Graphical determination of heat tolerance limits

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This paper describes a simple graphical method for determination of heat tolerance limits (HTL) for any situation in which air movement, metabolic heat production and clothing insulation are specified. HTL are presented as a function of operative temperature (abscissa) and water vapour pressure (ordinate). Comparison of results obtained graphically by this method with experimentally determined limits found in the literature shows good agreement.

1. Introduction

Setting environmental limits for work is difficult despite the numerous studies concerned with this problem (MacPherson 1960, Lind 1963, 1973, Belding and Kamon 1973, Kamon 1976, Kamon and Avellini 1976, 1979, Kamon et al. 1978). Limits may be set experimentally from measurements of metabolic rate, clothing, air velocity and radiant fields, but practical use of these limits is restricted to the same set of conditions. The only rational proposals for a heat tolerance limit for any environment and any clothing or metabolic rate are the humid operative temperature $T_{0h}$ proposed by Gagge and Nishi (1972) and its derivative $ET^*$, the New Effective Temperature developed by Gagge et al. (1971).

Practical application of $T_{0h}$ or $ET^*$ to determine heat tolerance limits is possible either using a two-node model of man's temperature regulation (Gagge 1973) or, as proposed by Nishi and Gagge (1974), by application of a simple graphical method. Their heat tolerance limits of both thermal indices $T_{0h}$ and $ET^*$ are the loci of fully wetted skin drawn on the psychrometric chart. Such limits are represented by straight lines and assume no limitation due to sweating rate as long as the standard operative temperature does not exceed 60°C or as long as the standard humid operative temperature does not exceed 39°C (Gagge 1973).

Kamon and Avellini (1976) showed that at each activity level the upper limit of the tolerable thermal zone, defined as the combinations of air temperatures and humidities above which rectal temperature no longer remains steady, is not one single straight line, but is described by a discontinuous line on the psychrometric chart. The first part extends over a range of lower air temperatures corresponding to limits of exposures where the skin is fully wetted; the second over a range of higher air temperatures representing limits of exposure where the skin is only partly wet. In the range covered by the second segment it appears that skin wetness decreases gradually with increasing air temperature. Lines of equal predicted 4-hour sweat rate (MacPherson 1960) and of equal sweating rates, suggested by Kerslake (1972) from experiments on a wetted cylinder, show discontinuities similar to the line suggested by Kamon and Avellini. Vogt et al. (1981) found that the upper tolerable limit of heat exposure is described by a succession of two or three lines (similar to those of Kamon), when taking into account maximal skin wetness, maximal sweating capacity and sweating efficiency (Candas et al. 1979).
The aims of this paper are (a) to develop Nishi and Gagge's (1974) graphical method of determination of heat tolerance limits to account for maximal regulatory sweat rate and its efficiency and (b) to compare the heat tolerance limits predicted by the developed method with results from the literature.

2. Analytical construction of a heat tolerance limit

Following Nishi and Gagge (1974), we can write the heat balance equation as

\[ 0 = \dot{M}_{sk} - h_{0}F_{cl}(\bar{T}_{sk} - T_{0}) - wh_{l}F_{pc}(P_{s,sk} - P_{a}) \]  

(1)

where \( \dot{M}_{sk} \) is the metabolic heat production transferred through the skin (W m\(^{-2}\)) (in hot conditions \( \dot{M}_{sk} \) equals the total metabolic heat production since respiratory heat loss can be neglected), \( h_{0} \) is the combined heat transfer coefficient (W m\(^{-2}\) \( ^{\circ}\)C\(^{-1}\)), \( F_{cl} \) is the clothing efficiency factor for dry heat exchange which is non-dimensional (nd), \( \bar{T}_{sk} \) is the mean skin temperature in \( ^{\circ}\)C and \( T_{0} \) is the operative temperature in \( ^{\circ}\)C. In the evaporative heat loss, \( w \) is skin wetness, expressed as the equivalent fraction of the total body surface which, if fully wetted would yield the observed evaporative heat loss, \( h_{l} \) is the evaporative heat transfer coefficient (W m\(^{-2}\) kPa\(^{-1}\)), \( F_{pel} \) is the clothing efficiency factor for water vapour permeance (nd), \( P_{s,sk} \) is the saturated water vapour pressure at skin temperature (kPa) and \( P_{a} \) is the ambient water vapour pressure (kPa). The quantities \( F_{cl} \) and \( T_{0} \) are defined by

\[ F_{cl} = 1/[1 + (h_{c} + h_{l})I_{cl}], \]  

(2)

\[ F_{pel} = 1/[1 + 0.923h_{l}I_{cl}], \]  

