ORIGINAL ARTICLE

Comparison of Outdoor Environmental Heat Index (OEHI) and Other Environmental and Physiological Heat Indices: A Case of Outdoor Workers in Low Thermal Stress Conditions

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Abstract

Background: This study aims to assess the consistency of the newly developed Outdoor Environmental Heat Index (OEHI) with existing environmental and physiological heat indices in low thermal stress conditions. This comparison is necessary due to potential variations in the performance of a heat stress index when applied in conditions different from those for which it was developed.

Methods: Two current and valid outdoor heat indices, including Wet Bulb Globe Temperature (WBGT) and Humidex (HD), were used in a descriptive-analytical study to compare the results obtained by OEHI and other indices in evaluating the same condition. Furthermore, the authors considered tympanic temperature as a physiological response to heat and assessed the work environment of 63 outdoor workers at three-hour intervals during the workday.

Results: The highest coefficient of determination was assigned to OEHI and Humidex index ($R^2>0.99$, $P<0.0001$). Regarding the correlation between the OEHI and the WBGT index, this correlation with and without considering the time of the measurement was higher than 0.98. Comparisons for the correlations of thermal indices with tympanic temperature showed poor and significant relations between thermal indices and tympanic temperature ($R^2<0.19$, $P<0.0001$).

Conclusion: OEHI can evaluate the thermal condition in low heat stress conditions, similar to other current and valid thermal stress indices, including WBGT and Humidex. The OEHI shows a better correlation with the Humidex than the WBGT index. However, due to the poor correlation observed between OEHI and tympanic temperature in low-stress conditions, it is recommended to use this index just as a screening index to estimate thermal environmental conditions.

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Introduction

Global warming is threatening the exposed populations' public health and occupational communities, and this is one of the current and future concerns of human societies.[1] This concern indicates the necessity of improving and developing new methods for assessing thermal environments that could inform people at risk of heat stress and reduce heat exposure damages, particularly during heat waves.[2, 3]

"Heat stress" refers to environmental conditions that cause responses in the human body beyond the human's physiological tolerance. Four environmental parameters, including air temperature (Ta), radiant temperature (Tr), air velocity (V), and relative humidity (RH), along with two personal parameters, including metabolism and thermal resistance of clothing, are the basic parameters causing heat stress.[4] There are several populations, including children, older people, and outdoor workers, that excessive heat threatens their health, and on-time notification can meaningfully reduce heat-related risks.[5]

Some studies suggested indoor and outdoor thermal indicators formulated based on the basic parameters.[6, 7] These indices could be easily determined using daily records of weather stations, and they can be used not only to assess the thermal environments but also to predict the thermal stress conditions and the severity of the consequences before the occurrence of heat waves.[8, 9]

Golbabaei et al. recently developed the Outdoor Environmental Heat Index (OEHI) based on the air temperature and enthalpy parameters to evaluate thermal exposure.[9]

This index relies on the hypothesis that the permissible tympanic temperature of a heat-exposed person outdoors is 37 degrees Celsius. When the temperature exceeds this degree, a person might experience heat strain. Tympanic temperature is suggested as an acceptable substitute for the rectal temperature when the measurement of the rectal temperature is restricted, particularly in field studies and for the adult measurements.[10, 11] According to the thermal environmental condition in which the OEHI was developed, a wide range of air temperature (14.6-46.0 °C) and relative humidity (20.9-93.8%) was considered for developing the index. Still, the mean and standard deviations of the Ta and RH were reported to be equal to 31.63±6.18 °C and 51.78±16.86%, respectively.[9] These values often indicate the moderate to severe hot and humid conditions in which heat stress can be expected. As the index's applicability may be limited when conditions significantly differ from those in which it was developed, it is essential to assess its applicability in various conditions. This problem might arise when the thermal condition can not cause heat stress, but the exposed person may experience thermal discomfort. This condition might happen when the discomfort index (DI) is ≥29 °C.[12]

In addition, it is very important that a thermal stress index is well related to the human body's physiological responses and reflects the thermal stress on the body.

