CHAPTER 3

Human Heat Tolerance in Simulated Environment
3

HUMAN HEAT TOLERANCE IN SIMULATED ENVIRONMENT

INTRODUCTION

Management of heat exposure is important to safeguard human health in the industrial and community environment. Heat stress is a potential health hazard for workers who are exposed high environmental heat for prolonged periods. A person exposed to heat stress beyond the upper limit of acceptable strain, often called tolerance time, may develop substantial heat strain, leading to heat casualty (Nunneley 1978). Several studies have examined the length of tolerance time for which humans can tolerate high temperature, either when they are at rest or working (Wyndham et al. 1965; Iampietro and Goldman 1965; Davies 1993). Bell and Walters (1969) studied the physiological reactions of men exposed to hot and humid environments ranging from 37.5/33.9°C to 53/48.3°C T_e/T_wb to construct an exponential curve of safe exposure time to work in hot environments. They observed safe exposure times of 53 minute at the lowest temperature to 6 minute at the highest temperature. Fambraio et al. (1996) observed that increasing environmental temperature from 20 to 40°C reduced exercise time to fatigue at 70% VO_{2 max}
from 67 to 30 minutes. Montain et al. (1994) examined the influence of exercise intensity, climate, and protective clothing on physiological tolerance to uncompensable heat stress — when the evaporative cooling requirements exceed the environment's cooling capacity (Belding and Kamon 1973). Under such conditions individuals fail to achieve thermal steady states and continue to gain heat until exhaustion (Sawka et al. 1992).

Human beings readily show signs of distress, and discomfort, affect body thermoregulation and symptoms of incipient heat exhaustion (Avellini et al. 1980). The level of heat stress at which these effects are discernible depends upon the environment (Galloway and Maughan 1995), the thermal state of a person on initiation of heat exposure and the heat tolerance capability of an individual (Davies 1993). The ability to withstand high heat mainly depends on two mechanisms, viz., the skin's sensitivity to pain and sensitivity to the accumulation of heat in the body (Webb 1963). At moderate hot environment, the $T_{sk}$ does not reach to painful level, when heat tolerance is limited by the rise in $T_{cr}$. The $T_{cr}$ ranging from 39-40°C and heart rate of 180 beats/minute is used as tolerance limits for humans working in the heat (Goldman et al. 1965; Pandolf et al. 1974; Wyndham et al. 1967). Iampietro and Goldman (1965) suggested the convergence of $T_{sk}$ towards $T_{cr}$ as indicator of tolerance time, i.e., when the difference between $T_{sk}$ and $T_{cr}$ approaches 1°C.

There are wide differences in the physiological criteria adopted by various investigators for finding out the imminent heat collapse or for
termination of heat exposure and these may in part, account for differences in tolerance times observed by different workers. Since the man's thermoregulatory adjustment (e.g., vasodilatation, $T_{cr}$, heart rate and sweating) depends on personal characteristics, e.g., age, sex, degree of obesity (Kenney and Havenith 1993; Shapiro et al. 1980), it is important to understand the magnitude of physiological strain that humans can tolerate and factors that modify the limit of tolerance. Knowledge of such information assists in forming guidelines for human heat exposure (Pandolf et al. 1986).

