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A new environmental heat stress index for indoor hot and humid environments based on Cox regression

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ABSTRACT

Physical work in hot and humid environments imposes health risks, productivity falling and safety problems on workers. Protection of workers from heat related problems requires quantitative heat stress assessment of the workplace. In this paper, a new index-equivalent temperature (ET) is proposed to measure the environmental heat stress in indoor hot and humid environments. A climate chamber was built to simulate the indoor hot and humid environment. And the safe working time of 144 male volunteers were studied under different climatic conditions in the chamber. Cox regression method is adopted to obtain the impacts of variables on the safe working time. Then the new index-ET is proposed based on the Cox regression results. The correlations between the ET and the common used indexes are determined to test the validity of this new index. Finally the safe working time concerned with the ET is summarized. The results show that the new index gives physiological correlates and physical means. The ET developed in this paper has the potential to be a practical index to measure the environmental heat stress in indoor hot and humid environments.

1. Introduction

According to the relationship between environment temperature and human thermal balance, living environments above 35 °C or working environments above 32 °C can be considered as hot environments, and environments with relative humidity above 70% can be considered as humid environments [1]. Hot and humid environments are prevalent in iron, steel, glass and ceramic units, rubber foundries, boiler room, coke ovens, mines and some military and special facilities. Physical work in a hot and humid environment imposes considerable physical strain on the workers, with significant associated health risks (heat rash, heat cramps, heat syncope, heat exhaustion and heat stroke), productivity falling and certain safety problems [2]. Protection of workers in hot environments requires a means of quantitative heat stress assessment of the workplace. A number of indexes have been constructed to measure the degree of heat stress imposed on an individual. These heat stress indexes may be categorized into three groups: rational, empirical, and direct [3].

Rational indexes integrate environmental and behavioral variables and are based on calculations involving the heat balance equation. Examples of the rational indexes include predicted 4 h sweat rate [4], operative temperature [5], skin wettedness [6] and the heat stress index [7,8].

Empirical indexes are constructed based on objective and subjective strain [9] and may incorporate physiological and perceptual responses to increased heat stress [3]. Examples of empirical indexes include the cumulative heat strain index (CHSI) [10], the perceptual strain index (PeSI) [11] and the physiological strain index (PhSI) [12,13].

Direct indexes are constructed based on environmental variables. They are either directly environmental variables or empirical variables. Examples of such indexes are the dry bulb temperature, the wet bulb temperature, the temperature-humidity index (THI) [14], the effective temperature [15], the Oxford Index [16], the wet bulb globe temperature (WBGT) [17] and the environmental stress index (ESI) [18].

Among these three groups, the rational indexes and empirical indexes are sophisticated. For they require continuous or regular measurement of the physiological variables, their practicality in daily use and application in the workplace is questionable.

The ideal heat stress index is one that is simple to determine, is reliable and unambiguous in its output, and does not require specialist knowledge for its interpretation [19]. The direct indexes only deal with the measurement of basic environmental variables, therefore they are simple and easy to use. Thus, many health and safety standards associated with the environmental heat stress use a direct approach. Among the direct indexes, the WBGT is now the

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most widely used heat stress index throughout the world [20,21]. However, the coefficients in the index were determined empirically and have no physiological correlates and physical means [22].

Hot and humid environments can be classified into: indoor hot and humid environments and outdoor hot and humid environments. This paper aims to develop a new environmental heat stress index with physiological correlates and physical means. It also aims to determine whether this new index can serve as a reliable and valid alternative for measuring environmental heat stress in indoor hot and humid environments.

2. Materials and methods

2.1. Survival analysis

Survival analysis is a class of statistical methods for analyzing the occurrence and timing of events, such as death, child-bearing, discharge, criminal recidivism, divorce, unemployment, symptom onset, and task completion.

Survival analysis takes the survival time of a group of subjects. Survival time is usually defined as the time from a particular starting time ("start" events) to a particular endpoint of interest ("end events"). The "start" events and the "end" events can be determined based on the study objective and the professional knowledge.

In survival analysis, the survival time is always non-negative and may contain complete data or censored data. Complete data, also known as uncensored data, is the time until the event of interest occurs [23]. Censored data is the time at which the observation of the failure event is terminated. It arises due to client attrition or study cut-off dates.

For the experiment is conducted within the experiment duration, the safe working time of the worker may be larger than the experiment duration, and they may be cut-off by the experiment duration. Therefore the safe working time may be censored data, and it can be regarded as the survival time. Consequently, the survival analysis method can be applied to study the safe working time in indoor hot and humid environments.

