A Novel Conceptual Model for Human Heat Tolerance

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BERNARD, T.E., S.T. WOLF, and W.L. KENNEY. A novel conceptual model for human heat tolerance. *Exerc. Sport Sci. Rev.*, Vol. 52, No. 2, pp. 39–46, 2024. *Human "heat tolerance" has no accepted definition or physiological underpinnings; rather, it is almost always discussed in relative or comparative terms. We propose to use environmental limits to heat balance accounting for metabolic rate and clothing, that is, the environments for which heat stress becomes uncompensable for a specified metabolic rate and clothing, as a novel metric for quantifying heat tolerance.* **Key Words:** climate change, critical environmental limit, wet-bulb globe temperature, heat stress, occupational exposure limit

KEY POINTS

- Heat tolerance is a nebulous term and almost always is discussed in *relative or comparative* terms.
- We propose a novel absolute metric for individual heat tolerance grounded in empirical human data, driven by multidimensional heat stress, and modified by personal factors.
- We make the case that individual heat tolerance based on critical environmental limits, the upper limit for heat balance across a wide range of ambient temperatures and humidity, is an appropriate metric.
- The effects of environment, exercise or work intensity, clothing, and personal factors can be quantified into a conceptual absolute heat tolerance category.

INTRODUCTION

Heat tolerance is an ambiguous term when applied to humans, with multiple physiological, psychological, pathological, and biophysical definitions and interpretations. Wyndham defined heat tolerance as the ability to "thermoregulate well enough to work under most conditions of heat stress" (1,2). While *heat intolerance* is not a medical or pathophysiological condition, it often is defined as a hypersensitivity to heat that may or may not have pathological consequences.

As such, heat tolerance almost always is discussed in *relative or comparative* terms, for example, improved physiological responses with heat acclimatization (3–5), performance differences between or among individuals or groups in stressful environments, or passing/failing a standardized test (*e.g.*, a heat tolerance test (6)). As an example of the latter, the Israeli Defense Forces (IDF) uses a treadmill-based heat tolerance test (HTT) as a screening tool to assist in decision-making on a soldier's return to duty after an episode of exertional heat illness. However, core temperature and heart rate responses to such a test are not finite markers of heat tolerance, but rather serve as a useful adjunct to the full medical record. There is no *absolute* or *categorical* measure of an individual's heat tolerance and, concomitantly, no understanding of how heat tolerance is distributed within a sample or population.

Part of the problem of describing heat tolerance is that heat stress and the resulting heat strain are multidimensional. Heat stress involves a combination of environmental factors and net metabolic heat production that is further modified by clothing (7). Therefore, at a minimum, a heat stress metric needs to account for these three factors. The individual response to heat stress (*i.e.*, heat strain) also is modified by personal factors such as body size, age, and sex at birth (8,9). Therefore, an absolute measure of heat tolerance would, by necessity, incorporate how heat tolerance is (1) driven by multidimensional determinants of heat stress and (2) modified by personal factors.

The purpose of this *Perspectives for Progress* is to introduce a novel conceptual model of individual heat tolerance grounded in empirical human subject data from two laboratories. The model describes how the ability to tolerate heat can be operationalized both for an individual and for a population. Knowing an individual's heat tolerance can inform a decision about specific heat stress exposures. Knowing the population distribution

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of heat tolerance can inform exposures that are sustainable for various percentages of the population. While relative measures of heat tolerance (*e.g.*, improved heat tolerance, individual X is more heat tolerant than individual Y, etc.) have utility and are pervasive in the literature, heat tolerance can be described as a continuous metric once the effects of environment, exercise or work intensity, clothing, and personal factors are known. This type of measure would enhance our understanding of contributors to heat strain and provide a basis for decision-making for sustainable exercise and occupational work performance in hot environments.

CONCEPTUAL MODEL OF INDIVIDUAL HEAT TOLERANCE

A simplified conceptual model for heat tolerance is shown in Figure 1. The central focus is the individual. **Heat stress** is a combination of environmental influences (ambient temperature, water vapor pressure, radiant heat load, effective air movement), metabolic rate (basal plus activity-based corrected for external work performed), and clothing (primarily area covered, insulation, and evaporative resistance). Heat stress also has a temporal spectrum of exposures both within a day and serial heat stress exposures over multiple days (*e.g.*, carryover effects) (10–12). In defining heat tolerance, the exposure conditions are specified as constant with a short exposure time on the order of an hour to avoid drift over longer periods (13).