The studies on heat tolerance limits with special reference to population in the tropics are limited (Nag et al. 1986; Nag et al. 1996). Some studies on thermal stress in Steel foundries (Ganguli et al. 1971; Sen 1982), Textile industry (Sen et al. 1965), Glass-moulding factory (Ganguli 1958), Jute mill (Subramanian and Majumdar 1951), and Ceramic industry (Parikh et al. 1978) and agriculture (Nag et al. 1980) have been reported. Based on Indian subjects, Sen Gupta et al. (1981) observed reduced work performance in hot-humid environments due to early attainment of maximum heart rate, reduction in $\text{VO}_2\text{max}$, rise in $T_{cr}$, narrowing of temperature gradient between the core and skin surface, and maximum sweating rate. Venkatswamy et al. (1979) assessed the heat tolerance of acclimatized Indians by exposing subjects to different combinations of hot-dry (46.3-51.5°C, 25% RH) and hot-humid environments (37-44°C, 54% RH) for 4 hours, and concluded that $T_{cr}$ of 39°C can be taken as the limit for termination of heat exposure and thermal
condition equivalent to 42.0°C (53% RH) can be considered as limiting environment to avoid occurrence of imminent heat collapse. There are inherent difficulties 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 (Montain et al. 1994; Nag and Nag 1992). Therefore, the present study was undertaken to examine the magnitude of physiological strain with reference to heat tolerance time, and to elucidate factors that influence the limit of tolerance, based on long-term experimental studies in simulated environment of hot-dry and hot-humid environment.

METHODS AND MATERIALS

Heat tolerance study was undertaken in a simulated environmental chamber condition. Selection of temperature conditions for exposure to human subjects was based on the extreme environmental conditions of the summer months, prevailing in this part of the country.

*Environmental Chamber*

The studies were carried out during daytime (11.00 - 16.00 h) in a Walk-in Environmental chamber (*Hotpack International, USA*) (10' x 10' x 15') of the institute. The chamber can be used for a variety of air temperature (-10°C to + 60°C) and relative humidity (20-100% RH) range. The air temperature and the ranges of humidification of the chamber were accurate to ± 1%. The design of the chamber was such as to prevent sensible radiant heat effect from the
ENVIRONMENTAL CHAMBER
nichrome coiled heating elements. The following basic environmental parameters were taken for the assessment of heat stress.

a) $T_a$ and $T_{wb}$ of the set environmental chamber conditions were checked using the sling psychrometer.

b) $V_a$ was measured using a Kata thermometer and also with a thermoanemometer. The silvered Kata with a cooling range of 130-125°F (54.4-51.7°C) was used in the present study. It was attempted to maintain airflow inside the chamber within 0.4 to 0.6 m/s.

c) $T_g$ — a standard 6 inches black globe thermometer was used to measure mean radiant temperature.

Subjects

Eleven healthy, motivated young male subjects were selected from the small-scale industrial sector. Selection of the subject was based upon evidence of their good health and absence of complicating factors such as cardiovascular problem and pre-existing pulmonary problems. A physician evaluated each subject's health status through a medical examination. The subjects were usually habituated to moderate physical work in their occupational field.

As Ahmedabad is very hot during the summer months (April-July), the experiments were undertaken during the winter months (December-February). Day temperature during that period ranged between 15-22°C $T_a$ with 45-55%
RH. Since the experiments were undertaken during the winter months, the subjects were temporarily free from natural acclimatization.

Each subject performed heat exposure programme in different hot-dry and hot-humid conditions. Prior to starting the experiment, each subject was familiarized with the standard test procedure and consent was taken. Each subject had undergone eight day of heat exposure, however, the total period of the study programme for each subject lasted about three weeks. Because consecutive days of exposure to heat may influence the individuals state of acclimatization (Nielsen 1994), the study was undertaken with randomized intermittent days of exposure (two to three days' interval). During the study period, the subjects were indoctrinated to remain indoors and to avoid heavy physical activity outside the experimental protocol.

**Heat Exposure Programme**

The range of exposure conditions selected in the environmental chamber varied from moderately hot (36-39°C $T_a$) to extremely hot (48-51°C $T_a$) and 30-80% RH. The exposures were combined load of metabolic and environmental heat. All volunteers were exposed to all seven conditions, in randomized order. The exposure conditions were designed to prevent any stepwise loading and to reduce acclimation effects. The subjects attended the laboratory each morning 1h before commencement of the experiment, and had had 30 min rest (lying/sitting) in a comfortable environment (22-25°C $T_a$, 50-55% RH) in an adjacent room of the climatic chamber. On day 1 of the
experiment, the maximal oxygen uptake (VO₂ max) of subjects was directly determined by step-increase bicycle ergometric work in a comfortable environment. The criteria to establish VO₂ max were one or more of the following:

1. The heart rate reached to the age-related maximum; for the present group of subjects the targeted heart rate was 180-190 beats/minute;
2. The oxygen consumption reached to a high level and attained a steady consumption, and no further increase in oxygen uptake with the increase in work load (Nag 1987); and
3. The subjects expressed inability to continue cycling due to perceived physical exhaustion.

