



WBGT Index Revisited After 60 Years of Use

Francesca R. d'Ambrosio Alfano¹, Jacques Malchaire²,
Boris Igor Palella^{3*} and Giuseppe Riccio³

1.Dipartimento di Ingegneria Industriale, Università di Salerno, Via Giovanni Paolo II 132, 84084 Fisciano (Salerno), Italy

2.Unité Hygiène et Physiologie du Travail, Université Catholique de Louvain, 75 Rue Rosier Bois, 1331 Rosières, Belgique

3.Dipartimento di Ingegneria Industriale, Università degli Studi di Napoli Federico II,

P.le Vincenzo Tecchio 80, 80125 Naples, Italy

*Author to whom correspondence should be addressed. Tel: +390817682618; fax: +390812390364; e-mail: palella@unina.it

Submitted 1 January 2014; revised 3 May 2014; revised version accepted 13 June 2014.

ABSTRACT

The Wet Bulb Globe Temperature (WBGT) seems to be still used world widely for the evaluation of heat stress conditions and it is recommended by ISO and American Conference of Governmental Industrial Hygienists as a screening method. Unfortunately, many occupational health practitioners and users appear to be unaware of its limitations. As the ISO 7243 Standard, based on WBGT, is presently under revision, it is an appropriate time to review the validity and applicability of this empirical approach to evaluate heat stress. This article underlines the main issues about the WBGT index from a rational perspective.

KEYWORDS: clothing adjustment factors; globe temperature; heat stress; physical agents risk assessment; WBGT

INTRODUCTION

The research of an index for the assessment of the heat stress in workplaces is still a much debated topic as confirmed by the impressive number of studies and indices that appeared in the literature of the last 50 years (Lee, 1980; Parsons *et al.*, 1995; Bethea and Parsons, 2002; d'Ambrosio Alfano *et al.*, 2011). Nowadays however, two methods apparently are approved internationally: the WBGT index (ISO, 1989) and the Predicted Heat Strain (PHS) model (ISO, 2004a).

The Predicted Heat Strain model was developed during the 90s by a team of European researchers (Malchaire *et al.*, 2000; d'Ambrosio Alfano *et al.*, 2004) and is the evolution of the Heat Stress Index by Belding and Hatch in 1955 (Kerslake, 1972), the Index of Thermal stress by Givoni (1964) and the required sweat rate by Vogt *et al.* (1981).

As the ISO 7243 standard is presently under revision, it is an appropriate time to review the validity and applicability of this approach to deal with heat stress. The origin of the Wet Bulb Globe Temperature (WBGT) index is usually traced to 1957. Based on an investigation to control heat illnesses in training camps of the US Army and Marine Corps, Yaglou and Minard (1957) introduced the WBGT index, accepted by ISO (1989) and American Conference of Governmental Industrial Hygienists (ACGIH, 2011) as a preliminary tool for the assessment of hot thermal environments. This empirical index combines the measurement of two derived quantities, the natural wet bulb temperature and the globe temperature together with the air temperature and claims therefore to take into account the main heat transfer phenomena (evaporation,

convection, and radiation) affecting the thermal sensation and strain. The index is calculated as follows:

without solar radiation:

$$\text{WBGT} = 0.7t_{\text{nw}} + 0.3t_{\text{g}} \quad (1)$$

in case of solar radiation:

$$\text{WBGT} = 0.7t_{\text{nw}} + 0.2t_{\text{g}} + 0.1t_{\text{a}} \quad (2)$$

where:

- t_{a} air temperature, °C;
- t_{g} black globe temperature measured by a globe 15 cm in diameter, °C; and
- t_{nw} natural wet bulb temperature, °C.

As stated by Budd (2008), ‘its origin, and its limitations are apparently being forgotten’. Budd (2008) recently attempted to recount the history of its evolution and underlined some of its limitations: particularly the fact that it does not reflect adequately the heat strain in case of high humidity and low air movements. Two documents can presently be considered to be the references of the WBGT index as it is now: the threshold limit value document of the ACGIH (2011) and the ISO standard 7243 (ISO, 1989).

Both ISO and ACGIH recommend considering the WBGT index as a screening tool, while the PHS approach must be used to investigate more severe working conditions in the heat. ISO standard 15265 (ISO, 2004b) describes a procedure for this purpose. Despite the recommendations by ISO and ACGIH, many occupational health (OH) practitioners and users still use only the WBGT index whatever the severity of the thermal environment and appear to regard it as an infallible measure of heat stress (Budd, 2008) for all people in the world, without questioning

the accuracy of the measurements, the corrections for clothing conditions, the relevancy of the limits, and what is the real physiological criterion at the base of the recommended work–recovery regimen.

ORDER OF MAGNITUDE OF THE WBGT

As the WBGT is calculated from temperatures, it is logical that it be called a temperature and given units of degree Celsius. Experience shows however that, due to this, the WBGT values are often confused with air temperatures and misinterpreted by workers and managers. Moreover, the WBGT is not an index of ‘perceived temperature’, as the effective temperature and other indices are, in the sense that those intend to represent the level of strain felt by the person in a given climatic environment (d’Ambrosio Alfano *et al.*, 2011; Jendritzky *et al.*, 2012).

Table 1 gives the WBGT values corresponding to a few combinations of the primary parameters. Our experience in the field is that everyone would consider conditions C3 and C4 to be very hot as temperatures of 40°C or more are reached. However, the WBGT values remain numerically quite low (‘only’ 30.8 and 34.1), and many workers and employers and even some OH practitioners tend to be influenced in their judgment by this numerical value and appreciate a WBGT value as if it was an air temperature: C3 and C4 are then considered not that hot.

The fact that the WBGT values are rather small numbers leads some users to accept the idea that, under these conditions, it can be envisaged to recover in the same environment: this will be discussed further in the last section.

In order to avoid such a confusion and misinterpretation, it would be preferable to consider the WBGT, not as a temperature, but as dimensionless index.

Table 1. Typical WBGT values under hot stress conditions

| Condition | Air temperature t_{a} (°C) | Globe temperature t_{g} (°C) | Air velocity v_{a} (m s ⁻¹) | Relative humidity RH (%) | Partial vapor pressure p_{a} (kPa) | Natural wet bulb temperature t_{nw} (°C) | WBGT |
|-----------|-------------------------------------|---------------------------------------|--|--------------------------|---|---|------|
| C1 | 30 | 30 | 0.5 | 35 | 1.5 | 19.4 | 22.6 |
| C2 | 35 | 35 | 0.5 | 35 | 2.0 | 23.1 | 26.7 |
| C3 | 40 | 40 | 0.5 | 34 | 2.5 | 26.6 | 30.6 |
| C4 | 45 | 45 | 0.5 | 31 | 3.0 | 29.5 | 34.1 |

ACCURACY OF THE DIRECT MEASUREMENT OF WBGT

ISO 7243 (1989) and ACGIH (2011) make reference to specific requirements (Table 2) for the globe and the natural wet bulb thermometers to be used for the measurement of the WBGT index.

It adds that ‘Any device for measuring the natural wet bulb temperature or the globe temperature which, after calibration in the specified measuring ranges provides results to the same degree of accuracy may also be used’.

As concluded by several authors, the use of non-standard instrumentations (Budd, 2008; Juang and Lin, 2007) or unsatisfactory calibration procedures (d’Ambrosio Alfano *et al.*, 2007, 2013; Dell’Isola *et al.*, 2012) can strongly affect its accuracy with unpredictable consequences.

