very little equipment for assistance. Field test 2 was performed in July 2008 on workers performing various skilled and unskilled tasks with varying exposure to direct sunlight. Field test 3 was performed in September 2008 on skilled workers performing tasks such as welding and wearing additional personal protective equipment as dictated by task. Field tests 1 and 2 had mandatory breaks from 12.30 to 3 pm in rest facilities provided on site due to area regulations. In this case, workers who were extensively trained to perform self-pacing successfully minimized heat stress. Self-regulation with educated workers tends to maintain heart rate in a sustainable range. This was found to be consistent in all three groups of this study. Further, the participants similarly adjusted their workload to avoid physiological strain as heart rates and thermal stress increased.

None of these studies actually measured or estimated the metabolic rate. They simply showed that the prevailing work practices were adequate to manage the heat strain to acceptable levels.

Miller and Bates performed an evaluation study on 12 participants in a controlled environment (Miller & Bates, 2007). During the controlled environment trials, the work load was stepped up in 10 W increments (40, 50 and 60 W on a bicycle ergometer) to find an upper limit of work load that allowed a physiological steady state based on core temperature and heart rate. Re-analyzing the data from their trials, all of the trials were below the TWL with 19 sustainable exposures (true negatives) and 5 unsustainable (false negatives) for sensitivity = 0.0 and specificity = 1.0. For occupational exposure limits, high sensitivity is more protective. Unfortunately, there were no data to test the sensitivity because all the exposures were below the TWL. It was somewhat distressing that about 20% of the trials were false negatives, which was not protective.

As a note, the results were exactly the opposite for the WBGT-based occupational exposure limits where all the trials were above the TLV by an average of 2°C. Thus, the sensitivity was 1.0 but specificity was 0.0. While the overall data were limited in range, they do support the concept that the WBGT-based thresholds are protective, even though about 80% of the trials could be sustained above the TLV. This outcome was not surprising.

The purpose of this study is to more fully evaluate the validity of the TWL as a heat stress assessment method. One set of study hypotheses were that there were no differences due to metabolic rate, relative humidity or clothing. Further the exposure response curve would articulate the probability of unsustainable exposures as a function of the difference between the observed metabolic rate and TWL.

METHODS

Data collected from two previous progressive heat stress studies at University of South Florida (USF) (Bernard, Caravello, & Schwartz, 2008; Bernard, Leucke, & Schwartz, 2005) were used for this study. The USF heat stress protocols were approved by the USF institutional review board. The two studies included five clothing ensembles: work clothes (140 g m^{-2} cotton shirt and 270 g m^{-2} cotton pants), and cotton coveralls (310 g m^{-2}) plus three nonwoven protective clothing ensembles: (1) particle-barrier (Tyvek® 1424 and 1427; similar to Tyvek® 1424A); (2) water-barrier, vapor permeable (NexGen® LS; microporous membrane), and (3) vapor-barrier (Tychem QC®, polyethylene-coated Tyvek). Table I provides the insulation and permeability index for each clothing ensemble. One study (Bernard et al., 2005) targeted a work demand (M) of 160 W m^{-2} to approximate moderate work over three levels of relative humidity (rh) at (20, 50 and 70%). The other study (Bernard et al., 2008) targeted M at 115, 175 and 250 W m^{-2} to approximate light, moderate, and heavy work at rh = 50%. In both studies, each participant wore each of the five clothing ensembles.

