Human heat tolerance in simulated environment

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The heat tolerance of 11 male volunteers was examined under seven climatic conditions in a climatic chamber. The conditions were 38 to 49°C dry bulb temperature and 45 to 80 per cent relative humidity, i.e., 32.3 to 40°C effective temperature -basic (ETB). The ETB values were equated to other heat stress indices, e.g., WBGT (Wet-bulb Globe Temperature Index) and Oxford Index. The subjects did ergometric work at an intensity of 60 per cent VO2max. The exposure durations were decided by the cardiorespiratory, body temperature and sweating responses. Of the climatic conditions studied, at 35.4, 38, 39 and 40°C ET (B), the body core temperature (Tc) reached over 39°C and heart rates attained 172 to 182 beats/min, which were taken as the tolerance limit. The total oxygen demand significantly varied with the increase in environmental warmth, i.e., increase or decrease of one litre of oxygen demand was equivalent to one minute change in tolerance time. The volunteers were not susceptible to heat; only in extreme hot situations beyond 35.4°C ET (B), were unacceptable levels of physiological and psychophysical reactions seen. The study suggests the acceptable and tolerable limits for human exposure in heat: (i) acceptable at 38 to 38.2°C Tc for a tolerance time of 80 to 85 min; and (ii) the tolerable limit of short duration (40-45 min) at 39°C Tc, that corresponded to 31.5 and 36.5°C ET (B).

Key words: Climatic chamber - core and skin temperature - effective temperature - oxygen uptake - sweat loss - tolerance time - WBGT

Management of heat exposure is important to safeguard human health in the industrial and community environment. The upper limit of acceptable strain, often called tolerance time, depends on the environment and the thermal state of a person on initiation of heat exposure. For populations in the tropics, the guidelines on human work tolerance to inclement high heat environment are inadequate. It is difficult to arrive at the heat susceptibility and tolerance limits of men and women due to the health risks in the direct determination by longitudinal studies. We describe here the heat tolerance limits and thermoregulatory responses of persons who work in high heat. This was based on longitudinal long-term experimental studies of simulated exposures to high heat (dry and humid environment).

Material & Methods

The study was conducted on 11 healthy, motivated young male volunteers from the small industrial sector. As Ahmedabad is very hot during the summer months (April-July), the experiments were undertaken during the winter months (December-February). Day temperatures during the period range between 15-22°C (dry-bulb temperature, DB), with 50-55 per cent relative humidity (RH). It was not within the scope of the study to include completely unacclimatized subjects, as the residents of Ahmedabad are naturally acclimatized (or usually exposed) to high heat during the summer months. Since the experiments were undertaken during the winter months, the volunteers were temporarily free
from natural acclimatization. The total period of the study programme for each subject lasted about three weeks.

Seven extremely hot climatic conditions, ranging from 38 to 49°C DB, 45 to 80 per cent RH, 40 to 53°C Globe temperature (GT) and air movements 0.4 to 0.5 m/sec, were selected for exposure in a walk-
in environmental chamber (Hotpack International, USA). There were four DB temperature ranges (i.e., Cond 1; Cond 2 and 5; Cond 3 and 6; Cond 4 and 7). Only two ranges of WB temperatures (Cond 1 to 4) and (Cond 5 to 7) were selected in the study. All volunteers were exposed to all seven conditions, in randomized order. The exposure conditions were designed to prevent any step-wise loading and to reduce acclimation effects. The heat stress and strain indices are given in Table 1. Because consecutive days of exposure to heat may influence the individual's state of acclimatization, the study was undertaken with randomized intermittent days of exposure (three to four days' interval). During the study period, the subjects were indoctrinated to remain indoors and to avoid heavy physical activity outside the experimental protocol.

The subjects came to the laboratory each morning 1 h before commencement of the experiment, and had had 30 min rest (lying/sitting) in a comfortable environment (22-25°C DB, 50-55% RH) in an adjacent room of the climatic chamber. On day 1 of the experiment, the maximal oxygen uptake (VO_{max}) of subjects was directly determined by step-increase bicycle ergometric work in a comfortable environment. The criteria to establish VO_{max} were the following: (i) the heart rate reaching the age-related maximum (i.e., 190 beats/min); (ii) the oxygen consumption reaching a high level with subsequent steady consumption, and no further increase with the increase in work load.

