original article

Combination of wet bulb globe temperature and heart rate in hot climatic conditions: The practical guidance for a better estimation of the heat strain

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ABSTRACT

Aims: The aim of this study is to evaluate the combined application of wet bulb globe temperature (WBGT) and physiological strain Iindices based on heart rate (PSI_{HR}) for the estimation of heat strain, in hot climatic conditions.
Materials and Methods: This cross-sectional study was conducted on 122 men including 71 and 51 workers from the Assaluyeh National Petrochemical Company and Isfahan Steel Company in the center and south of Iran, respectively. The WBGT index, heart rate, and auditory canal temperature were measured at rest and when working. The data were analyzed using descriptive statistics and logistic regression.
Results: The results of the logistic regression indicated that the WBGT index was a poor predictor of heat strain and its sensitivity and specificity were 53 and 65%, respectively. However, the combined application of the WBGT and PSI_{HR} indices was a better predictor of heat strain, and the sensitivity and specificity of this combination were 75 and 69%, respectively.
Conclusion: According to the results of this study, the combined application of the WBGT and PSI_{HR} indices can be used as a valid estimator of heat strain in hot climatic conditions in the center and south of Iran.

Key words: Heat strain estimation, Iran, PSI_{HR} index, WBGT index

INTRODUCTION

On account of the geographical situation and the nature of most industrial processes, heat exposure in many industrial processes (such as melting, casting, textiles, and so on) and non-industrial units (such as, construction activities, agriculture, and fishing) are common in Iran, especially in the hot seasons of the year. Moreover, the application of protective clothing, such as different protective clothes and personal protective equipment, for protecting workers from dangerous substances, limits the thermal exchange level of the body and the environment and prepares the condition for thermal strain.[1,2] Long-term exposure to heat leads to physical disorders (heat exhaustion, heat syncope, muscle cramps, and heat stroke), decrease in physical and mental performance, decrease in productivity, increase in accidents, and a decrease in safety level.[3,4]

Different indices have been presented for evaluating thermal strain; however, few of them have been widely used. One

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of these indices is the WBGT index, which enters the environmental factors into its calculation structure[5,6] (Equations 1 and 2).

$$WBGT = 0.7T_w + 0.2T_g + 0.1T_a \text{ (Outdoor)} \quad (1)$$

$$WBGT = 0.7T_w + 0.3T_g \text{ (Indoor)} \quad (2)$$

Where T_w, T_a and T_g in Eqs. 1 and 2 indicate wet bulb temperature, dry bulb temperature, and Globe temperature, respectively. In the calculation structure of this index, important non-environmental factors are not considered for thermal strain and only clothing, metabolism level, and a person's acclimatization condition are used as correction coefficients, for interpreting the WBGT index. Also, many changes are usually observed in the estimation of the metabolism level, for interpreting this index, which fluctuates the results obtained from index interpretation.[7] One of the other disadvantages of this global index is that it underestimates thermal strain for short-term exposure in very hot conditions.[8] In long-term heat exposure, the WBGT index overestimates the thermal strain of people exposed to heat in many developing countries like China, India, Thailand, and the United Arab Emirates.[9,10] In Canada, the application of this index has some limitations because rest-work cycles of the WBGT index based on the American Conference of Industrial Hygienists (ACGIH) Standard do not support any amount higher than 30**°C**.[11] The WBGT index correlates well with skin temperature in hot and humid conditions and in light work; however, it correlates poorly with other physiological variables like heart rate, rectal temperature, and weight loss caused by sweating.[12] Furthermore, as far as the performance of light work is concerned in hot seasons and in the Persian Gulf weather conditions, the rest-work cycles of the WBGT index do not have the required performance and acceptance in terms of efficiency and people's operation. For instance, the means and standard deviation of the WBGT index in August 2010, were measured in 72 workstations in the National Company of Petrochemical Industries (Southern Pars Region, Assaluyeh) between 9 a.m. and 6 p.m., as 33.2°C and 2.0°C, respectively.

