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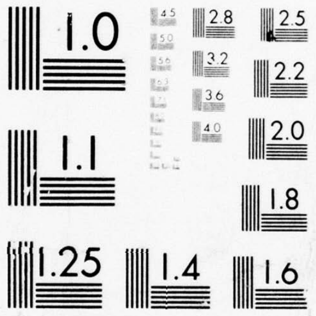

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Prediction of Human Heat Tolerance

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Running head: Human heat tolerance

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ASSESSMENT OF A "HOT" ENVIRONMENT

Man interacts with his thermal environment by four different avenues of heat exchange: conduction, convection, evaporation and radiation. Assessment of heat stress clearly requires measurement of those environmental factors which control the heat transfer between man and his environment by these four avenues.

Conduction of heat occurs at the interface between the body's skin surface and the surface of any contacting substance, be it solid, liquid or gas. The transfer of energy occurs as the result of a microcosmic billiard game, with direct contact of the molecules at the interface transferring thermal energy in proportion to the temperature difference of the two objects until the two surfaces come to equal temperatures; at that point, although the surface electrons continue to "bang" each other, both surfaces have essentially equal energy. The heat exchange between them is balanced, so no net heat flow occurs between the surfaces. When the human body is in contact with a finite body, the amount of heat exchanged until this equilibrum is established depends on the relative masses (kg) of the two bodies, their specific heats (kcal/kg°C) and the initial temperature difference.

The specific heat of the human body tissues averages 0.83 kcal/kg°C. We can calculate an average "comfortable" body temperature ($T_b \approx 35^\circ C$) by considering the body as a two compartment model with 1/3 of its mass at skin temperature ($\bar{T}_s = 33^\circ C$) and the remaining "core" at rectal temperature ($T_{re} = 37^\circ C$). Thus:

$$\bar{T}_b = 1/3\bar{T}_s + 2/3T_{re} \qquad \text{Eq 1}$$

Assume an average man (defined as a man of 70 kg weight (m), 18.5% body fat, 173 cm tall, with $1.8 m^2$ of body surface area (A)) ingests one liter of 60°C water-carefully, since this is near the maximum tolerable temperature for a hot beverage. Then, since the mass of one liter of water is one kg and the specific heat of water is one kcal/kg °C, his mean body temperature must rise as a result of the extra 25 kcal of heat energy (i.e. for the water, c_p x m x (60-35) = 1 kcal/kg·°C x 1 kg x 25°C). Assuming none of these 25 kcal are transferred from the body's skin to the environment, then mean body temperature will rise by ~ 0.4°C (i.e. by 25/(0.83 x 70)). Note that this relationship, i.e. that an average man (m=70kg) changes his body temperature ($\overline{T}_b$) by 1°C when there is a 58.1 kcal (i.e. 0.83 x 70) change in his heat content, is the same whether heat is gained or lost from the body. Thus, a measured change in mean body temperature can be calculated to represent a change in body heat storage (ΔS) of a given number of kcal over a period of time: i.e.

$$\Delta S = 0.83 \times m \times (T_{b_1} - T_{b_0}) \qquad \text{Eq 2}$$

where T_{b_0} represents the initial mean body temperature at some initial reference time and T_{b_1} represents the temperature at the end of the time interval for which the change in heat storage is being calculated.

Conduction of heat is generally of limited interest in thermal environmental heat physiology, since man is seldom immersed in hot water and he rarely lies down on hot desert sand. Thus, the surface area across which heat conduction occurs is limited and, since all heat transfer is a linear function of the surface area involved, the magnitude of human heat transfer by conduction is generally small enough to be ignored. Nevertheless, the equation for conductive heat exchange (H_{con}):

$$H_{con} = k \ \ A \ \ (\overline{T}_s - T_{obj}) \qquad \text{Eq 3}$$

where k is the coefficient of conduction, A is the contact area, $\overline{T}_s$ is the body skin temperature and T_{obj} is the object surface temperature

is of significance in calculating time/temperature relationships for contact burns, with long (3-5 hour) contacts with 42°C wires producing pin point blisters even though the pain threshold for skin contact is closer to 45°C (14).

Heat transfer by convection occurs only as a sequel to conductive heat transfer; the initial transfer of heat energy is by "billiard ball" conduction at the interface of any solid, liquid or gas. However, with liquids or gases, the initial energy received by conduction can set up a flow of energy away from the surface by "convection" currents. This close association of convection with conduction is reflected in the terminology of earlier thermal physiologists, who occasionally used the terms interchangeably. Heat transfer by convection in air is, again, a linear function of surface area (A); generally the entire $1.8m^2$ surface area can be considered as available for convective transfer for the average man, with no allowance for dead air space between the extremities and the torso. Any imprecision introduced is probably no worse than that induced by estimating another value for the available skin surface area, and by the effects of local turbulance around the various body cylinders, since the convective heat transfer coefficient (h_c) is a function of the ambient air motion (V) taken to the 0.6 power ($V^{0.6}$). The amount of heat lost by convection depends upon the difference between the skin surface temperature ($\bar{T}_s$) and the air temperature (T_a).

There is an insulating film of still air (I_a) surrounding every physical object; its thickness depends on the relative motion of the air layer. To avoid errors in measuring air temperature which might result from heat stored in the thermometer being retained by this insulating film, the usual measurement of air temperature is with a dry thermometer bulb exposed to an air motion > 3 m/sec. This movement is produced by using a thermometer slung at the end of a chain (a "sling" psychrometer), or an "aspirating" psychrometer with air drawn over the thermometer by a fan. The "dry bulb temperature" (T_{db}) measured is taken as the air temperature.