Many studies have indicated that monitoring some physiological responses (rectal temperature, sweat rate, etc.) in different thermal situations could reflect an increased safety and health risk.[8, 13, 14]

As a noninvasive and fast measure of core temperature with a limited risk of nosocomial infection, Tympanic temperature is recommended for evaluating heat stress in outdoor environments.[10] Moreover, researchers in that study concluded that the amount of humidity and temperature can influence the consistency of the heat index and physiological response.

This study aims to investigate the Outdoor Environmental Heat Index (OEHI) by comparing it with two established outdoor heat stress indices, namely the Wet Bulb Globe Temperature (WBGT) and Humidex (HD) index. The objective is to assess OEHI's applicability and extend its usability range for thermal monitoring in low heat stress conditions characterized by low humidity and air temperature. Moreover, the correlations of the heat stress indices with tympanic temperature as a physiological response to heat were assessed to determine the relationship between environmental and physiological monitoring appropriateness.

Methods

Subjects

Sixty-three healthy municipal service male workers from Qom City, Iran (mean age: 41.35, range: 20-55 years) were randomly enrolled in the study. Participants had at least one year of outdoor work experience. The authors excluded participants with heart-related diseases such as cardiovascular, renal diseases, hypertension, and diseases with fever. This study was approved by the Golestan University of Medical Sciences Ethics Committee (approval no. IR.GOUMS.REC.1400.183). To comply with the ethical points, all participants were informed of the study's objectives, and written informed consent was obtained from them before enrolment. The participants worked outdoors with different duties, including sweeping, pruning flowers and trees, carrying plant wastes, and irrigating plants, and they wore the same uniform (thermal insulation of the ensemble was estimated <1 CLO based on ISO 9920).[15] The participants' metabolic rate in different duties was estimated from low to moderate according to ISO-8996, 2004. Cloth thermal resistance and metabolic rate were used in this study to determine exposure limits of WBGT.

Environmental Parameters and Thermal Stress Indices

The current study was conducted in spring 2021. The value of two valid heat stress, including WBGT and Humidex, was estimated according to standard[16] using an advanced thermal stress meter (WBGT meter, Casella) and calculated by Eq. (1),[17, 18] respectively. These indices were used to compare the results in the same situations with OEHI.

Humidex=(air temperature)+h (Eq.1)

H=(0.5555)(e-10.0)

e=6.11 exe (5417.7530((1/273.16)-(1/dew point)))

The threshold limit value for the WBGT, after cloth and metabolic rate corrections, was considered 28 °C.[19, 20] Table 1 shows the comfort zones based on the Humidex.

Table 1: Limit values and ranges of the Humidex index[17]

Thermal discomfort level	Range
Comfort	20≤Humidex≤29
Some discomfort	30≤Humidex≤39
Great discomfort, avoid exertion	40≤Humidex≤45
Dangerous	46≤Humidex≤54
Heat stroke imminent	Humidex>54

Air temperature (Ta), relative humidity (RH), dew point (Dw), and barometric pressure (Pa) were measured using a calibrated device (name of the device?) (Lotron PHB 318, Taiwan). Air velocity (Va, m.s-1) was also measured using a calibrated thermal anemometer (Kimo, France). All parameters were measured at 9 a.m., 12 a.m., and 3 p.m. during a work shift, representing the morning, midday, and afternoon. This way, the authors tried to cover a wider range of environmental parameters through a working day.

Two environmental parameters, including air temperature and enthalpy, are needed to calculate OEHI. The authors calculated the air enthalpy's general equation of moist air (Eq. 2).[21]

$$i = 1.006t + \frac{RH}{P_B} . 10\left(\frac{7.5.t_a}{237.3+t_a}\right).(71.28 + 0.052.t_a) \text{(Eq.2)}$$

Where is:

i: air enthalpy (KJ. Kg^{-1})

t_a: air temperature (°C)

RH: relative humidity (%)

P_B: barometric pressure (mm. Hg)

We calculated OEHI using Eq. 3.