Another accredited index for evaluating thermal strain is the Physiological Strain Index (PSI), which was developed by Moran *et al*. (1998). This index compares changes in rectal temperature (T_{re}) and heart rate (HR) at two rest and work states, according to Equation 3:

$$PSI = 5(T_{re\,t} - T_{re0})(39.5 - T_{re0})^{-1} + 5(HR_t - HR_0) \cdot (180 - HR_0)^{-1} \quad (3)$$

$$PSI_{HR} = 5(HR_t - HR_0) \cdot (180 - HR_0)^{-1} \quad (4)$$

where $T_{re\,t}$ and HR_t are simultaneous measurements taken at any time during the exposure and T_{re0} and HR_0 are the initial measurements. The numerical (without units) amount of the PSI index ranges from 0 to 10, where 0 indicates lack of thermal strain and 10 indicates maximum thermal strain. The amount of the physiological strain index, based on the heart rate or PSI_{HR} (Eq. 4) has the numerical range (without units) between 0 and 5, indicating lack of strain and maximum strain, respectively.[13] The validity of the PSI index has been investigated for males and females in different conditions. This physiological index evaluates the amount of strain caused by different environmental factors like clothing, activity intensity, and individual characteristics like gender and age.[14-18]

The application of the PSI index for evaluating thermal strain requires the measurement of heart rate and deep body temperature.[13-15] Heart rate is measured using traditional methods or using a heart rate monitor. However, measuring methods of deep temperature with required accuracy, such as, esophageal temperature, rectal temperature, and wireless core temperature–sensing capsules are all considered invasive methods[19,20,21] and their application in workplaces in developing countries like Iran is impractical. Therefore, to overcome this problem (inherent limitations of the WBGT index and impracticality of measuring deep body temperature in workplaces for estimating thermal strain), the idea of a combined application of the WBGT index and the modified form of the PSI index or PSI_{HR}, which is calculated based on the number of heart rates, has been developed. Although the PSI_{HR} index only estimates the cardiovascular load, Mr. Moran, believes that this index can indicate the load of the cardiovascular system to some extent, when it is not possible to measure deep body temperature.[12] Thus, the aim of this study is to investigate the efficiency of the combined application of WBGT and PSI_{HR} indices for estimating heat strain in hot-humid and hot-dry weather conditions.

MATERIALS AND METHODS

This cross-sectional study was performed on 71 people from the Iranian National Company of Petrochemical Industries located in the Southern Pars Region of Iran, who were exposed to hot-humid weather conditions, and 51 people from the staff of the Isfahan Steel Company, who were exposed to hot-dry weather conditions, from July until September 2010. The samples, which were selected by simple random sampling, were taken from people working in hot workplaces. These people did not suffer from cardiovascular, respiratory or infectious diseases, diabetes or hyperthyroidism, and did not take cardiovascular medicine. In this study, a Gold Standard for deep body temperature was needed for determining the efficiency level of a combined application of the WBGT index and PSI_{HR} index for diagnosing the thermal strain, which was measured by a deep temperature monitoring device via ear external auditory canal (Questemp II, Personal Heat Stress Monitor). This temperature monitor contains a temperature sensor, which is plugged inside the external ear canal,[22] The processing system and a monitor are placed in the person's belt. When measuring deep temperature, the sensor is surrounded by insulation foam (similar to an air plug) in order to minimize the influence of weather conditions on the measured temperature.[23] To estimate the physical activities, the Persian version of the Rating Perceived Exertion of the Eston-Parfitt is used.[24] The heart rate is measured with a heart rate monitor ((RS100, Polar, Oy Finland)). This equipment has a sensor and a receiver (similar to a wrist watch), which are placed on the chest and wrist, respectively.

One day before measurement, the participants were reminded of points like sufficient rest at night and not using coffee or alcohol. On the day of measurement, the heart rate and deep body temperature were measured in two stages based on the ISO9886-2001 Standard, after determining the height and weight. In the first stage, after 30 minutes resting in a cool room (WBGT = 22.6 ± 1.9), the heart rate and deep temperature were measured at in intervals of 20, 25 and 30 minutes and their mean was recorded as a base line. In the second stage, after completion of the measurement at rest, the participant was asked to return to the workplace, while carrying the measurement tools to start his work. If his workplace was farther than 50 m from the cool room, he was taken by a car. After starting work, the heart rate and deep temperature were measured and recorded after 20, 40, and 60 minutes under the researcher's constant surveillance.[25,26] At the same time, dry bulb temperature, wet bulb temperature, Globe temperature, and WBGT index were measured, based on the ISO7243 Standard, at rest and at work using the Casella Microtherm WBGT meter.[5] All the measurements were done outdoors and indoors in the Assaluyeh region and in the Isfahan Steel Company, respectively, from 9 to 12 p.m. and 15 to 18 a.m.