2.2. Cox regression

Cox regression method, developed by Cox [24], is the most widely used method of survival analysis [25]. It has been very popular in the analysis of survival data in medicine [26–30] and is becoming increasingly popular in the other fields [31–34]. Based on a modeling approach to the analysis of survival data, Cox regression method aims to simultaneously explore the effects of several variables on survival. And it has become the most used procedure for modeling the relationship of covariates to a survival or other censored outcome [35,36].

Interpreting the Cox regression method involves examining the coefficients for each variable. When the regression coefficient is positive, it means that the corresponding variable is a hazard factor, and the larger the coefficient is, the shorter the survival time is. When the regression coefficient is negative, it means that the variable is a protective factor, and the larger it is, the longer the survival time is. Moreover, the larger the absolute value of the regression coefficient is, the more significant the effect of the covariate is.

2.3. Experiment

2.3.1. Chamber

A chamber with 3 m × 2.5 m × 2.2 m (length × width × height) was built to simulate the indoor hot and humid environments. There were four working locations (WL) for subjects to perform prescriptive tasks. The heat source was provided by two heat pump unit air conditioners and a reserve electric heater. The humidity source was provided by an electrode steam humidifier fixed in the air supply system. The envelopes of the chamber were insulated by thermal insulation materials. The heat and humidity source equipments were laid outside the chamber. To record the temperature and humidity in the chamber, the temperature and humidity data loggers were installed. In addition, a WBGT measuring instrument was used to directly measure wet bulb temperature, globe temperature, air temperature and WBGT respectively. And in order to maintain the actual temperature and humidity in a stable condition, the electric heater and the electrode steam humidifier can be regulated. Therefore, the hot and humid environment with different combination of temperature and humidity can be simulated.

Table 1
Parameters and instruments.

Parameter type	Parameter name	Measuring instrument	Model	Range
Environmental parameters	Dry bulb temperature, wet bulb temperature, relative humidity	Temperature and humidity data loggers		
	Airflow velocity	Anemometer		
	WBGT	WBGT index meter	2000	20–120 °C
Physiological indexes	Oral temperature, body temperature	Thermometer		35–42 °C
	Body weight	Electronic body scale	TSC150	0–150 kg
	Heart rate	Blood pressure monitor	HEM-632	40-180Beats/minute
	Blood pressure	Blood pressure monitor	HEM-632	0–280 mmHg
	Mean skin temperature	Infrared thermometer	ST80	−30–760 °C

2.3.2. Subjects

One hundred and forty four male university students were chosen as subjects with two main principles: voluntary participation and no disease history. The subjects with rapid heart rate and high blood pressure were not allowed to participate in the experiments.

Most of the subjects came from North China. Their height, body mass and surface area were 171 ± 6 cm, and 66.2 ± 4.8 kg, 1.67 ± 0.12 m^2, respectively. All subjects were dressed in long-sleeved cotton shirts, long trousers, socks and shoes. The clothing

Table 2
The experiment conditions and their corresponding subject numbers.

Temperature (°C)		Relative humidity (%)		Number of subjects		
Design	Actual[a]	Design	Actual	Heavy work	Moderate work	Light work
30	30.3 ± 0.7	40	40.2 ± 0.6	1	2	1
30	30.7 ± 0.4	60	60.4 ± 0.5	1	2	1
30	30.4 ± 0.6	80	80.4 ± 0.3	1	2	1
34	34.1 ± 0.6	40	40.0 ± 1.0	3	6	3
34	34.2 ± 0.5	60	60.2 ± 0.6	3	6	3
34	34.0 ± 0.6	80	80.2 ± 0.5	3	6	3
36	36.1 ± 0.5	40	38.5 ± 3.5	3	6	3
36	36.0 ± 0.6	60	60.1 ± 0.5	3	6	3
36	36.1 ± 0.3	80	79.9 ± 0.7	3	6	3
38	38.1 ± 0.5	40	40.2 ± 0.6	3	6	3
38	38.3 ± 0.5	60	59.9 ± 0.4	3	6	3
38	38.2 ± 0.4	80	79.6 ± 0.4	3	6	3
40	40.2 ± 0.6	40	39.9 ± 0.6	2	4	2
40	40.0 ± 0.5	60	60.2 ± 0.5	2	4	2
40	40.6 ± 0.2	80	79.4 ± 0.6	2	4	2

[a] The actual condition is expressed in Mean ± Standard Deviation (M ± SD).