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Using Predicted Heat Strain to Evaluate Sustainable Exposures

by

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A thesis submitted in partial fulfillment
of the requirements for the degree of
Master of Science in Public Health
Department of Environmental and Occupational Health
College of Public Health
University of South Florida

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John C. Smyth Ph.D.

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Keywords: PHS, exposure assessment, occupational hazard, rational model

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ABSTRACT

The most commonly used exposure assessment for heat stress is based on Wet Bulb Globe Temperature (WBGT), and the limits are based on empirical relationships that demonstrate a sustainable exposure. The ISO 7933 (2017) describes Predicted Heat Strain (PHS), which is a rational model for heat stress assessment that is used to assess time-limited exposures. Investigators have examined PHS validity under a variety of time-limited conditions. The purpose of this paper is to evaluate if PHS can predict sustainable exposures.

The data used for this study were from two previous heat stress studies using a progressive heat stress protocol. The studies included 29 participants wearing four different ensembles (woven clothing, particle barrier, water barrier, and vapor barrier coveralls) at three levels of metabolic rate and relative humidity. Each trial provided data for a fully compensable (sustainable) exposure and an uncompensable (time-limited) exposure. The heat stress data from each condition were used to see if PHS demonstrated a steady-state response indicating a sustainable exposure.

From the analysis, the sensitivity and specificity respectively for the ensemble types were: 1.00 and 0.18 for woven clothing, 0.95 and 0.60 for particle barrier, 0.91 and 0.83 for water barrier, 0.91 and 0.80 for vapor barrier, and 0.94 and 0.65 for all ensembles. The data show that while the sensitivity of PHS (correctly identifying unsustainable conditions) is good for the different ensembles, PHS specificity (correctly identifying sustainable exposures) was weak. From an occupational health and safety perspective, using PHS to identify sustainable exposures leads to protective decisions.

INTRODUCTION

Several million workers are exposed to heat stress in the United States, emphasizing the significant presence of heat stress as an occupational hazard (Adelakun, 1999). It is important to maintain the safety of workers in all industries from heat stress related conditions, and critically important in hot and humid climates, where the severity of these illnesses can increase (Adelakun, 1999; Malchaire, 2006; Malchaire et al., 2002; Wang, Gao, Kuklane, & Holmer, 2011). Creating a guideline that can be applied to protect workers from heat related conditions involves considering the factors that influence heat stress.

In order to protect workers from heat stress, the ACGIH and the National Institute for Occupational Safety and Health (NIOSH) developed guidelines for heat stress exposure during work (ACGIH, 2017; Jacklitsch et al., 2016). The ACGIH Threshold Limit Values (TLVs) and NIOSH Recommended Exposure Limits (RELs) are based on the Wet Bulb Globe Temperature (WBGT) (Jacklitsch et al., 2016). The WBGT is an environmental measure that takes into account dry air temperature, humidity, and radiant energy, which contribute to thermal load for workers (Jacklitsch et al., 2016). This measure was adopted by ACGIH as the index for environmental heat stress in 1974 and then used in NIOSH RELs as well (ACGIH, 2017). The TLVs and RELs were created to protect almost all healthy, acclimatized workers by establishing conditions under which thermal equilibrium can be maintained, with no adverse effects from repeated exposure (Jacklitsch et al., 2016). This criteria was adopted because WBGT is easy to measure and incorporates humidity, temperature, radiation, and air movement to give a temperature value (Jacklitsch et al., 2016). Though the WBGT has been widely accepted an used for years, it has been challenged and deemed inconsistent in many aspects that encourage the transition into a more representative model to protect workers from heat stress (d'Ambrosio Alfano, Malchaire, Palella, & Riccio, 2014). While these guidelines represent a protective index for heat stress, other aspects should be considered to create a more detailed and diverse model for preventing heat related illness.

Predicting the risk of heat stress is highly variable because individual differences, work environments, and activities can vary greatly (Lucas, Epstein, & Kjellstrom, 2014; Wang, Gao, Kuklane, & Holmer, 2013). The physiological strain placed on the worker can change due to the environment where the work is being done, physical exertion of work, and clothing types required (d'Ambrosio Alfano, Palella, Riccio, & Malchaire, 2016; Wang et al., 2013). Because the environment affects heat exchange, work intensity dictates the body's metabolic rate, and clothing modifies heat exchange, it is important that these interactions are used to determine overall heat stress and resulting strain on the body (Malchaire, Kampmann, Havenith, Mehnert, & Gebhardt, 2000; Wang et al., 2013). These factors and their implications must be considered when addressing the problem of heat stress.

Individual variation plays an important role in the regulation of heat stress. As physiological responses vary across persons, it is important to be able to protect the majority of workers (Malchaire, Kampmann, et al., 2000). As these differences make it difficult to accurately calculate the levels where heat stress will occur; it must be determined what amount of risk is acceptable (Lucas et al., 2014; Malchaire, Kampmann, et al., 2000).

Protective clothing types or uniform requirements can impact a person's thermal regulation, making clothing an important factor when addressing heat stress (Lucas et al., 2014; Malchaire et al., 2002; Malchaire, Piette, et al., 2000). Clothing has an impact on convective and evaporative heat losses that create significance in the type of clothing worn in different climates (Malchaire et al., 2002; Malchaire, Piette, et al., 2000). The body's ability to maintain thermal equilibrium is impacted by clothing, which can reduce sweat evaporation (Lucas et al., 2014; Malchaire, 2006). Incorporating clothing differences into the guidelines for heat stress can account for these variations.