The equation for convective heat loss (H_c) can therefore be written as:

$$H_c = kV^{0.6}\ A\ (\bar{T}_s - T_{db}) \qquad \text{Eq 4}$$

The heat transfer coefficient (h_c) equals $kV^{0.6}$, and k depends on such properties of the surrounding medium as its density, viscosity, etc. and a dimension/shape factor for the body, etc. While these details can be calculated fairly rigorously from physical principles for the nude man, the confounding effects of clothing generally defy rigorous physical analysis and less rigorously derived approximations are used. Belding (1) suggests a value of 12 kcal/hr °C for an average "nude" laboratory *subject* (1.8 m^2) *with a* 35°C *skin temperature in a hot environment* (i.e. convective heat gain) wearing shorts and tennis shoes at a given air motion (V in m/s): e.g.

$$H_c = 12\ V^{0.6}\ (T_{db} - 35) \qquad \text{Eq 5}$$

and suggests that adding a light, long sleeved shirt and trousers reduces h_c, and thus H_c, by 40%. An approach involving direct measurement of clothing insulation (clo) can also be used to determine h_c.

Two factors from the thermal environment have thus far been identified if one is to assess a hot environment; air temperature (T_{db}) and air velocity (V). A third factor is required in environments where the temperature of walls, or other objects in the surround, differs from air temperature. Indeed, heat transfer by radiation is not only independent of air temperature but occurs whether air is present or not. Even in a vacuum, heat is transferred by radiant energy exchange; the wave lengths of the radiant beams exchanged between any two objects are related to the temperature of their surfaces, and the net heat transfer by radiation is proportional to the difference between their absolute temperatures to the fourth power and to the relative reflective and absorptive properties of the two surfaces. Generally, the temperatures of objects which surround the human body, except for the sun, are still low enough that the wave length of the heat radiation allows almost total absorption of the energy at the skin or clothing surface; i.e. the body surface behaves like a black body and its temperature is raised above the ambient air temperature to an extent determined by the rate at which convection prevents the still air layer at the surface from entrapping all the radiant heat arriving at the surface. Mean radiant temperature, as it effects the human body, is most readily assessed using an instrument where the relationship between its convection (h_c) and its radiation coefficient (h_r) is approximately the same as the relationship for a human body. A 15.4 cm globe, painted flat black, has a value of 0.178 for the ratio h_c/h_r which closely approximates the corresponding ratio for an average human body (16). The globe temperature, measured by a thermometer whose bulb is at the center of the hollow, thin walled, blackened 15.4 cm sphere, is used directly in several environmental heat stress indices. However, the net radiant heat exchange between a man and his radiant surroundings requires estimation of an average, or mean radiant temperature (MRT); MRT can be calculated from the black globe temperature (T_g) as:

$$MRT = T_g + 1.8\sqrt{V}(T_g - T_{db}) \qquad \text{Eq 6}$$

Such an approach is, again, of greatest use for assessing the net radiant heat gain (or loss if $MRT < T_s$) for a nude body. Belding suggests estimation of radiant heat exchange for a subject wearing shorts and tennis shoes by the relationship:

$$H_R = 11 \quad (MRT - \bar{T}_s) \qquad \text{Eq 7}$$

with the same reduction to 60% of this level as for convection when a long sleeved shirt and trousers are worn. The area of an average man for radiant exchange is some 20% smaller than the total $1.8m^2$ of skin surface, because some of the skin surfaces (e.g. legs, arms) face each other rather than the ambient radiant environment. Nevertheless, few workers make any distinction and the entire $1.8m^2$ is used in the calculations. Direct measurement of clothing insulation with a heated copper manikin avoids this problem, and provides a combined measurement of $H_C + H_R$.

Solar heat load poses a different set of problems. We have suggested (2) that the three components of a solar heat load[1] received by the body can be handled by three pairs of equations, one of each pair treating the fraction of the total solar load absorbed at the body surface, the other that fraction transmitted through the clothing to the skin surface. The total solar heat load to the surface of a clothed man can, we suggest (12), be estimated from the solar constant, zenith angle, cloud cover, humidity and dust content of the air and the like. Although complex, this approach seems preferable to the oversimplification of simply increasing the T_{db} by 7^oC to compensate for a maximum solar load in the desert, as suggested by Lee (9).

The fourth, and final environmental factor that must be assessed to describe a thermally hot environment is only relevant for physical objects with water available at their surface, for evaporation. The capacity of air to take up water is limited by the temperature of the air; a thermometer with a wick, saturated with water, surrounding its bulb is used to measure the ability of air to take up additional moisture. Air holding all the water it can is said to be "saturated", at 100% relative humidity. In such an environment, no water will be evaporated from the wetted wick and, thus, the measured "wet bulb temperature" (T_{wb}) will be the same as the air temperature (T_{db}). When the environmental air is at less than 100% relative humidity, evaporation can take place, but may be limited by the still