Natural wet bulb temperature

The thermodynamic wet bulb temperature (ASHRAE, 2013) is the temperature a volume of air would have if cooled adiabatically to saturation by evaporation of water into it, all latent heat being supplied by the volume of air. The quantity defined that way is independent of measurement technique but is very hard to be measured due to the peculiarities of the adiabatic saturation process (ASHRAE,

2013). Fortunately, only small corrections have to be applied to a common thermometer whose bulb is wrapped in cloth—called a sock—provided that (i) the sock is kept wet with distilled water; (ii) it is shielded from radiant heat exchange from its surroundings; (iii) air flows past the sock quickly enough to prevent evaporated moisture from affecting evaporation from the sock; (iv) the water supplied to the sock is at the same temperature as the thermodynamic wet bulb temperature of the air. If these requirements are met by a wet bulb thermometer, the measured value is called the psychrometric wet bulb temperature.

Obviously, as the natural wet bulb thermometer does not fulfill these criteria, t_{nw} depends on both radiative and convective heat flows around the sensor (Romero-Blanco, 1971; Malchaire, 1976; Buonanno *et al.*, 2001; Gaspar and Quintela, 2009). This was initially presented by the developers of the WBGT as an advantage as, therefore, WBGT ‘integrates’ the four basic parameters of the thermal environment (air temperature, humidity, and velocity and radiation). The separate measurement of air velocity (considered to be difficult and costly) is not needed, and the index is simple to use.

Unfortunately, since the conditions of the adiabatic cooling are not met, the measured value is also

Table 2. Main requirements for globe and natural wet bulb thermometers for the evaluation of the WBGT index (ISO, 1989 and ACGIH, 2011)

| | Globe | | Natural wet bulb thermometer | |
|----------------------|-----------------------------------|----------------|------------------------------|----------------|
| | ISO | ACGIH | ISO | ACGIH |
| Shape | Sphere | Sphere | Cylinder | — |
| Diameter | 150 mm | 150 mm | 6 ± 1 mm | — |
| Thickness | As thin as possible | — | — | — |
| Measurement range | 20–120°C | –5 to 100°C | 5–40°C | –1.1 to 48.9°C |
| Accuracy | 20–50°C: ±0.5°C 50–120°C: ±1°C | ± 0.5°C | ±0.5°C | ± 0.5°C |
| Mean emissivity | 0.95 | — | 1.0 | — |
| Length of the sensor | — | — | 30 ± 5 mm | 30 ± 5 mm |
| Response time | As short as possible ^a | 25 min minimum | — | — |

^aAccording to ISO 7726 (1998).

influenced by such odd factors as the length, thickness, capillarity, and tightness of the sock. Strangely, while the economy of an anemometer was presented as an advantage, many expensive instruments were developed to measure the three parameters and calculate the WBGT. Although their transducers vary drastically in shape and size and that some cannot simply be calibrated, they all claim to meet the ISO 7243 requirements. To the knowledge of the authors, no study has compared these instruments, and it is taken for granted by the users that these instruments give 'reliable' results.

Globe temperature

As stressed by several authors (Graves, 1974; Humphreys, 1977; McIntyre, 1980; Budd, 2008), using a globe thermometer with a smaller diameter (usually a 38-mm tennis ball) results in shorter response time (only few minutes instead of about 30 min in case of globes 15 cm in diameter) and allows more continuous monitoring of the environment.

It is, however, well known that the convective heat transfer around a small globe and therefore the globe

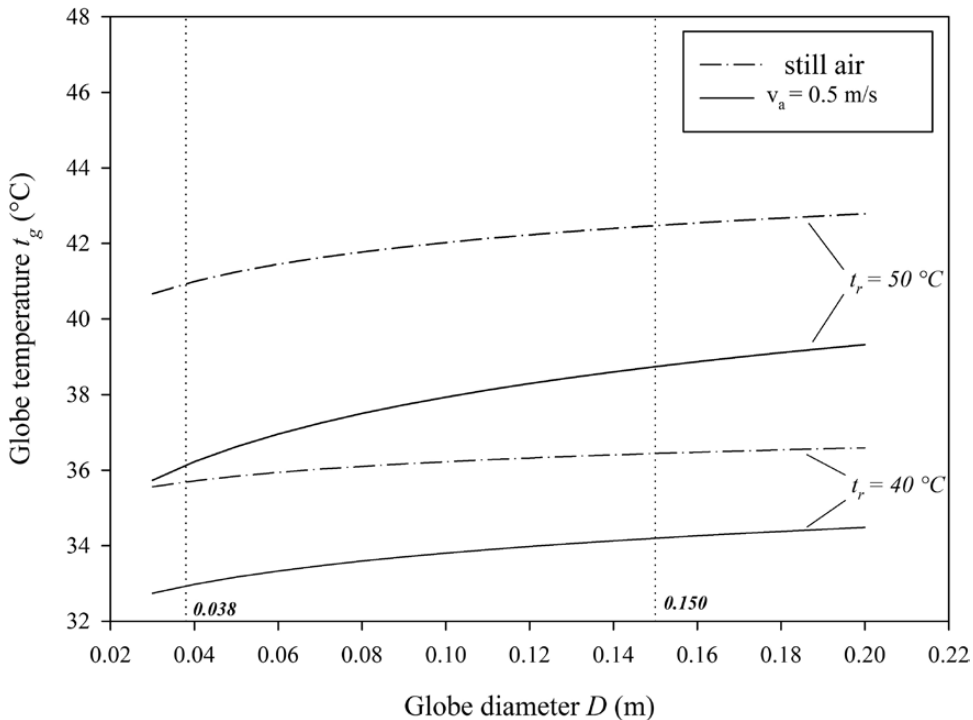
temperature vary as a function of the diameter as shown in Fig. 1.

In particular, according to Fig. 1, under free (forced) convection conditions, for $t_a = 30^\circ\text{C}$ and $t_r = 50^\circ\text{C}$, using a 38-mm tennis ball instead of a standard 150-mm globe results in calculated globe temperature values of 41°C (36.2°C) and 42.5°C (38.9°C), respectively.

According to equation (1), such differences lead to underestimations of the WBGT index by 0.5-1.0 units, depending upon the air velocity. Although small, this difference can result in a meaningful underestimation of the thermal strain.

The possibility to correct the measurement made by unconventional globes has been also investigated in the past. In particular, by linearizing the heat balance equation on the globe, Graves (1974) and McIntyre (1980) proposed a correction of t_g value based on the definition of the mean radiant temperature t_r (ISO, 1998) according to the following equation:

$$t_g = (1-g) t_a + g t_r \quad (3)$$



1 Examples of the variations of predicted globe temperature as a function of the diameter of the globe under natural and forced conditions.

with:

g , radiant response ratio (dimensionless) given by:

$$g = \frac{h_r}{h_c + h_r} \quad (4a)$$

By substituting in equation (4a), a typical value for $h_r = 5 \text{ W m}^{-2} \text{ K}$ (McIntyre, 1980) and well-known empirical correlations for the heat transfer coefficient by forced convection around a sphere (ISO, 1989, 1998) radiant response ratio can be calculated as:

$$g = \frac{1}{1 + 1.13 v_a^{0.6} D^{-0.4}} \quad (4b)$$

Finally, by applying equations (3) and (4b) in the same environment (e.g. with the same value of t_r , v_a , and t_a) to a standard 15-cm globe and a globe with the same emissivity but with different diameter D , we will obtain:

$$\frac{t_{g,15} - t_a}{t_{g,D} - t_a} = \frac{1 + 1.13 v_a^{0.6} D^{-0.4}}{1 + 2.41 v_a^{0.6}} \quad (5a)$$

Hence:

$$t_{g,15} = t_a + \frac{1 + 1.13 v_a^{0.6} D^{-0.4}}{1 + 2.41 v_a^{0.6}} (t_{g,D} - t_a) \quad (5b)$$

