Journal of Thermal Biology xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Journal of Thermal Biology

journal homepage: www.elsevier.com/locate/jtherbio

Heat balance model for a human body in the form of wet bulb globe temperature indices

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ARTICLE INFO

Keywords:
Heat stress
Clothing
Thermal environment
Solar radiation
Wet bulb globe temperature
Adjustment factor

ABSTRACT

The purpose of this study is to expand the empirically derived wet bulb globe temperature (WBGT) index to a rational thermal index based on the heat balance for a human body. We derive the heat balance model in the same form as the WBGT for a human engaged in moderate intensity work with a metabolic heat production of 174 W/m^2 while wearing typical vapor-permeable clothing under shady and sunny conditions. Two important relationships are revealed based on this derivation: (1) the natural wet bulb and black globe temperature coefficients in the WBGT coincide with the heat balance equation for a human body with a fixed skin wettedness of approximately 0.45 at a fixed skin temperature; and (2) the WBGT can be interpreted as the environmental potential to increase skin temperature rather than the heat storage rate of a human body. We propose an adjustment factor calculation method that supports the application of WBGT for humans dressed in various clothing types and working under various air velocity conditions. Concurrently, we note difficulties in adjusting the WBGT by using a single factor for humans wearing vapor-impermeable protective clothing. The WBGT for shady conditions does not need adjustment depending on the positive radiant field (i.e., when a radiant heat source exists), whereas that for the sunny condition requires adjustments because it underestimates heat stress, which may result in insufficient human protection measures.

1. Introduction

The wet bulb globe temperature (WBGT) is widely used as a measure for evaluating heat disorder risk. The WBGT was originally proposed as a simplified index of the effective temperature (Houghton and Yagloglou, 1923) to prevent heat disorders (Yaglou and Minard, 1957), and has since been adopted in standards defined by the National Institute for Occupational Safety and Health (NIOSH, 2016) and the International Organization for Standardization (ISO, 1989a) and in threshold limit values (TLVs) defined by the American Conference of Governmental Industrial Hygienists (ACGIH, 2015). The WBGT inside of buildings or outside of buildings when there is no solar load (*shady*) is determined as the weighted average of the natural wet bulb temperature, T_w, and the black globe temperature, T_g. Meanwhile, the WBGT outside of buildings when there is solar load (*sunny*) is determined as the weighted average of T_w, T_g, and the air temperature, T_a. The shady and sunny formulations for the WBGT are respectively

$$\mathrm{WBGT} = 0.7\ T_w + 0.3\ T_g \quad (1)$$

and

$$\mathrm{WBGT} = 0.7\ T_w + 0.2\ T_g + 0.1\ T_a. \quad (2)$$

The simplicity of these WBGT calculations encourages risk screening in the workplace. The WBGT has been widely used to express heat stress (Chan et al., 2016; Danks et al., 2016; Gonzalez et al., 2010; Holm et al., 2016; Li et al., 2016; Moura et al., 2016; Wang et al., 2016); hence, the thermo-physiological meaning of the WBGT must be clarified, and its characteristics must be considered. Two measurement approaches exist for the natural wet bulb temperature, T_w: (1) a sensor is placed in the shade to prevent any solar influence (NIOSH, 2016), or (2) a sensor is placed in the sun (ASHRAE, 2013). This study assumes the latter approach given that the existence of radiation is what distinguishes the natural wet bulb temperature from the psychrometric wet bulb temperature.

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http://dx.doi.org/10.1016/j.jtherbio.2017.10.002
Received 18 October 2017; Accepted 19 October 2017

The WBGT was developed from the empirically derived effective temperature for preventing heat disorder. Therefore, it is regarded as an empirically derived thermal index. As an empirically derived thermal index, it must be accurate across all conditions on which the index was based. The application of an empirically derived thermal index outside of the conditions on which it was based requires additional rationale. The thermal indices based on both experimental results and the heat balance equation for the human body offer some rationale for wider application. The NIOSH (2016); ISO (1989a), and ACGIH (2015) defined human heat stress limits based on the WBGT for conventional single-layer clothing, clothing with a thermal insulation of 0.6 clo, and lightweight work clothes, respectively, based on singular clothing types. Bernard et al. (2008) and Bernard and Ashley (2009) defined different heat stress limits based on the clothing type because human heat stress varies by clothing type. Two approaches for adjusting the WBGT were defined to accommodate the potential variety of clothing types. The first approach, which was recommended by the NIOSH (2016), the ISO (1989a); Ramsey (1978), and Kenney (1987), adjusts the heat stress limit based on the clothing type:

$$Limit.s = Limit – AF_0, \tag{3}$$

where *Limit.s* is the heat stress limit based on a specified clothing type [°C]; *Limit* is the heat stress limit for the evaluated condition [°C]; and AF_0 is the adjustment factor for the heat stress limit [°C].

The second approach, which was recommended by the ACGIH (2009, 2015), Bernard et al. (2005, 2008), and Bernard and Ashley (2009), converts the measured WBGT for the evaluated condition to an *effective* WBGT ($WBGT_{eff}$) based on the heat stress limit for a specified clothing type. In Eq. (3), the human heat stress for the WBGT of *Limit* for the evaluated condition must be the same as the heat stress based on the specified clothing type of *Limit.s* if conditions are consistent. Because *Limit* applies to the WBGT for the evaluated condition and *Limit.s* applies to $WBGT_{eff}$, both *Limit* and *Limit.s* express the same heat stress for the occupants respective to WBGT and $WBGT_{eff}$; therefore, an equation relating WBGT to $WBGT_{eff}$ can be obtained by substituting them for *Limit* and *Limit.s*, respectively, in Eq. (3). By combining Eqs. (1)–(3), given the above substitutions, $WBGT_{eff}$ for shady and sunny conditions can be respectively formulated as

$$WBGT_{eff} = 0.7\,T_w + 0.3\,T_g + AF_1 \tag{4}$$

and

$$WBGT_{eff} = 0.7\,T_w + 0.2T_g + 0.1T_a + AF_1, \tag{5}$$

provided that $AF_1 = -AF_0$, where AF_1 is the adjustment factor for the heat stress conversion [°C]. The $WBGT_{eff}$ can therefore be calculated using these formulations by simply adding AF_1 to the WBGT. It is worth noting that the $WBGT_{eff}$ formulation used by the ACGIH (2009, 2015), Bernard et al. (2005, 2008), and Bernard and Ashley (2009) considers an adjustment factor, AF_1, that differs from AF_0 in Eq. (3).