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[1] 1) Incident direct radiation, 2) Diffuse indirect solar radiation and 3) Albedo terrain reflected solar radiation

air layer surrounding the wet bulb as it becomes saturated. In the measurement of T_{db}, any radiant heating was minimized by using a sling psychrometer or aspirated measurement of dry bulb temperature; the same approach (inducing air movement) is used to maximize evaporative cooling. The psychrometric wet bulb temperature (T_{wb}), so measured, is converted to an equivalent relative humidity with a psychrometric chart. Indeed, one can plot tolerance time for heat (and cold) on such a chart (Fig. 1A); note that the T_{db} are represented as perpendicular lines (and cold tolerance follows these lines), while the T_{wb} are diagonal lines, and heat tolerance falls along these diagonals. The point of intersection of the perpendicular T_{db} and diagonal T_{wb} lines representing a pair of psychrometric measures for a given environment, gives the relative humidity for that combination of T_{db} and T_{wb}. More importantly, it also establishes the vapor pressure of the water contained in the air; the ambient vapor pressure is given on the y axis, at the level of the intersection of $T_{db}+T_{wb}$. The saturated vapor pressure (P_a) for a given T_{db} is only a function of the T_{db}; P_a is obtained from the chart at a level parallel to the point on the 100% RH line where T_{db} equals T_{wb}. The vapor pressure at different relative humidities (ϕ_a) can be calculated as $\phi_a P_a$. Note that the slope of the T_{wb} lines is constant across all temperatures, and approaches $2.2^{o}C/mmHg$; this 2.2 value can be derived from the physical relationship between the evaporative heat transfer coefficient (h_e) and the convective heat transfer coefficient (h_c), and is called the "Lewis number" or psychrometric constant. The actual slope of the T_{wb} lines is closer to $2^{o}C$, because of radiant and convective heat gained by the cooler, wet surface even with a psychrometric wet bulb measurement. However, the Lewis relationship implies that the evaporative heat transfer coefficient should be directly related to the convective heat transfer coefficient, with the relationship $h_e=2.2\ h_c$.

Water will actually condense out on any surface which is below air temperature in a saturated environment, since vapor pressure in the air is greater than the vapor pressure at the surface. Water will accumulate on the surface, imposing a heat load of 0.58 kcal/cc of water so condensed; i.e. the specific heat of condensation of water is 0.58 kcal/gram. Thus, a substantial heat load can be incurred in a typical 49°C "Turkish" steam bath just from the heat of condensation. Conversely, evaporative cooling can occur from a wetted surface even into a saturated environment, as long as the surface temperature is above air temperature. The controlling difference for evaporative cooling is not, therefore, a relative humidity gradient but the gradient between the vapor pressure of water at the surface temperature (P_s) and the water vapor pressure of the air ($\phi_a P_a$). One can consider that the water evaporates from the skin surface into the adjacent, still air layer, which is unsaturated because its temperature is above the air temperature, and then moves away by convection to condense at the interface between the still air layer and the ambient air. Such a reaction produces a readily observed mist when one removes a sweaty glove or sock from the skin in a cold environment. Evaporative cooling removes 0.58 kcal/cc of water evaporated; i.e. the latent heat of evaporation is 0.58 kcal/gm.

Evaporative heat transfer (H_E) for a human body is almost always a heat loss (except in a steam room as noted above) and can be quantified as:

$$H_E = 2.2 \; h_c \; i_m \; A \; (P_s - \phi_a P_a) \qquad \text{Eq 8}$$

where the area for evaporation is generally considered to be the entire surface area ($1.8 m^2$ for an average man), P_s is taken as the vapor pressure of water at skin temperature (without adjustment for any solute content), h_c is the convective coefficient, as before, and i_m, a dimensionless constant ranging from zero to one, represents the permeability of any clothing and/or the still air layer around the body to evaporative transport of water. This physical relationship is, as for convection and radiation, rigorously definable only for a nude man. Clothing impermeability (i_m) to water vapor transfer, and also the insulation of clothing (clo) involved in the h_c term confounds its application to the clothed man. Belding (1) suggests estimation of evaporative heat loss for a subject wearing shorts and tennis shoes as:

$$H_E = 23V^{0.6} (42 - \phi_a P_a) \qquad \text{Eq 9}$$

under the assumption that the skin temperature of a "nude," sweating man is fixed at 35°C (hence, P_s=42mmHg); for a man wearing a long sleeved shirt and trousers, he estimates H_E as, again, 60% of the "nude" value. Note that, although Belding's work was carried out before physiologists generally became aware of the Lewis relationship, his empirically derived h_e is not too remote from 2.2 times his h_c (cf. Eq 5 and 9; h_e=23/12 h_c, or 1.92). Note also that the H_E defined above represents the maximum evaporative cooling (E_{max}) allowed by the environment, and is in no way related to the level of required evaporative cooling (E_{req}) needed by the man. The calculated E_{max} assumes a 100% sweat wetted surface area, while, if the man does not need any evaporative cooling, his skin will be dry.

The four thermal environmental characteristics which must be assessed to characterize any hot environment have now been detailed: T_{db}, T_{wb} and its associated RH and $\phi_a P_a$; V; and T_g and its associated MRT. Solar heat load, although beyond the scope of this paper, has also been referenced. Whether or not a given hot environment represents a heat stress requires consideration of two additional factors. One has already been invoked, clothing, in terms of the extent to which its insulation (clo) alters convective and radiative transfer and its permeability (i_m/clo) alters evaporative transfer between the body surface and the environment (cf. Eq 8). The difficulties of dealing rigorously with the effects of clothing have been detailed above; the direct measurement of insulation (clo; one inch of clothing thickness provides ~1 clo of insulation) and permeability (i_m; about 0.45 for conventional clothing) is a simpler approach. The second "human" factor which determines whether a given hot environment is stressful is the rate of metabolic heat production by the individual. As shown in Table 1, this depends on any physical work required of the body, from the 0.8 MET[1] required for the central nervous system, for circulation of blood, for respiration and digestion at rest, to 12.5 MET for exhausting physical work; e.g. 70kg lifted a distance of 1 meter 9 times per minute represents 630 kgm of physical work which, assuming a gross efficiency of 20% for moderate work by the whole body, requires ~ 5 MET of heat production (cf. Table 1 for Physical Work of 640 kgm/m).

