

Validation of Environmental Stress Index by Measuring Infrared Radiation as a Substitute for Solar Radiation in Indoor Workplaces

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Abstract

Background: The exposure of individuals to heat at different jobs warrants the use of heat stress evaluation indices.

Objectives: The aim of this study was to validate environmental stress index using an infrared radiation (IR) measurement instrument as a substitute for pyranometer in indoor workplaces.

Methods: This study was conducted on 2303 indoor workstations in different industries in Isfahan, Iran, during July, August, and September in 2012. The intensity of the Infrared Radiation (IR) (w/m^2) was measured at five-centimeter distances in six different directions, above, opposite, right, left, behind and below the globe thermometer. Then, the dry globe temperature (T_a), wet globe temperature (T_{nw}), globe temperature (T_g) and relative humidity (RH) were also simultaneously measured. The data were analyzed using correlation and regression by the SPSS₁₈ software.

Results: The study results indicate that a high correlation ($r = 0.96$) exists between the environmental stress index (ESI) and the values of wet bulb globe temperature ($P < 0.01$). According to the following equation, $\text{WBGT} = 1.086 \times \text{ESI} - 1.846$, the environmental stress index is able to explain 91% ($R^2 = 0.91$) of the WBGT index variations ($P < 0.01$).

Conclusions: Based on the results, to study heat stress in indoor workplaces when the WBGT measurement instrument is not available and also in short-term exposures (shorter than 30 minutes) when measuring the wet bulb globe temperature shows a considerable error, it is possible to calculate the environmental stress index and accordingly to the WBGT index, by measuring the parameters of dry bulb temperature (T_a), relative humidity (RH), and infrared radiation intensity that can be easily measured in a short time.

Keywords: Environmental Stress Index, Wet Bulb Globe Temperature, Heat Stress Estimation, Infrared Radiation

1. Background

Exposure to heat increases the risk of heat-induced illness occurrence (1). Heat stress at the workplace can be measured in terms of environmental, physiological and perceptual parameters. Environmental parameters including the ambient temperature, radiant temperature, humidity rate and air velocity as well as personal physical activity and clothing, are of the most important agents that cause heat-induced stress. Many attempts have been made to estimate the stress inflicted by a wide range of work conditions and climates, or to estimate the corresponding physiological strain and to combine them into a single index, a heat stress index (2).

Nearly one century ago, Haldane offered a heat stress evaluation index to describe the environmental heat stress that was acceptably correlated with physiological strain elements (3). Sohar et al. (4) defined the thermal discomfort index (DI) based on dry bulb temperature (T_a) and wet bulb temperature (T_w).

Out of the thermal stress indices based on measuring environmental parameters, the wet bulb globe tempera-

ture (WBGT) is the most popular index developed by Yaglou and Minard in 1957 (5), which was used then to interpret the possible adverse effects of heat loads on navy military and their training staff. In 1989, the international organization of standardization (ISO), as an international standard, introduced this index for heat load evaluation. This index enables the assessment of heat load at a certain time in terms of activity level as well as clothing (6, 7). The wet temperature (T_w), globe temperature (T_g), and dry air temperature (T_a) (for outdoor environments) are used to determine the value of this index (8). Recently, some restrictions have been reported for using the WBGT index (1-3, 6-12). One of the restrictions to be mentioned is the fact that since measuring the globe temperature requires making a thermal balance, the measurement process takes a long time compared to that of dry bulb temperature or wet bulb temperature, so that many WBGT index measurement instruments need approximately 20 to 30 minutes to complete the measurement. Furthermore, the instrument is expensive and difficult to afford particularly in developing countries.

Accordingly, Moran et al. (13) introduced the environmental stress index as a substitute for the WBGT index. The

calculation of the environmental stress index (ESI) is based on measuring dry bulb temperature (T_a), relative humidity (RH) and solar radiation (SR).

One of the advantages of this index is that the measurement of the dry bulb temperature, relative humidity and solar radiation is possible directly and in a short time. Using this index, is therefore practical, easy to use, and with a fast response time compared to those of the ESI index.

Furthermore, it has been reported that the environmental stress index and the WBGT index are highly correlated ($R^2 = 0.92$).

A few studies have been conducted on validation of the environmental stress index outdoors. In these studies, the intensity of solar radiation was measured using pyranometer, which is nearly impractical in developing countries as cannot be easily obtained commercially.

2. Objectives

Therefore, the purpose of the present study was to validate the environmental stress index using an instrument to measure infrared radiation as a substitute for pyranometer in indoor workplaces.