For a given heat exposure, the individual exhibits measurable physiological responses (*i.e.*, **heat strain)**. The magnitude of the strain response is moderated by personal factors. To categorize personal factors in the context of heat stress/strain, we propose four categories: physical characteristics, situational factors, modifiable factors, and inherent factors. Physical characteristics are regularly reported in describing the participants, and include anthropometrics such as height, weight, body surface area, adiposity or body mass index (BMI), age, and sex. Situational factors are transient or short-term factors, lasting hours or days, and can often be managed by policies and practices of the supervising organization, or by the individual when self-directed. Modifiable factors are those that may be modified by the individual with some effort but are less amenable to organization oversight, such as fitness or wellness. Inherent personal factors are inherited or acquired, are chronic, and are not easily changed without extraordinary intervention, if at all. These groupings have flexible boundaries and are offered to focus research questions and develop interventions.

In the conceptual model, we consider heat strain as a generic descriptor of integrated physiological changes. Following the arrow pointing down, heat strain is evidenced by changes in heart rate, body temperatures, and sweating rate as well as other physiological adjustments (*e.g.*, water turnover, fluid balances, hormonal adjustments) and psychophysiological outcomes (*e.g.*, perceived exertion, thermal sensation, and thermal comfort). At some point, the heat strain leads to deleterious outcomes including heat-related illness (11), acute injury (14,15), and decreased performance with lost productivity (16,17). The probability associated with the deleterious outcomes increases with heat stress, but the levels of *de minimus* or acceptable probability are not well defined.

Due to the complex nature of heat strain, the model shown in Figure 1 operationalizes heat strain by placing it into a category. Categories are described on the right side of Figure 1 and are based on the proposed upper limit of the prescriptive zone (ULPZ) by Lind (18). The ULPZ is the highest environmental heat stress in which the participant can maintain at relatively constant core temperature (T_c) at a given metabolic heat production and has more recently been redefined at the critical environmental limit (CEL), illustrated as the Critical Condition in the figure. The CEL forms the basis of our proposed metric for heat tolerance. The CEL is defined as the maximal heat stress at which the T_c depends solely on the metabolic rate and is relatively independent of the ambient environment (19). Above the CEL, heat loss (a function of integrated physiological responses) can no longer offset heat production plus heat gain, internal heat storage occurs, and core temperature increases. The Lind method for determining the CEL was modified by Belding and Kamon (1973), and refined in a series of articles by Kenney (20–23) and Bernard (24). In summary, the proposed heat tolerance metric is the CEL, which indicates a condition where heat stress can be sustained with no change in T_c. It is not a clear defining point for conditions safe from deleterious outcomes.

The lower end of the spectrum in the figure (green, compensable) represents a low level of heat stress, a level that the individual can tolerate for prolonged periods of time with minimal physiological adjustment. As the magnitude of heat stress increases, the collection of physiological adjustments (*i.e.*, heat

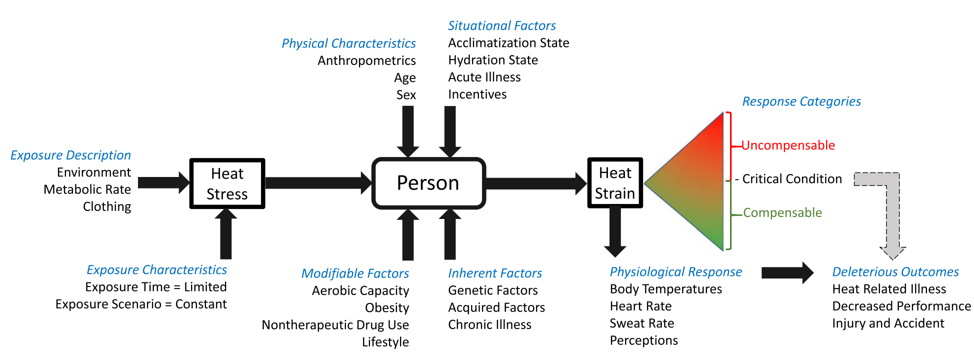

Figure 1. Conceptual model of heat tolerance with heat stress factors and personal factors driving an individual's heat stress response (heat strain). Heat tolerance is the limiting sustainable response at the transition from compensable to uncompensable heat stress, also known as the critical environmental limit (CEL), at a specified metabolic rate and clothing ensemble. The distal outcomes of a heat stress exposure and the resulting heat strain are heat-related illnesses, decreased performance, and increased risk of injury. The response category (*i.e.*, compensable vs CEL vs uncompensable) may provide an alternative classification for overall heat strain that modulates the risk of deleterious outcomes (illustrated by the gray arrow).

strain) increases, but the response remains compensable at a steady T_c driven only by the metabolic rate (19). That is, a sustainable thermal equilibrium can be established for at least the short term (25). This heat strain category is compensable. The upper limit of the compensable category is the CEL, which is our proposed environmental metric for heat tolerance. As a note, there is a marginal zone above the CEL in which thermal equilibrium can be maintained for a short period, albeit with higher heat strain (26). Finally, increasing levels of heat stress move the individual out of the compensable category and into the category of uncompensable heat stress. The uncompensable category is marked by non-steady state responses and time-limited exposures (25).