The physiologic response of the body to these physical stresses of the workload and thermal load of the environment can be assessed using the classic (15) heat balance equation for the human body:

$$M \pm H_R \pm H_C - E = \Delta S \qquad \text{Eq 10}$$

where: M is the metabolic heat production demanded by the work (cf. Table 1)
H_R is the radiant heat exchange (cf. Eq. 7)
H_C is the convective heat exchange (cf. Eq. 4 and 5)
E is the actual evaporative heat loss
ΔS is the heat storage (or debt) in the body (cf. Eq. 2)

This simplified form of the human heat balance equation ignores respiratory heat and water loss, and also any evaporation of the moisture continuously diffusing through the semipermeable human skin. These respiratory and moisture diffusion

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[1] The MET is a basic unit of heat production found useful in thermal environmental physiology; 1 MET, by definition = 50 kcal/m^2 hr

avenues contribute equally to a heat loss totaling about 25% of M at rest in a comfortable environment. The respiratory portion increases with increasing work, but decreases with increasing ambient vapor pressure, while the relatively small, diffusional evaporative loss (~20 ml/hr or about 12 kcal/hr) becomes an insignificant portion of the overall evaporative cooling when the man is actively sweating.

Ideally, the left hand side of the heat balance equation equals zero; i.e. heat production plus heat load equals heat loss, and there is no need for heat storage or debt by the body. Such a balance may be equated to an absence of heat stress but, in fact, may not be achieved without considerable heat strain. The sum of the first three terms (heat production ± heat exchange by radiation and convection) provides a useful estimate of the evaporative cooling required (E_{req}), if any; i.e.:

$$E_{req} = M \pm (H_R) \pm H_C \qquad \text{Eq 11}$$

The maximum obtainable evaporative cooling (E_{max}) is constrained by three factors: the ability of the body to produce sweat, the ($\bar{P}_s - \phi_a P_a$) difference discussed above and the extent to which the clothing and still air permeability and insulation, acting in combination (i_m/clo), allow evaporation between the skin surface and the ambient air.

Body temperature is regulated by a variety of behavioral and physiological mechanisms. Homeothermic animals, including man, tend to become less active in the heat, thus reducing M, and to increase their insulation in the cold, fluffing feathers or raising fur (which in man produces "goose flesh" but little benefit). Man can also adjust his clothing, adding in the cold and opening closures or removing layers (at least to the social limits of an increasingly permissive society) in the heat; however, the effect of solar heat load is much greater on bare skin than with clothing. These behavioral mechanisms are supplemented by physiological mechanisms, with adjustment of skin temperature by vasomotor regulation serving as the first line of defense in both heat and cold. As the skin receives an increasing heat load from the thermal environment, vasoconstrictor tone is reduced, thus increasing skin blood flow from the core and raising skin temperature. As evident from equations 4, 5, and 7, raising $\overline{T}_s$ alters convective and radiant heat exchange, either increasing losses or reducing gains. An increase in core temperature may also trigger active vasodilation over most of the body skin surface (but not hands and feet?), resulting in a further increase in $\overline{T}_s$ (13).

As this first line of defense proves inadequate to balance heat losses by radiation and convection against heat production, a second, more powerful defense against heat storage, sweating is initiated. Sweating seldom begins simultaneously over the entire skin surface, but is progressively recruited as the various skin surface areas increase from a "comfortable" 33°C level to a level where sweating begins, generally, at a skin temperature of about 35°C. Sweat production is closely linked with obtaining the required evaporative cooling. Indeed, the "Predicted 4 hour Sweat Rate" (P4SR) Nomogram (Fig 1b) has been used as a measure of the stress of work in a given environment (10).

As seen in Table 1, a heat production of 700 Watt represents "Heavy Work," sustainable for only about one hour for a man of average fitness as judged by his maximum oxygen uptake capacity ($\dot{V}O_{2max}$). The sustainable level of sweat production is about one liter per hour which, at ~ 0.58 kcal of potential cooling per ml of sweat evaporated, approaches 700 Watt (580 kcal/hr) of skin surface evaporative cooling. Sweat production can be at higher rates for shorter periods, with short term maximum rates exceeding three liters per hour, providing a potential maximum cooling rate of about 2000 Watt.

By comparison with the maximum short term heat production rates in Table 1, it is obvious that sweat production is not usually limiting; the body can produce enough sweat to compensate for most working heat productions with a reasonable surplus of sweat production capacity to offset most convective and radiative heat loads, unless the man is seriously dehydrated, has a heat rash covering a significant portion of his skin surface or has congenital absence of sweat glands. Otherwise, capacity is clearly adequate to produce enough sweat to meet E_{req} (cf. Eq. 11). The problem for most heat stress situations is the limitation on E_{max} (cf. Eq. 8 and 9) imposed by elevated ambient vapor pressures at high temperatures (i.e. $(\overline{P}_s - \phi_a P_a)$ or by clothing impermeability (i_m) and thickness (clo) which limit evaporation by their combined effect (i_m/clo).

Regardless of whether the limiting problem is with sweat production or is with E_{max}, the degree of heat stress placed upon the body can be predicted by comparing the required (E_{req}) and maximum (E_{max}) evaporative losses. Gagge et al. (3) have considered the simple ratio E_{req}/E_{max} as a measure of the percent of the skin surface that is sweat wetted (% SA_w) or as the effective relative humidity of the total skin surface; they suggest that values of $E_{req}/E_{max} < 20\%$ are compatible with comfort, while increasing percentages indicate tolerance limits. Belding and Hatch (1) use E_{req}/E_{max} as their Heat Stress Index (HSI) (Fig 1C). HSI values of <30% are uncomfortable, and may decrement mental and fine motor performance, but are tolerable; values of 40-60% decrement performance and may result in finite tolerance times; and values of 70-100% represent severe, tolerance limiting situations.