3. Methods

The current study was performed in Isfahan city (Iran), during the hottest months of the year (July, August and September) in 2012. The study was conducted on 2303 hot indoor workstations located in different industries between 7 am and 4 pm. The dry bulb temperature, wet bulb temperature, globe temperature and globe temperature were simultaneously measured every five minutes during two hours. The monitoring of dry bulb temperature, wet bulb temperature, and globe temperature was done and recorded using a Casella Microtherm heat stress monitor. Moreover, the infrared radiation intensity was measured every five minutes in six different directions (above, opposite, right, left, behind and below) of the globe thermometer, for two hours using Hagner EC1 IR with a spectral sensitivity of 750 - 1150 nm over a range of 0.01 - 20,000 W/m². The WBGT index and ESI index were calculated based on equations 1 to 2, respectively (1).

$$1) \text{WBGT} = 0.7t_{nw} + 0.3t_g$$

$$2) \text{ESI} = 0.63 T_a - 0.03RH + 0.002SR + 0.0054 (T_a \times RH) - 0.073 (0.1 + SR)^{-1} (^\circ\text{C})$$

The relationship between the environmental stress index and the wet bulb globe temperature was assessed using the Pearson correlation coefficient and regression analysis tests. The data were analyzed using the SPSS18 software.

4. Results

Table 1 illustrates mean and standard deviation of the wet bulb globe temperature and environmental stress indices parameters in six main directions from the globe thermometer.

Table 2 indicates the results of Pearson correlation between the WBGT and ESI indices in six main directions from the globe thermometer. The results indicated that there was a high correlation between these two indices ($P < 0.001$).

The regression analysis results indicated a significant relationship between WBGT and ESI $\text{WBGT} = 0.848 \times \text{ESI} + 3.414$, so that 93% of WBGT index variations was explainable by ESI index ($P < 0.001$).

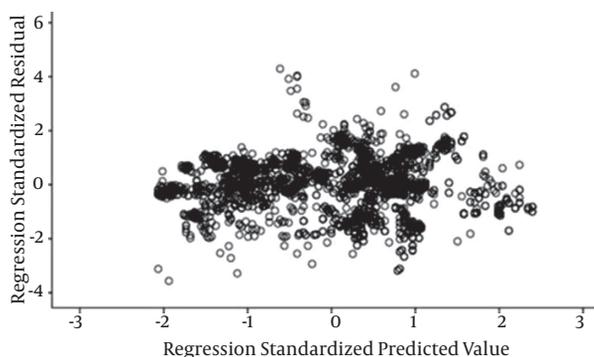


Figure 1. The Residuals Scatter Gram Obtained From Comparisons Between the Wet Bulb Globe Temperature and Environmental Stress Indices During Two Hours

5. Discussion

Heat stress indices are mostly used to assess environmental conditions (14). Based on the recommendations made by the national institute for occupational safety and health (NIOSH), when assessing indoor environments, the WBGT index should be measured during summer and winter to be able to interpret climatic conditions of the workplace. In this study, validation of environmental stress index was achieved by measuring infrared radiation as a substitute for solar radiation in indoor workplaces using the commonly used WBGT.

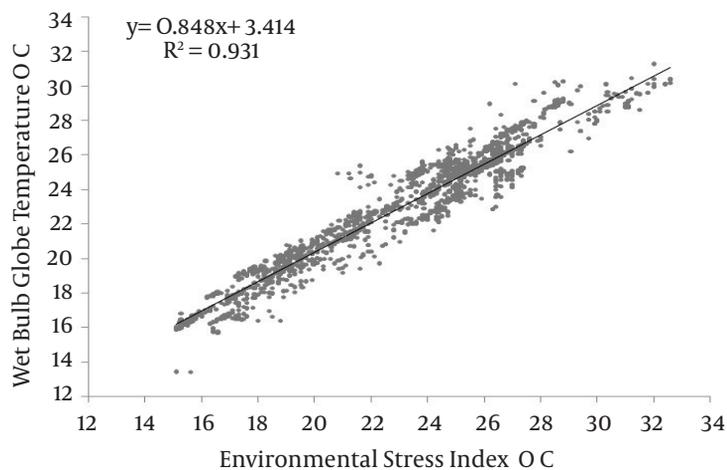
In 1950, the WBGT index was introduced as a heat stress evaluator. At the same time many empirical indices such as the effective temperature index (ET) (15), Corrected effective temperature index (CET) (16), modified discomfort index (MDI), and WBGT were introduced. These indices are all calculated based on T_a , T_w and T_g .