During the various exposures, the subjects did ergonomic work at an intensity of about 60 per cent VO_{max}. This continued till the level of tolerance was reached. In extreme intolerable hot environment, skin pain is the critical limiting factor with tolerance time less than 15 min; a needless gasp sets off an uncontrolable fit of coughing, which limits heat exposure. At usual high environmental heat, the skin temperature does not reach the painful level, when heat tolerance is limited by the rise in body core temperature (T_{c}). Eventually, the exposed person shows subjective distress and personality changes. In the present study, the criteria taken for the level of tolerance were incipient collapse or the T_{c} limits of

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<th>Table 1. Heat stress and strain indices of the experimental conditions (Values are means ± SD (No of environmental measurements = 33))</th>
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<tr>
<td><strong>Index</strong></td>
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<tr>
<td>Dry-bulb temp., DB (°C)</td>
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<tr>
<td>Wet-bulb temp., WB (°C)</td>
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<tr>
<td>Effective temp. - Basic. ET (B) (°C)</td>
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<tr>
<td>Heat Stress Index, HSI (dimensionless)</td>
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<tr>
<td>Wet-bulb globe Temp., WBGT (°C)</td>
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<tr>
<td>Index of thermal Stress, ITS (g/h)</td>
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<td>Oxford index (°C)</td>
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<td>Predicted 4h Sweat Rate, P,SR (l)</td>
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39°C and/or the cardiovascular load reached a peak level (i.e., the heart rates attained 170-180 beats/min). In addition, the psychophysical responses were included, i.e., the perceived tolerance time, and sensation of warmth as predicted mean comfort voting. The subjective responses to the level of tolerance were irritation, nausea, dizziness, etc. The subjective feelings of the extent of inability to continue heat exposure were noted, since motivation is an important factor and discontinuation of heat exposure on demand is mandatory.

The Tm was continuously monitored, using a deep body thermometer (Deep Body Thermometers Ltd UK), designed by the British Medical Research Council. The measurement reliability of the device is described elsewhere. Care was necessary for placing the probe pad on the chest (upper sternum) and the device required an equilibrium time of about 30 to 40 min; subsequent minute to minute recording were satisfactory. The skin temperature profiles of local areas were monitored using a multi-channel telethermometer (Aplab. India). Weighted average skin temperature (Tm) was obtained from the fractionated weights of body segments of subjects and the surface area of the segments using the Meeh constants. Further details of the method of calculation are given in Nag et al. The weighting factors of different local areas are given below to calculate average Tm:

\[ T_m = 0.095 \text{ Head} + 0.245 \text{ Back} + 0.255 \text{ Trunk} + 0.125 \text{ Upper Arm} + 0.035 \text{ Hand} + 0.205 \text{ Thigh} + 0.040 \text{ Feet} \]

The heart rate changes were continuously monitored by recording ECG through a Beckman R612 Dynograph (Beckman, USA), a 4-channel storage oscilloscope (Electronics Corp., India) and on-line storing of analog signals in an Instrumentation Tape Recorder (Hewlett Packard, USA), for subsequent retrieval and digitization. The minute to minute pulmonary ventilation was recorded using a calibrated KM respirometer (Zentralwerkstatt Gottingen, Germany). The oxygen content of the expired air was measured using a paramagnetic oxygen analyzer (Sybron Taylor, UK). The analyzer was routinely calibrated against a known gas concentration. The sweat loss was obtained from the initial and final body weight, with correction for water intake, urination and clothing. The weighing balance was accurate to ±25 g. The evaporation through skin (Evap) and the skin wettedness ratio were estimated. Though all subjects were highly motivated for the study, protective care (e.g., medical attention, water cooled assistive garment, as a standby) was taken to prevent any adverse situation. The summary statistics, test of significance, correlation analysis, simple and multiple regression analysis were done to assess heat tolerance.

**Results**

The volunteers had a mean (± SD) age of 19.7 ± 1.2 yr, weight of 47.2 ± 10.1 kg, height of 164.6 ± 7.2 cm, BSA of 1.55 ± 0.18 m² and maximum O2 uptake of 2.33 ± 0.40 l/min. The ergometric work done in different days of heat exposure was maintained at a similar level (i.e., 75 W).

From the different heat stress indices given, this study emphasizes on the ET (B) index as a possibly better indicator of environmental warmth, primarily because of the simulated conditions of heat exposure. The trends of the heat stress and strain indices shown in Table I show variations with the increasing ET (B). This may be attributed to inherent limitations in the basic equations and its range of application. The heat stress index (HSI)28, index of thermal stress (ITS)28 and the predicted h sweat rate (PR SR)28 are useful physiological strain indicators of sweating response/evaporative cooling. In the present study, the wet bulb global temperature (WBGT) index has been widely used for ease of measurement and calculation52, the prediction equation between WBGT and ET (B) is suggested, i.e., WBGT (Inside) = 1.047 ET (B). Accordingly, the physiological responses were expressed with reference to ET (B).