The conceptual model also points to alternative descriptions for heat strain via the gray arrow from categories to deleterious effects. In epidemiological studies, the classification of exposure by these categories may help to parse out the health and well-being outcomes.

For the purpose of this model, heat tolerance for a specific metabolic rate and clothing ensemble is defined by the CEL — the transition from compensable to uncompensable heat stress (18,23,24,27–31) as shown in Figure 2.

Establishing Critical Environmental Limits

The ability to define the CEL is based on the historical work of Lind (18,32–34) and Belding and Kamon (28). The protocols have been optimized by more recent projects in our respective laboratories at the University of South Florida (USF) (24,35,36) and Penn State University (PSU) (20–23,29,30). In most applications, metabolic rate and clothing are fixed and a starting environment is selected in the compensable range based on experience. After a 30- to 45-min equilibration period, the environmental heat stress is increased in small increments every 5 min in stepwise fashion. Heart rate begins to increase slowly as the CEL is approached (Cottle 2023). In environments beyond the CEL, T_c increases approximately 0.5–1.5°C per hour (25). As previously described, the CEL is determined as the environmental conditions immediately before the T_c inflection point during a progressive heat stress protocol. An example time course for T_c is shown in Figure 2. We previously have reported excellent reliability and validity of this protocol to identify CELs (37).

In practice, the PSU and USF progressive heat stress protocols differ slightly in how the environment is controlled. The essential element to the progressive heat stress protocol is systematically changing environmental heat stress in small steps that allow a steady state response within approximately 5 min. At PSU, there is a critical dry bulb temperature (T_{crit}) approach that starts with a fixed water vapor pressure and T_{db} is increased approximately 1°C per 5-min step. The critical water vapor pressure (P_{crit}) approach starts with a fixed T_{db} and P_a is increased approximately 1 mm Hg per step. At USF, the critical environment is found by increasing T_{db} in 1°C steps at a fixed relative humidity. In this approach both T_{db} and P_a are increased concurrently, and the CEL is reported as the critical wet bulb globe temperature ($WBGT_{crit}$). Data from both approaches can be combined into multiple psychrometric parameters, including (psychrometric) wet bulb temperature (T_{wb} or T_{pwb}). Cottle *et al.* (2021) demonstrated that the T_{crit} and P_{crit} approaches yield the same CEL.

Alternative approaches to finding critical environmental conditions have been proposed. For instance, Lind (18) and Kuhlemeier (38,39) used a series of 1-h exposures to heat stress with a rest break between increasing levels of heat stress. The data can then be inspected to find the inflection point for T_c. Another example of a progressive heat stress protocol is to increase the metabolic rate in a constant environment (40). In theory, the progressive heat stress protocol can be used for any condition that can be changed in small, monotonic steps in the direction of increasing heat stress. Miller and Bates used consecutive periods of 30 min in a constant environment in which they adjusted metabolic rate up or down in search of a steady state T_c at the highest metabolic rate (41).

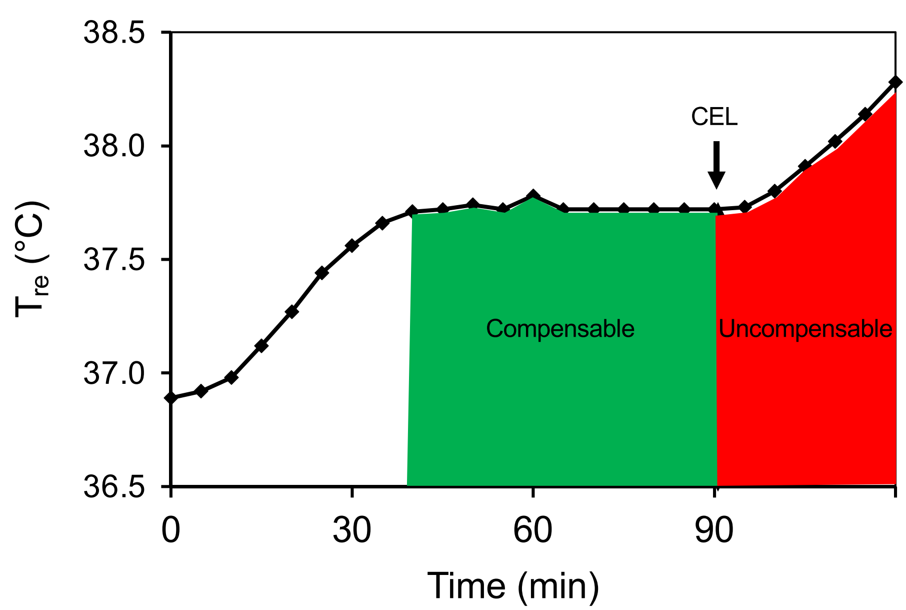

Figure 2. Illustration of zones of compensable and uncompensable heat stress based on the core temperature response of an individual to increasing levels of environmental heat stress at a given metabolic rate. Heat tolerance is defined as the transition from compensable to uncompensable heat stress, that is, the critical environmental limit (CEL).