Table I - Insulation and permeability index for the four clothing ensembles

Clothing Ensemble	Insulation [clo]	Permeability Index (i_m)
Woven Clothing	0.61	0.38
Particle Barrier Coveralls	0.69	0.37
Water Barrier Coveralls	0.68	0.31
Vapor Barrier Coveralls	0.65	0.17

The progressive heat stress protocols began with an environment that allowed the participants to achieve thermal equilibrium. Once equilibrium was established, air temperature (T_{db}) and humidity (water vapor pressure) were slowly increased in 5 minutes intervals at a constant rh; the steps were designed to establish a quasi-steady-state physiological response for each step increase in heat load. Rectal temperature (T_{re}), heart rate (HR), skin temperature (T_{sk}), and ambient conditions were monitored continuously and recorded every 5 minutes. M was estimated from the assessment of oxygen consumption via expired gases sampled with a Douglas bag every 30 minutes in a trial. The transition from a stable core temperature to values that were steadily increasing was the critical condition. These critical conditions were used to evaluate the association of TWL with M, rh, and clothing and to describe the exposure-response relationships.

All study participants were acclimatized over five successive days by 2-h exposures to dry heat (50ºC and 20% rh) at 160 W m^{-2} while wearing shorts and tee shirt. The characteristics of the 29 participants who took part in these trials are summarized in Table II.

Table II - Baseline Characteristics (mean ± standard deviation) of Participants

	N	**Age (yr)**	**Height (cm)**	**Weight (kg)**	**Body Surface Area (m^2)**
Relative Humidity Study (Bernard et al., 2005)					
Men	9	29 ± 6.8	183 ± 6	97 ± 19	2.18 ± 0.20
Women	5	32 ± 9.1	161 ± 7	64 ± 17	1.66 ± 0.23
Metabolic Rate Study (Bernard et al., 2008)					
Men	11	28 ± 10	176 ± 6	82 ± 12	1.98 ± 0.47
Women	4	23 ± 5	165 ± 6	64 ± 18	1.70 ± 0.22
Pooled					
Men	20	29 ± 9	179 ± 11	89 ± 23	2.07 ± 0.41
Women	9	28 ± 8	163 ± 7	64 ± 17	1.74 ± 0.29

No differences in critical conditions ($WBGT_{crit}$) were found between woven clothes and cotton coveralls in previous investigations (Bernard et al., 2008; Bernard et al., 2005), thus the two ensembles were categorized as woven cotton clothing in the present study. There were 190 trials for woven cotton clothing (WC), 119 for particle barrier (PB), 91 for water barrier (WB), and 94 for vapor barrier (VB) over the two studies.

TWL was computed from the clothing characteristics provided in Table I, recorded dry bulb (T_{db}), psychrometric wet bulb (T_{pwb}) temperatures, globe temperature (radiant heat), and the wind speed with acclimatized participants. The dependent variable was the difference between the TWL expressed as metabolic rate and the observed metabolic rate (M_{obs}) in the trial. That is, $\Delta TWL = M_{obs} - TWL$, where a positive value is protective.

JMP v15 was used for all the statistical analysis. The analysis used the transition data found at the critical condition; that is, the transition point from Sustainable to Unsustainable. The dependent variable was ΔTWL. A 3-way analysis of variance (ANOVA) was employed. The treatments were M categorical at three levels (Low, L; Moderate, M; and High, H); rh categorical at three levels (20, 50 and 70%), and ensembles categorical at four levels (Woven Clothing, WC; Particle Barrier Coveralls, PB; Water Barrier Coveralls, WB; and Vapor Barrier Coveralls, VB). Based on previous WBGT studies, an interaction between rh and clothing was expected (Bernard et al., 2005) and included in the ANOVA.

In a parallel approach, a logistic model using the critical conditions (transitions at $WGBT_{crit}$) data to model a dose-response curve. For each clothing ensemble and all ensembles (five models altogether), the data were rank ordered from lowest to highest ΔTWL. Then the odds were estimated for each observation of ΔTWL as the number of trial critical conditions at or below the ΔTWL divided by the total number of observations above the ΔTWL plus 1. Finally, a logistic regression was computed as the $\ln(\text{odds}) = a + b\,\Delta TWL$.