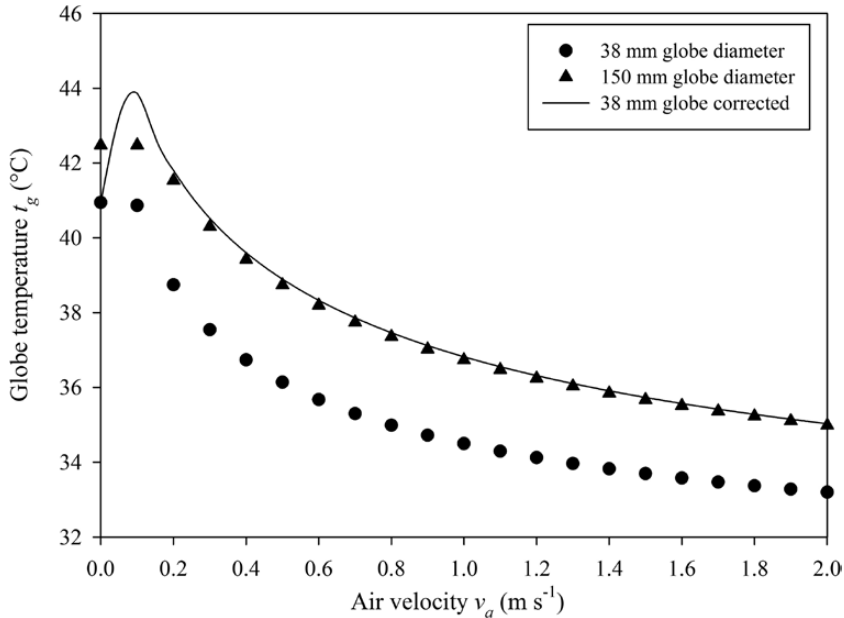
with:

- $t_{g,15}$ predicted globe temperature value of a 15-cm globe, °C;
- $t_{g,D}$ measured globe temperature of a unconventional globe, °C; and
- D diameter of the unconventional globe, m.

The correction is clearly a function of the air velocity and obviously an instrument that does not measure it (as all the WBGT meters on the market) cannot apply this correction.

Figure 2 compares the variations of the globe temperature as a function of air velocity in case of 150 mm and 38 mm (tennis ball) diameters with and without correction (condition: $t_a = 30^\circ\text{C}$, $t_r = 50^\circ\text{C}$). It shows that t_g values measured by a 38 mm and corrected by equation (3) are in perfect agreement with those given by a 150-mm globe under the same conditions only for v_a values $> 0.2 \text{ m s}^{-1}$. At lower air velocity, the corrected values differ in this case by $\sim 2^\circ\text{C}$.

In conclusion, the use of non-standard globes should be strongly discouraged in the presence of low air velocity values (e.g. under indoor conditions where this situation is very likely). On the contrary, in the presence of high velocity values (e.g. outdoor), non-standard globes provide reliable measurements if air velocity is known.



2 Variation of the globe temperature as a function of air velocity in case of 150 mm and 38 mm diameters ($t_a = 30^\circ\text{C}$, $t_r = 50^\circ\text{C}$).

In any case, it should be pointed that indoors in the presence of directional radiation (e.g. in metal or glass manufacturing units) and outdoors in the presence of direct solar radiation, mathematical models to take into account are different and can lead to inconsistent results as recent studies seem to highlight (Lemke and Kjellstrom, 2012; Tan *et al.*, 2013). This is particularly true for the egg-shaped globe presently available on the market.

INDIRECT MEASUREMENT OF WBGT

As many OH practitioners, industrialist, and biometeorologists are using the WBGT index worldwide, it appears necessary to eliminate at least the measuring errors in order to improve as much as possible its use. Contrary to what said by some author (Parsons, 2006), it is then relevant or meaningful to calculate the WBGT index from the four basic parameters t_a , t_r , v_a , and air humidity). This is also needed if the WBGT has to be estimated from meteorological measurements (Lemke and Kjellstrom, 2012; Bernard and Barrow, 2013) or to exploit the databases of environment assessments available in the literature (Mehnert *et al.*, 2000) where the four basic parameters rather than WBGT are given.

Although, from a practical perspective, the indirect assessment of the globe temperature from t_a , t_r , and v_a seems to be a well-consolidated topic, under indoor conditions at least (e.g. in the absence of solar radiation; Gaspar and Quintela, 2009; Lemke and Kjellstrom, 2012), the indirect assessment of the t_{nw} is a topic still under discussion. The reason is that t_{nw} is not a thermodynamic parameter (ASHRAE, 2013) but only a quantity measured by a specific sensor.

Two kinds of formulas were published and will be here briefly discussed:

1. equations based on the heat balance equation on the sensor (Malchaire, 1976; Sullivan and Gorton, 1976; Brake, 2001; Buonanno *et al.*, 2001; Gaspar and Quintela, 2009; d'Ambrosio Alfano *et al.*, 2012) and validated under specific experimental conditions.
2. empirical formulas based on the measurement of t_{nw} under controlled conditions (Romero-Blanco, 1971; Bernard and Cross, 1999).

Heat balance approach

From a theoretical perspective, the indirect assessment of the natural wet bulb temperature from the four basic parameters characterizing the thermal environment (t_a , t_r , v_a , RH, or p_a) can be carried out by means of a heat balance equation on the wet wick written under steady-state conditions. This leads to the following equation that has to be solved by means of an iterative procedure:

$$av_a^c(t_a - t_{nw}) + 10^{-8} \left[(t_r + 273)^4 - (t_{nw} + 273)^4 \right] - bv_a^d \left[p_{as}(t_{nw}) - RH \cdot p_{as}(t_a) \right] = 0 \quad (6)$$

where the first term represents the exchange by convection; the second by radiation; and the third by evaporation.

Coefficients in equation (6) can be obtained by fitting experimental data under controlled conditions (Malchaire, 1976) or using the most common equations for the calculation of heat and mass-transfer coefficients (Buonanno *et al.*, 2001; d'Ambrosio Alfano *et al.*, 2012; see Table 3).

These models provide quite reliable results: the uncertainty is of the order of magnitude of 1°C and, according to equation (1), the uncertainty on the WBGT value is of about the same order of magnitude. However, equation (6) can be used only under forced convection conditions as proved by d'Ambrosio Alfano *et al.* (2012) who showed that under natural convection up to three values satisfying equation (6) can be obtained.

The empirical approach

From Romero-Blanco's experiments carried out in a wind tunnel in the absence of solar radiation (1971), Bernard and Cross (1999) proposed the following algorithm for the calculation of t_{nw} :

$$t_{nw} = \begin{cases} t_a - \delta(t_a - t_w) & \text{if } t_g - t_a \leq 4^\circ\text{C} \\ t_w - 0.2 + 0.25(t_g - t_a) + \varepsilon & \text{if } t_g - t_a > 4^\circ\text{C} \end{cases} \quad \delta = \begin{cases} 0.85 & \text{if } v_a \leq 0.03 \text{ ms}^{-1} \\ 0.069 \log v_a + 0.96 & \text{if } 0.03 < v_a < 3 \text{ ms}^{-1} \\ 1 & \text{if } v_a \geq 3 \text{ ms}^{-1} \end{cases} \quad \varepsilon = \begin{cases} 1.3 & \text{if } v_a \leq 0.1 \text{ ms}^{-1} \\ \frac{0.1}{v_a^{1.1}} & \text{if } 0.1 < v_a < 1 \text{ ms}^{-1} \\ 0.1 & \text{if } v_a \geq 1 \text{ ms}^{-1} \end{cases} \quad (7)$$