Quantifying Individual Heat Tolerance

Data at the CEL are important indicators of the transition from compensable to uncompensable heat stress at specified metabolic rates and clothing ensembles, as demonstrated by the PSU Heat project described hereafter (25,29). For the purposes of operationalizing a heat tolerance as a single metric or index, we start by recognizing that heat stress is a combination of environment and metabolic rate and, thus, needs a single metric to represent both. On a psychrometric chart, a constant wet bulb globe temperature (WBGT) index has a slope of $-0.18°C \cdot kPa^{-1}$. Kenney reported WBGT slopes of −0.20 and $-0.16°C \cdot kPa^{-1}$ for woven clothing (*i.e.*, work clothes and coveralls) (42) and Bernard reported slopes of −0.16 and $-0.17°C \cdot kPa^{-1}$ for similar clothing (36). Because the WBGT and woven clothing have similar slopes, we chose the WBGT as the best index to represent the environment. We, therefore, propose three methods using $WBGT_{crit}$ and adjust it for metabolic rate and clothing.

The first method for using $WBGT_{crit}$ is an industry-based approach driven by investigators from the U.S. National Institute for Occupational Safety and Health (NIOSH) (43). NIOSH guidelines use a relation between WBGT and metabolic rate that describes a limiting WBGT at a given metabolic rate. This relation is termed the recommended exposure limit (REL) by NIOSH (44), the Threshold Limit Value® (TLV®) by the American Conference of Governmental Industrial Hygienists (45), and simply a limit value by the International Organization for Standardization (46). The WBGT-based *occupational exposure limit* (OEL) is a general description of these limits. The operational method is to relate the measured $WBGT_{crit}$ outcome to the OEL (27,47). Referencing heat tolerance to the OEL has the advantage of immediate applicability in WBGT-based exposure assessments. Using the WBGT-based OEL, the difference between $WBGT_{crit}$ and the OEL can be defined as ΔOEL as a function of metabolic rate (M) in watts (27,47) such that

$$\Delta OEL = WBGT_{crit} - OEL = WBGT_{crit} - [56.7 - 11.5 \ \log_{10} M] \qquad \text{Eq1}$$

In this manner, a positive value for ΔOEL (≥0) means that the individual has a heat tolerance greater than that required to work at the OEL. In contrast, a negative ΔOEL (<0) means that the individual does not have sufficient heat tolerance for a sustainable exposure at the OEL. We also demonstrated that this approach fully accounts for the relation between $WBGT_{crit}$ and metabolic rate (48). While this is called an occupational limit, it is based on the Lind ULPZ, which is applicable to non-occupational exposures as well.

A second method (47) normalizes the heat stress exposure by adjusting the value of $WBGT_{crit}$ to a reference metabolic rate (47). Garzón and colleagues reported a slope in a linear relation between $WBGT_{crit}$ in degrees Celsius and metabolic rate in watts as $-0.0201°C \cdot W^{-1}$ (27). Based on this relation, WBGT referenced to a steady state work intensity of 300 W ($WBGT_{300W}$) is

$$WBGT_{300W} = WBGT_{crit} + 0.0201^{*}(M - 300) \qquad \text{Eq2}$$

This approach to normalization means that $WBGT_{300W}$ is greater than $WBGT_{crit}$ when the metabolic rate is greater than 300 W and is less than $WBGT_{crit}$ when the metabolic rate is less than 300 W. This method still allows an approximate comparison to the OEL by comparing $WBGT_{300W}$ to the OEL at 300 W (*i.e.*, 28°C) (44,45).

The third approach follows the same procedure for $WBGT_{300W}$ but uses the metabolic rate divided by body surface area (BSA). Garzón and colleagues reported a slope in a linear relation between $WBGT_{crit}$ in degrees Celsius and metabolic rate in watts divided by BSA in square meters as $-0.0367°C\ m^2/W$ (27). Based on this relation, WBGT referenced to a steady state work intensity of 150 W/m^2 ($WBGT_{150W/m^2}$) is

$$WBGT_{150W/m^2} = WBGT_{crit} + 0.0367^{*}(M/BSA - 150) \qquad \text{Eq3}$$

The advantage of this method is that it accounts for the relation between $WBGT_{crit}$ and BSA (48). The downside of this method is many exposure assessment methods do not use metabolic rate adjusted for BSA.