Because of all the influencing factors, setting heat stress limits has been a debated topic modeled differently over the past 70 years, to improve health and safety by predicting and representing heat stress (d'Ambrosio Alfano et al., 2016; Lundgren-Kownacki et al., 2017). Models created have helped to predict the expected response of the body when exposed to heat stressors (Wang et al., 2011). The main goal of model use is to create safe levels across all industries to protect workers from heat related illnesses (Lundgren-Kownacki et al., 2017; Malchaire, 2006; Malchaire et al., 2002). Occupational health professionals use models to better protect workers by reducing the risks of heat related conditions and prevent unnecessary costs of injury (Malchaire, 2006; Malchaire et al., 2002). Using heat stress models has contributed to reduced morbidity and mortality relating to heat in many different industries (Lundgren-Kownacki et al., 2017).

Among heat stress models, the Predicted Heat Strain model is a rational model that uses calculations from the heat balance equation to predicted time-limited heat stress exposures (Lundgren-Kownacki et al., 2017). The Predicted Heat Strain model was derived from the heat balance equation to predict the thermo-physiological responses of a person exposed to hot environments (Lundgren-Kownacki et al., 2017; Wang et al., 2013). The wide acceptance of PHS was recognized in its adoption as an ISO standard.

The purpose of this paper is to evaluate if PHS can predict a sustainable exposure.

LITERATURE REVIEW

The Predicted Heat Strain model is the current ISO 7933 rational model used for evaluation heat stress. Determining heat stress with a rational model requires use of the heat balance equation to incorporate heat exchange between the environment and body. The heat balance equation is represented as

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

where

S = 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

As demonstrated by the heat balance equation, humans exchange heat with the environment mainly through convection, radiation, and evaporation. This relationship can be used to assess the heat-related risks of illness as a function of these factors. Establishing thermal equilibrium is crucial to eliminate the risk of heat stress, but when thermal equilibrium cannot be maintained, rational models allow the prediction of heat storage limits (Plog & Quinlan, 2012).

To create the PHS model and show its validity in terms of predicting heat stress, it was important to use a large database and create parameters that will be used to test the algorithms.

From a collaboration of data collected over many years, roughly nine hundred data points representing laboratory and field experiments relating to heat stress were collected (Malchaire, Kampmann, et al., 2000; Malchaire, Piette, et al., 2000). Six PHS model parameters were used to compare data between experiments based on their applicability to heat stress including air temperature, humidity, radiation, air velocity, metabolic rate, and clothing insulation (Malchaire, 2006; Wang et al., 2011). The PHS model was used to predict the rectal temperatures and sweat rates to be compared to the data used for validation (Malchaire, 2006; Malchaire, Kampmann, et al., 2000; Malchaire, Piette, et al., 2000). With the particular set of data it was decided that the validation was only applicable within the parameters of the available database (Malchaire, Piette, et al., 2000). For laboratory experiments, the PHS model was validated when accounting for inter-individual differences with correlation coefficients of 0.76 and 0.66 for sweat rate and rectal temperature respectively (Malchaire, 2006; Malchaire et al., 2002; Malchaire, Piette, et al., 2000). The field experiment correlation coefficients were lower at 0.74 for sweat rate and 0.59 for rectal temperature, but the PHS model was validated for field experiments because less quality data is often obtained in the field (Malchaire, 2006; Malchaire et al., 2002; Malchaire, Piette, et al., 2000). From this validation and comparison to the Required Sweat Rate index, the PHS model gives more reliable predictions for both laboratory and field experiments and better differentiated the WBGT index for severity potential of heat stress (Lundgren-Kownacki et al., 2017; Malchaire et al., 2002; Malchaire, Piette, et al., 2000). For field experiment sweat rates in particular, the PHS model follows the observed values closely (Malchaire et al., 2002; Malchaire, Piette, et al., 2000). Because of successful validation of the PHS model, the PHS model was adopted by ISO 7933 to create a better international standard for protecting workers against heat stress (Lundgren-Kownacki et al., 2017; Malchaire, 2006).

Though validation has been concluded based on several studies with large sample sizes, other sets of data identified problematic areas that should be addressed. The variety of different climate types and work attires has lead to additional research applying the model to clothing types and conditions similar to work settings with mixed results. It is also important that models have practical application to contribute to the goal of reducing heat stress related conditions.

Based on studies where the data are not representative of the PHS model in varying conditions, it has been suggested that the model be revised in order to be more applicable in expanded situations (Lucas et al., 2014; Lundgren-Kownacki et al., 2017; Wang et al., 2011). Heavy protective clothing studies have shown that the PHS model is not applicable and had protective predictions of evaporation rate and duration of exposure for these types of clothing (Wang et al., 2011, 2013). The PHS model was inaccurate in predicting the skin temperature for light summer clothing types (Wang et al., 2011). Clothing types that are not breathable in humid environments also resulted in model inaccuracies in predicting skin temperature (Wang et al., 2013). While the PHS model was designed to predict minute-to-minute sweat rate conditions for workers, the model over estimates the cooling effects of sweat in break periods between work cycles (Lundgren-Kownacki et al., 2017).