One can also use the classic Effective Temperature Nomogram (ET) (17) as a predictor of heat intolerance, with or without the T_g substituted for the T_{db} to correct for a radiant heat load (CET). Although primarily used for delineating conditions where deficits are likely for psychomotor, cognitive or light office work performance, the ET nomogram can be modified to reflect the maximum sustainable heat production at a given ET or CET (Fig 1d).

These four charts of environmental effects (Figure 1, Psychrometric Chart, P4SR, HSI and ET) can all be used to delineate potential heat tolerance problems. Another environmental index, the Wet Bulb Globe Temperature (WBGT), uses the evaporative cooling of a non psychrometric, naturally convected wet bulb ($T_{wb_{np}}$). $T_{wb_{np}}$ is obviously a better characterization of the evaporative cooling available to a man who is not being slung by the heels or ventilated by a fan, than the psychrometric T_{wb}. WBGT is calculated as:

$$WBGT = 0.7T_{wb_{np}} + 0.2T_g + 0.1T_{db} \qquad \text{Eq 11}$$

and values <80°F should produce no concern, 80-85° indicate potential problems during work by men not acclimatized (5-7 days of prior exposure at work for ~ 2 hours/day in that heat level), above 85° even acclimatized men may have problems, while above 88° work by fit, acclimatized men will be limited to about 8 to 10 hours (11).

The heat balance equation (Eq 10) can also be used to indicate heat tolerance problems and to predict tolerance times when the left hand side of the equation cannot be forced to equal zero; i.e. actual evaporative heat loss $E < E_{req}$. The heat which cannot be eliminated and must be stored by the body (ΔS) is calculated using the estimates for the individual terms in the heat balance equation. Heat storage of 0-25 kcal may not be sensed if incurred at a slow rate, while ΔS of + 80 kcal represents the usual voluntary tolerance limit for continued exposure, ΔS of + 160 kcal represents a 50% risk of heat exhaustion collapse ($T_{re} \sim 39.5^{\circ}C$ and HR ~ 180 b/m) and $\Delta S \geq 240$ kcal cannot be tolerated by fit young men. The time required to incur these totals may be used as estimates of the corresponding tolerance limit; voluntary, 50% or 100% risk of collapse.

Givoni and I, although relying on the above concepts, have taken a different approach (4). We postulate that there exists a level at which the body could achieve a stable state, with no further heat storage, for any combination of metabolic and environmental heat stress. Although it may not be possible to reach such a level before heat exhaustion or death intervenes, nevertheless the body will be driven, inexorably, toward this "equilibrium" level. There are three factors which drive rectal temperature to this equilibrium ($T_{re_{eq}}$). The first two, metabolic and convective plus radiative heat loads are treated, essentially, as described in the heat balance equation. First, rectal temperature is elevated by 0.4°C per 100 Watts of heat production, above a baseline 36.7°C, independently of *ambient temperature* (as suggested by Nielsen in 1938). Second, it is adjusted by the combined radiative and convective heat transfer predicted by the clothing insulation (clo units)[1], by 0.0128°C /clo ($\bar{T}_s - T_{db}$); $\bar{T}_s$ is considered clamped at 35°C for the nude man, and at 36°C for the clothed man. The third term driving T_{re} is, as might be anticipated from the heat balance equation, a function of the E_{req} in relation to the E_{max}. However, rather than use the ratio E_{req}/E_{max} which suggests that the stress is the same whether the body requires 50 Watts and can get a maximum 100 or requires 500 and can get a maximum of 1000, we use the difference between the E_{req} and E_{max} as an exponential forcing function. T_{re} at equilibrium then is predicted as:

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[1] 1 clo allows a combined total radiation and convective exchange of 6.45 Watts per °C difference between $\bar{T}_s$ and T_o, where T_o is the operative temperature defined as $T_o = [(hcT_{db} + h_r MRT)/(hr + hc)]$. With MRT $\approx T_{db}$, T_{db} per se is used instead of T_o).

$$T_{re_{eq}} = 36.75 + 0.004M + 0.0128/clo\,(T_{db} - 36) + 0.8e^{0.0047(E_{req} - E_{max})} \quad \text{Eq 12}$$

Where $E_{req} = M + 11.6/clo(T_{db} - 36)$

and $E_{max} = 25.5(i_m/clo)(44 - \phi_a P_a)$

The similarity with the terms of the heat balance equation (Eq 10) of the body is obvious, although the coefficients are empirically derived.

The time constant for rectal temperature response is also variable, with equilibrium achieved earlier (1 to 2 hours) under low stress conditions; under severe stress, although collapse may occur in 15 to 30 minutes, the projected time to reach the unattainable balance point may be 5 hours or more. The time constant (k) for the rectal temperature response is a function of the difference (ΔT_{re}) between initial (T_{re_0}) and equilibrium rectal temperature ($T_{re_{eq}}$):

$$k = 0.5 + 1.5e^{-0.3\,\Delta T_{re}} \quad \text{Eq 13}$$

so that the formula for rectal temperature, at any time t in hours (T_{re_t}), becomes:

$$T_{re_t} = T_{re_0} + \Delta T_{re}\,(1 - e^{-k(t-58/M)}) \quad \text{Eq 14}$$

where (T-58/M) reflects the time delay of rectal temperature response. This time based relationship allows one to not only predict whether there are tolerance problems, but also the time to incur them. Whether the problem is an excessively high work load, convective and/or radiative heat transfer or difficulty in obtaining the required evaporative cooling, is delineated, respectively, by the last three terms in Eq 12. A level of 38°C has been selected as an upper deep body temperature, as a guide for setting industrial heat stress limits under OSHA. With rising $\bar{T}_s$, a T_{re} of 39.2°C can induce about 10% frank heat exhaustion collapse in fit young men (risk of heat exhaustion estimated as 25%), while T_{re} levels of 39.5°C, with rising $\bar{T}_s$, represent about a 50% risk of heat exhaustion collapse; T_{re} levels rising above 40°C suggest a risk of heat stroke (when $T_{re} > \sim 42°C$) for the very few, extremely fit individuals whose cardiovascular system allows them to continue to work at $T_{re} > 40^{\circ}C$ with elevated T_s.