The rate of oxygen uptake (l/min), total oxygen demand (l), the relative demand of work as percentage of VO2max, tolerance time and safe exposure time are given in Table II. The oxygen uptake varied from 0.92 to 1.24 l/min (42-65% VO2max), i.e., at the initial exposure [32.2°C ET (B)] the demand of work was only 42 per cent VO2max. The difference in oxygen uptake in the environmental conditions of 32.3 and
39°C ET (B) was 23 per cent VO₂max. Up to 34.5°C ET (B) (36.3°C WBGT), the total oxygen demand (67.0 ± 23.3 l) and the tolerance time (63 ± 9 min) remained at a higher level, and the significantly decreased demand in total oxygen uptake (P < 0.05) at 35.4°C ET (B) and above, was associated with lower tolerance time (P < 0.05).

In view of tolerance time distribution of the sample group, the safe exposure times were assessed, as given in Table II. As the tolerance time is stated as being normally distributed about the mean value within each climatic condition, the lower 95 per cent confidence limit value for each set of data was estimated from the standard error of the mean and standard deviation of the distribution of the tolerance time (about imminent collapse time) for all conditions.

The Tₑ and heart rate at the end point of exposure in different conditions are given in Table III. The group average of both Tₑ and heart rate responses had a similar trend with the increase in environmental warmth. The highest heart rate attained was 182 beats/min. For the temperature conditions of 38, 39 and 40°C ET (B), the Tₑ reached well over 39°C, which was taken as one of the criteria of the tolerance limit. The coefficient of variations (CV) of the variables showed minimum inter-individual variation, however, the behaviour is markedly different in case of tolerance time, as given in Table II. The inter-individual variation in tolerance time was greater in higher environmental warmth, as the CV exceeded 30 per cent.

As shown in Fig. 1, the average Tₑ and mean body temperature (weighted mean of Tₑ and Tₑ) had a consistent upward trend, with the increase in ET (B). Data presented in Table III and Fig. 1 indicate that the body temperature gradient for heat transfer was significantly (P < 0.01) reduced beyond 34.5 and 35.4°C ET (B). The thermoregulatory responses such as the sweat loss and Eₑ (Fig. 2) were compared. The subjects had a consistent rise in sweating with higher environmental warmth. Since each litre of sweat

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<th>Table II. Oxygen demand of the 11 male volunteers at various heat exposures (Values are means ± SD; N = 11)*</th>
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<tr>
<td>Effective Temp (B) (°C)</td>
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<td>------------------------</td>
</tr>
<tr>
<td>32.3</td>
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<tr>
<td>33.7</td>
</tr>
<tr>
<td>34.5</td>
</tr>
<tr>
<td>35.4</td>
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<td>38.0</td>
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<td>39.0</td>
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<td>40.0</td>
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<tr>
<th>Table III. Body core temperature and heart rates in different environmental conditions (Values are means ± SD; N = 11)</th>
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<tr>
<td>Parameters</td>
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<tr>
<td>Tₑ (°C)</td>
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<tr>
<td>Heart rate</td>
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<td>Tₑ, body core temperature</td>
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1 (132)
Fig. 1. Mean skin temperature ($T_s$) and mean body temperature (MBT) in different hot environments. ●●●●●●● MBT; O-O-O $T_s$.

Fig. 2. Sweat loss and evaporation through skin ($E_w$) in hot environment. ●●●●●●● $E_w$; O-O-O Sweat loss.

evaporated from the skin surface represents a loss of about 675 W of heat, the extent of sweating was a large potential source of cooling, provided all the sweat was evaporated. The $E_w$ corresponded to the trend of sweat loss, i.e., up to 35.4°C ET (B), both sweat loss and $E_w$ had a consistent rise, followed by
shallowing of its effect. This was further evident from the skin wettedness ratio (Fig. 3), i.e., the subjects almost reached unity at 38, 39 and 40°C ET (B). These regulatory responses are controlled by the difference in water vapour pressure on the sweat-wetted skin surface and air layer next to the skin surface, and air movement. That is, for hot-humid environment beyond 35.4°C ET (B), there appears a limit of the amount of sweat that can be evaporated.

Discussion

Human tolerance to work in heat depends on the degree of environmental exposure, personal characteristics and the physical activity performed25, 26. The study included a wide range of environmental conditions to examine their influence on thermoregulatory responses, with reference to limit of tolerance.