**Workload**

Fahrrad's bicycle ergometer was used for the subjects to perform the physical work in the climatic chamber. During the exposure conditions, the subjects performed continuous ergometric work at an intensity of about 60% of one's VO₂ max, and this continued till one reached the level of tolerance.

In extreme intolerable hot environment, skin pain is the critical limiting factor with tolerance time being less than 15 min (Webb 1963); sometimes, a heedless gasp sets off an uncontrollable fit of coughing, which limits heat exposure. At usual high environmental heat, the Tₘₚ does not reach
the painful level, when heat tolerance is limited by the rise in $T_{cr}$. 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 $T_{cr}$ limit of $39^\circ C$ and/or the cardiovascular load reached a peak level (i.e., the heart rate attained 170-180 beats/minute). The observed time was taken as tolerance time. In addition, the subjective feeling of the extent of inability to continue heat exposure was noted (i.e., the perceived tolerance time, and sensation of warmth as predicted mean comfort voting) (ISO 7730, 1994), since motivation is an important factor and discontinuation of heat exposure on demand is mandatory. The subjective responses to the level of tolerance were irritation, nausea, dizziness, etc.

In spite that all subjects were highly motivated to heat exposure programme protective care (e.g. medical attention, water-cooled assistive garment as a standby) was taken for any eventuality (Nag et al. 1998).

**Measurement of Heat Strain**

The physiological responses (strain) to the heat stress are the biological corrective actions designed to counteract the stress. The responses such as heart rate, $T_{cr}$, $T_{sk}$, sweat production, metabolic demand of work were recorded and the magnitude of these responses were taken as the indicators of heat load on the body.
Body Core Temperature ($T_{oc}$)

The $T_{oc}$ of the subjects were continuously monitored, using a deep body thermometer (Type NPT2, Deep Body Thermometer ltd, UK), originally designed by the British Medical Research Council (Fox et al. 1973; Solman and Dalton 1973). The measuring device is based on the principle of creating a zone of zero heat flow across the body shell. A sensing probe pad (6 x 6 x 0.6 cm) was fitted over the right sternum. 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 minute; subsequent minute-to-minute recording were satisfactory. The pad was made of two closed matched thermistors, a piece of nylon gauze and a thin-film heater element closely enclosed in silicone rubber. The signals from the thermistor in contact with the skin surface was fed to the measuring amplifier and recorded every minute. The measurement reliability of the device has been described elsewhere (Nag and Pradhan 1985).

Heart Rate

Heart rate is a useful index of physiological strain, with reference to work demand as well as heat stress. The heart rates were continuously monitored by recording ECG through a Backman R612 Dynograph.

Skin Temperature ($T_{sk}$)

Since skin is the interface between the body tissues and the environment, its temperature is critically important in governing the quantity and direction of
heat flow from the body. The $T_{sk}$ profiles of local areas were monitored using a multi-channel telethermometer \textit{(Aplab, India)}. Seven skin thermistors were attached to different body locations of the subjects in order to calculate the average $T_{sk}$. The locations were: Forehead, Back, Trunk, Upper arm, Hand, Thigh, and Feet. At the beginning of the heat exposure, resting $T_{sk}$ was noted and then every 10 min measurements were recorded during the whole period of heat exposure and recovery period thereafter. Weighted average skin temperature ($\bar{T}_{sk}$) was obtained from the individual fractionated weightages for body segments of subjects and the surface area of the segments using the Meeh (1879) constants, as given in Nag \textit{et al.} (1980 ). A computer routine was developed to estimate the weighting factors of different local areas and to calculate $\bar{T}_{sk}$. Based on the data of Indian subjects, the equation was derived:

$$\bar{T}_{sk} = 0.095 \text{ Head} + 0.245 \text{ Back} + 0.255 \text{ Trunk} + 0.125 \text{ Upper Arm}$$
$$+ 0.035 \text{ Hand} + 0.205 \text{ Thigh} + 0.040 \text{ Feet}$$