Table 3. Ranges of application, maximum deviation from experimental data, and values of the coefficients in equation (6)

| Coefficient | Author | | | | Units |
|--|--|---|---|---|---|
| | Malchaire (1976) | Sullivan and Gorton (1976) | Buonanno <i>et al.</i> (2001) | Bernard and Cross (1999) | |
| a | 4.18 | 7.98 | 7.42 | Not applicable | (s m ⁻¹) ^c .K |
| b | 77.1 | 24.2 | 122 | | kPa ⁻¹ (s m ⁻¹) ^d .K |
| c | 0.444 | 0.466 | 0.466 | | — |
| d | 0.421 | 0.466 | 0.466 | | — |
| Ranges of physical quantities | $t_a = 18-30^\circ\text{C}$ $t_w = 15-25^\circ\text{C}$ $t_g = 18-66^\circ\text{C}$ $v_a = 0.15-3 \text{ m s}^{-1}$ | $t_a = 0-49^\circ\text{C}$ $w_a = 0-32 \text{ g kg}^{-1}$ $t_r = 21-65^\circ\text{C}$ $v_a = 0.25-10.2 \text{ m s}^{-1}$ | $t_a = 30-50^\circ\text{C}$ RH = 20–80% $t_r = 20-60^\circ\text{C}$ $v_a = 0.1-1.5 \text{ m s}^{-1}$ | $t_a = 26-48^\circ\text{C}$ $t_w = 18-29^\circ\text{C}$ $t_g = 32-64^\circ\text{C}$ $v_a = 0.05-3.10 \text{ m s}^{-1}$ | |
| Maximum deviation from experimental data | 1°C | 1.5°C | 1.7°C | Unavailable | |

Comparison of the two approaches

Figure 3 compares the estimations of t_{nw} using expression (Malchaire, 1976) and algorithm (Bernard and Cross, 1999), within their ranges of validation (summarized in Table 3). This analysis shows that the two methods give consistent results only under uniform conditions (mean radiant temperature near to air temperature); on the contrary, in the presence of high radiation, the differences vary from -3°C to $+1^\circ\text{C}$ as humidity increases. These differences cannot be neglected as they lead to a meaningful uncertainty of -2 to $+0.7$ units on the WBGT index.

To decide the best practice, a direct comparison with experimental data is obviously required. By analyzing data reported in Table 3, where the state of the art on the indirect assessment of t_{nw} is briefly summarized, it appears that all expressions based on the heat balance equation on the sensor provide a mean deviation of $\sim 1^\circ\text{C}$, whereas no information about the accuracy exhibited by equation (7) are available. This occurrence strongly reduces the possibility to use Bernard and Cross equation especially because, as recently reviewed by Lemke and Kjellstrom (2012) who compared different models for the indirect evaluation of WBGT from meteorological data, equation

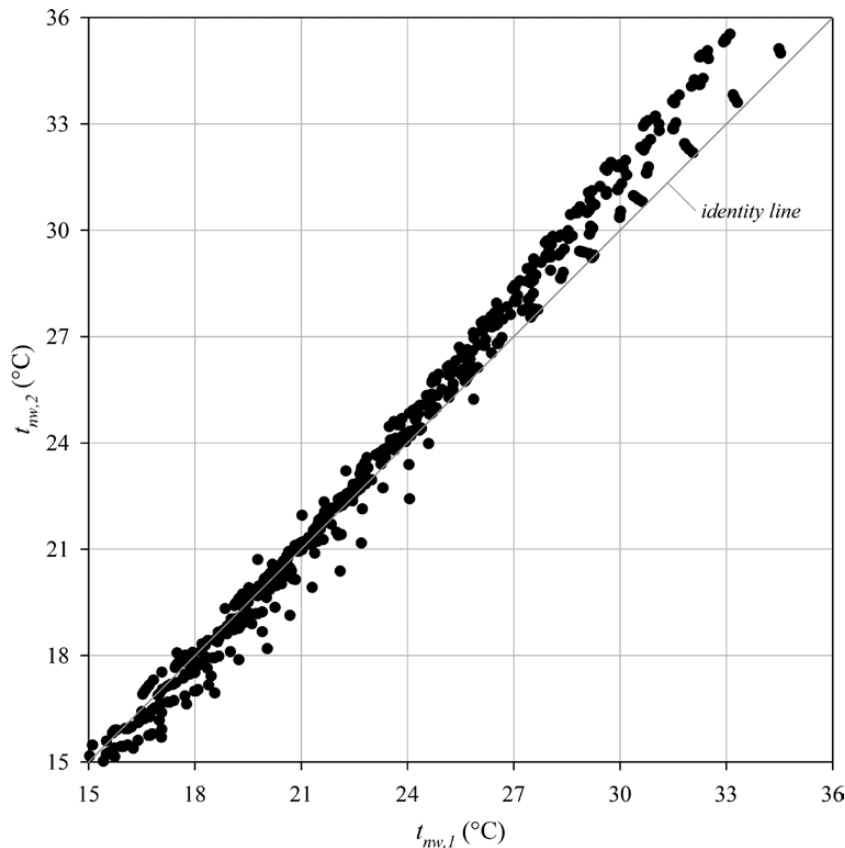
(7) exhibits good performances only under conditions near uniformity ($t_g = t_a$). In the other cases, rational methods based on the heat balance should be preferred.

Another critical issue to be highlighted is the prediction of t_{nw} under free convection conditions, only sketched in the previous section. The equation (7) solves this problem in simply assuming constant values for the coefficients δ and ε at very low air velocities. A theoretical investigation (d'Ambrosio Alfano *et al.*, 2012) has shown that, under free convection conditions and in the presence of even slight values of the difference ($t_r - t_a$ or $t_g - t_a$), equation (6) can be solved by up to three different steady state values.

It must therefore be concluded that the indirect assessment of t_{nw} is possible only under full-forced convection conditions with an uncertainty value of $\sim 1^\circ\text{C}$. Under free convection conditions, none of equations (6) and (7) should be used and direct measurement is required.

EVALUATION OF THE METABOLIC RATE

Both ISO 7243 and the ACGIH document propose a table defining four classes of metabolic rates. For each class, they give metabolic rates in W m^{-2} with the



3 Comparison between the values of predicted natural wet bulb temperature calculated according to Malchaire (1976) $t_{nw,1}$ and Bernard and Cross (1999) $t_{nw,2}$ in the ranges summarized in Table 3.

heading ‘related to a unit skin surface area’ and in watts, with the heading ‘for a mean skin surface area of 1.8 m²’. The documents leave it to the users to decide what data to use to evaluate the metabolic rate in the field.

Historically, thermo physiologists are expressing the metabolic rate in watts per square meter as heat losses depend on the body surface, while work physiologists express it in watts per kilogram as the hardness of a dynamic activity is more related to the weight of the subject. However, for many activities, two persons have the same energy expenditure in watts and not in W m⁻². This is true for all activities that are not depending on the height and the weight of the worker. This means that, contrary to what is indicated in ISO Standard 8996 (ISO, 2004c), the evaluation of the metabolic rate must be done in watts and not in W m⁻², and the headings of the tables should be ‘Metabolic rate in watts per unit skin area in case

of a body surface area of 1.8 m²’ and ‘Metabolic rates in watts’. This point, which has apparently escaped the attention, is very significant. For example, two persons (A with a body surface of 2 m² and B with 1.5 m²), working with a pneumatic hammer, will have the same energy expenditure in watts (300 W) and not in W m⁻² (165 W m⁻²). Indeed, if the W m⁻² data are used, the metabolic rate would be 330 W for subject A and 250 W for B, and the WBGT limits would be, respectively, 27.7 and 29.1. Subject B would erroneously be considered as being able to tolerate hotter climate.

Besides, the WBGT limits values were derived from studies conducted essentially in the USA and Europe 30 to 50 years ago for a population with average body areas around 1.8 m². These data may not be used without considering the average increase in body sizes in the last decades and paying, at last, attention to the populations with different sizes in emerging countries.