As the intention of the PHS model was to create a more applicable system for practical use, the intricacies can prevent it from being applied properly in work settings (Lucas et al., 2014; Malchaire, 2006; Wang et al., 2011). It has been suggested that modifications should be made so that the model can be referenced without full understanding, which would make it more functional in work environments (d'Ambrosio Alfano et al., 2016; Malchaire et al., 2002). The importance for accurate predictions in hot working environment suggests the need to develop the model further so that it more accurately represents an intermittent workday in hot environments

(Lundgren-Kownacki et al., 2017; Malchaire, Piette, et al., 2000). While there are areas of potential expansion, it is important that the model is applied correctly in a state of steady exposure so that it can be used to help reduce heat stress.

METHODS

The data used for this paper were taken from two previous studies at USF (Bernard, Caravello, Schwartz, & Ashley, 2008; Bernard, Luecke, Schwartz, Kirkland, & Ashley, 2005), which were approved by the USF institutional review board. The progressive heat stress protocol used in these studies began with comfortable environments already described that were easily compensable. After thermal equilibrium was established, the temperature and water vapor pressure were slowly increased in 5-minute intervals at constant rh and 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. Metabolic rate 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 steady value for T_{re} to values that were steadily increasing were marked as the critical condition. A compensable point where the individual clearly could maintain thermal equilibrium was selected as 15 minutes before the critical condition; and an uncompensable point where the individual clearly could not maintain thermal equilibrium was selected as 15 minutes after the critical condition is shown in FIGURE 1 (Garzón-Villalba, Yougui, Ashley, & Bernard, 2017). The 15-min period before and after the critical condition was selected to be near the critical condition to minimize the difference in WBGT but with high confidence that the characterizations of compensable and uncompensable were correct (Garzón-Villalba et al., 2017).

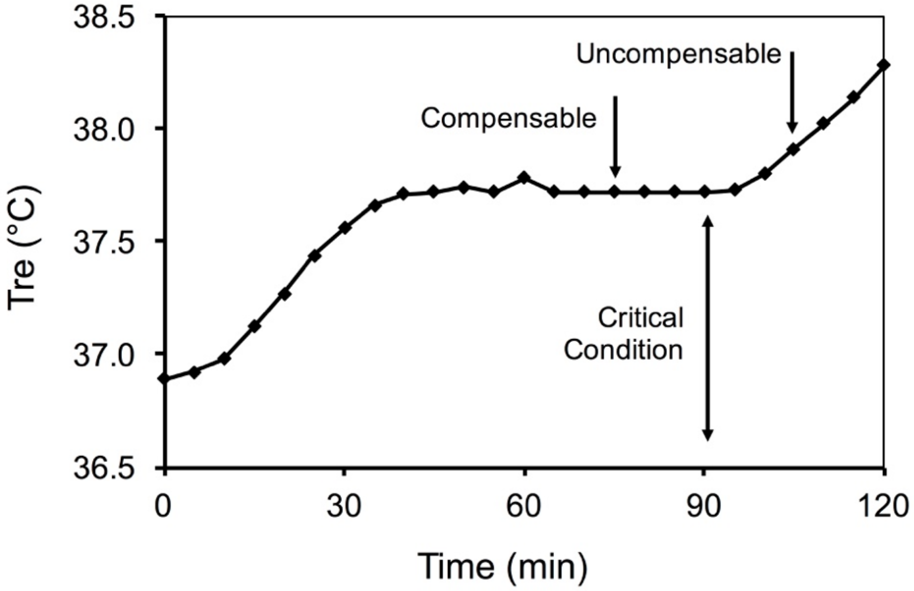

FIGURE 1. The time course of T_{re} for an example trial with arrows to indicate the critical condition, the compensable condition established 15 minutes before the critical condition, and uncompensable 15 minutes after it (Garzón-Villalba et al., 2017).

There were 176 trials for each 29 participants. One USF study (Bernard et al., 2005) used a progressive heat stress protocol to find the rh on $WBGT_{crit}$ for five clothing ensembles that included 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 coveralls. The nonwoven coveralls were characterized as (1) particle-barrier (Tyvek® 1424 and 1427; similar to Tyvek® 1422A); (2) water-barrier, vapor-permeable (NexGen® LS 417; microporous membrane), and (3) vapor-barrier (Tychem QC®, polyethylene-coated Tyvek). The target M was 160 W m^{-2} to approximate moderate work performed on a level treadmill, at three levels of relative humidity: warm humid at 30 ºC and 70% rh; hot dry, at 40 ºC and 20% rh; and a midrange of 34 ºC with rh of 50%. The other USF study (8) used a progressive heat stress protocol to evaluate the five ensembles described above, but assessed the effects of varying M at a rh of 50%. The three target Ms on a level treadmill were 115, 175 and 250 W m^{-2} to approximate light, moderate, and heavy work.

The characteristics of the 29 participants who took part in these trials are summarized in TABLE I (Garzón-Villalba, Wu, Ashley, & Bernard, 2018). All participants were acclimatized by 2-h exposures over five successive days to dry heat (50 °C and 20% rh) at 160 W m^{-2} while wearing shorts and tee shirt.