Heat Tolerance Within a Population

The preceding sections described (1) methods to identify heat tolerance for an individual followed by (2) three methods that can be used to normalize heat tolerance data. Also of interest would be the distribution of heat tolerance within a population, for example, a particular workforce. For instance, a heat tolerance profile for healthy, hydrated, and acclimatized participants wearing woven clothing over a range of metabolic rates and humidity conditions using the ΔOEL metric is illustrated in Figure 3a. It is clear from the figure that there was a wide range of heat tolerance values from 0 at the OEL to 12°C above the OEL with a mean value at 6°C above the OEL. A similar outcome was found when $WBGT_{300W}$ was used (see Fig. 3b) where 28°C was equivalent to the OEL. Finally, the distribution standardized to BSA is offered (Fig. 3c). These figures represent heat tolerance profiles for the selected population of young, healthy, acclimatized, and hydrated individuals wearing a single layer of woven clothing over shorts and tee shirt/sports bra.

To develop a heat tolerance profile for a specific group of interest, such as middle-distance track athletes or workers with diabetes, the ΔOEL (or $WBGT_{300W}$ or $WBGT_{150W/m^2}$) data are rank ordered from the lowest to highest (47,49). The probability (p) for each observation is the rank (i, starting at 1) divided by the number of observations (n) plus 1; that is, $p_i = \frac{i}{n+1}$. The odds for each observation is $odds_i = \frac{p_i}{1-p_i}$. Then an ln(odds) linear regression estimates

$$ln\,(odds) = a + b\Delta OEL \qquad \text{Eq4}$$

for the intercept (a) and slope (b). Finally, the data are plotted as p versus ΔOEL and the descriptive line is

$$p = \frac{e^{(a+b\Delta OEL)}}{1 + e^{(a+b\Delta OEL)}}. \qquad \text{Eq5}$$

UTILITY OF HEAT TOLERANCE METRICS

Heat tolerance metrics have been used 1) to describe the effects of clothing on heat stress (49), 2) to estimate the effect of heat acclimatization on heat tolerance (48), and 3) to prescribe heat stress limits for everyday life (PSU HEAT), as described in the following sections.

Clothing Adjustment Values

The OELs originally were developed with individuals wearing long-sleeved cotton shirts and trousers, and this cotton work uniform was used as the reference value. $WBGT_{crit}$ was used to demonstrate that there is no difference between the cotton work uniform and cotton coveralls (35,36), or compared with cotton