(3)

\[ T_{0} = (h_{c}\bar{T}_{a} + h_{l}\bar{T}_{r})/(h_{c} + h_{l}), \]  

(4)

where \( I_{cl} \) is the thermal insulation of the clothing in units of m\(^{2}\)K\(^{-1}\)W\(^{-1}\), \( \bar{T}_{a} \) and \( \bar{T}_{r} \) are the dry bulb air temperature and the mean radiant temperature, respectively, in \( ^{\circ}\)C, and \( h_{c} \) is the convective heat transfer coefficient (W m\(^{-2}\) \( ^{\circ}\)C\(^{-1}\)). \( h_{c} \) is a function of the effective air velocity \( V_{ae} \) (m s\(^{-1}\)). According to Missenard (1973) \( h_{c} \) is 3.5 + 5.2\( V_{ae} \) if \( V_{ae} \leq 1 \) m s\(^{-1}\) and 8.7\( V_{ae}^{0.6} \) if \( V_{ae} > 1 \) m s\(^{-1}\). Finally, \( h_{l} \) is the linearized radiative heat transfer coefficient, assumed to be equal to 5 W m\(^{-2}\) \( ^{\circ}\)C\(^{-1}\).

Nishi and Gagge rewrite equation (1) in the form

\[ T_{0} - T_{M} = (w/\psi)(P_{s,sk} - P_{a}), \]  

(5)

where \( T_{M} = \bar{T}_{sk} - \dot{M}_{sk}/h_{0}F_{cl} \) corresponds to a virtual temperature for which the evaporation rate equals zero (\( ^{\circ}\)C), while \( \psi = h_{l}F_{cl}/h_{l}F_{pel} \) expresses the relationship between the respective decrease in vapour pressure and increase in operative temperature for which the skin will remain fully wet (kPa \( ^{\circ}\)C\(^{-1}\)).

Equation (1) can also be rewritten in the form

\[ T_{0} - T_{M} = \dot{m}_{sw} \cdot \eta_{sw}/h_{0}F_{cl}, \]  

(6)

where \( \dot{m}_{sw} \) is the sweat rate expressed in W m\(^{-2}\), \( \eta_{sw} \) is the sweating efficiency (nd) and therefore the product \( \dot{m}_{sw} \cdot \eta_{sw} \) is the rate of evaporative heat transfer in W m\(^{-2}\), equal to \( wh_{l}F_{pel}(P_{s,sk} - P_{a}) \).

Givoni (1963) has shown that \( \eta_{sw} \) is a function of skin wetness, \( w \), for working subjects. Similar results have recently been obtained by Candas et al. (1979) for resting subjects. An equation fitted to the results of table 3 from the paper by Candas et al. (1979), shows that for 0.5 < \( w < 1.0 \), the relationship between these variables is

\[ \eta_{sw} = 1 - 0.42 \exp[-6(1.0 - w)]. \]  

(7)
In order to simplify this equation, we can take $\eta_{sw} = 1$ as long as $w < 0.5$ and consider that for $0.5 < w < 1.0$, $\eta_{sw}$ decreases linearly with increasing $w$ until $\eta_{sw} = 0.5$. Such a simplification underestimates $\eta_{sw}$, thus introducing a safety factor for working subjects, since equation (7) was obtained for resting supine subjects. The upper limit of the tolerable zone can then be defined as the thermal conditions for which (a) the required sweat rate, $\dot{m}_{sw}$, is equal to the maximal sweating capacity, $\dot{m}_{sw,max}$, and (b) the skin wetness $w$ equals the maximal skin wetness consistent with the heat balance equilibrium $w_{max}$.

When plotted on a psychrometric chart with operative temperature as the abcissa and vapour pressure as the ordinate, the upper limit of a tolerable zone is delineated by at most three straight lines as drawn in figure 1. The main features of these lines are fixed as follows. Point A is set by conditions for which the evaporative rate would equal zero; thus its coordinates are $T_m = T_{sk} - M_{sk}/h_{cl}$ and $P_v = P_{sk}$. Lines AB and AC correspond to wetness ($w$) of 1 and 0.5, respectively, according to equation (5) and line AD represents the maximal wetness consistent with the heat balance equilibrium (taken as $w = 0.85$ in figure 1).