Most of the adjustment factors used in Eqs. (3)–(5) were empirically derived. We can consider the WBGT and its adjustment factors from a rational heat balance approach given that the heat between a human body and its surrounding environment must remain balanced. In our prior studies considering the WBGT (Mochida and Sakoi, 2010; Mochida et al., 2007, 2006; Sakoi and Mochida, 2015, 2009; Sakoi et al., 2010), we expressed a heat balance equation for the human body using the natural or psychrometric wet bulb, black globe, and air temperatures to clarify the WBGT from a thermo-physiological perspective. We expand upon this work in the present study.

In this study, we consider a representative occupational environment in which humans engage in moderate intensity work. Building on our previous studies, we derive the heat balance models for the human body in the same form as Eqs. (4) or (5) with $AF_1 = 0$ for *the standard WBGT condition*—vapor-permeable clothing with a thermal insulation of 0.6 clo. We then consider the meaning of WBGT from the viewpoint of the rational heat balance approach and propose an adjustment factor calculation method for the WBGT based on this derivation.

2. Methods

2.1. Heat balance equation for a human body in shady conditions

The following equations are used to obtain the heat balance for a human body in the same form as Eq. (4) under the shady conditions. Specifically, Eq. (6) describes the heat balance for a human body; Eq. (7) defines the operative temperature, T_o; Eq. (8) describes the heat balance for a natural wet bulb thermometer; Eq. (9) describes the heat balance for a black globe thermometer:

$$M - S = (h_c + h_r)f_{cl}F_{cl}(T_{sk} - T_o) + LRh_cF_{pcl}f_{cl}(P_{sk}{}^* - P_a)w + 0.0014M(35 - T_a) + 0.0173M(5.624 - P_a) + W\ , \tag{6}$$

$$T_o = \frac{h_cT_a + h_rT_r}{h_c + h_r}, \tag{7}$$

$$h_c{}'(T_w - T_a) + h_r{}'(T_w - T_r) + LRh_c{}'(P_w{}^* - P_a) = 0, \tag{8}$$

$$h_c{}''(T_g - T_a) + h_r{}''(T_g - T_r) = 0, \tag{9}$$

where M, S, and W are the metabolic rate, heat storage rate, and external work, respectively [W/m^2]; f_{cl} is the clothing area factor [nondimensional (ND)]; F_{cl} and F_{pcl} are the clothing heat transfer and clothing vapor transfer coefficients [ND], respectively; h_c, $h_c{}'$, and $h_c{}''$ are the convective heat transfer coefficients [W/(m^2 °C)] for the human body, natural wet bulb thermometer, and black globe thermometer, respectively; h_r, $h_r{}'$, and $h_r{}''$ are the linear radiative heat transfer coefficients [W/(m^2 °C)] for the human body, natural wet bulb thermometer, and black globe thermometer, respectively; LR is the Lewis ratio [°C/kPa]; P_a is the environmental vapor pressure [kPa]; $P_{sk}{}^*$ and $P_w{}^*$ are the saturated vapor pressures [kPa] at T_{sk} or T_w, respectively; T_o, T_r, and T_{sk} are the operative, mean radiant (without solar influences), and skin temperatures [°C], respectively; and w is the skin wettedness [ND]. We assume that w reaches a fixed value, i.e., the practical upper limit for sustained activity, because the WBGT serves as a risk-screening index against heat disorder.

In Eq. (6), the expressions for convective and evaporative heat exchange accompanied by respiration are adopted from the general heat balance equation for the human body for a moderate thermal environment (ASHRAE, 2013). However, unlike the general expressions for a moderate thermal environment, the adopted expressions utilized the temperature and vapor pressure of exhaled air to determine the required sweat index for a hot environment (ISO, 1989b). Although Eq. (6) differs from the general heat balance equation in the aforementioned aspect, because Eq. (6) expresses the evaporative heat exchanges using the difference of vapor pressure, we refer to Eq. (6) as the *standard-form* heat balance equation for a human body to distinguish it from the transformed heat balance equations for the human body that appear later.

We assume that T_a, T_r, and P_a are the same for the human body, natural wet bulb thermometer, and black globe thermometer. We approximate $P_{sk}{}^*$ and $P_w{}^*$ using the following linear equations, respectively, given the relatively narrow ranges of T_{sk} and T_w for evaluating the heat disorder risk:

$$P_{sk}{}^* \approx \kappa T_{sk} + \zeta = 0.312T_{sk} - 5.27, \tag{10}$$

$$P_w{}^* \approx \kappa' T_w + \zeta' = 0.222T_w - 2.37. \tag{11}$$

It is worth noting that the relative error for $P_{sk}{}^*$ with T_{sk} in the range 33–37 °C is < 0.5%. Similarly, the relative error for $P_w{}^*$ with T_w in the range 23–33 °C is < 3%.

The air temperature, T_a, can be expressed from Eq. (9) as

$$T_a = T_g + \Delta T, \tag{12}$$