It is then necessary, before estimating the WBGT limit, to correct the estimated metabolic rate by a factor K given by:

$$K = \frac{1.8}{A_{du}} \tag{8}$$

where the body area A_{du} is given by the [DuBois and DuBois \(1916\)](#) formula:

$$A_{du} = 0.202 \cdot W^{0.425} \cdot H^{0.725} \tag{9}$$

with the weight W expressed in kilograms and the height H in meters. In the above example, the WBGT limit would then be estimated from $300 \times (1.8/2) = 270\text{ W}$ for subject A ($WBGT_{lim} = 28.7$) and $300 \times (1.8/1.5) = 360\text{ W}$ for subject B ($WBGT_{lim} = 27.3$). Subject A is therefore able to tolerate hotter climates due to his larger body area (contrary to the assessment made without this correction).

temperature will not be recuperated after 30 min of rest in C2. According to the WBGT, the time-weighted values are $M = 230\text{ W}$ and $WBGT = 25$, well below the limit corresponding to 230 W (29.5), so that the work organization can be considered as quite satisfactory. Obviously, this is not the case, and the averaging of the WBGT and M values is not valid.

A time-weighted averaging assumes implicitly that the WBGT limits vary linearly as a function of the metabolic rate, and this is not the case since the relation proposed for acclimatized subjects is logarithmic ([ACGIH, 2011](#); for M expressed in watts):

$$WBGT_{lim} = 56.7 - 11.5 \log_{10} M \tag{10}$$

At least, the validity of the averaging of WBGT should be limited to a small range of values; this comes down to approximating the logarithmic curves by straight lines only in ranges of 5 units WBGT.

EVALUATION OF THE AVERAGE CONDITION WHEN THE CLIMATIC CONDITIONS ARE VARYING IN TIME

According to ISO 7243, 'If a task analysis of the workplace and activities suggests that WBGT is not a constant value in time due to changes in process or location, a representative mean value has to be determined by calculating the time-weighted average'. Similarly, if the metabolic rate varies for the different activities, a time-weighted average value is calculated and the interpretation is based on these average values. This time-weighted averaging procedure leads to unacceptable results as shown by the following example. Let us assume that in each hour a person is working for 30 min in condition C1 ([Table 4](#)) and recuperating for 30 min in condition C2. According to the PHS, the core temperature of the person will reach 38°C after 29 min in the conditions C1, and the initial core

VALIDITY OF THE CLOTHING ADJUSTMENT FACTORS

The limits of the WBGT index are said to set for workers wearing clothes made in cotton with a clothing thermal insulation of 0.6 clo ([ISO, 1989](#); [Parsons, 2006, 2013](#)). This value corresponds to light trousers and T-Shirt ([ISO, 2007](#)), and it is a reasonable estimate for most work clothes in hot environments throughout the world. For other clothing conditions, a correction factor clothing adjustment factor (CAF) is added to the WBGT limit value index ([ACGIH, 2011](#)).

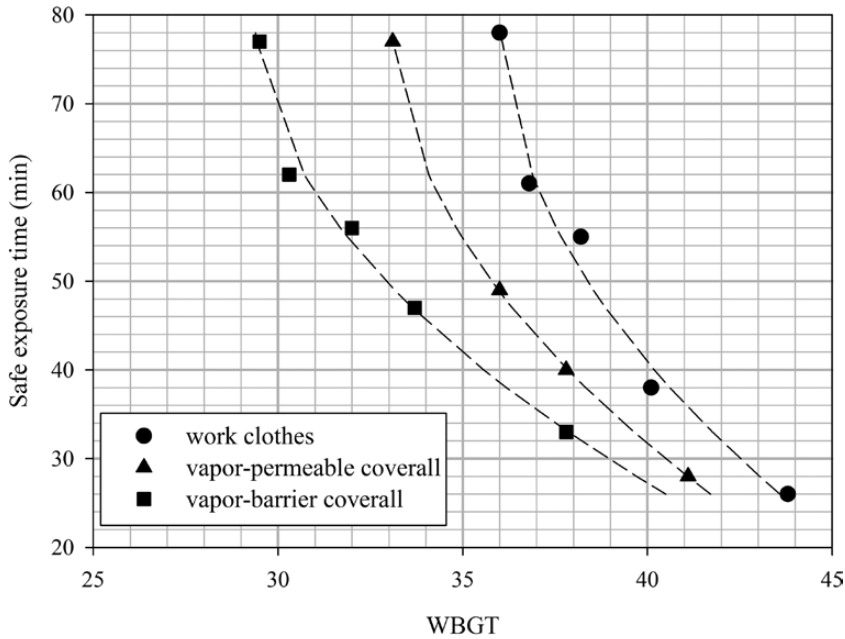
Recently, following researches carried out at the US College of Public Health ([O'Connor and Bernard, 1999](#); [Bernard et al., 2005, 2008](#); [Bernard and Ashley, 2009](#)), CAFs have been proposed for garments with low vapor permeability and protective clothing. Furthermore, it has been suggested to use them for

Table 4. Example of work situation with alternating between hot and moderate climatic conditions

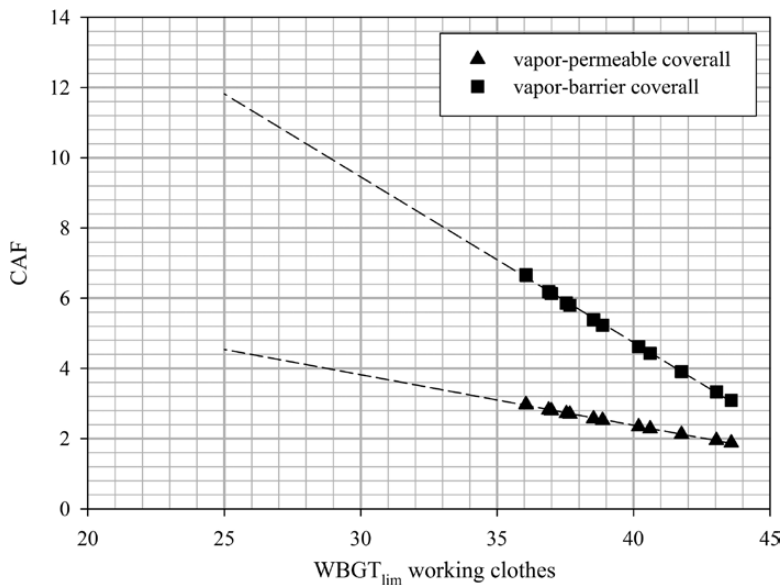
| Condition | Duration (min) | t_a ($^\circ\text{C}$) | t_g ($^\circ\text{C}$) | t_r ($^\circ\text{C}$) | RH (%) | v_a (m s^{-1}) | p_a (kPa) | t_{nw} ($^\circ\text{C}$) | WBGT | M (W) | $WBGT_{lim}$ |
|-----------|----------------|----------------------------|----------------------------|----------------------------|--------|-----------------------------|-------------|-------------------------------|------|---------|--------------|
| C1 | 30 | 37 | 45 | 48.6 | 54 | 0.2 | 4.0 | 32.5 | 36.3 | 350 | 27.4 |
| C2 | 30 | 26 | 20 | 20 | 30 | 0.5 | 0.7 | 11.1 | 13.8 | 110 | 33.2 |
| Average | | | | | | | | | 25.0 | 230 | 29.5 |

setting short-term heat stress exposure limits. Bernard *et al.* (2008) proposed an equation for safe exposure time as a function of the WBGT values for three different clothes: normal work clothes, vapor-permeable

coverall, and vapor-barrier coverall. Figure 4 shows the mean results of the experiments as reported in the article. Figure 5 gives, for identical safe exposure times, the decreases of WBGT values in the case of the two



4 Safe exposure times as a function of the WBGT for work clothes, vapor-permeable coverall, and vapor-barrier coverall (adapted from Bernard *et al.*, 2008).



5 Variation of the clothing adjustment factor for vapor-permeable coverall and vapor-barrier coverall as a function of the WBGT.

last clothes with respect to the values for normal working clothes. These differences are actually the CAF to apply when wearing these clothes. Figure 5 shows that CAFs are not constant values but vary linearly and strongly as a function of the environment: these special clothes are obviously reducing the safe exposure times, but this reduction decreases when the environment is more severe and, by extrapolating these regression lines to 0, would become negative (protection of the subject) in environments with WBGT > 56.5 and 50.0, respectively.

