The WBGT Index: A Primer for Road Race Medicine

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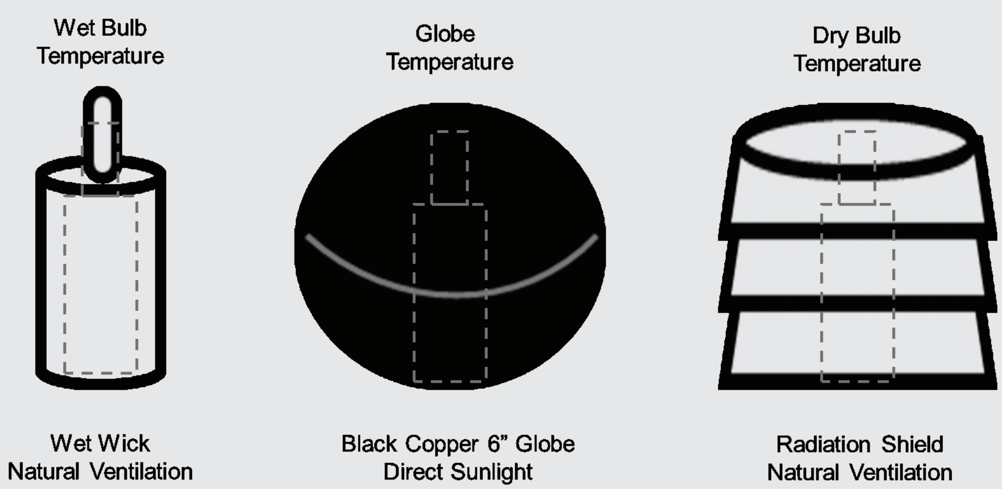
The mission of the International Institute for Race Medicine (IIRM) is to promote the health and safety of athletes participating in endurance events through education, research, and the development of medical best practices. This primer is written in support of the IIRM mission and describes the basic science and practice of using the wet bulb globe temperature (WBGT) index to aid in mitigating the risk of exertional heat illnesses.

What is the WBGT Index?

High air temperature, high humidity, thermal radiation, and low air movement are causes of environmental heat stress. The WBGT index encompasses all of these environmental causes of heat stress into one number that is used to characterize the potential effects of hot environments on runners. Figure 1 illustrates the three WBGT components and the formula for calculation. A traditional WBGT apparatus measures air temperature from a shaded dry bulb thermometer (Tdb). The contribution of humidity is determined from a wet bulb temperature (Twb), which is measured by covering a thermometer bulb with a wet wick. Radiant heat (solar load) is assessed by a black globe thermometer (Tbg) which consists of a 6-inch hollow copper sphere, painted matte black on the outside, and containing a thermometer at the center of the sphere. The traditional WBGT apparatus is comprised of non-standard instruments that can be cumbersome to use and maintain. However, comparable results (1) can now be obtained with several modern and highly automated WBGT monitoring systems that use smaller diameter black globes, waterless wet bulb temperatures, or other advances that afford miniaturization and improved portability. The reader interested in the history and many detailed assumptions and limitations of using the WBGT index should consult Budd (2).

The Importance of All Three WBGT Components

When runners start a race they instantly begin using energy at a rate that is 5 to 10 times greater (or more!) than resting metabolism (1 MET). However, only 20% (or less) of the energy is used for work—the rest is converted to heat. The metabolic heat



$$0.7\ T_{wb} + 0.2\ T_{bg} + 0.1\ T_{db}$$

Figure 1.
WBGT index components and formula.
Dashed line image represents a standard thermometer within each component.

being generated by runners is the principal reason for increases in blood flow and sweating, referred to as exercise thermoregulation. Specifically, increased blood flow to the skin produces dry heat loss (radiation and convection) and the evaporation of sweat secreted on the skin surface produces evaporative heat loss.