TABLE I. Physical Characteristics (Mean ± Standard Deviation) of Participants (Garzón-Villalba et al., 2018)

	N	Age (yrs)	Height (cm)	Weight (kg)	Body Surface Area (m^2)
Relative Humidity Study (9)					
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 (8)					
Men	11	28 ± 10	176 ± 11	82 ± 12	1.98 ± 0.47
Women	4	23 ± 5	165 ± 6	64 ± 18	1.70 ± 0.22
Pooled					
Men	20	29 ± 9	179 ± 34	89 ± 23	2.07 ± 0.41
Women	9	28 ± 8	163 ± 7	64 ± 17	1.74 ± 0.29

Because no differences in $WBGT_{crit}$ and apparent total evaporative resistance were found between work clothes and cotton coveralls in previous studies (Bernard et al., 2008; Bernard et al., 2005; Caravello, McCullough, Ashley, & Bernard, 2008; Garzón-Villalba et al., 2017), these trials were combined under the category of woven clothing. There were 176 trials for woven cotton clothing over the two studies. The number of trials for the nonwoven coveralls were 119 for particle barrier, 91 for water barrier, and 94 for vapor barrier, are represented in TABLE II (15 at 20% rh, 64 at 50% rh, and 15 at 70% rh), (Garzón-Villalba et al., 2018).

The study had a crossover design within a trial; and each individual served as their own control across fabric types; thus, observations on individuals were dependent observations. Within a trial, the observation 15 min after the critical condition (uncompensable) was classified

TABLE II. Number of Observations as Sustainable and Unsustainable Overall and By Fabric Type, and the Associated Number of Trials. (Garzón-Villalba et al., 2018)

	All	Woven	Particle Barrier	Water Barrier	Vapor Barrier
Sustainable	728	273	184	131	140
Unsustainable	712	255	173	142	142
Trials	480	176	119	91	94

as Unsustainable and the observation 15 min prior to the critical condition was classified as Sustainable (compensable).

The Compensable outcome was defined as being 15 minutes prior to the critical condition where thermal equilibrium can be maintained. The Uncompensable outcome was defined as being 15 minutes past the critical condition where thermal equilibrium cannot be maintained. Using the trial data from previous studies, the predicted core temperatures for each trial were computed at two and four hours of exposure. To test if the PHS model could predict sustainability, core temperatures that did not exceed 38°C at four hours and did not increase ±0.05°C between two and four hours of exposure were considered to be at a Steady State (SS). The core temperatures that exceeded 38°C at four hours of exposure or increased ±0.05°C between two and four hours were considered to be at a not Steady State (nSS).

2x2 Tables were completed for 1478 data pairs representing woven clothing, particle barrier clothing, water barrier clothing, vapor barrier clothing, and all of the ensembles collectively. The PHS State was tested based on the State Code as the outcome of each data pairing.

RESULTS

For data from the woven clothing types, TABLE III shows the 2x2 table of the test of PHS State and the outcome of State Code based on the comparison of core temperatures after two and four hours of exertion, and includes the sensitivity and specificity.

TABLE III. Woven Clothing 2x2 Table

	State Code		
PHS State	Uncompensable	Compensable	Total
nSS	143	117	260
SS	0	26	26
Total	143	143	286
	Sensitivity	Specificity	
	1.00	0.18	

TABLE IV – VI show the 2x2 tables of the test of PHS State and the outcome of State Code for the other ensemble types (particle barrier, water barrier, and vapor barrier respectively) based on the comparison of core temperatures after two and four hours of exertion, and includes the sensitivity and specificity.

TABLE IV. Particle Barrier Clothing 2x2 Table

	State Code		
PHS State	Uncompensable	Compensable	Total
nSS	129	54	183
SS	7	82	89
Total	136	136	272
	Sensitivity	Specificity	
	0.95	0.60	

TABLE V. Water Barrier Clothing 2x2 Table

	State Code		
PHS State	Uncompensable	Compensable	Total
nSS	176	34	210
SS	18	160	178
Total	194	194	388
	Sensitivity	Specificity	
	0.91	0.83	

TABLE VI. Vapor Barrier Clothing 2x2 Table

	State Code		
PHS State	Unompensable	Compensable	Total
nSS	243	54	297
SS	23	212	235
Total	266	266	532
	Sensitivity	Specificity	
	0.91	0.80	

TABLE VII shows the 2x2 table of the test of PHS State and the outcome of State Code based on the comparison of core temperatures after two and four hours of exertion, and includes the sensitivity and specificity.

TABLE VII. All Ensembles 2x2 Table

	State Code		
PHS State	Uncompensable	Compensable	Total
nSS	691	259	950
SS	48	480	528
Total	739	739	1478
	Sensitivity	Specificity	
	0.94	0.65	

DISCUSSION

To ensure the PHS model can be useful in occupational exposure settings of heat stress, it is important that the model accurately predicts unsustainable exposures. One goal of this study was to determine if the PHS model could predict sustainability instead of relying on time limiting as an alternative to WBGT-based thresholds. Because an unsustainable exposure can be dangerous and lead to heat related health conditions, PHS's ability to predict the unsustainable exposures when incorporating environment, metabolic rate, and clothing type is essential. The accuracy that the PHS model can predict unsustainable exposures will lead to the greatest protection of workers who experience heat stress.

Sensitivity for this study is defined as the ability of PHS to predict unsustainable exposures, while specificity is defined as the ability of PHS to predict sustainable exposures. It is important that unsustainable exposures are detected to protect workers from heat stress. The high sensitivity determined by the PHS tests show that it is good at predicting unsustainable exposures and therefore protecting workers from dangerous situations.