RESULTS

All of the data were transitional data from Sustainable to Unsustainable; that is, at the threshold that forms the goal of the TWL. An ANOVA was performed to test the main effects (M, RH, Clothing) and one interaction (RHxClothing) for ΔTWL. Interaction between the relative humidity and the clothing factors was expected, but the interaction was not statistically significant ($p = 0.48$). The ANOVA was recalculated with only the main effects. Clothing, metabolic rate, and relative humidity were all highly significant at $p < 0.001$.

Table III provides the least squares means of ΔTWL for the clothing ensembles in the order of increasing evaporative resistance. The multiple comparison test indicated that vapor barrier clothing was significantly less than the other three clothing ensembles; and there was no difference among WC, PB, and WB. There was sufficient evidence to suggest a rejection at the $\alpha=0.05$ level of the null hypothesis that all four clothing ensemble means are equal, in favor of an alternative hypothesis that vapor barrier clothing exhibited a different true population mean from WB, WC, and PB.

Table III. Least Squares Mean of ΔTWL [W m^{-2}] and Standard Error – Clothing Ensembles

Level	Least Squares Mean of ΔTWL [W m^{-2}]	Standard Error
Vapor Barrier	50	5.6
Water Barrier	62	5.7
Cotton Clothing	66	5.3
Particle Barrier	68	5.5

Table IV reports the least squares mean of ΔTWL for the three levels of metabolic rate. There were significant differences among all three values based on the multiple comparison tests. There was sufficient evidence to suggest a rejection at the α=0.05 level of the null hypothesis that all metabolic rate population means are equal, in favor of an alternative hypothesis that all three metabolic rates exhibited a different true population mean from each other. The pattern of these means also suggests that as the work levels increase, the least squares mean increases as well.

TABLE IV Least Squares Mean of ΔTWL [W m^{-2}] and Standard Error – Metabolic Rates

Level	Least Square Mean of ΔTWL [W m^{-2}]	Standard Error
Low	30	5.9
Medium	55	4.9
High	98	5.9

Table V reports the least squares mean of ΔTWL for the three levels of relative humidity. The 20% rh level was significantly lower than the 50% and 70% rh levels. There was sufficient evidence to suggest a rejection at the α=0.05 level of the null hypothesis that all relative humidity means are equal, in favor of an alternative hypothesis that the 20% relative humidity level exhibited a different true population mean from the 50% and 70% levels.

Table IV. Least Squares Mean of ΔTWL [W m^{-2}] and Standard Error – Relative Humidity

Level	Least Square Mean of ΔTWL [W m^{-2}]	Standard Error
20%	48	5.8
50%	67	4.9
70%	68	5.8

The transitional data were further reviewed for each clothing ensemble separately and all combined together against the distribution of ΔTWL and were plotted against the probability of Unsustainable. All five of these graphs are shown in Figures 1 and 2.