The effects of the environment on heat balance are normally indirect; that is, the environment affects how much body heat can be lost by dry or evaporative means, rather than contributing directly to heat gain (with exceptions). A runner's skin is normally warmer than the surrounding air, which allows for heat loss from body to environment; however, when the Tdb is > 36^0 (97^0F), hot air causes dry heat gain. The Tdb represents 10% of the WBGT index. The Tbg is lower than Tdb at night and similar before sunrise and after sunset, but otherwise variable based on cloud cover and time of year. In mid-morning and early afternoon on a cloudless summer day, the Tbg can be 1.5 to 2.0 times higher than Tdb. Furthermore, the solar load on the body can equal 2 METS, which would increase body heat storage similarly to running 30 seconds faster per mile! The Tbg represents 20% of the WBGT index. Significant sweating can occur even in cool environments because, as mentioned above, metabolism is the primary driving force behind body heat production. Cool skin will reduce sweating in proportion to larger dry heat losses (by radiation and convection), but as Tdb increases the dependence of sweat evaporation for body cooling becomes paramount. In warm and hot environments, sweat evaporation can provide all the cooling necessary, if the air is dry. But when the Tdb approaches skin temperature and the air is also humid, the water vapor pressure in the air can become higher than it is for sweat on the skin, thus preventing evaporation. For this reason, Twb represents 70% of the WBGT index as saturation of air dictates the upper limit for heat dissipation when the air is warm or hot. Lastly, high air flow will reduce the WBGT index by altering the rate of convective and evaporative heat loss, but this is a smaller concern for runners who generate their own air flow equivalent to running velocity. The absolute contribution that each component contributes to the overall WBGT naturally depends on the prevailing weather. Figure 2 provides one example.

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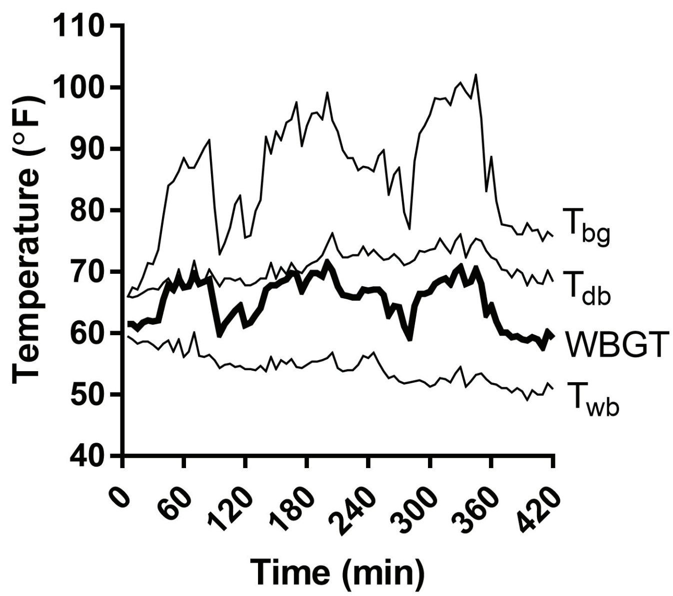

Figure 2.
The WBGT and components measured on-site at five minute intervals for seven hours during the 2017 Boston Marathon. Fluctuations between green and yellow flag categories this day were driven principally by changes in cloud cover which produced spikes in the black globe temperature. *(Unpublished report from S. Cheuvront to the Boston Athletic Association, April 26, 2017).*

Table 1.
Generalized heat stress flag color warnings for runners based on the Wet Bulb Globe Temperature (WBGT) index.[1]

Flag Color	WBGT, °C (°F)	Risk for Hyperthermia	Warning
WHITE	< 10 (< 50)	Low but possible risk for hypothermia	Wind, rain, longer races, and slower pace increase risk
GREEN	< 18 (< 64)	Low	Remain alert as exertional heat illness may still occur
YELLOW[2]	18-23 (65-73)	Moderate	Caution and slower pace[3] recommended
RED	23-28 (73-82)	High	Extreme caution and slower pace[3] strongly recommended
BLACK	> 28 (> 82)	Extremely High	Race cancellation or non-participation recommended

1 Adapted from Hughson et al. (1983) and ACSM (1987)
2 Sometimes referred to as AMBER
3 Performance impairments make personal best (PB) performances very unlikely and attempts to PB increase exertional heat illness risk significantly; see also Table 2

WBGT Index Flag Categories

The WBGT is used to manage the risk of exertional heat illness using color-coded heat stress flag categories. The development and first formal recommendation for using WBGT categories for road race risk management, as defined and described in Table 1, was by Hughson et al. in 1983 (3). The American College of Sports Medicine adopted the recommendations in their 1987 position stand on the prevention of thermal injuries during distance running (4) and continues to advocate for the same today. Table 2 provides important running performance information not normally considered in the discussion of WBGT and exertional heat illness risk management. It is important to teach runners that heat stress impairs performance before it increases the risk of exertional heat illness. A slower pace is recommended to reduce risk when the WBGT reaches yellow and red flag status (Table 1). Runners determined to attempt a personal best in those conditions are unlikely to succeed but will significantly increase their risk of illness. As pointed out above, a fast pace has the single greatest influence on body heat storage.