Table 1. Mean And Standard Deviation of Wet Bulb Globe Temperature and Environmental Stress Indices

T _a , °C	T _w , °C	RH, %	T _g , °C	WBGT, °C	V _a , m·s ⁻¹
27.14 ± 4.00	19.73 ± 3.49	54.08 ± 16.58	31.40 ± 6.13	23.24 ± 3.92	0.16 ± 0.29
IR, W·m ⁻² , Above	IR, W·m ⁻² , Opposite	IR, W·m ⁻² , Right	IR, W·m ⁻² , Left	IR, W·m ⁻² , Behind	IR, W·m ⁻² , Down
3.44 ± 3.12	1.74 ± 1.49	1.98 ± 1.70	1.77 ± 1.53	2.75 ± 2.52	0.99 ± 0.89

Table 2. Pearson Correlation Coefficient Between Wet Bulb Globe Temperature and Environmental Stress Indices in Six Directions

IR, W·m ⁻² , Above	IR, W·m ⁻² , Opposite	IR, W·m ⁻² , Right	IR, W·m ⁻² , Left	IR, W·m ⁻² , Behind	IR, W·m ⁻² , Below	IR, W·m ⁻² , Mean
r = 0.954	r = 0.954	r = 0.954	r = 0.955	r = 0.954	r = 0.955	r = 0.955

**Figure 2.** Scatter Plot Showing the Relationship Between Wet Bulb Globe Temperature and Environmental Stress Indices

The ESI index (13) is possible to be measured in a short time using the measurement of three parameters including the dry temperature (T_a), relative humidity (RH) and the solar radiation (SR). This index also is easy to use and needs the least amount of time to be balanced with the surrounding environment.

The ESI differs from other indices that have been suggested in the past in two aspects. First, this stress index uses for the first time direct measurements of SR and RH. The measurements of these variables are not as cumbersome as measuring T_g and T_w , which are used in the calculation of the WBGT. Second, the three meteorological variables used in ESI are characterized by fast-reading responses that require only a few seconds to reach equilibrium.

This study, therefore, was performed with the intent of validating the environmental stress index indoors using the infrared measurement device as a substitute for the pyranometer (the device specialized for measuring solar

radiation).

In the present study, ESI was evaluated for extreme climatic conditions: hot/dry covering a T_a range of $27.14 \pm 4^\circ\text{C}$ and an RH range of $54.08 \pm 16.58\%$.

Previously, the ESI was validated only in comparison to other stress indices [WBGT, DI and MDI] in outdoor workplaces, but in a recent study, ESI was evaluated in indoor workplaces.

According to the results, a high correlation exists between the WBGT and the ESI index (calculated based on indoor IR measurement). These results are consistent with those of the study done by Moran et al. in 2001 (17), on the evaluation of the environmental stress index validity, and indicated a high correlation between the WBGT and ESI index.

In another study carried out by Moran et al., the ESI index was measured through assessing some meteorological variables such as the dry temperature (T_a) and relative humidity (RH), using pyranometer at six different stations lo-

cated in places higher and lower from sea levels and the results showed a high correlation ($R^2 = 0.993$) between ESI and WBGT index (18).

Moran et al. performed another study on outdoor environments in New Zealand and found that there was a high correlation ($R^2 = 0.973$) between ESI and WBGT (19). Moreover, the ESI index can be easily measured using three important environmental parameters (T_a , RH, and SR) in both hot/dry and hot/humid environments (20, 21).

In another study on the evaluation of three indices including the simple index (SI), discomfort index (DI), modified discomfort index (MDI) and the ESI index in three different meteorological conditions including extremely hot/dry, hot/dry and hot/humid conditions, Moran et al. found a high correlation ($P < 0.001$, $R^2 = 0.981$) between the ESI index and SI, DI, and MDI (13, 22).

5.1. Conclusion

In the current study, it was found that although in many industries and organizations the WBGT index is the most applicable index for evaluating heat strain, some restrictions have been found related to this index especially when the WBGT device is not accessible or in short-time heat exposures during which the WBGT index measurement can not be accurate. Therefore, the ESI index, which can be easily calculated measuring three parameters of T_a , RH and IR in a short time, can be considered as a reliable alternative to the WBGT index.

The present study validated the evaluation of indoor ESI index using IR measurement device as a substitute for pyranometer for the first time. Therefore, to investigate the correlation between the two indices more precisely, more extensive studies are required to be performed especially in hot / humid climatic conditions both indoors and outdoors and during different seasons.

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Footnotes

Authors' Contribution: Study concept and design, Habibollah Dehghan; acquisition of data, Peymaneh Habibi; analysis and interpretation of data, Peymaneh Habibi;

drafting of the manuscript, Peymaneh Habibi and Mahnaz Shakerian; critical revision of the manuscript for important intellectual content, Peymaneh Habibi; statistical analysis, Peymaneh Habibi; administrative, technical, and material support, Peymaneh Habibi; study supervision, Habibollah Dehghan.