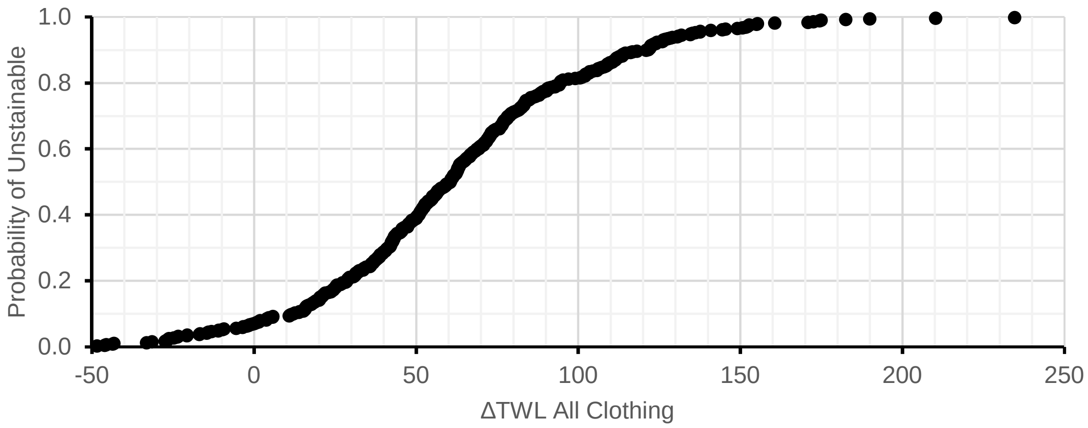

Figure 1 - Probability of Unsustainable for All Clothing Ensembles

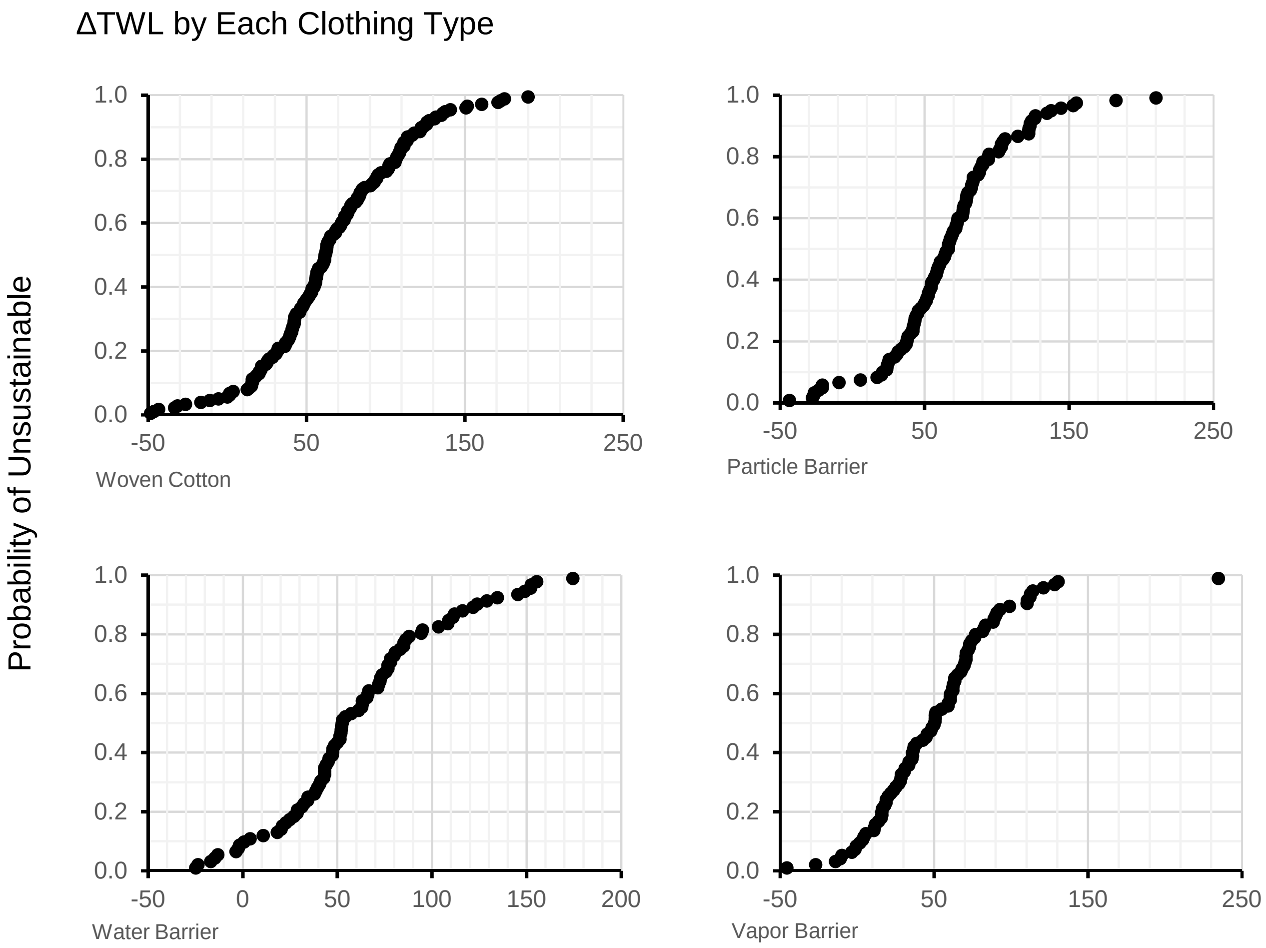

Figure 2 - Probability of Unsustainable by Clothing Type

DISCUSSION

The data used for this validation covers four sets of clothing ensembles (woven cotton, particle barrier, water barrier, and vapor barrier); low, medium, and high metabolic rates (ranging from 170-500 Watts); and three levels of relative humidity (20, 50, and 70%). The dataset covered different combinations that represented a broad range of occupational exposures. The use of multiple potential combinations was important to ensure that varying types of potential exposures were included when reviewing the validity of the TWL method.

The dependent variable was ΔTWL, which was the difference between the measured metabolic rate for a given trial and the computed TWL for that trial. In this way, a positive value for ΔTWL was protective. Table IV shows the least squares means of ΔTWL for the clothing ensembles. Vapor barrier ensembles were found to be significantly different from the other three ensembles. The least squares means for woven cotton, water and particle barrier ranged from 62 to 68 W m^{-2}, while the vapor barrier ensemble had a value of 50 W m^{-2}. The vapor barrier ensemble was the ensemble that tended to have the least protective profile. The probability of Unsustainable at ΔTWL = 0 was 0.07. This was similar to the other clothing ensembles at 0.06 (WC), 0.07 (PB) and 0.09 (WB). That means that the slope was steeper, which is suggested by the plots in Figure 2.

Table IV shows the least squares means for the metabolic rates. All three metabolic rates were significantly different from each other. As the work level increased, the least square mean value also increased. That suggested that the level of protection also increased with the work demands. From a heat balance perspective, the TWL model underrepresented the amount of heat dissipation with increasing internal heat loads.