Table 2.
Distance-specific WBGT index thresholds for impaired running performance are lower than those for exertional heat illness risk.

Race Distance (km)	Exertional Heat Illness Risk (°C/°F)	Performance Impairment (°C/°F)
5	> 29 / 84	> 25 / 77
10	> 28 / 82	> 20 / 68
42	> 21 / 70	> 15 / 59

Data compiled from McCann and Adams (5), Ely et al. (6), and Roberts (7).

WBGT Measurement and Forecasts

Traditional WBGT thermometers (e.g., military) are suspended in the sun at a height of 4 feet above the ground and a period of 20 minutes is allowed

(photo by S. Cheuvront).

Figure 3.
WBGT index measurement made on-site using a sample portable WBGT system. (Runners in Newton, Massachusettes, at the 30 km mark of the 2013 Boston Marathon.)

to elapse before readings are taken. Modern 'all-in-one' WBGT instruments should be placed on a tripod 4 feet (1.2 m) above the ground and a similar warm-up period allowed before making a first measurement. The WBGT index is best measured on location (Figure 3) or as close as possible to the location of interest in real time (8). This can be a challenge for road races that span 5 to 42 km.

As a replacement for on-site WBGT instruments, various WBGT estimation models have also been proposed that utilize conventional measurements taken at local weather stations such as air temperature, relative humidity, solar radiation, and wind speed (9). For example, a formula developed by the Australian Bureau of Meteorology (ABM) requires just the air temperature and relative humidity for estimating the WBGT. This makes the formula a field-friendly solution since the air temperature and humidity data can be easily obtained via weather forecasts, meteorological updates, or with relatively inexpensive devices. However, the formula is not sensitive to the change in the amount of solar radiation (e.g., Figure 2) and wind currents at a given combination of air temperature and humidity, which limits its accuracy and usefulness as described above. Another tool that is commonly used by researchers is called the Liljegren model, which estimates WBGT using air temperature, relative humidity, solar radiation and wind speed. Because the components of the Liljegren model closely align with the traditional WBGT, it has been shown to produce WBGT estimates that are close to the actual WBGT values (9). Nevertheless, the distance from the weather station and other factors can still influence the accuracy of the estimated values.

WBGT forecasting may become possible if the spatial accuracy needed to calculate a WBGT estimate that is close (enough) to the actual WBGT is determined. However, since every location has its own unique geographical and climate characteristics, use of off-site data requires special considerations. For any race directors that are considering the use of off-site data to estimate local WBGT, it is highly recommended to monitor and compare the on-site course measurements with the weather station data in advance of the race to determine its accuracy (8).

Summary

Maintenance of thermoregulation is vital to sustaining health and optimizing running performance in the heat. The WBGT is an objective measure that can inform race participants about the environmental allowance under which they can safely run in warm conditions. Race directors should consider using one of many 21st century devices for measuring on-site WBGT (1,8) and implementing the flag notification system to systematically address the risk of heat stress. Effective use of WBGT alerts can help modify runners' behaviors as environmental heat hazards become imminent.

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Visit the IIRM blog, authored by Marine Corps Marathon Medical Coordinator Michele "Shelly" Weinstein, PT, MS, SCS, ATC, USN Retired. Shelly is also co-owner of Cogent Steps, LLC (medical education and emergency management education), an emergency response instructor for the American Physical Therapy Association's Sports Section, and faculty member of the US Navy Sports Physical Therapy Residency. Among the topics discussed in the blog are testing and treatment of hyponatremia, youth and long distance running, race participation of athletes with disabilities, the cost of managing safety for events, and making sense of the supplies list for the endurance event medical tent. To view or contribute to the blog, go to https://racemedicine.blogspot.com. We welcome your contributions!