\textit{Oxygen Consumption/Metabolic Heat}

The minute-to-minute pulmonary ventilation was recorded using a calibrated KM respirometer \textit{(Zentralwerkstatt Gottingen, Germany)}, which was directly connected to a paramagnetic oxygen analyzer \textit{(Syvtron-Taylor, U.K.)} to obtain the concentration of oxygen content in the expired air. The analyzer was routinely calibrated against a known gas concentration. The amount of oxygen
consumed, and the metabolic heat production of the activities performed was determined.

*Sweat Rate*

Man's capacity to perform work while exposed to thermal environment is also attributed to his sweating ability. Sweating may be considered from the following points of view:

- The problem of maintaining a balance of body water and salt, and the operating capacity of the sweat glands;
- Its usefulness as a criterion of the total heat load placed on the thermoregulatory system;
- Sweat rate provides an indication of the heat load under conditions of high vapour pressure, of the extent to which evaporation of sweat is impeded.

The sweat rate was measured as the net change in the body weight, *i.e.* weight change corrected for fluid intake, clothing, and urinary output. The difference in the body weight was obtained from accurate weighing of subjects before and after the heat exposure. The weighing balance was accurate to ± 25 gm.

**Thermal Indices**

In this part of the study, the following heat stress and stress indices were used. As all the experiments were carried out inside the climatic chamber, Corrected Effective Temperature index was not included in the study.
1. Effective Temperature ET (B) (Houghton and Yaglou 1923)
2. Wet Bulb Globe Temperature Index (WBGT) (Yaglou and Minard 1957)
3. Oxford Index (WD) (Lind 1958)
4. Predicted Four Hour Sweat Rate (P₄SR) (McArdle et al. 1947)
5. Heat Stress Index (HSI) (Belding and Hatch 1955, 1956)
6. Index of Thermal Stress (ITS) (Givoni 1969)
7. Skin wettedness ratio (Gagge 1937)

RESULTS

The physical characteristics of the subjects participated in this part of the study, are given in Table 3.1. The ergometric work done in different days of heat exposure was maintained at a similar level (i.e., 75 W).

Table 3.2 shows the various heat stress and strain indices estimated in the study. From the different indices selected, this study emphasized 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 showed variations with the increasing ET (B). This may be attributed to inherent limitations in the basic equations and its range of application. The HSI, ITS, and P₄SR, are useful physiological strain indicators of sweating response/evaporative cooling. In the present study, beyond 34.5°C ET (B), HSI values exceeded 100 and P₄SR exceeded 5 l, showing considerable body heating. Since the WBGT index has been widely used for
ease of measurement and calculation (Pulket et al. 1980), the prediction 
equation between WBGT and ET (B) was suggested, i.e., WBGT (I) = 1.047 
ET (B). Accordingly, the physiological responses were expressed with 
reference to ET(B).

The rate of oxygen uptake (I/min), oxygen demand (I), the relative 
demand of work as percentage of VO₂ max and tolerance time and safe 
exposure time are given in Table 3.3. The oxygen uptake varied from 0.92 to 
1.24 I/min (42-65% VO₂ max), i.e., at the initial exposure [32.3°C ET (B)] the 
demand of work was only 42% VO₂ max. The difference in oxygen uptake in