Table V summarizes the least square means for the relative humidity values used. The rh values of 50 and 70% were not significantly different, but the value of 20% had a lower least square mean. Under drier conditions, the average level of protection was lower. It was not clear why there should be a difference, but it appeared to suggest that the rate of evaporative cooling was influenced by something more than the water vapor pressure gradient between the skin and the environment.

Because TWL was designed for broad application regardless of the clothing and prevailing conditions, the validation should include a reasonable range. In this study, there was a substantial range of clothing, humidity and metabolic rate to be applicable to many working conditions. The further requirement of TWL was the ability to self-pace. In this study, instead of self-pacing, the goal was to use data at a limiting metabolic rate at a barely sustainable exposure and the progressive heat stress protocol found the balance point for each trial at the critical conditions. The overall probability of an unsustainable exposure was at the limiting TWL (ΔTWL = 0) was 0.07.

The TWL was also promoted as being less restrictive than WBGT-based occupational exposure limits. Garzón and colleagues found that the probability of unsustainable following the ACGIH TLV was 0.01 for woven clothing. In the terms of a greater probability of being unsustainable, the TWL is less restrictive. But the relaxed restriction comes with an increased level of risk acceptance and not a fundamentally better approach.

In conclusion, this thesis demonstrated that the TWL can be a viable method for use as a heat stress assessment method. The data show that in multiple combinations of clothing, environmental factors, and workloads, the method can be used to effectively predict heat stress. While TWL predictions are less restrictive than the traditional WGBT predictions, the TWL method requires the exposed to have a working knowledge of hydration and self-pacing for the TWL assessment to be effective. These factors should be considered when a method for heat stress assessment is selected to ensure that the exposed parties are properly protected.

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