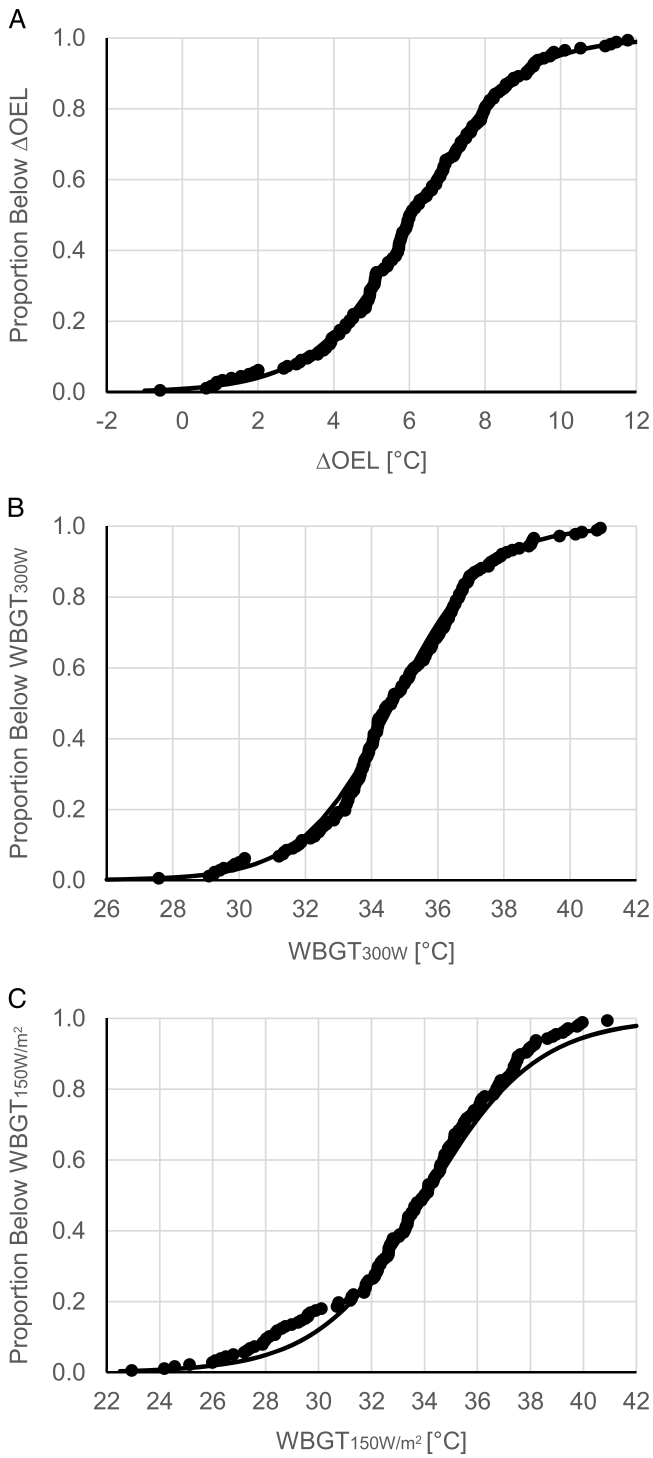

Figure 3. Population distribution of heat tolerance in terms of the difference from the occupational exposure limit (ΔOEL) (A), $WBGT_{300W}$ (B), and $WBGT_{150/m^2}$ (C). The population was young, healthy, acclimatized, and hydrated individuals wearing a single layer of woven clothing over shorts and tee shirt/sports bra. WBGT, wet bulb globe temperature.

versus flame-resistant fabrics based on treated cotton or man-made fibers (50). The approach was also used to demonstrate that full-face negative pressure respirators do not add to the level of heat stress (51). In contrast, nonwoven, particle barrier, water barrier, and vapor barrier fabrics add the equivalent of 1, 3, and 10°C WBGT, respectively, to the critical exposure (35,36). As another example, the effect of wearing a hood (head and neck covering) added 1°C to the WBGT (50). In addition, $WBGT_{crit}$ was used to demonstrate that the effective air permeability of clothing explained the evaporative resistance better than moisture vapor transfer rate (40).

A clothing adjustment value (CAV) is used to quantify the effective change in environmental WBGT with respect to the reference work clothes. CAVs (24,35,36,52) were adopted by the American Conference of Governmental Industrial Hygienists in promulgating their TLVs (45) for work in hot environments as well as the ISO WBGT-based exposure assessment (46). Whereas CAV values are based on averages, the exposure-response profiles for four different clothing ensembles described shift by the average amount for woven and vapor-permeable nonwoven fabrics (49). In the context of the conceptual model, the personal risk factors were controlled by a balanced, crossover design so that the different contributions of clothing could be investigated independent of the person.

Further, CAVs can be used in equations 1 to 3 to adjust data for different clothing ensembles (47). The CAV is subtracted from the observed $WBGT_{crit}$ to obtain an effective $WBGT_{crit}$. For example, equation 4 is representative of equation 1 for ΔOEL with the addition of CAV.

$$\Delta OEL = WBGT_{crit} - CAV - OEL$$
$$= WBGT_{crit} - CAV - [56.7 - 11.5\ \log_{10} M] \qquad \text{Eq4}$$

Heat Acclimatization

Most occupational and sport-based guidelines and standards use the term "acclimatization" to encompass both the short-term, often artificial (acclimation) and longer term, natural (acclimatization) physiological adjustments to heat stress. The conceptual model for quantifying heat tolerance can be used to investigate the contributions of acclimatization to heat tolerance. For example, occupational health and safety policy allows that acclimatization increases the acceptable WBGT exposure limit by approximately 2.5 to 3°C (43). The exposure response curve for nine women and nine men who were unacclimatized and seminude working at 30% of their individual maximum aerobic capacity based on ΔOEL (47) helps demonstrate the shift. There were two exposures each at high and low humidity levels. ΔOEL allowed for adjusting the different metabolic rates. The effects of acclimation were explored further over a broader range of metabolic rates and environmental conditions (48). The unacclimatized curve shifted 3°C to the left from Figure 3a and demonstrated a wider variability due to individual differences than the difference assigned to acclimatization.

Demonstration of Safe Limits for Everyday Life

Using the single-metric approach to defining heat tolerance described in the previous section is not the only way to quantitatively describe heat tolerance. The PSU HEAT project demonstrates the utility of the CEL directly. Identification of CEL values at metabolic rates associated with activities of daily living provides important information regarding heat tolerance limits for free-living individuals during heat waves. Recently, the PSU HEAT project has demonstrated the CEL for young adults (18–34 y) at two low rates of metabolic heat production across a wide range of environments (25,29). Subjects were tested in eight distinct environments ranging from warm-humid (P_{crit} trials) to hot-dry (T_{crit} trials) during light ambulation on a treadmill (LightAmb; M_{net} = ~130 $W \cdot m^{-2}$) and during minimal activity performed on a cycle ergometer (MinAct; M_{net} = ~80 $W \cdot m^{-2}$).

Those two metabolic rates were intended to approximate the demands of leisurely walking and activities of daily living performed in the home, respectively.