$OEHI=35+0.025, t_a+0.016, i$ (Eq.3)

Where is:

OEHI: Outdoor environmental heat index (°C)

t_a: air temperature (°C)

i: air enthalpy (KJ. Kg^{-1})

The validity of the OEHI was presented in previous research, and the cut-off point for OEHI has been suggested as 37 °C.[9]

Tympanic Temperature Measurement

A non-contact digital ear thermometer (Omron model-510, China) was used to measure tympanic temperature. The precision was 0.1 °C and could measure this physiological parameter in the 34-42.2 °C range. All measurements were performed in the participants' right ear contractually and repeated thrice at 2-minute intervals. The highest value of tympanic temperature was considered if there were no significant differences between the results.

The acceptable limit for tympanic temperature was considered at 37 °C.[10]

Statistical Analysis

The mean and standard deviation of environmental and physiological parameters were compared using One-way ANOVA and the Kruskal-Wallis test. The correlation of variables was tested using the Pearson correlation coefficient test. The linear regression was also used to show the scatter plots and the line equation. The data were analyzed using SPSS software, Version 26, and the significance level was considered less than 0.05 (P<0.05).

Results

The mean and standard deviation of participants' age in this study was 41.35±7.72 years. They had work experience between 1 and 25 years (7.40±4.73 years). The participants' metabolic rate was estimated to range from 203.65 to 486.07 W (336.89±59.52 W). These values indicate the metabolic rate of low to moderate based on ISO-8996, 2004. The mean and standard deviation of thermal insulation of the cloths were 0.72±0.23 CLO. The recent two variables were used to determine the allowable exposure limit of the WBGT index based on ISO-72433, 1989. Table 2 shows characteristics of environmental thermal parameters at different times

Table 2: Environmental parameters at different times of the study*

Parameter	Time		
	9 AM** (mean±SD****)	NOON *** (mean±SD)	3 PM (mean±SD)
Air temperature, t_a (°C)	26.37±0.52	29.89±1.27	28.49±0.79
Natural wet temperature, t_{nw} (°C)	13.93±0.55	15.26±0.77	14.86±0.44
Radiant temperature, t_g (°C)	33.05±1.45	39.68±2.51	37.70±1.98
Relative humidity, RH (%)	25.77±1.46	21.51±0.87	23.60±0.87
Air velocity, V_a (m.s^{-1})	0.75±0.23	0.47±0.20	0.60±0.21
Enthalpy (KJ. Kg^{-1})	42.21±1.61	46.19±2.42	44.95±1.32
Dew point, Dw (°C)	5.22±1.03	5.56±1.05	5.84±0.65

Significant differences were seen between all the parameters at different times (P<0.001). **AM: Ante meridiem; ***PM: Post meridiem; ****SD: Standard deviation

Table 3: Thermal stress and strain indices at different times of day

Parameter	Time								
	9 AM*			NOON**			3 PM		
	Min	Max	mean±SD***	Min	Max	mean±SD	Min	Max	mean±SD
Thermal stress indices									
WBGT	18.2	20.6	19.00±0.70	20.9	25.0	22.01±1.15	19.8	22.3	20.79±0.76
Humidex	20.3	23.1	21.28±0.82	23.5	29.3	24.92±1.61	22.3	25.3	23.58±0.93
OEHI	36.3	36.4	36.33±0.04	36.4	36.6	36.48±0.07	36.3	36.5	36.43±0.04
Thermal strain Index									
Tympanic temperature	35.0	36.4	35.37±0.40	35.1	37.2	36.38±0.47	36.0	37.2	36.68±0.29

A significant difference was observed between all the thermal stress and strain indices at different times ($P<0.001$). *AM: Ante meridiem; **PM: Post meridiem; ***SD: Standard deviation