TABLE III for woven clothing with 272 trials shows high sensitivity of 1.00 and a low specificity of 0.18. Garzon et al. (2017) was also conducted using work clothes with 176 trials and resulted in a high sensitivity of 1.00, but a lower specificity of 0.05. This study supports the evidence shown in Garzon et al. (2017) that PHS has high sensitivity for predicting unsustainable exposures.

Though PHS specifies use with woven clothing exclusively, the results of this study suggest that it can be useful for predicting unsustainable exposures in different ensembles. The sensitivities and specificities for particle barrier, water barrier, and vapor barrier clothing from TABLE IV-VI are 0.95 and 0.60, 0.91 and 0.83, 0.91 and 0.80 respectively. This demonstrates that while the particle barrier clothing has the highest sensitivity of this group, the sensitivities for water barrier and vapor barrier clothing are also high. The specificities of these different clothing types are higher than that of woven clothing, suggesting PHS is better at predicting sustainable exposures in these cases. When combining all of the data as shown in TABLE VII, the sensitivity is 0.94 and specificity is 0.65. Because high sensitivity is important for protecting workers by predicting unsustainable exposures, this data suggests that PHS can be useful for other clothing types as well as woven clothing.

The analysis presented by the 2x2 tables in this study show that PHS is highly sensitive to unsustainable exposures for the data set tested. While this study focuses on the sustainable and unsustainable exposure points determined by core temperature greater than 38°C, the transitional data showing the point of increase in between the two also exhibited protective decisions. Transitional data should show an even split between unsustainable and sustainable exposures in transition. For this data set, the transitional data favor the sustainability at the transition point, suggesting the model is still protective. Because of the protective qualities suggested by the transitional data in addition to the 2x2 table analyses showing high sensitivity, this study suggests PHS is highly protective of unsustainable exposures.

CONCLUSIONS

This study was designed to determine the ability of the Predicted Heat Strain model to identify unsustainable exposures to heat stress. The predictions from the PHS model were highly sensitive to unsustainable states when comparing to the compensable and uncompensable data collected in the previous studies. The data show that PHS is highly sensitive for woven clothing types, which it was validated and also for the three other clothing types represented by the study. This study suggests that PHS is capable of determining unsustainable exposures to heat stress.

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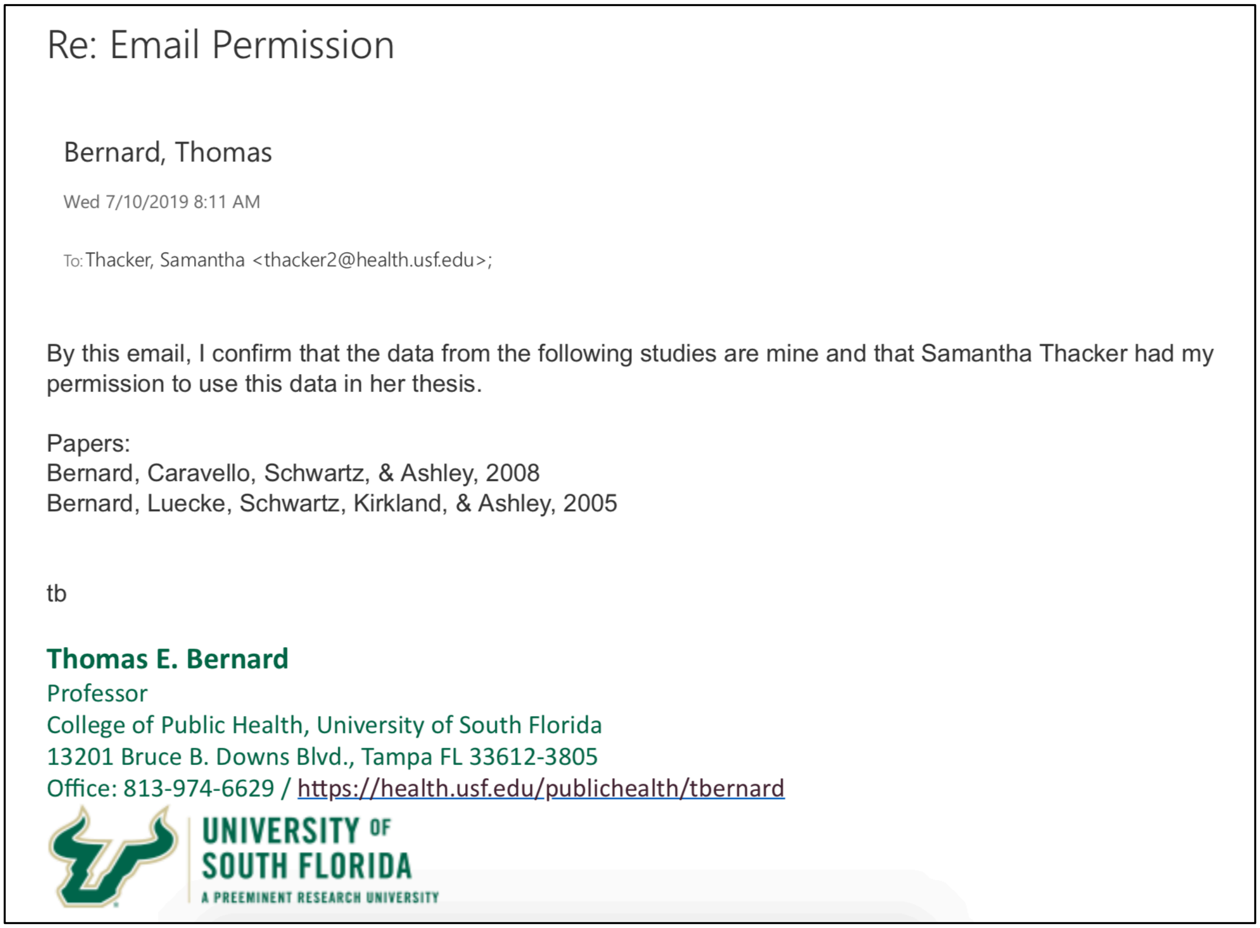
APPENDICES