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References

1. Moran DS, Pandolf KB. Wet bulb globe temperature (WBGT)–to what extent is GT essential?. *Aviat Space Environ Med.* 1999;**70**(5):480–4. [PubMed: 10332944].
2. Epstein Y, Moran DS. Thermal comfort and the heat stress indices. *Ind Health.* 2006;**44**(3):388–98. [PubMed: 16922182].
3. JCH. The influence of high temperature. *J Hyg.* 1905:404–9.
4. Sohar E, Tennenbaum J, Robinson N. A Comparison of the Cumulative Discomfort Index (Cum. D.I.) and Cumulative Effective Temperature (Cum. E.T.), as Obtained by Meteorological Data. 1962 :395–400. doi: 10.1016/b978-0-08-009683-4.50052-8.
5. Yaglou CP, Minard D. Control of heat casualties at military training centers. *AMA Arch Ind Health.* 1957;**16**(4):302–16. [PubMed: 13457450].
6. Parsons KC. International heat stress standards: a review. *Ergonomics.* 1995;**38**(1):6–22. doi: 10.1080/00140139508925081. [PubMed: 7875120].
7. Moran DS, Pandolf KB, Shapiro Y, Laor A, Heled Y, Gonzalez RR. Evaluation of the environmental stress index for physiological variables. *J Thermal Biol.* 2003;**28**(1):43–9. doi: 10.1016/s0306-4565(02)00035-9.
8. Gonzalez RR, Sexton GN, Pandolf KB. Biophysical evaluation of the wet globe temperature index (Botsball) at high air movements and constant dew point temperature. DTIC Document; 1985.
9. Kreider JF. Handbook of heating, ventilation, and air conditioning. US: CRC press; 2000.
10. ISO 1 7243 . Hot Environments-Estimation of Heat Stress on Working Man Based on the WBGT Index (Wet Bulb Globe Temperature). Geneva: International Organization for Standardization; 1989.
11. Matthew WT, Thomas GJ, Armstrong LE, Szlyk PC, Sils IV. Botsball (WGT) performance characteristics and their impact on the implementation of existing military hot weather doctrine. DTIC Document; 1986.
12. ISO E. 7730 Ergonomics of the thermal environment, Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria. 2005
13. Moran DS, Pandolf KB, Shapiro Y, Heled Y, Shani Y, Mathew WT, et al. An environmental stress index (ESI) as a substitute for the wet bulb globe temperature (WBGT). *J Therm Biol.* 2001;**26**(4-5):427–31. doi: 10.1016/s0306-4565(01)00055-9.
14. Moran DS, Epstein Y. Evaluation of the Environmental Stress Index (ESI) for Hot/Dry and Hot/Wet Climates. *Industrial Health.* 2006;**44**(3):399–403. doi: 10.2486/indhealth.44.399.
15. Yaglou CP. Temperature, humidity, and air movement in industries: the effective temperature index. *J Industrial Hygiene.* 1927;**9**:297–309.
16. Bedford T. The Warmth Factor in Comfort at Work. A Physiological Study of Heating and Ventilation. *Industrial Health Research Board Report. Medical Research Council.* 1936(76).
17. Moran DS, Pandolf KB, Shapiro Y, Frank A, Heled Y, Shani Y, et al. The role of global radiation measured by a light sensor on heat stress assessment. *J Therm Biol.* 2001;**26**(4-5):433–6. doi: 10.1016/s0306-4565(01)00056-0.
18. Moran DS, Pandolf KB, Heled Y, Gonzalez RR. Evaluation of the environmental stress index (ESI) for different terrestrial elevations

- below and above sea level. *J Therm Biol.* 2004;**29**(6):291-7. doi: [10.1016/j.jtherbio.2004.05.007](https://doi.org/10.1016/j.jtherbio.2004.05.007).
19. Moran DS, Pandolf KB, Vitalis A, Heled Y, Parker R, Gonzalez RR. Evaluation of the environmental stress index (ESI) for the southern hemisphere. *J thermal biol.* 2004;**29**:535-8.
 20. Bhanarkar AD, Srivastava A, Joseph AE, Kumar R. Air pollution and heat exposure study in the workplace in a glass manufacturing unit in India. *Environ Monit Assess.* 2005;**109**(1-3):73-80. doi: [10.1007/s10661-005-5839-3](https://doi.org/10.1007/s10661-005-5839-3). [PubMed: [16240190](https://pubmed.ncbi.nlm.nih.gov/16240190/)].
 21. Dehghan H, Habibi E, Habibi P, Maracy MR. Validation of a questionnaire for heat strain evaluation in women workers. *Int J Prev Med.* 2013;**4**(6):631-40. [PubMed: [23930180](https://pubmed.ncbi.nlm.nih.gov/23930180/)].
 22. Habibi P, Dehghan H, Rezaei S, Maghsoudi K. Thermal, physiological strain index and perceptual responses in Iranian Muslim women under Thermal Condition in order to Guide in Prevention of Heat Stress. *Iran J Health, Safety Enviro.* 2014;**1**(4):172-6.