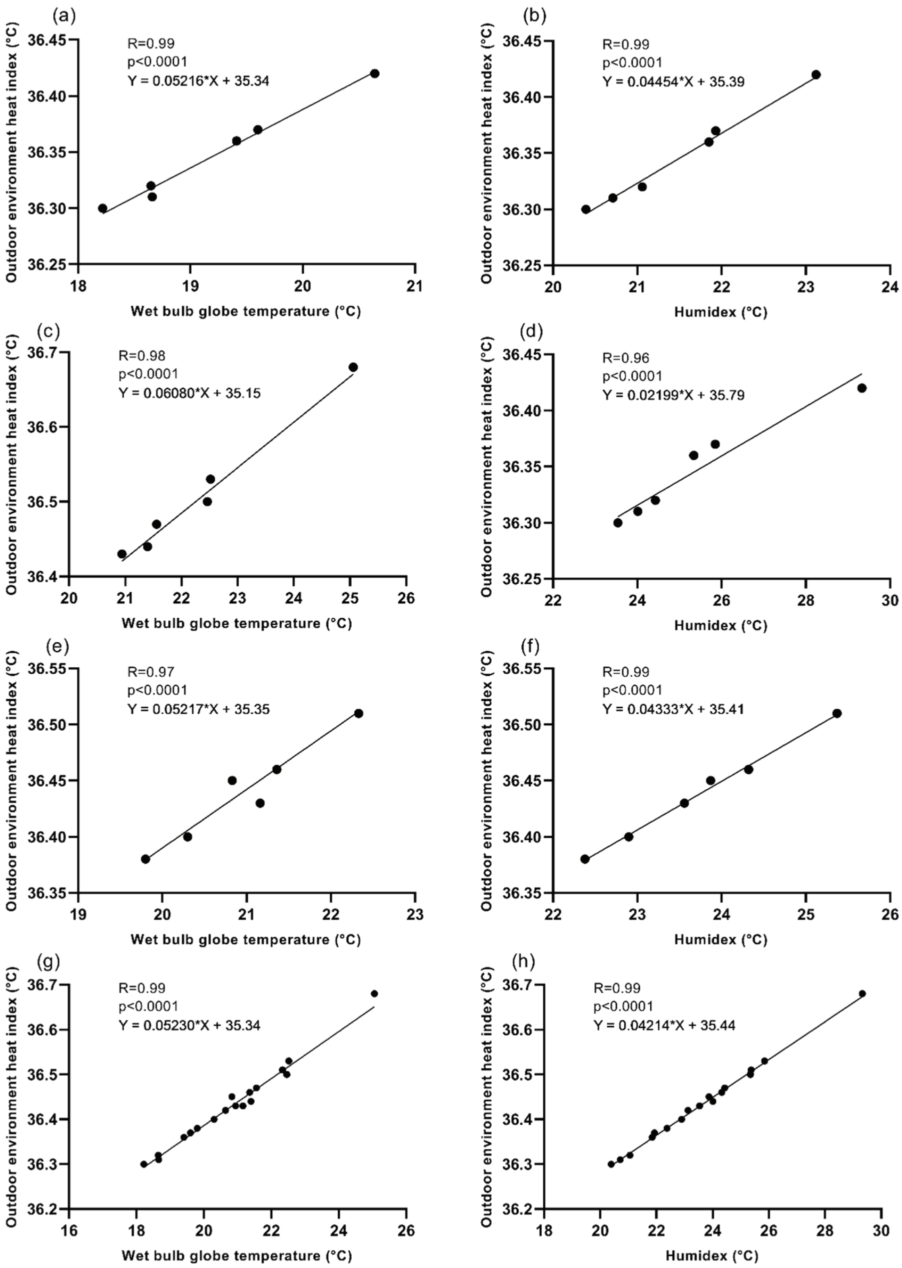

Figure 1: The scatter plot and correlation coefficient of the OEHI* with WBGT** and Humidex in the morning (a and b), the midday (c and d), the afternoon (e and f), and the whole (g and h) workday, respectively. *OEHI: Outdoor Environmental Heat Index; **WBGT: Wet Bulb Globe Temperature

of the day. The maximum mean values of thermal parameters were observed during noon.

Table 3 describes thermal indices and strain index at the three-time points of the day.

The findings indicated a high correlation (P<0.001, R>0.95) between OEHI and WBGT, and Humidex in the morning (Figure 1a and b), the midday (Figure 1c and d) and the afternoon (Figure 1e and f). Additionally, a high correlation (P<0.001, R>0.99) was found between OEHI and other indices for the whole workday.

The consistency findings showed a statistically significant correlation (P<0.001, R>0.43) between assessment indices and the body's physiological response to heat (Figure 2).

Discussion

Since the OEHI index was developed based on an experimental method, it is fit for specific conditions, and its applicability should be tested in other conditions. Therefore, the applicability of this index was examined in low heat stress or thermal discomfort situations by comparing it with two current and valid heat indexes, WBGT and Humidex.