Despite the workload being maintained constant at different exposures, the non-linear increase in metabolic demand (i.e., 42% VO$_{max}$ at 32.3°C ET-B) raised to 65% VO$_{max}$ at 40°C ET-B) observed may be attributed to the environmental effects on the cardiorespiratory system. This emphasizes that caution is needed in applying strict limits for prolonged work in high heat. The total metabolic energy demand and tolerance time decreased with the higher environmental load. On an average an increase or decrease of oxygen demand of one litre was equivalent to a corresponding one minute change in tolerance time.

The average heart rate and T$_v$ responses obtained in this study suggest relative thermal loading. Most of the subjects attained heart rates approximating the age related maximum. Since the average oxygen demand reached only to 65 per cent of VO$_{max}$, such an increased cardiovascular load was probably a limiting factor to stop the exposure to heat. Also the T$_v$ reached over 39°C in high heat, e.g., 38, 39 and 40°C ET-B, showing non-steady state situations in T$_v$ adjustment with narrow body temperature gradient for heat exchange25,26. The high T$_v$ might adversely affect the function of the motor centers, reduce the ability to recruit motor units for the required work and decrease work motivation.

Different thermal strategies are adopted to work in high heat, and the human responses are the joint adjustment of the cardiovascular and sweating re-

![Graph](image)

**Fig. 3.** Skin wettedness ratio (O-O-O) and thermal sensation (O-O-O) as predicted mean voting (PMV) in different effective temperatures, ET (B).
sponses. The thermoregulatory responses (e.g., sweating and $E_a$) obtained by us suggest that the subjects, in general, were not susceptible to high heat. Only in extremely hot situations, they had unacceptable level of physiological and psychological reactions. The PMV (predicted mean voting) supports this. The observed sweating responses suggest that for environmental conditions beyond 35.4°C ET-B (37.4°C WBGT, 34.3°C Oxford Index), there may be a limit to the sweat that is evaporated. That is, when heavy sweating takes place with insufficiently evaporation, this may pose a threat to thermoregulation, because of progressive peripheral feedback. Hypohydration by itself affects thermoregulation and results in a rise of $T_a$. This suggests that the subjects had both cardiovascular and thermoregulatory limitations, which is reflected in the decrement in human performance/heat tolerance.

A variety of assumptions have been examined on the relations between tolerance time and heat stress. Craig et al. suggested that the tolerance end point was not complete exhaustion, but a state that the subject was willing to reach once a day, five days a week for five weeks (i.e., voluntary tolerance times).

Leithhead and Lind recommended the Oxford Index for all air movements, work rates and clothing. Wyndham et al. found that the inverses of the tolerance times in each environment were normally distributed, the variance being independent of the environment, and suggested the best fit weighting coefficients as 0.88 $T_a + 0.12 T_e$ for resting and 0.85 $T_a + 0.15 T_e$ for working subjects. We obtained the multiple regression line between $T_a$, $T_v$ and tolerance time (TT, min), as $TT = 278 - 3.0 T_a - 2.9 T_v$ ($R^2 = 0.613, P < 0.001$). Further, the $T_a$ and tolerance time has statistically significant relationships with the environment. That is, when the maximum $T_a$ has a linear build up, the tolerance time has an exponential decay with the increase in ET (B) (Fig. 4). The regression equations are as follows: $T_a = 32.8 + 0.17$ ET (B) ($r = 0.722, P < 0.01$); and $TT = 3005 e^{0.15}$ ET (B) ($r = 0.844, P < 0.01$).

The data corroborate earlier studies that the $T_a$ of 39 to 40°C may be taken as the tolerance limits for men at work in heat, in view of critical thermal maximum (i.e., the least high $T_a$ that is lethal to a human being). It is difficult to identify heat intolerant persons to avoid possible placement in

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig4.png}
\caption{Exponential pattern of tolerance time, TT (●) and build up body core temperature $T_a$, (O) with increase in effective temperatures, ET(B). Cut-off levels of acceptable and tolerable limits of $T_a$ are shown.}
\end{figure}
high heat, and the intolerants are usually the most vulnerable\(^2\). Based on the regression analysis, one may arrive at the \(T_a\) of 39\(^°\)C and heat tolerance time of 45 min at 36.5\(^°\)C ET (B). Accordingly, about \(T_a\) and cardiorespiratory criteria, the exposure ranges may be grouped as acceptable, and/or tolerable limits, (i) acceptable\(^1\) at 38 to 38.2\(^°\)C \(T_a\), for a tolerance time of 80 to 85 min, and (ii) tolerable limit of short duration (40 to 45 min) at 39\(^°\)C \(T_a\), that correspond to 31.5 and 36.5\(^°\)C ET (B) respectively. This optimization with data from studies on men and women of different ages will have wider application to avoid heat illnesses and disorders.

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References


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