Elevated heart rates are associated with these elevated T_{re}; prediction of equilibrium heart rate and time patterns of heart rate response allows prediction of time to heat exhaustion collapse based on heart rates reaching >190 beats/min (5). Factors for heat acclimatization adjustments to T_{re} and HR have been published (6), and factors for dehydration are being developed; both alter the equilibrium levels and time responses of T_{re} and HR, with T_{re_0} reduced by acclimatization.

These predictions have been validated by a number of subsequent experiments and also by reported exposures, with fit young men wearing a variety of clothing (shorts, work clothing, reduced permeability coveralls, armor, etc.) across a range of T_{db} (20-50°C), humidities (10-100%) and work rates, at low to high windspeeds. Adjustments for fitness (perhaps as a function of $\dot{V}O_2$ demand as a % of $\dot{V}O_{2max}$), for age (perhaps based on the relation $HR_{max} = 220\text{-age}$) and for females (perhaps only as a function of $\dot{V}O_2$ demand/$\dot{V}O_{2max}$) are being sought.

In earlier work, (7,8) concern has been expressed for the contribution of hyperventilation, and the resultant hypocapnia, in heat exhaustion collapse. However, preliminary results from current studies (unpublished) on patients with core temperatures elevated to the 42°C level as part of a cancer therapy regime has failed to show the severe hyperventilation anticipated from our earlier studies. Thus, it appears that the hyperventilation may be more a part of the experimental situational stress, and may not need to be factored into the prediction of heat intolerance.

Prediction of $\bar{T}_s$ and core-skin conductance is also available (unpublished) and we are currently addressing convergence of $\bar{T}_s$ toward T_{re} as a heat tolerance limit in cases where E_{max} is severely limited by very high $\phi_a P_a$ or very low i_m/clo. While more work remains to be done, the three approaches given above (charts, heat balance equation or prediction of T_{re}) should serve as a useful basis for prediction of heat tolerance problems.

Summary: The physical and physiologic bases for heat tolerance have been delineated. The psychrometric chart, P4SR, ET, HSI and/or WBGT can all be used as indices of heat intolerance but not, usually, as predictors of tolerance time per se. Use of the human heat balance equation and use of validated prediction models of heart rate and rectal temperature can be used to predict tolerance times. Using the latter approach, adjustments can be made for acclimatization and dehydration and adjustments are being developed to account for age, sex and physical condition differences.

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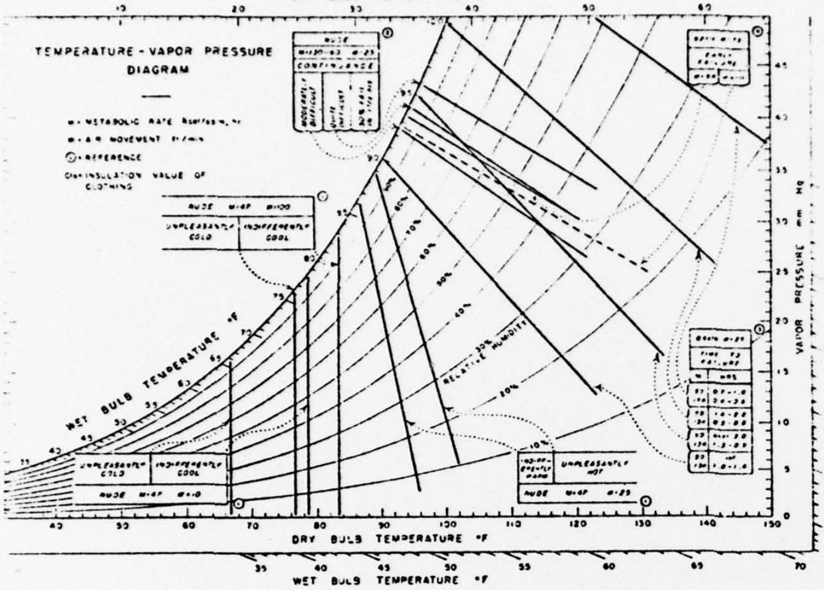
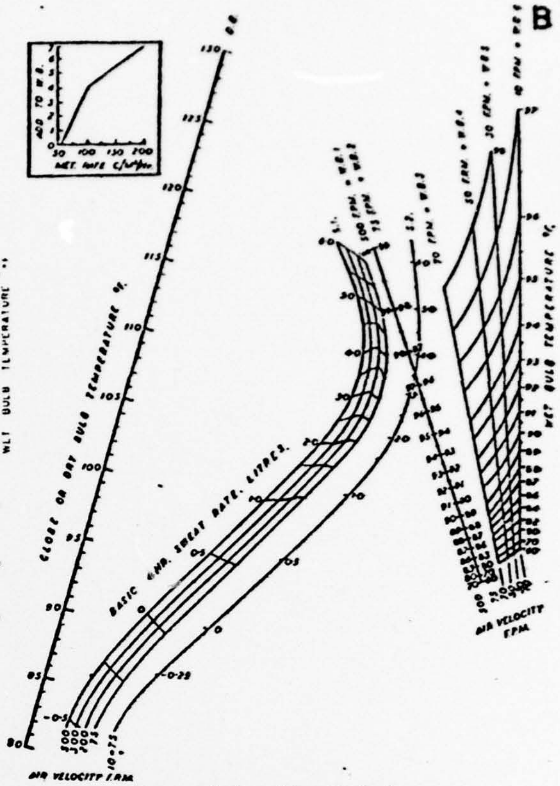
Figure 1. Estimation of heat stress using charts/nomograms: a) Psychrometric chart, with observed responses on tolerance limits indicated; b) McArdle's P4SR nomogram, where values above 3 or 4 liters in 4 hours represent severe strain; c) Belding's HSI nomogram; d) Effective temperature nomogram, indicating maximum sustainable metabolic rates at various ET levels.