From these data from Bernard *et al.* (2008), it must be concluded that the adoption of fixed CAF values of 2.5 and 6.5 units for the two clothes investigated is not justified.

As any clothing influences the evaporative, convective, and radiative exchanges and as it is unlikely that these influences are the same, it can hardly be accepted that the correction of the WBGT (the CAF) is a constant whatever the combinations of primary parameters, giving an identical WBGT value.

RELEVANCY OF THE LIMITS

Different WBGT limit values as a function of the metabolic rate have been proposed over the years. Table 5 gives the limits as fixed in the ISO 7243 (ISO, 1989) Standard and in the ACGIH (2011) document. It appears clearly that the ACGIH limits are less severe for acclimatized subjects and more severe (except for

very heavy work) for unacclimatized workers. The precise reasons for these opposite evolutions and of the abandonment of the distinction between still and moving air are unknown.

In both cases, it is claimed that the WBGT limits are derived initially from a work by Lind on three nude subjects (rescue workers walking on a treadmill) published in 1963 and primarily on one figure (number 3) of this article reporting the results of one subject only. This figure is reproduced in Fig. 6, each point giving the rectal temperature after 30–40 min of work in a hot environment ($t_a = 18\text{--}42^\circ\text{C}$; $t_w = 10\text{--}34^\circ\text{C}$; $t_r = t_a \pm 0.5^\circ\text{C}$). It shows that the rectal temperature increases due to the metabolic rate but remains constant up to a point called the limit of the ‘prescriptive zone’ (delimited by the straight line). A similar graph presented in the ACGIH document indicates that the limits were derived from this line. Therefore, the assertion that it is ‘the criteria values in the table decrease [as a function of the metabolic rate] to ensure that most workers will not have a core body temperature above 38°C’ (ACGIH, 2011) is not correct. As shown in Fig. 6, the differences are very important, as, for instance for 210 W, the limit would be 33.3 instead of 29.4 (in Lind’s figure) or 30 (according to the ACGIH documents, 2011). It is obvious that these later values are more ‘protective’ than the first ones, but it must be clearly stated and understood that their purpose is not to avoid reaching 38°C of core temperature but to avoid any increase of the central temperature above the steady-state value associated with the metabolic rate.

According to Saltin and Hermansen (1966), in a neutral condition, the equilibrium core temperature t_{co} (°C) at a given metabolic rate is given by:

$$t_{co} = 36.6 + 0.002M \tag{11}$$

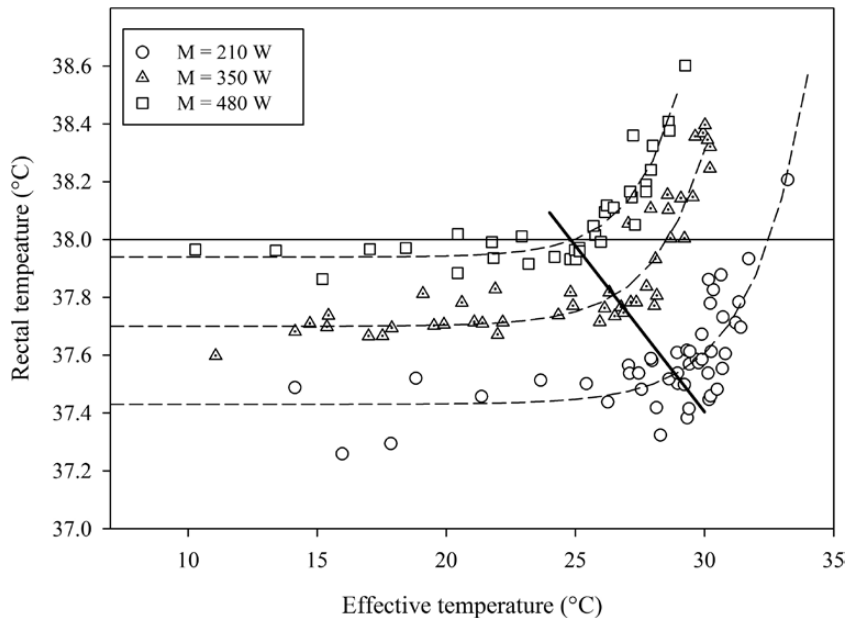
with M in watts.

This means that the WBGT limits correspond to limits of core temperatures of 37.0, 37.2, 37.4, and 37.6 for light ($M = 180$ W), moderate ($M = 300$ W), heavy ($M = 415$ W), and very heavy work ($M = 520$ W), respectively.

In addition, Lind’s article reports, for conditions within the ‘prescriptive zone’, weight losses ≤ 10 g kg^{-1} h^{-1} . Assuming an average weight (not reported in Lind’s article) of 70 kg, this means water losses of ≤ 700 g h^{-1} . As recommended by Malchaire *et al.* (2000) and adopted

Table 5. WBGT limit values given by ISO (1989) and ACGIH (2011)

| Metabolic rate (W) | WBGT limit values | | | | | |
|--------------------|-----------------------|-------|-------|-------------------------|-------|-------|
| | Acclimatized subjects | | | Unacclimatized subjects | | |
| | ISO | | ACGIH | ISO | | ACGIH |
| 105 | 33.0 | | 33.5 | 32.5 | | 31.4 |
| 180 | 30.0 | | 30.8 | 29.0 | | 28.1 |
| 300 | 27.5 | | 28.2 | 25.7 | | 25.0 |
| | Still | Air | | Still | Air | |
| | air | draft | | air | draft | |
| 415 | 25.0 | 26.0 | 26.6 | 22.0 | 23.0 | 23.0 |
| 520 | 23.0 | 25.0 | 25.6 | 18.0 | 20.0 | 21.7 |



6 Rectal temperature after 30–40 min of work at metabolic rates of 210, 350, and 480 W in environments with WBGT values from 10 to 35 (adapted from Lind, 1963).

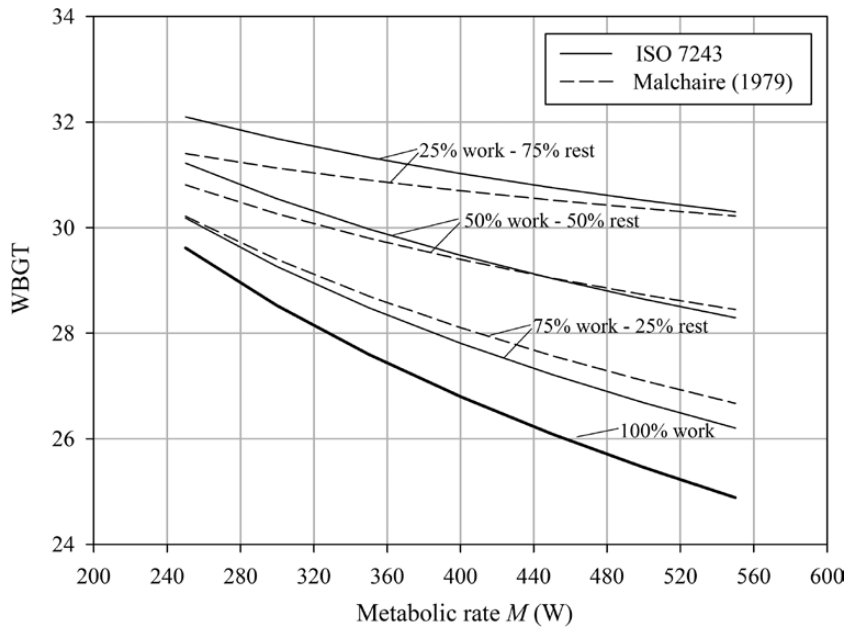
in ISO 7933 (2004), the maximum water loss should be limited to 5% of the body weight in order to avoid further increased heart rate and depressed sweating sensitivity. This indicates that in Lind's conditions, although the increase of core temperature is said to be acceptable in the 'prescriptive zone', there is a risk of excessive water loss and therefore dehydration (in the above case, after 5 h). It must be concluded that the WBGT index does not consider the risk of dehydration due to excessive sweating, which is the main criterion for limiting the exposure in the very warm but not too hot work environments.