In addition to thermal indices, tympanic temperature was considered an appropriate physiological response to thermal stress. Vatani et al. examined the applicability of the Universal Temperature Climate Index (UTCI) using WBGT and the physiological responses.[22] Galan et al. assessed the applicability of the UTCI, WBGT, and PHS as a heat stress index in military environments.[23] The applicability of WBGT and Heat index (HI) for heat waves criteria,[24] Humidex for evaluating hot and dry environments,[25] and the enthalpy index in outdoor environments[8, 26] were other examples of such works.

The results showed that the air temperature and humidity in the measuring stations were not enough to cause significant heat stress but could cause some degree of thermal discomfort. In addition, although the maximum values are related to noon, no heat stress can be expected for exposed workers now. The results obtained by thermal stress and strain indices (Table 1 and Table 3) confirmed that no heat stress conditions existed during the study. As mentioned in the method section, OEHI calculation relies on air temperature and enthalpy. Air enthalpy, a commonly calculated and reported environmental parameter derived from meteorological data, measures air heat content and is suitable for predicting the thermal conditions within a space.[27] Air temperature and relative humidity are the main environmental parameters influencing heat stress. Both of them are included in the calculation of enthalpy.[8] Another study reported the higher significance of environmental parameters such as air temperature and relative humidity in assessing heat strain.[5]

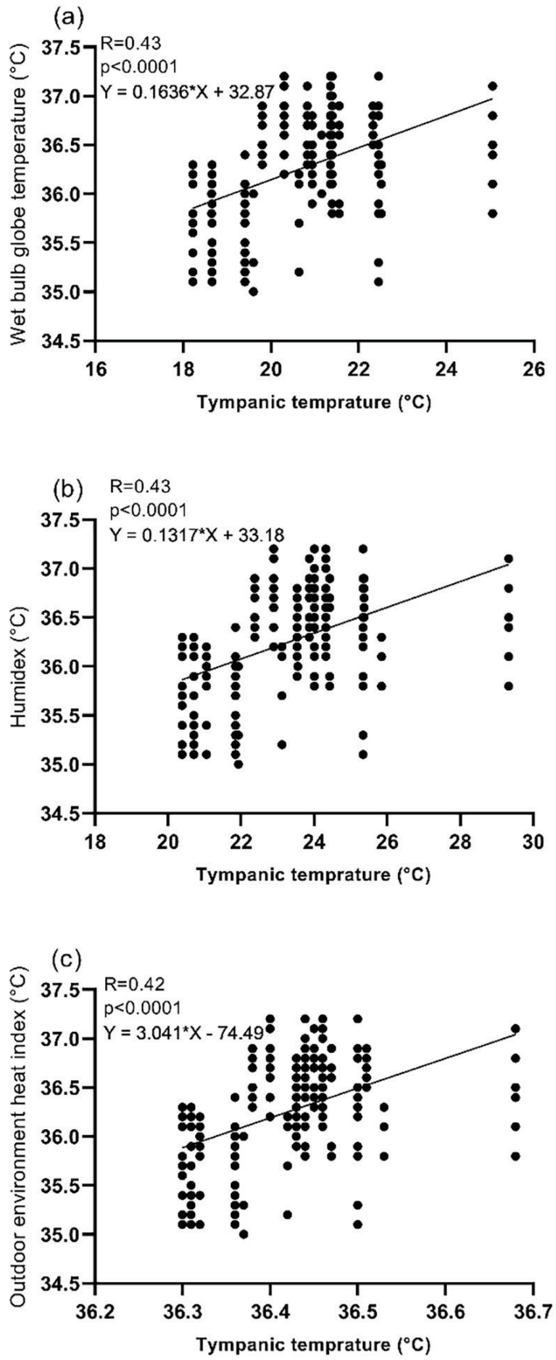

Figure 2: The scatter plot and correlation coefficient of the WBGT**, Humidex, and OEHI* with the tympanic temperature for a whole workday. *OEHI: Outdoor Environmental Heat Index; **WBGT: Wet Bulb Globe Temperature

To assess the applicability of OEHI for this condition, the performance of the WBGT, Humidex, and OEHI was compared at different times of the workday. The results indicated a high correlation between OEHI, WBGT, and Humidex in all test situations.