Appendix A: Data Permission



Re: Email Permission

Bernard, Thomas

Wed 7/10/2019 8:11 AM

To: Thacker, Samantha <thacker2@health.usf.edu>;

By this email, I confirm that the data from the following studies are mine and that Samantha Thacker had my permission to use this data in her thesis.

Papers:
Bernard, Caravello, Schwartz, & Ashley, 2008
Bernard, Luecke, Schwartz, Kirkland, & Ashley, 2005

tb

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Appendix B: Visual Basic Code

Function Call from Spreadsheet

```
=fPHS2017(75, 1.8, 36.8, 1, 1, 120, M2, O2, 15, P2, R2, L2, 0, (T2-0.72), U2, 1, 0, 0, 0)
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Function fPHS2017(Weight, Height, Tre0, Accl, Drink, Duration, Ta, Tg, Diam, Va, PvRH, M, Work, Icl, imst, Posture, defspeed, Walksp, defdir)
' Predicted Heat Strain (PHS) model
' This is an adaptation of the code provided in ISO7933 (2017)

 ' The major change is that the code is called as a function rather than a subroutine
' Other changes include allowing for either RH or Pa to indicate humidity with the variable PvRH;
' blank values are set to defaults; and initial Tre can be entered

' Returns Tre at Duration
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Dim Time As Integer

' EXPONENTIAL AVERAGING CONSTANTS
ConstTeq = Exp(-1 / 10): ' Core temperature as a function of M: time constant: 10 min
ConstTsk = Exp(-1 / 3): ' Skin Temperature: time constant: 3 min
ConstSW = Exp(-1 / 10): ' Sweat rate: time constant: 10 min
' INPUT OF THE MEAN CHARACTERISTICS OF THE SUBJECTS
' The user must make sure at this point in the programme that the following parameters are available.
' Standard values can be replaced by actual values.
If Weight = 0 Or IsEmpty(Weight) Then Weight = 75: ' Body mass kilogram
If Height = 0 Or IsEmpty(Height) Then Height = 1.8: ' Body height metres
If IsEmpty(Accl) Then Accl = 1: ' =1 if acclimatised subject, =0 otherwise
If IsEmpty(Drink) Then Drink = 1: ' Water replacement: =1 if the workers can drink freely, =0 otherwise

' COMPUTATION OF DERIVED PARAMETERS
Adu = 0.202 * Weight ^ 0.425 * Height ^ 0.725: ' Body surface area m2
aux = 3490 * Weight / Adu: ' Heat for 1°C increase of the body per m2 of body surface
SWmax = 400: If Accl = 1 Then SWmax = 500: ' Maximum evaporative capacity
wmax = 0.85: If Accl = 1 Then wmax = 1 ' Maximum wettedness
DMax = 0.05 * Weight * 1000: ' Maximum water loss in grams
If Drink = 0 Then DMax = 0.03 * Weight * 1000: ' if no free drinking

' INPUT OF THE PRIMARY PARAMETERS
' The user must make sure that, at this point in the program, the following parameters are available.
' In order for the user to test rapidly the program, the data for the first case
' in annex E of the ISO 7933 standard are introduced as default values.
If IsEmpty(Duration) Then Duration = 480: ' Duration of the work sequence in minutes
If IsEmpty(Ta) Then Ta = 40: ' Air temperature in degrees Celsius
If IsEmpty(Tg) Then Tg = Ta: ' Black globe temperature: °C
If IsEmpty(Diam) Then Diam = 15: ' Diameter of the black globe, in cm
If IsEmpty(Va) Then Va = 0.3: ' Air velocity metres per second
Tr = ((Tg + 273) ^ 4 + 1.1579 * 10 ^ 8 / 0.95 / (Diam / 100) ^ 0.4 * Va ^ 0.6 * (Tg - Ta)) ^ 0.25 - 273

' Parse out Pv and RH to find partial water vapour pressure kilopascals
If IsEmpty(PvRH) Then PvRH = 35 ' Relative humidity
If PvRH > 5.7 Then
RH = PvRH
Pa = 0.6105 * Exp(17.27 * Ta / (Ta + 237.3)) * RH / 100:
Else
Pa = PvRH
End If
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If IsEmpty(M) Then M = 300: ' Metabolic rate, watts
Met = M / Adu: ' Metabolic rate, Watts per square metre
If IsEmpty(Work) Then Work = 0: ' Effective mechanical power watts per square metre

If IsEmpty(Icl) Then Icl = 0.5: ' Static thermal insulation clo