VALIDITY OF THE WORK—RECOVERY REGIMEN ORGANIZATION

ISO 7243 reports, in its annex C, curves showing WBGT reference values for different work–recovery cycles (see Fig. 7). These reference values are given on the assumptions that the WBGT at the recovery location is very close (± 1) to the WBGT value at the workplace. No indication is given regarding the organizing of work–recovery cycles if the recovery environment is cooler. As an example, in an environment with WBGT = 31, a subject A could work at a metabolic rate of 260 W for 50% of each hour (30 min), while a subject B could work at a rate of 400 W for only 25% of the time (15 min).

A first comment concerns the wisdom of such a work organization. Actually, a condition with WBGT = 31 (e.g. $t_a = 38^\circ\text{C}$, $t_g = 44^\circ\text{C}$, $v_a = 0.5 \text{ m s}^{-1}$, and $p_a = 2 \text{ kPa}$) is quite severe. Although it might be that, in some cases, recovering on the workplace is the only solution, this should be an exception and strongly discouraged, instead of being the only scenario envisaged in a standard. In this particular case, the simple elimination of the additional radiation (then $t_g = 38^\circ\text{C}$) would reduce the WBGT to 28.3 and small actions on the temperature ($t_a = 36^\circ\text{C}$) and humidity ($p_a = 1.5 \text{ kPa}$) would further reduce it to 25.8. It must therefore be considered unfortunate that the standard envisages only a work organization with recovery in an environment with an identical WBGT value.

A second comment concerns the reasoning behind these curves, which neither the ISO 7243 standard nor the ACGIH document explains. A common gross error in the field is to believe that, in the examples above, after 30 or 15 min, the core temperature has increased to 38°C . This is obviously erroneous, and this must be understood as that, with these work–recovery cycles and under the same microclimatic conditions, the core temperature at the end of the work shift will not exceed 38°C . Still, this does not explicate the rationale behind the recommended regimens. It appears reasonable that



7 Limit values for 75, 50, and 25% of work regimen estimated by using Malchaire's equation (1979) and the ISO limit values for acclimatized subjects (ISO, 1989).

the work duration be limited more for worker B since he is working harder, but one would expect that the physiological criteria for limiting the work duration are the same in both cases and, therefore, that A and B are in the same physiological condition at the end of the work period. If this is the case, it is incomprehensible that subject B has to recover during 45 min, while subject A needs 30 min only. If indeed these recovery times are needed, this means that the strain of B after 15 min is greater than the strain of A after 30 min. Therefore, it is unclear why A has to be stopped and what is the strain level (core temperature) in both cases.

Malchaire (1979) proposed a rationale explaining the curves given in the ACGIH document published in 1971. This rationale has never been criticized, nor adopted by others. It ventures the hypothesis that the work–recovery regimen is organized so that the elevation of core temperature during each work phase is recuperated during the rest of the time (the hour). The duration of work is then given by:

$$\text{Work duration per hour} = 60 \frac{\text{WBGT}_{\text{lim,R}} - \text{WBGT}}{\text{WBGT}_{\text{lim,R}} - \text{WBGT}_{\text{lim,W}}} \quad (12)$$

where

WBGT is the value of the index for the climatic conditions where both work and recovery take place;

$\text{WBGT}_{\text{lim,R}}$ is the WBGT limit value corresponding to the recovery metabolic rate; and

$\text{WBGT}_{\text{lim,W}}$ is the WBGT limit value corresponding to the work metabolic rate.

Figure 7 shows the very good agreement based on the values given in ISO 7243 (1989).

It must be noted that this does not validate but simply explain the proposed work–recovery regimens. If it is assumed that the core temperature during each work phase does not reach 38°C and is compensated during the following recovery phase, there is no cumulated effect and the temperature at the end of the 8-h day will neither reach 38°C.

CONCLUSIONS

The objective of the article was to revisit the WBGT index, not through the more than 50 years of existence but as it is proposed now.

The WBGT index is said to be simple to understand, to use, and to have validity to organize the work–recovery regimen. The analysis in this article shows that this is not the case. In particular,

1. The index does not appropriately communicate on the severity of the climate and is frequently interpreted by workers and managers in the field on the basis of the scale of temperature sensation that they usually experience. WBGT values ~ 30 are then not considered to be very severe, many people think reasonable to organize recovery in the same environment and the heat stress is underestimated.
2. Many instruments are available on the market to measure the WBGT. Sometimes they are very expensive (2–10 times the price of a portable computer), but they are in some cases impossible to calibrate and, since not using standard sensors, can lead to large errors.
3. When the evaluation of the WBGT index is required (e.g. for compliance reasons), the indirect evaluation from the four basic parameters appears preferable. Models based on the heat balance on the natural wet bulb thermometer in general give quite consistent results, except for very low air speeds. In that case, several different solutions to the heat balance model are observed and thus this approach cannot be used. Direct measurement of the natural wet bulb temperature is then necessary.
4. The evaluation of the metabolic rate must be done in terms of watts and not of $W m^{-2}$, and, for the determination of the WBGT limit values, it must be corrected as a function of the mean surface area of the local population.
5. As the WBGT limits values do not vary linearly as a function of the metabolic rate, the averaging of very disparate WBGT or M values will lead to absurd results that can be very detrimental for the health and safety of the exposed persons. The averaging procedure should be restricted to environmental situations characterized by narrow variations of parameters.
6. It is proposed to add a CAF to the WBGT index to take account of the effect of the clothes when different from 'normal working clothes'. These CAF are claimed to be

independent of the climate and the WBGT values. By reanalyzing the experimental data from literature, it has been shown that the CAF at the contrary vary strongly as a function of the climate.

7. Contrary to what is usually claimed, the WBGT limits are not set for a maximum core temperature of $38^{\circ}C$ but to avoid any increase of the core temperature above the equilibrium level corresponding to the metabolic rate.
8. The organization of work–recovery regimen on the basis of one hour might be logical in the same comfortable environment and for repetitive work. It is not so relevant in hot environment and certainly not in very hot climate where people have to intervene occasionally and for short period of time. Recovering in such environment should be an exception. If it is indeed the case, the reasoning for the work–recovery regimen proposed in the standard is not intelligible.

In conclusion, it may be said that, 60 years after its first formulation, the WBGT index has not changed, despite its approximations and inconsistencies. While it is usually considered to be user friendly and simple to understand, the reasoning for taking account of the clothes, for setting the limits, for evaluating changing working conditions, and for organizing the work–recovery regimen is unknown, incomprehensible or erroneous.

The reasons for its development being outdated, it is therefore recommendable to move on to something else for a more adequate protection of the people working in hot conditions all over the world.

FUNDING

Italian Ministry for Education, University and Research.

REFERENCES

- ACGIH. (2011) *Threshold limit values for chemical substances and physical agents and biological exposures indices, 2011*. Cincinnati, OH: American Conference of Governmental Industrial Hygienists.
- ASHRAE. (2013) *ASHRAE handbook - fundamentals, American society of heating, refrigerating and air-conditioning engineers*. Atlanta, GA: ASHRAE.