Like Humidex, OEHI does not depend on globe temperature, which is one of the key components for determining WBGT. On the other hand, some studies showed that monitoring thermal conditions using WBGT is accompanied by an overestimation.[8, 28, 29] This can be the reason for the slightly better correlation between OEHI and Humidex than the WBGT index, especially in the afternoon (3 p.m.).

The correlations of thermal indices with tympanic temperature showed a moderate but statistically significant relationship ($R^2 \geq 0.42$, $P<0.0001$). The correlation between thermal indices and tympanic temperature has been studied in several investigations, and most of these studies reported poor to moderate correlations between physiological indicators and thermal indices. These reports were in line with the current findings. Nassiri et al. found a moderate (r=0.477) correlation between Humidex and tympanic temperature in the open pit mines.[30] In another study in Iran's arid and semi-arid climates, a strong correlation was obtained between WBGT and Humidex in both regions (r=0.98). Still, the correlation between Humidex and tympanic temperature was moderate (r=0.5-0.8). Based on the obtained Kappa value, the agreement coefficient between Humidex and WBGT was 0.878. This value was 0.226 for the Humidex and tympanic temperature.[25]

According to the objects of the study, the tympanic temperature was measured only in environmental conditions with low heat stress or heat discomfort. Under these conditions, no significant changes in tympanic temperature are expected. Therefore, while the relationship was statistically significant (P<0.001), a poor correlation coefficient was seen between tympanic temperature and thermal stress indices. In a study to determine the accuracy of an infrared tympanic membrane thermometer (Tty) against rectal temperature (Tre), the researchers found that the infrared tympanic membrane thermometer closely matched Tre measurements at rest. In the early stages of exercise, Tty appeared to underestimate thermal strain once significantly Tre exceeded 37.5 °C.[31] They concluded that determining whether these differences result from selective brain cooling or imperfections in the tympanic membrane thermometer methodology is necessary. In a different study involving steel plant workers, researchers assessed fatigue and physiological responses at various levels of heat stress. They found that when heat stress levels were insufficient to affect physiological parameters significantly, there was no significant relationship between physiological responses before and after heat exposure.[32]

Similar results have been seen between oral temperature and WBGT.[33] It means that the heat strain can rise by increasing the heat stress. These findings suggest that tympanic temperature cannot reflect the heat strain imposed on individuals under conditions of low thermal stress, such as in the present study, or under very high thermal stress conditions. Anyway, confirmation of this issue needs further study. Field measurements of environmental and physiological parameters can provide more realistic results than laboratory studies, and many factors in laboratory studies which cannot be accurately evaluated when comparing thermal indicators (such as accurate estimation of metabolism, the thermal effect of clothing and personal protective equipment, etc.), can easily be considered in the field studies. Hence, conducting this study in real-world conditions can be considered a strength in the results. However, based on the study's results, the sensitivity of the tympanic temperature response in assessing the thermal conditions when the temperature changes are in a narrow range is low and cannot well reflect the thermal strain conditions. It is suggested that future studies overcome this limitation by using more sensitive and applicable heat strain indices, such as skin temperature or heart rate.[29, 34]

Generally, because of the high correlations observed between OEHI and other thermal indices (r>0.96, P<0.0001), as well as the significant but moderate correlations of thermal indices and tympanic temperature (r<0.42, P<0.0001), it could be concluded that OEHI could acceptably be used in low heat stress conditions. However, because of the poor correlation of the index with tympanic temperature, it is strongly recommended that this index be applied as a primary index for screening the thermal conditions, the same as WBGT. Moreover, as an advantage, OEHI can be calculated using the meteorological parameters that are recorded and reported daily in meteorological stations and can also be used to announce the thermal condition of an interested environment to the exposed populations to take preventive measures.

Conclusion

In low heat stress conditions, or when people experience some extent of thermal discomfort, OEHI can be used for evaluation of thermal condition (high correlations observed between OEHI and other thermal indices (r>0.96, P<0.0001), similar to other current and valid thermal stress indices. Moreover, as an advantage, this index can be estimated accurately using weather parameters recorded daily in the meteorological stations.

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