If IsEmpty(imst) Then imst = 0.38: ' Static moisture permeability index
' Effective radiating area of the body
Posture = 1: ' Posture = 1 standing, =2 sitting, =3 crouching
If Posture = 1 Then Ardu = 0.77
If Posture = 2 Then Ardu = 0.7
If Posture = 3 Then Ardu = 0.67
' Refective clothing
Ap = 0.54: ' Fraction of the body surface covered by the reflective clothing
Fr = 0.97: ' Emissivity of the reflective clothing (by default: Fr=0.97)

' Air motion displacements
defspeed = 0: ' =1 if walking speed entered, =0 otherwise
Walksp = 0: ' Walking speed, m/s
defdir = 0: ' =1 if walking direction entered, 0 otherwise
THETA = 0: ' Angle between walking direction and wind direction degrees

' CLOTHING INFLUENCE ON EXCHANGE COEFFICIENTS
Iclst = Icl * 0.155: ' Static clothing insulation
fcl = 1 + 0.3 * Icl: ' Clothing area factor
Iast = 0.111: ' Static boundary layer thermal insulation in quiet air
Itotst = Iclst + Iast / fcl: ' Total static insulation
' Relative velocities due to air velocity and movements
If defspeed > 0 Then
If defdir = 1 Then
Var = Abs(Va - Walksp * Cos(3.14159 * THETA / 180)): ' Unidirectional walking
Else
If Va < Walksp Then Var = Walksp Else Var = Va: 'Omni-directional walking
End If
Else
Walksp = 0.0052 * (Met - 58)
If Walksp > 0.7 Then Walksp = 0.7: 'Stationary or undefined speed
Var = Va
End If
' Dynamic clothing insulation
Vaux = Var: If Var > 3 Then Vaux = 3
Waux = Walksp: If Walksp > 1.5 Then Waux = 1.5
' Clothing insulation correction for wind (Var) and walking (Walksp)
CORcl = 1.044 * Exp((0.066 * Vaux - 0.398) * Vaux + (0.094 * Waux - 0.378) * Waux)
If CORcl > 1 Then CORcl = 1
CORia = Exp((0.047 * Var - 0.472) * Var + (0.117 * Waux - 0.342) * Waux)
If CORia > 1 Then CORia = 1
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CORtot = CORcl
If Icl <= 0.6 Then CORtot = ((0.6 - Icl) * CORia + Icl * CORcl) / 0.6
Itotdyn = Itotst * CORtot
Iadyn = CORia * Iast
Icldyn = Itotdyn - Iadyn / fcl
' Dynamic evaporative resistance
' Correction for wind and walking
CORe = (2.6 * CORtot - 6.5) * CORtot + 4.9
imdyn = imst * CORe: If imdyn > 0.9 Then imdyn = 0.9
Rtdyn = Itotdyn / imdyn / 16.7

' INITIALISATION OF THE VARIABLES OF THE PROGRAMME
If IsEmpty(Tre0) Then Tre = 36.8 Else Tre = Tre0: ' Initial rectal temperature, °C
Tcr = Tre: ' Initial core temperature, °C, same as rectal temperature
Tsk = 34.1: ' Initial skin temperature, °C
Tcreq = 36.8: ' Initial core temperature associated with resting M, °C
TskTcrwg = 0.3 ' Initial skin – core weighting
SWp = 0: ' Initial sweat rate, W/m2
SWtot = 0: ' Initial total sweat rate, W/m2
Dlimtcr = 999: ' Duration limit of exposure due to increase in temperature, min
Dlimloss = 999: ' Duration limit of exposure due to excessive water loss, min

' ITERATION OF THE PROGRAMME
For Time = 1 To Duration
' Initialisation min per min: value at beginning of time i = final value at time (i-1)
Tre0 = Tre: Tcr0 = Tcr: Tsk0 = Tsk: Tcreq0 = Tcreq: TskTcrwg0 = TskTcrwg
' Equilibrium core temperature associated to the metabolic rate
Tcreqm = 0.0036 * Met + 36.6
' Core temperature at this minute, by exponential averaging
Tcreq = Tcreq0 * ConstTeq + Tcreqm * (1 - ConstTeq)
' Heat storage associated with this core temperature increase during the last minute
dStoreq = aux / 60 * (Tcreq - Tcreq0) * (1 - TskTcrwg0)
' SKIN TEMPERATURE PREDICTION
' Skin Temperature in equilibrium
' Clothed model
Tskeqcl = 12.165 + 0.02017 * Ta + 0.04361 * Tr + 0.19354 * Pa - 0.25315 * Va
Tskeqcl = Tskeqcl + 0.005346 * Met + 0.51274 * Tre
' Nude model
Tskeqnu = 7.191 + 0.064 * Ta + 0.061 * Tr + 0.198 * Pa - 0.348 * Va
Tskeqnu = Tskeqnu + 0.616 * Tre
' Value at this minute, as a function of the clothing insulation
If Icl >= 0.6 Then Tskeq = Tskeqcl: GoTo Tsk