For Logistic Regression Analysis, the participants were categorized into two groups: With thermal strain and without thermal strain; therefore, in this study, the group with thermal strain was attributed to the group with a difference in deep temperature at work and rest states (**ΔT**) equal or more than 1°C, and the class without thermal strain was attributed to the group with **ΔT** less than 1°C.[27] To determine the efficiency level of the predictor variables (WBGT and PSI_{HR}) for separating the people with thermal strain from the ones without thermal strain, the Logistic Regression Test of the SPSS-16 Software was used. To investigate the effect of the combined application of the WBGT index and the PSI_{HR} index for determining classes, only the WBGT index at the first state and both indices (WBGT and PSI_{HR}) at the second state were used as the input data for the Logistic Regression Equation and the results were compared with each other.

RESULTS

In this study 122 people participated; 71 people (58%) were working in hot-humid conditions (Assaluyeh) and 51 people (42%) were working in hot-dry conditions (Isfahan Steel Company). According to the data in Table 1, the mean age, body mass index, and PSI_{HR} index of the working people were not significantly different in the two regions, but the PSI and WBGT indices and the difference in deep body temperature at work and rest states (**ΔT**) were statistically different for the people in the two regions ($P < 0.001$).

The results of the Logistic Regression Test with WBGT and WBGT and the PSI_{HR} indices in predicting the thermal strain in the two regions of Assaluyeh and the Steel Company are given in Table 2. In the Logistic Regression Equation in Assaluyeh and the Steel Company, 71 and 51 people were analyzed, respectively, and a combination of the two indices for estimating thermal strain at the three states (Assaluyeh, Steel Company, Assaluyeh and Steel Company) led to an increase in chance ratio and an increase in the model fit index (Hosmer and leme show) in the Regression Equation.

Table 3 demonstrates a percentage of correct diagnosis and changes of specificity and sensitivity in the application of WBGT and WBGT and PSI_{HR} indices for estimating thermal strain in different activities. A combination of the two indices led to an increase of correct diagnosis in the light and heavy activities; it also improved the sensitivity level in the very light and light activities, and enhanced the specificity level in the medium and heavy activities.

The predicted amounts of thermal strain by WBGT and PSI_{HR} and WBGT, for separate locations, are given in Table 4. Entrance of the WBGT index (alone) to the Regression Equation led to an accurate prediction of 65 and 53% for the group with thermal strain and the one without thermal strain,

Table 1: Statistical characteristics of people and thermal strain indices in two regions of assaluyeh and the isfahan steel company

Location of variable	Assaluyeh (71 people)		Steel company (51 people)		*P* value
	Minimum-maximum	Mean (standard deviation)	Minimum-maximum	Mean (standard deviation)	
Age (year)	(20 – 55)	31.6 (8.6)	(23 – 42)	32.1 (4.8)	0.685
Body mass index	(17.5 – 37)	25.0 (4.0)	(18.9 – 31.7)	25.0 (3.1)	0.967
WBGT index	(26.6 – 38.8)	33.3 (2.0)	(22.3 – 40.8)	30.8 (4.4)	< 0.001
PSI index	(0.6 – 7.6)	2.7 (1.4)	(0.6 – 8.0)	30.8 (4.4)	< 0.001
PSI_{HR} index	(0.3 – 3.2)	1.5 (0.8)	(0.2 – 4.0)	1.7 (1.0)	0.271
ΔT_1	(0.1 – 2.1)	0.8 (0.5)	(0.1 – 2.4)	1.1 (0.6)	< 0.001

[1] Difference of deep body temperature at work and rest states

respectively; in general, 50% of predictions were correct. The combined entrance of WBGT index and PSI_{HR} index for the prediction of deep body temperature in the Regression Equation led to 75 and 69% correct prediction for the group with thermal strain and the one without thermal strain, respectively; in general, 72% of predictions were correct. Moreover, the WBGT index (alone) had weak sensitivity (31%) and specificity (53%) in estimating the thermal strain in hot-humid conditions (Assaluyeh) and hot-dry conditions (Steel Company); however, its combination with the PSI_{HR} index increased the sensitivity (46%) and specificity (65%) of estimating the thermal strain. Furthermore, in general, the percentage of correct diagnosis of thermal strain in the Assaluyeh and Steel Company increased with the combination of these two indices; in fact, a higher amount of increase was observed in the Isfahan Steel Company.