The discontinuous line EFGH describes the thermal conditions for which the required sweat rate is equal to the maximal sweating capacity ($\dot{m}_{sw,max}$). Segment EF corresponds to those conditions requiring skin wetness lower than 0.5, for which sweating efficiency equals 1 and sweat rate is not influenced by ambient water vapour pressure. Segment FGH corresponds to those conditions for which sweat efficiency decreases. According to equation (6), and to the approximation of equation (7), the

![Graphical method proposed in the present work for the determination of a heat tolerance limit. Point A co-ordinates are given by equation (5). Lines AB, AC and AD correspond to skin wetness of 1.0, 0.5 and 0.85 according to equation (5). A'E, A'F and A''H values are calculated according to equations (9) and (8) (metabolic heat production $= 100 \text{ W m}^{-2}$; clothing insulation = 0.5 Clo or 0.077 m$^2$ K W$^{-1}$; air velocity = 0.4 m s$^{-1}$; possible sweat rate taken to be 300 g hour$^{-1}$ m$^{-2}$).]
operative temperature difference corresponding to $A'E$ and $A''F$ is

$$A'E = A''F = T_0 - T_M = \dot{m}_{\text{sw, max}}/h_0 F_{cl}$$  \hspace{1cm} (8)$$

while $A''H$ is

$$A''H = T_0 - T_M = \dot{m}_{\text{sw, max}}/2h_0 F_{cl}.$$  \hspace{1cm} (9)$$

The upper limit of a tolerable zone thus becomes the curve EFGI. Below this limit sweat rate is less than $\dot{m}_{\text{sw, max}}$ and skin wetness is consistent with the heat balance equilibrium. Above this limit, sweat rate and/or skin wetness exceed the maximum values considered consistent with the heat balance equilibrium.

3. General procedure for setting heat tolerance limits

For any situation in which air movement, clothing and metabolic heat production are specified, heat tolerance limits (HTL) can, therefore, be drawn on a psychrometric chart by this graphical procedure, which is based on the estimation of the upper limits of sweating capacity (equation (6)) and of skin wetness (equation (5)).

In order to compare the HTL determined by this method with limits reported in the literature we must (a) consider the clothing, metabolic heat production and effective air movements reported by the authors and (b) assess values of sweating capacity and skin wetness. Most of the experimental determinations of HTL that we will now consider are consistent with the definition given by Leithead and Lind (1964) for 'just-tolerable limits': the loci of ambient conditions for which a 4-hour continuous exposure is acceptable without any serious health threat, especially of a continuous increase in body temperature.

This corresponds to the following limits: (a) The maximum sweating capacity consistent with a 4-hour exposure can be fixed at 400 W m$^{-2}$ (McArdle et al. 1947, Belding and Hatch 1956) for acclimatized humans. We suggest it is reduced to 250 Wm$^{-2}$ for unacclimatized humans. (b) The maximal wetness consistent with the heat balance equilibrium can be fixed at 0.5 for unacclimatized and 0.85 for acclimatized humans (figure 5 from Candas et al. 1979).

On the basis of these values it becomes possible to draw the HTL on a psychrometric chart (by the method developed in figure 1) for different sets of conditions, and to compare them with limits reported in the literature.

3.1. Effect of air velocity on HTL

Kamon and Avellini (1979) compared the effect of three air velocities (1, 2 and 4 m s$^{-1}$) on the HTL for clothed (0.093 m$^2$ K W$^{-1}$ = 0.6 Clo) acclimatized male subjects working at levels requiring 191 W m$^{-2}$ of metabolic heat production. The subjects walked on a treadmill at a speed of 1.56 m s$^{-1}$, and we evaluated the effective air velocities as 1.16, 2 and 4 m s$^{-1}$ according to Nishi and Gagge (1970). For this evaluation we considered that each region of the body (table 4 of Nishi's paper) experienced a relative air velocity corresponding at least to that generated by walking, and at most to that corresponding to the air movement itself. On figure 2 we have plotted the experimental values obtained by Kamon (points) and the limits drawn according to the above defined limits of maximal sweating capacity and maximal skin wetness (lines). The location of these lines as well as their differences for the three air velocities are in good agreement with Kamon's observed values.
Figure 2. Comparison between heat tolerance limits drawn with the present method for three air velocities \( V_a \) (lines) and experimentally determined limits by Kamon and Avellini (1979) (points).

3.2. Effect of clothing insulation on HTL

Kamon (1976) and Kamon and Avellini (1976) determined the limits for prolonged exposure to work under hot conditions for acclimatized women clothed with 0.15 or 0.6 Clo (0.023 and 0.093 m² K W⁻¹) garments. Metabolic heat production was 196 W m⁻² during the experiments with 0.6 Clo garment insulation and 152 W m⁻² during the experiments with 0.15 Clo garment insulation. Effective air velocity was estimated as 1.16 m s⁻¹. The theoretical locus of HTL, drawn according to the suggested method, is again in close agreement with Kamon's experimental values, as shown in figure 3.