If Icl <= 0.2 Then Tskeq = Tskeqnu: GoTo Tsk
' Interpolation between the values for clothed and nude subjects, if 0.2 < clo < 0.6
Tskeq = Tskeqnu + 2.5 * (Tskeqcl - Tskeqnu) * (Icl - 0.2)
' Skin Temperature at this minute, by exponential averaging
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Tsk:
Tsk = Tsk0 * ConstTsk + Tskeq * (1 - ConstTsk)
If Time = 1 Then Tsk = Tskeq
' Saturated water vapour pressure at the surface of the skin
Psk = 0.6105 * Exp(17.27 * Tsk / (Tsk + 237.3))
' Mean temperature of the clothing: Tcl
Z = 3.5 + 5.2 * Var
If Var > 1 Then Z = 8.7 * Var ^ 0.6
auxR = 5.67E-08 * Ardu
FclR = (1 - Ap) * 0.97 + Ap * Fr
Tcl = Tr + 0.1
Tcl:
' Dynamic convection coefficient
Hcdyn = 2.38 * Abs(Tcl - Ta) ^ 0.25
If Z > Hcdyn Then Hcdyn = Z
' Radiation coefficient
HR = FclR * auxR * ((Tcl + 273) ^ 4 - (Tr + 273) ^ 4) / (Tcl - Tr)
Tcl1 = ((fcl * (Hcdyn * Ta + HR * Tr) + Tsk / Icldyn)) / (fcl * (Hcdyn + HR) + 1 / Icldyn)
If Abs(Tcl - Tcl1) > 0.001 Then Tcl = (Tcl + Tcl1) / 2: GoTo Tcl
' HEAT EXCHANGES
texp = 28.56 + 0.115 * Ta + 0.641 * Pa: ' temperature of the expired air
Cres = 0.001516 * Met * (texp - Ta): ' Heat exchanges through respiratory convection
Eres = 0.00127 * Met * (59.34 + 0.53 * Ta - 11.63 * Pa): ' through respiratory evaporation
Conv = fcl * Hcdyn * (Tcl - Ta): ' Heat exchanges through convection
Rad = fcl * HR * (Tcl - Tr): ' Heat exchange through radiation
Emax = (Psk - Pa) / Rtdyn: ' Maximum Evaporation Rate
Ereq = Met - dStoreq - Work - Cres - Eres - Conv - Rad: ' Required Evaporation Rate
' INTERPRETATION
wreq = Ereq / Emax: ' Required wettedness
' If no evaporation required: no sweat rate
If Ereq <= 0 Then Ereq = 0: SWreq = 0: GoTo SWp
' If evaporation is not possible, sweat rate is maximum
If Emax <= 0 Then Emax = 0: SWreq = SWmax: GoTo SWp
' If required wettedness greater than 1.7: sweat rate is maximum
If wreq >= 1.7 Then wreq = 1.7: SWreq = SWmax: GoTo SWp
Eveff = (1 - wreq ^ 2 / 2): ' Required evaporation efficiency
If wreq > 1 Then Eveff = (2 - wreq) ^ 2 / 2
SWreq = Ereq / Eveff: ' Required Sweat Rate
If SWreq > SWmax Then SWreq = SWmax: ' limited to the maximum evaporative capacity
SWp:
' Predicted Sweat Rate, by exponential averaging
SWp = SWp * ConstSW + SWreq * (1 - ConstSW)
If SWp <= 0 Then Ep = 0: SWp = 0: GoTo Storage
' Predicted Evaporation Rate
k = Emax / SWp
wp = 1
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If k >= 0.5 Then wp = -k + Sqr(k * k + 2)
If wp > wmax Then wp = wmax
Ep = wp * Emax
' Heat Storage
Storage:
dStorage = Ereq - Ep + dStoreq
' PREDICTION OF THE CORE TEMPERATURE
Tcr1 = Tcr0
TskTcr:
' Skin - Core weighting
TskTcrwg = 0.3 - 0.09 * (Tcr1 - 36.8)
If TskTcrwg > 0.3 Then TskTcrwg = 0.3
If TskTcrwg < 0.1 Then TskTcrwg = 0.1
Tcr = dStorage / (aux / 60) + Tsk0 * TskTcrwg0 / 2 - Tsk * TskTcrwg / 2
Tcr = (Tcr + Tcr0 * (1 - TskTcrwg0 / 2)) / (1 - TskTcrwg / 2)
If Abs(Tcr - Tcr1) > 0.001 Then Tcr1 = (Tcr1 + Tcr) / 2: GoTo TskTcr
' PREDICTION OF THE RECTAL TEMPERATURE
Tre = Tre0 + (2 * Tcr - 1.962 * Tre0 - 1.31) / 9
' TOTAL WATER LOSS RATE AFTER THE MINUTE (in W / m2)
SWtot = SWtot + SWp + Eres: ' Total evaporation loss in watts per m2
SWtotg = SWtot * 2.67 * Adu / 1.8 / 60 ' Total water loss in grams

' COMPUTATION OF THE DURATION LIMIT OF EXPOSURE DLE IN MIN
' DLE for water loss, 95 % of the working population, in min
If Dlimloss = 999 And SWtotg >= DMax Then Dlimloss = Time
' DLE for heat storage, in min
If Dlimtcr = 999 And Tre >= 38 Then Dlimtcr = Time
' End of loop on duration
Next Time

' Function fPHS is set to limiting time with dehydration marked by negative value
If Dlimtcr < Dlimloss Then Dlim = Dlimtcr Else Dlim = -Dlimloss

fPHS2017 = Tre

End Function
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