DISCUSSION

According to the data in Table 1, it can be observed that the mean of the WBGT index in both regions of the Assaluyeh and Steel Company (33.3°C and 30.8°C, respectively) were higher than the threshold level of the ACGIH Standard (30°C), even for light (continuous) work. However, the mean of the PSI index in both regions of the Assaluyeh and Steel Company (2.7 and 3.8, respectively) and also the PSI_{HR} (1.5 and 1.7, respectively) indicated that physiological strain intensity of people was in the range of low to medium.

The WBGT index is an empirical index, which only measures environmental factors and ignores other important non-environmental factors for thermal strain, like, intensity of working activity, type of clothing when working, personal protective devices, person's acclimatization, age, and body mass index. However, while interpreting the results of this index, some of these factors are used as correction coefficients.

In the present study, one of the reasons for lack of agreement between the WBGT index and the physiological strain indices (such as PSI and PSI_{HR}) was the phenomenon of regulating the activity intensity or self-pacing by the person, for decreasing the thermal strain intensity, which occurs as a protective behavior in people while being exposed to very hot weather conditions.[28] This situation was demonstrated in the results of studies by Miller *et al.* and Bate *et al.*, with regard to the relationship between the physiological strains and environmental thermal changes in the United Arab Emirates and Australia.[10,21] Moreover, Rastogi *et al.* investigated the relationship between the Globe temperature and heart rate of workers in a glass industry in India and concluded that the Globe temperature could not estimate the thermal strain by itself,[29] which was in line with the findings of the present study.

The self-pacing phenomenon of activity intensity by the people exposed to very hot conditions in Assaluyeh (the WBGT index was more than 32.3°C in 73% of the stations) and the Steel Company led the WBGT index to present a weak estimation of deep body temperature in this study,

Table 2: Chance ratio, confidence level, model fit index, and regression equations of the WBGT index with and without PSI_{HR} in predicting deep body temperature, among the workers of the assaluyeh region and the steel company

Location	Assaluyeh (*n* = 71)		Steel Company (*n* = 51)		Assaluyeh and Steel Company (*n* = 122)	
Index/statistics	WBGT	WBGT and PSI_{HR}	WBGT	WBGT and PSI_{HR}	WBGT	WBGT and PSI_{HR}
Chance ratio	1.427	3.104	1.367	4.507	1.202	3.605
Confidence interval 95%	1.075 – 1.894	1.486 – 6.482	1.130 – 1.653	1.470 – 13.815	1.062 – 1.359	2.076 – 6.260
Model fit index (Hosmer)	0.123	0.560	0.415	0.435	0.008	0.36
P value	0.014	0.003	0.001	0.008	< 0.001	< 0.001
Logistic regression equation	Y = 0.356WBGT - 12.445 Y = 0.239WBGT + 1.133 PSI_{HR} - 10.487		Y = 0.312WBGT -8.815 Y = 0.200WBGT + 1.506 PSI_{HR} - 7.684		Y = 0.184WBGT - 6.002 Y = 0.067WBGT + 1.282 PSI_{HR} - 4.405	

Table 3: Percentage of correct diagnosis and sensitivity and specificity changes in detecting deep body temperature in the intensity of different activities by the WBGT and WBGT and PSI_{HR} indices among the staff of Assaluyeh and the Steel Company

Activity intensity	Number of people	Percentage of correct diagnosis		Percentage of specificity changes	Percentage of sensitivity changes
		WBGT	WBGT and PSI_{HR}		
Very light (seated)	19	89.5	89.5	From 100 to 94	From 33 to 67
Light	52	67.3	71.2	From 82 to 79	From 48 to 61
Medium	36	66.7	66.7	From 33 to 53	From 90 to 76
Heavy	15	86.7	100	From 0 to 100	Without change

Table 4: Predicted amounts of deep body temperature by WBGT and WBGT and PSI_{HR} indices among the staff in assaluyeh and the steel company regions

Characteristics			WBGT		WBGT and PSI_{HR}	
			Thermal strain (prediction) + -	Percentage	Thermal strain (prediction) + -	Percentage
Assaluyeh and steel company	Thermal strain (observation)	+	33 29	53	19 43	69
		-	21 39	65	45 15	75
	Percentage of correct diagnosis		59		72	
Assaluyeh	Thermal strain (Observation)	+	42 3	93	39 6	87
		-	18 8	31	14 12	46
	Percentage of correct diagnosis		70.4		72	
Steel company	Thermal strain (Observation)	+	9 8	53	6 11	65
		-	5 29	85	29 5	85
	Percentage of correct diagnosis		74.5		87	

so the correlation between the WBGT index and deep temperature (criteria index) was obtained as 0.36. In the Regression Analysis, only 65% of the people with thermal strain (sensitivity) and 53% of the people without thermal strain (specificity) were correctly identified by the WBGT index.