- Bernard TE, Ashley CD. (2009) Short-term heat stress exposure limits based on wet bulb globe temperature adjusted for clothing and metabolic rate. *J Occup Environ Hyg*; 6: 632–8.
- Bernard TE, Barrow CA. (2013) Empirical approach to outdoor WBGT from meteorological data and performance of two different instrument designs. *Ind Health*; 51: 79–85.
- Bernard TE, Caravello V, Schwartz SW *et al.* (2008) WBGT clothing adjustment factors for four clothing ensembles and the effects of metabolic demands. *J Occup Environ Hyg*; 5: 1–5; quiz d21–3.
- Bernard TE, Cross RR. (1999) Heat stress management: case study in an aluminum smelter. *Int J Ind Ergonom*; 23: 609–620.
- Bernard TE, Luecke CL, Schwartz SW *et al.* (2005) WBGT clothing adjustments for four clothing ensembles under three relative humidity levels. *J Occup Environ Hyg*; 2: 251–6.
- Bethea D, Parsons K. (2002) *The development of a practical heat stress assessment methodology for use in UK industry (Research Report 008)*. Loughborough, UK: Department of Human Sciences, Loughborough University.
- Brake DJR. (2001) Calculation of the natural (unventilated) wet bulb temperature, psychrometric dry bulb temperature and wet bulb globe temperature from standard psychrometric measurements. *J Mine Ventil Soc S Afr*; 54: 108–12.
- Budd GM. (2008) Wet-bulb globe temperature (WBGT)—its history and its limitations. *J Sci Med Sport*; 11: 20–32.
- Buonanno G, Frattolillo A, Vanoli L. (2001) Direct and indirect measurement of WBGT index in transversal flow. *Measurement*; 29: 127–35.
- d'Ambrosio Alfano FR, Dell'Isola M, Palella BI *et al.* (2013) On the measurement of the mean radiant temperature and its influence on the indoor thermal environment assessment. *Build Environ*; 63: 79–88.
- d'Ambrosio Alfano FR, Palella BI, Riccio G *et al.* (2004) Criteria for assessing severely hot environments: from the WBGT index to the PHS (predicted heat strain) model. *Med Lav*; 95: 255–74.
- d'Ambrosio Alfano FR, Palella BI, Riccio G. (2007) The role of measurement accuracy on the heat stress assessment according to ISO 7933: 2004. *WIT Trans Biomed Health*; 11: 115–24. doi:10.2495/EHR070131
- d'Ambrosio Alfano FR, Palella BI, Riccio G. (2011) Thermal environment assessment reliability using temperature–humidity indices. *Ind Health*; 49: 95–106.
- d'Ambrosio Alfano FR, Palella BI, Riccio G. (2012) On the problems related to natural wet bulb temperature indirect evaluation for the assessment of hot thermal environments by means of WBGT. *Ann Occup Hyg*; 56: 1063–79.
- Dell'Isola M, Frattolillo A, Palella BI *et al.* (2012) Measurement uncertainties influence on the thermal environment assessment. *Int J Thermophys*; 33: 1616–32.
- DuBois D, DuBois EF. (1916) A formula to estimate the approximate surface area if height and weight be known. *Arch Intern Med*; 17: 863–71.
- Gaspar AR, Quintela DA. (2009) Physical modelling of globe and natural wet bulb temperatures to predict WBGT heat stress index in outdoor environments. *Int J Biometeorol*; 53: 221–30.
- Givoni B. (1964) A new method for evaluating industrial heat exposure and maximum permissible work load. *Int J Biometeorol*; 8: 115–24.
- Graves KW. (1974) Globe thermometer evaluation. *Am Ind Hyg Assoc J*; 35: 30–40.
- Humphreys MA. (1977) The optimum diameter for a globe thermometer for use indoors. *Ann Occup Hyg*; 20: 135–40.
- ISO. (1989) *Hot environments - estimation of the heat stress on working man, based on the WBGT-index (wet bulb globe temperature) - ISO 7243 Standard*. Geneva, Switzerland: International Organization for Standardization.
- ISO. (1998) *Ergonomics of the thermal environment - instruments for measuring physical quantities - ISO Standard 7726*. Geneva, Switzerland: International Organization for Standardization.
- ISO. (2004a) *Ergonomics of the thermal environment - analytical determination and interpretation of heat stress using calculation of the predicted heat strain - ISO 7933 Standard*. Geneva, Switzerland: International Organization for Standardization.
- ISO. (2004b) *Ergonomics of thermal environments - strategy of evaluation of the risk for the prevention of constraints or discomfort under thermal working conditions - ISO Standard 15265*. Geneva, Switzerland: International Organization for Standardization.
- ISO. (2004c) *Ergonomics of the thermal environment - determination of metabolic rate - ISO Standard 8996*. Geneva, Switzerland: International Organization for Standardization.
- ISO. (2007) *Ergonomics of the thermal environment - estimation of thermal insulation and water vapour resistance of a clothing ensemble - ISO Standard 9920*. Geneva, Switzerland: International Organization for Standardization.
- Jendritzky G, de Dear R, Havenith G. (2012) UTCI—why another thermal index? *Int J Biometeorol*; 56: 421–8.
- Juang YJ, Lin YC. (2007) The effect of thermal factors on the measurement of Wet Bulb Globe Temperature. *J Occup Saf Health*; 15: 191–203.
- Kerslake DM. (1972) *The stress of hot environments*. Cambridge, UK: Cambridge University Press.
- Lee DH. (1980) Seventy-five years of searching for a heat index. *Environ Res*; 22: 331–56.
- Lemke B, Kjellstrom T. (2012) Calculating workplace WBGT from meteorological data: a tool for climate change assessment. *Ind Health*; 50: 267–78.
- Lind AR. (1963) A physiological criterion for setting thermal environmental limits for everyday work. *J Appl Physiol*; 18: 51–6.

- Malchaire JB. (1976) Evaluation of natural wet bulb and wet globe thermometers. *Ann Occup Hyg*; 19: 251–8.
- Malchaire JB. (1979) The TLV work-rest regimens for occupational exposure to heat: a review of their development. *Ann Occup Hyg*; 22: 55–62.
- Malchaire J, Kampmann B, Havenith G *et al.* (2000) Criteria for estimating acceptable exposure times in hot working environments: a review. *Int Arch Occup Environ Health*; 73: 215–20.
- McIntyre D.A. 1980. *Indoor climate*. London, UK: Applied Science Publisher LTD.
- Mehnert P, Malchaire J, Kampmann B *et al.* (2000) Prediction of the average skin temperature in warm and hot environments. *Eur J Appl Physiol*; 82: 52–60.
- O'Connor DJ, Bernard TE. (1999) Continuing the search for WBGT clothing adjustment factors. *Appl Occup Environ Hyg*; 14: 119–25.
- Parsons KC. (2006) Heat stress standard ISO 7243 and its global application. *Ind Health*; 44: 368–379.
- Parsons K. (2013) Occupational health impacts of climate change: current and future ISO standards for the assessment of heat stress. *Ind Health*; 51: 86–100.
- Parsons KC, Fox JG, Metz B. (1995) The Commission of the European Communities Seminar on heat stress indices. *Ergonomics*; 38: 1–5.
- Romero-Blanco H. (1971) Effect of air speed and radiation on the difference between natural and psychrometric wet bulb temperatures. Dissertation, University of Pittsburgh.
- Saltin B, Hermansen L. (1966) Esophageal, rectal, and muscle temperature during exercise. *J Appl Physiol*; 21: 1757–62.
- Sullivan CD, Gorton RL. (1976) A method of calculation of WBGT from environmental factors. *ASHRAE Transactions*; 82: 279–92.
- Tan CL, Wong NH, Jusuf SK. (2013) Outdoor mean radiant temperature estimation in the tropical urban environment. *Build Environ*; 64: 118–29.
- Vogt JJ, Candas V, Libert JP *et al.* (1981) Required sweat rate as an index of thermal strain in industry. *Stud Environ Sci*; 10: 99–110. doi:10.1016/S0166-1116(08)71083-5
- Yaglou CP, Minard D. (1957) Control of heat casualties at military training centers. *AMA Arch Ind Health*; 16: 302–16.