The mean CEL data with lower bounds of the 95% confidence intervals (CI; *i.e.*, the one-tailed 5th percentile) were plotted as psychrometric limits (*i.e.*, properties of atmospheric air that influence heat balance such as temperature and humidity) on a standard psychrometric chart (Fig. 4) (29). Using this graphical approach, the compensability of any combination of temperature and humidity can be assessed. Environments that are below and to the left of the 95% CI lines are considered to be compensable, and, therefore, reasonably well tolerated for prolonged exposures, for 95% of the population in this age range. Combinations that are above and to the right of the limit lines are uncompensable and, therefore, may be unsafe for prolonged exposures without any mitigating measures.

By examining the rate of rise in T_c below and above the CEL, projections can be made from and to any theoretical T_c to assess risk in real-world scenarios. In one investigation (25), heat storage and the rate of rise in T_c were examined below and above the CEL in MinAct and LightAmb. The rate of rise in T_c below or above the CEL was not significantly influenced by the environment or metabolic rate. Using the slopes established in that study, during physical activity in environments below the CEL, it would take an average of approximately 36 h without any intervention to reach a T_c > 40°C. In environments above the CEL, however, it would take as little as 3–7 h. These data may lend to development of recommendations for safe exposure times in environments that are above CEL.

FUTURE PERSPECTIVES

The preceding sections summarized past and current applications of the heat tolerance model. The two sections that follow describe some future applications as examples of other possibilities to demonstrate how the conceptual model can be used to frame research and practice questions.

Role of Heat Stress Contributors in the Conceptual Model

From the basic premise that heat stress can be described as the combined effect of environment (*i.e.*, WBGT), metabolic rate, and clothing, the discussion of CAVs demonstrates how the model is used for differentiating among clothing ensembles with a crossover design to control for personal factors. In a similar approach, the cost of lower evaporative resistance on productivity was demonstrated by adjusting metabolic rate rather than WBGT, controlling for personal factors in a crossover design (40).

There are few controlled studies on how well radiant heat is accounted for in WBGT. The question can be addressed by asking if ΔOEL (or $WBGT_{300W}$ or $WBGT_{150/m^2}$) and its profile are the same with and without one or more levels of radiant heat and the incidence angle of that radiant heat on the person.

In the context of communicating heat risk to the general population, various heat metrics that consider T_{db} and other environmental characteristics including humidity, wind velocity, and radiative heat gain have been proposed. Along with the WBGT, these indices include the heat index (HI), the universal thermal climate index (UTCI), and the humidex. Charts have been constructed for each of those metrics to denote danger

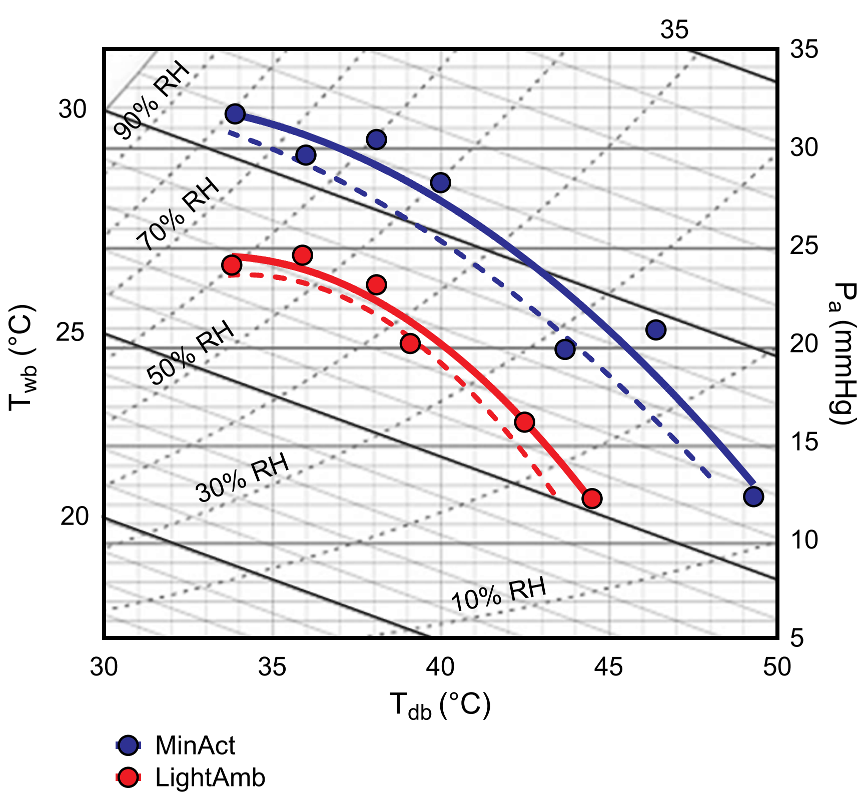

Figure 4. A standard psychrometric chart demonstrated critical environmental limits for young, healthy adults during light ambulation on a treadmill (LightAmb; M_{net} = ~130 W·m^{-2}) and during minimal activity performed on a cycle ergometer (MinAct; M_{net} = ~80 W·m^{-2}). Psychrometric curves for LightAmb are shifted downward and to the left relative to MinAct as a result of increased metabolic heat production. Figure updated and redrawn from (29).

thresholds at different combinations of temperature and humidity, although it is unclear how the thresholds were established.