Table 3.1 Physical characteristics of the subjects

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Mean ± SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (years)</td>
<td>19.7 ± 1.2</td>
</tr>
<tr>
<td>Body Weight (kg)</td>
<td>47.2 ± 10.1</td>
</tr>
<tr>
<td>Body Height (cm)</td>
<td>164.6 ± 7.2</td>
</tr>
<tr>
<td>Body Surface Area (m²)</td>
<td>1.55 ± 0.18</td>
</tr>
<tr>
<td>Maximal Oxygen Uptake (I/min)</td>
<td>2.23 ± 0.40</td>
</tr>
</tbody>
</table>

N = 11

the environmental conditions of 32.3 and 39°C ET (B) was 23% VO₂ max. Up 
to 34.5°C ET (B) (36.3°C WBGT), the total oxygen demand (67.0 ± 23.3 I) 
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).
Table 3.2 Heat stress and strain indices of the experimental conditions

<table>
<thead>
<tr>
<th>Index</th>
<th>Cond 1</th>
<th>Cond 2</th>
<th>Cond 3</th>
<th>Cond 4</th>
<th>Cond 5</th>
<th>Cond 6</th>
<th>Cond 7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ambient Temperature ($T_a$) °C</td>
<td>38.3</td>
<td>42.4</td>
<td>45.7</td>
<td>48.7</td>
<td>41.7</td>
<td>45.6</td>
<td>48.2</td>
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<td>±</td>
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<tr>
<td>Wet Bulb Temperature ($T_{wb}$) °C</td>
<td>30.1</td>
<td>31.1</td>
<td>31.7</td>
<td>32.7</td>
<td>38.0</td>
<td>39.1</td>
<td>40.1</td>
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<td>±</td>
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<td>±</td>
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<tr>
<td>Effective Temperature, ET(B) °C</td>
<td>32.3</td>
<td>33.7</td>
<td>34.5</td>
<td>35.4</td>
<td>38.0</td>
<td>39.0</td>
<td>40.0</td>
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<td>±</td>
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<tr>
<td>Wet-Bulb Globe Temperature, WBGT (°C)</td>
<td>33.5</td>
<td>34.8</td>
<td>36.3</td>
<td>37.4</td>
<td>39.5</td>
<td>41.3</td>
<td>43.2</td>
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<td>±</td>
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<td>±</td>
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<tr>
<td>Oxford Index (°C)</td>
<td>33.3</td>
<td>32.8</td>
<td>33.9</td>
<td>34.3</td>
<td>38.6</td>
<td>40.1</td>
<td>41.6</td>
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<tr>
<td>Heat Stress Index, HSI (N.D)</td>
<td>88</td>
<td>87</td>
<td>94</td>
<td>94</td>
<td>170</td>
<td>136</td>
<td>137</td>
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<tr>
<td>±</td>
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<td>±</td>
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<td>±</td>
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<td>±</td>
</tr>
<tr>
<td>Predicted 4h Sweat Rate, $P_s$SR (L)</td>
<td>3.0</td>
<td>3.6</td>
<td>4.5</td>
<td>5.3</td>
<td>5.1</td>
<td>5.5</td>
<td>6.0</td>
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<td>±</td>
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<td>±</td>
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<td>±</td>
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<tr>
<td>Index of Thermal Stress, ITS (gm/h)</td>
<td>293</td>
<td>322</td>
<td>370</td>
<td>376</td>
<td>691</td>
<td>480</td>
<td>518</td>
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<td>±</td>
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(Values are Mean ± SD, No of observations N = 33)