In the weather conditions of the Persian Gulf in hot seasons, dry bulb temperature and radiant temperature were equal to 37.4°C (3.7°C) and 38.9°C (2.8°C), respectively. Due to the high mean temperatures, the mechanisms of heat loss from the body via radiation and convection were not efficient enough and the only way for heat loss from the body was sweating. The cardiovascular system played a significant role in this process, by increasing the heart rate. Thus, some studies showed that the heart rate increases to between 15 and 30 beats per minute for every one degree increase in deep body temperature.[17] Investigations have widely confirmed the relationship between heart rate and deep body temperature.[2,25,30,31] It should be mentioned that when exposed to the desirable environmental conditions, the level of activity was the main stimulus for heart rate, and the temperature regulatory system did not have any problem for heat loss; therefore, the heart rate was less affected by environmental conditions, more indicates the amount of body metabolism and is more affected by non-environmental factors. On the other hand, while exposed to high temperature (dry bulb temperature or radiant temperature), the thermal load of the body increases, which should be rejected; therefore, the body temperature regulation system increases the heart rate.

Even when exposed to the hot-humid environmental conditions of Assaluyeh or the hot-dry conditions of the Steel Company and considering the physical activity of the workers, a significant part of the heart rate increase is related to the thermal strain imposed on the body and this thermal strain is affected by environmental and non-environmental factors. Therefore, entering the heart rate component into the estimation of the thermal strain is equal to the effective non-environmental components that affect the thermal strain. In other words, by entering a combination of the WBGT and PSI_{HR} indices, both environmental and non-environmental factors that affect the thermal strain were used for estimating the thermal strain. Thus, the sensitivity (ratio of correct prediction of the people with thermal strain) and specificity (ratio of correct prediction of the people without thermal strain) of the WBGT index, for predicting deep body temperature in all the people in the two regions, were equal to 65 and 53%, respectively, which improved to 75 and 69% after entering the PSI_{HR} index. In fact, in very hot conditions of the Assaluyeh and Steel Company, the WBGT index predicted 47% of the people without thermal strain in the class of people with thermal strain (low specificity), which was probably caused by the self-pacing phenomenon in these people. However, after entering the heart rate, considerable improvement was obtained in the correct detection of people without thermal strain (increase of specificity), because many people reduce their physical activity in very hot conditions, in order to decrease the thermal strain, which is revealed in their heart rate. Using this factor for estimating the strain led to a more accurate detection of people without thermal strain. Also, Mr. Moran *et al*. suggested the combined application of environmental strain index and PSI_{HR} for estimating the thermal strain,[32] which is in line with the idea presented here. Moreover, the result of this study is in agreement with the analysis by Mr. Malchaire, who stated that the WBGT index is not appropriate for screening purposes.[33] Low correlation ($r = 0.36$) of the WBGT index with deep body temperature, in this study, confirmed that point. Therefore, the results of the present research support the idea of combined application of these two indices for better estimation of the thermal strain.

The advantage of the combined application of these two indices is that in addition to a better estimation of the thermal strain, it is possible to measure both indices using the available equipment in developing countries. The disadvantage of this study is that it has been done in very hot-humid and very hot-dry weather conditions and its results cannot be generalized to other weather conditions. Therefore, considering that this is the first research on the combined application of WBGT and PSI_{HR}, for estimating thermal strain, it is necessary to conduct more extensive studies in other weather conditions using factors like physical fitness, types of clothing, acclimatization, and dehydration, in order to investigate the efficiency of the combined application of these two indices.

CONCLUSION

The results obtained from this research state that the combined application of two indices, WBGT and $PSI_{HR,}$ can be a useful tool for better estimation of the thermal strain in the hot weather conditions of Central and South Iran.

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