3.3. Effect of acclimatization on HTL

It is generally agreed that acclimatization increases both the maximal sweating capacity and the maximal skin wetness consistent with the heat balance equilibrium. We can draw, on a psychrometric chart, the HTL for acclimatized and unacclimatized subjects wearing a 0.15 Clo (0.023 m² K W⁻¹) garment and working at a metabolic heat production of 216 W m⁻² in an effective air velocity of 1.3 m s⁻¹. The two limits can be compared to those suggested for similar conditions by Wenzel (1970), Lind (1973) and Robinson (1945). Figure 4 shows reasonable agreement between prediction and observation in both cases.

3.4. Effect of metabolic heat production on HTL

From Lind's experiments (1963) it is possible to suggest three limits located at 26.5, 28.2 and 30.2°C corrected effective temperature, respectively, for 270, 190 and 115 W m⁻² of metabolic heat production. In Lind's experiments subjects were not
Figure 3. Comparison between heat tolerance limits drawn with the present method for two clothing insulations $I_{cl}$ (lines) and experimentally determined limits by Kamon et al. (1976, 1979) (points).

Figure 4. Comparison between heat tolerance limits drawn with the present method for acclimatized and unacclimatized male subjects (thick lines) and limits suggested by several authors (fine lines).
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acclimatized, had 0.15 Clo (0.023 m² kW⁻¹) insulation and were exposed to a 1.2 m s⁻¹ effective air velocity. Figure 5 again shows good agreement between our calculated curves and Lind's corrected effective temperature limits.

3.5. Sex differences in HTL
Kamon et al. (1978) compared the upper tolerable limit for steady state rectal temperatures in acclimatized men and women. During these experiments subjects had a metabolic heat production of 194 W m⁻², effective air velocity was 1.16 m s⁻¹ and clothing insulation was 0.4 Clo (0.062 m² kW⁻¹). Kamon observed maximum sweating rates of 450 W m⁻² for men and 380 W m⁻² for women. Applying these values of maximal sweating capacity in equation (6) we plotted the HTL in figure 6. Agreement with experimental values is good and is consistent with sex differences.

4. Conclusion
The assumption of a maximum sweating capacity of 400 W m⁻² for acclimatized and 250 W m⁻² for unacclimatized subjects, together with maximum wetnesses of 0.85 for acclimatized and 0.50 for unacclimatized subjects allows estimates of HTL which are in good agreement with experimental values in the literature. Differences between the theoretical curves and either the experimental values or the curves from other authors are generally within a range of ±2°C for a fixed pressure or ±0.2 kPa for a fixed temperature. Graphical determination of just-tolerable limits, as defined by Leithead and Lind (1964), therefore, becomes possible for any situation in which air movement, clothing and metabolic heat production are specified.
Limits for easily-tolerable conditions (Leithead and Lind 1964) may be set at lower values of maximal sweating capacities in order to prevent hydromineral disorders. In agreement with a World Health Organization expert committee (1966), a maximal sweat loss of 2000 Wh m\(^{-2}\) over the whole duration of a shift can be proposed for acclimatized male operators, with a sweating rate of 250 Wm\(^{-2}\) for an 8-hour shift. Lower values have to be considered for unacclimatized humans. These values, together with maximum skin wetnesses of 0·85 for acclimatized and 0·50 for unacclimatized operators, would allow the setting of limits for easily-tolerable conditions, by applying the proposed procedure.

As shown in figure 6, differences of maximum sweating capacity, which is the most difficult parameter to assess, have a relatively small effect on HTL. The difference of 70 Wm\(^{-2}\) between males and females lowers the limit by 3°C ambient temperature or by 0·5 kPa vapour pressure, since only a part of this difference is effective in terms of evaporative heat loss.

Dans cet article on décrit une méthode graphique simple pour la détermination des limites de tolérance à la chaleur (HTL) pour toutes les situations où la vitesse de l'air, la production métabolique de chaleur et l'isolation vestimentaire ont été spécifiées. Les HTL sont présentées en fonction de la température opérative (abscisses) et de la pression de vapeur d'eau (ordonnées). On constate un bon accord entre les résultats obtenus par voie graphique et les résultats obtenus par l'expérimentation et rapportés dans la littérature.

In diesem Beitrag wird ein einfaches graphisches Verfahren zur Bestimmung der Hitzetoleranzgrenzen (HTL) beschrieben, wobei die Windgeschwindigkeit, der Energieumsatz und die Isolationswirkung der Kleidung bekannt sein müssen. Die HTL werden als Funktion der Operativtemperatur (Abszisse) und des Wasserdampfdruks (Ordinate) dargestellt. Die mit dieser Methode erhaltene Ergebnisse sind in guter Übereinstimmung mit experimentell bestimmten Grenzen aus der Literatur.
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References


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