A

REPORTED TOLERANCES FOR NUDE AND PARTIALLY CLOTHED MEN

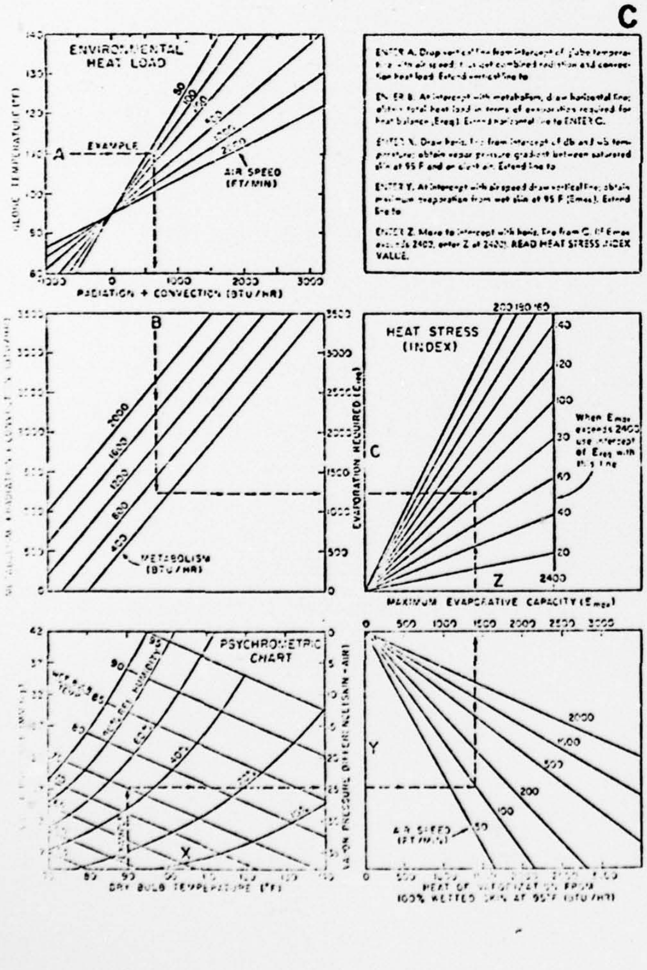


B



Nomogram for the prediction of the four-hour sweat rate.

C



ENTER A. Drop vertical line from intercept of globe temperature with air speed; thus get combined radiation and convection heat load. Extend vertical line to

ENTER B. At intercept with metabolism, draw horizontal line; obtain total heat load in terms of evaporation required for heat balance (Ereq). Extend horizontal line to ENTER C.

ENTER X. Draw horiz. line from intercept of db and wb temperature; obtain vapor pressure gradient between saturated skin at 95 F and ambient air. Extend line to

ENTER Y. At intercept with air speed draw vertical line; obtain maximum evaporation from wet skin at 95 F (Emax). Extend line to

ENTER Z. Move to intercept with horiz. line from C. If Emax exceeds 2400, enter Z at 2400. READ HEAT STRESS INDEX VALUE.

D

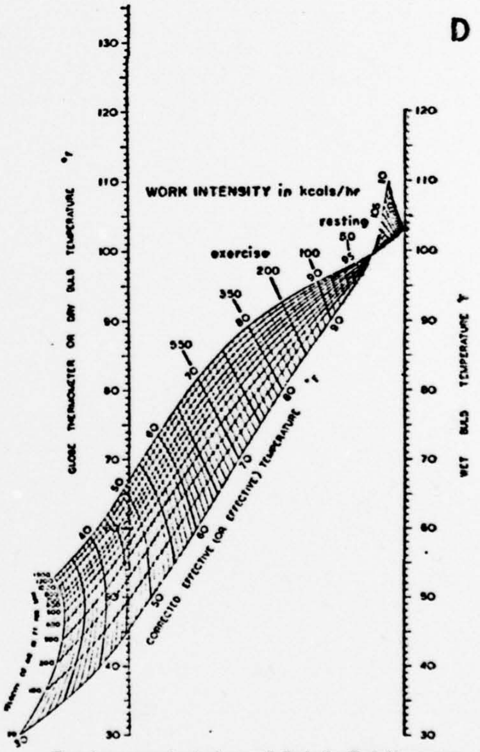


Chart showing normal scale of corrected effective (or effective) temperature.

Table 1. Relation between physical work and physiological cost (assuming 20% efficiency), with some representative observations on fit young men.