Empirical CEL data from the PSU HEAT project were used to examine the effectiveness of WBGT, the HI, and the UTCI danger thresholds for predicting the temperature-humidity relation at the transition from compensable to uncompensable heat stress (53). For each metric, the two highest danger thresholds were used to compare against the mean and 95% CI CEL data. At very low metabolic rates, the HI was adequate for describing the temperature-humidity relation at the upper limit of compensability, whereas the WBGT was less suitable and the UTCI was not at all effective. At increasing metabolic rates, however, none of the indices adequately described the transition from compensable to uncompensable heat stress.

Role of Personal Factors in the Conceptual Model

Personal factors are a key feature of the conceptual model. Asking questions about the effects of individual or combined factors on heat tolerance is a straightforward process.

Anthropometrics

Anthropometric factors help characterize a population and can be used as a treatment effect in a study design. For instance, comparing men versus women, young versus old, or lean versus obese. For these questions, the control of situational factors is common. More difficult is the control of modifiable and inherent factors. To the extent that contrasting populations with identified modifiable or inherent factors can be identified, the heat tolerance of each population can be compared. The unidentified factors are usually confined to the error term.

Situational personal factors

The situational personal factors in the conceptual model are those factors that can be controlled in a study and where an intervention can be easily and obviously part of the supervising organization's policies and practices. It is widely recognized that acclimatization state and hydration state affect heat strain and, thus, heat tolerance. In addition, situational factors such as performance expectations, voluntary and forced overtime, work practices, and incentives can affect heat tolerance. Another situational factor is the pattern of exposures over days, in which high heat exposures on a previous day (12) or days (10,11) influence the risk of heat disorders on the current day. Among personal factors, acclimatization and hydration are easily managed by policies and practices with some cooperation from the individual. Other situational factors may be less obvious but can be controlled by the organization. There may be times that the organization must include the formal cooperation of labor such as setting pay and overtime rules, or the athletic organization sets policies on the needed recovery time from a previous endurance event (*e.g.*, distance running). In this regard, some considerations may include:

- Tracking heat tolerance following different protocols for recovery within a day or across days;
- Track progression of heat tolerance following different acclimation/acclimatization protocols;
- Compare the effects of prescribed versus self-directed recovery at work or during team practices.

Modifiable personal factors

Modifiable personal factors may reduce heat tolerance but may be changed by the individual outside of the context of a research study or heat stress management. These factors include, among others, obesity, use of certain medications and drugs, lack of sleep, and low fitness level. This group of personal factors can be modified by the individual; however, there is a need to educate individuals about how these intrinsic factors can negatively impact their heat tolerance. For instance, many may not know that sleep deprivation may make them more susceptible to heat stroke (9). Although the organization may have no control over these personal factors, organizational policies and support can promote the risk reduction of these personal factors.

- Compare obese to lean with matching of fitness (using $WBGT_{150/m^2}$);
- Compare heat tolerance to use versus nonuse of over-the-counter supplements;
- Well rested and recovered from previous exposure due to lack of sleep.

Inherent personal factors

The fourth group of personal factors are inherent to the individual and are generally refractory to interventions. These personal factors include genetics, physiological capacity, and chronic disease.

- Contrast healthy to specific diseases that may impair heat tolerance;
- Contrast normal genetic/epigenetic markers to those associated with increased heat susceptibility.

Personal factors collectively contribute to the interindividual variability and may explain intraindividual variability. Further, there may be interactions between heat stress and personal factors that can be explored. The conceptual model provides a framework to see how they change heat tolerance.

SUMMARY

Determination of the CEL at a specified metabolic rate and clothing condition using a progressive heat stress protocol is an efficient and effective method to assess a threshold environmental limit between compensable and uncompensable heat stress, *i.e.*, heat tolerance. It is then a simple step to quantify heat tolerance with the addition of metabolic rate and clothing. The conceptual model provides a framework to assess the effects on heat tolerance due to personal factors. The model divides risk factors into four categories of demographics and how easily the risk factors can be a focus of intervention. The current article demonstrates how the CEL and heat tolerance were used to demonstrate quantitatively the difference between unacclimatized and acclimatized participants, to assign clothing adjustment values to account for different clothing, and to map out psychrometric limits for defined activity and clothing.

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