PHYSICAL WORK			ENERGY COST - η=20%			ACTIVITY	"MET"	MEASURED "NORMAL" MEN			H.P.	Efficiency
kgm/m	ft-lb/m	watt	kcal/m	watt	$\dot{V}O_2$ L/min		(50 kcal/ m^2.hr)	RMV L/min	$\dot{V}O_2$ L/min	H.R. b/min	(η=20%)	(η - %)
13	93	2	.15	10	.03	Circ + resp. rest	0.1					
26	185	4	.30	21	.06	C.N.S.	0.2					
38	278	6	.45	31	.09	Circ + resp. work	0.3					
64	463	10	.75	52	.15	Gut at rest	0.5					
102	741	17	1.2	84	.24	Basal (sleep)	0.8					
128	926	21	1.5	105	.30	Sit at rest	1.0					
192	1389	31	2.25	157	.45		1.5					
224	1621	37	2.63	183	.53	Very light	1.75	10	0.5	<75	.05	
256	1852	42	3.00	209	.60		2.0					
320	2316	52	3.75	262	.75	Walk 2.75 MPH	2.5					
384	2779	63	4.50	314	.90		3.0					
416	3010	68	4.88	340	.98	Light	3.25	20	1.0	75-100	0.1	15.7
448	3242	73	5.25	366	1.05		3.5					
512	3705	84	6.00	419	1.20		4.0					
640	4632	105	7.50	523	1.50	Moderate	5.0	35	1.5	100-125		
864	6253	141	10.13	707	2.03	Heavy 1 hr $\dot{V}O_2$ max	6.75	50	2.0	125-150	.2	20
1056	7642	173	12.38	864	2.48	Very heavy	8.25	65	2.5	150-175		20
1280	9263	209	15.00	1047	3.00	10' $\dot{V}O_2$ max	10.00	85	3.0	>175	.3	20
1600	11579	262	18.75	1308	3.75	Exhausting	12.50				.35	
2202	15933	360	25.8	1800	5.16	2 mile record anaerobic (10')	17.2				.5	

Prediction of Human Heat Tolerance

by

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Human tolerance to heat exposure is limited by body heat storage (ΔS), as the body is unable to eliminate all the heat it produces and/or receives from the environment, and by the physiologic consequences of such storage. Heat storage of about 80 kcal represents the "voluntary heat tolerance" limit at which an average, fit, 70 kg man usually decides he is not willing to work much longer in the heat; an increase of 160 kcal in his heat content is associated with a 50% risk of heat exhaustion collapse. As the difference between skin and air temperatures ($\bar{T}_s - T_a$) decreases, a demand for evaporative cooling (E_{req}) in the heat is imposed by the interplay of 3 three factors: a) the metabolic heat production (M); b) the "effective" solar heat load (Q_s); and (c) c) the radiative and convective heat exchange (H_{R+C}) through the clothing insulation (I_{clo}). This demand (E_{req}) may be greater than the maximum evaporative cooling (E_{max}) allowed by three (3) other factors: a) the body's maximum sustainable sweat production (about 1L/hr ≈ (approximately = to) 675 Watts of cooling power); b) the limit to sweat evaporation imposed by clothing moisture permeability and thickness (i_m/clo); (thickness; and (c) c) the difference between the vapor pressure of sweat at the skin surface and the ambient vapor pressure ($P_s - \phi_a P_a$). Gagge has pointed out that the ratio E_{req}/E_{max} reflects the percentage of the skin that must be sweat wetted ($\%A_{sw}$) and suggested that values up to 20% were compatible with comfort. This same ratio was adopted by Belding as a Heat Stress Index (HSI), with values from 10 to 30 representing mild to moderate heat strain, 40-60 severe heat strain,

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and 70 to 90 severe heat strain. While the E_{req}/E_{max} ratio is useful in these early approximations to predicting comfort and/or heat stress boundaries, clearly a situation with E_{req} equal to 50 Watt while E_{max} is 100 does not represent the same physiologic stress as another where E_{req} is 500 and E_{max} is 1000. Although E_{req}/E_{max} is 0.5 for both cases, the body is driven toward very different equilibrium states under these conditions. My laboratory, working with these same parameters, has adopted a different approach; we predict the deep body temperature (T_{re}) at which a balance can be struck between heat load and heat loss. This final, equilibrium rectal temperature (T_{re_f}) may not be tolerable, with heat exhaustion collapse or heat stroke intervening before T_{re_f} is reached, but the body will be driven toward this equilibrium. We formulate T_{re_f} as equal to a basic, resting (M = 105 Watt) T_{re} of 37.1°C, incremented by 3 factors: a) an increase of 0.4°C per 100 Watts of working heat production (i.e. M-105) as suggested by Nielsen in 1938; b) a linear change (+ or -) of $(.025/I_{clo})$ °C for each degree of difference between air temperature and the average 36°C $\overline{T}_s$ maintained by a clothed man (or 35°C T_s unclothed) working in the heat; and c) an exponential increase in T_{re_f} as a function of the <u>difference</u> between E_{req} and E_{max}. We have indicated how to predict the time course of T_{re} to reach T_{re_f}, with the appropriate lag and overshoot coefficients, during any schedule of rest, work and recovery; how heart rate (HR) can be predicted from this approach; also how, day by day, acclimatization to heat modifies these T_{re} and HR responses. We can now include factors for prediction of $\overline{T}_s$, core to skin heat flow (conductance) and the effects of various levels of dehydration. We are working on adjustments for sex, age and physical condition. Initially it seems that such sex differences as exist, primarily reflect differences in body mass and mass to surface area ratio, plus differences in

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the state of physical fitness and heat acclimatization (particularly of the sweat glands) rather than other physiologic male-female differences. We also project that adjustments for less fit individuals, and for older individuals, can be developed in terms of the $\dot{V}O_{2_{demand}}/\dot{V}O_{2_{max}}$ ratio more readily than in terms of E_{req}/E_{max}.

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