In view of tolerance time distribution of the sample group, the safe exposure time was assessed, as given in Table 3.3. As the tolerance time is stated (Bell and Walters 1969) as being normally distributed about the mean value within each climatic condition, the lower 95% confidence limit value for each set of data was estimated from the standard error of the mean and
<table>
<thead>
<tr>
<th>ET (B) (°C)</th>
<th>WBGT (°C)</th>
<th>OXYGEN UPTAKE (L/min)</th>
<th>MAX. OXYGEN UPTAKE (%)</th>
<th>TOTAL OXYGEN DEMAND (L)</th>
<th>TOL. TIME (min)</th>
<th>SAFE EXPOSURE TIME (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>32.3</td>
<td>33.5</td>
<td>0.92 ± 0.27</td>
<td>42 ± 17</td>
<td>68.3 ± 40.3</td>
<td>68 ± 13</td>
<td>50</td>
</tr>
<tr>
<td>33.7</td>
<td>34.3</td>
<td>0.98 ± 0.28</td>
<td>56 ± 24</td>
<td>67.6 ± 28.1</td>
<td>67 ± 10</td>
<td>48</td>
</tr>
<tr>
<td>34.5</td>
<td>36.3</td>
<td>1.04 ± 0.25</td>
<td>57 ± 22</td>
<td>67.0 ± 23.3</td>
<td>63 ± 9</td>
<td>54</td>
</tr>
<tr>
<td>35.4</td>
<td>37.4</td>
<td>1.03 ± 0.23</td>
<td>56 ± 21</td>
<td>51.3 ± 16.0</td>
<td>50 ± 9</td>
<td>38</td>
</tr>
<tr>
<td>38.0</td>
<td>39.5</td>
<td>1.20 ± 0.20</td>
<td>63 ± 16</td>
<td>43.8 ± 12.6</td>
<td>37 ± 12</td>
<td>21</td>
</tr>
<tr>
<td>39.0</td>
<td>41.3</td>
<td>1.24 ± 0.16</td>
<td>65 ± 15</td>
<td>38.3 ± 11.6</td>
<td>31 ± 9</td>
<td>18</td>
</tr>
<tr>
<td>40.0</td>
<td>43.2</td>
<td>1.17 ± 0.29</td>
<td>62 ± 20</td>
<td>34.3 ± 14.8</td>
<td>29 ± 10</td>
<td>15</td>
</tr>
</tbody>
</table>

(Values are Means ± SD, N = 11)

The standard deviation of the distribution of the tolerance time (about imminent collapse time) for all conditions.

The $T_c$ and heart rate at the end point of exposure in different conditions are given in Table 3.4. The group average of both $T_c$ and heart rate responses had a similar trend with the increase in environmental warmth.

The highest heart rate attained was 182 beats/minute. For the temperature conditions of 38.0, 39.0, and 40.0 ET (B) the $T_c$ reached well over 39°C,
Table 3.4 Physiological responses in different exposure conditions

<table>
<thead>
<tr>
<th>Parameters</th>
<th>COND 1</th>
<th>COND 2</th>
<th>COND 3</th>
<th>COND 4</th>
<th>COND 5</th>
<th>COND 6</th>
<th>COND 7</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Tₜₑ (°C)</td>
<td></td>
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<td></td>
</tr>
<tr>
<td></td>
<td>± 38.2 ± 1.0</td>
<td>± 38.5 ± 0.3</td>
<td>± 38.9 ± 0.4</td>
<td>± 39.1 ± 0.3</td>
<td>± 39.6 ± 0.4</td>
<td>± 39.6 ± 0.7</td>
<td></td>
</tr>
<tr>
<td>Heart Rate</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Beats/min</td>
<td>± 175 ± 17</td>
<td>± 167 ± 19</td>
<td>± 166 ± 15</td>
<td>± 172 ± 18</td>
<td>± 175 ± 17</td>
<td>± 180 ± 12</td>
<td>± 182 ± 13</td>
</tr>
</tbody>
</table>

(Values are means ± SD, N=11)

which was taken as one of the criteria of tolerance limit. The coefficient of variations of the variable showed minimum inter-individual variation; however, the behaviour was markedly different in case of tolerance time, as given in Table 3.3. The inter-individual variation in tolerance time was greater in higher environmental warmth, as the coefficient of variations exceeded 30 per cent.

As shown in Figure 3.1, the average Tₛₚ and mean body temperature (weighted mean of Tₛₚ and Tₑₜ) had a consistent upward trend, with the increase in ET (B). Data presented in Table 3.4 and Figure 3.1 indicated 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 Eₛₚ (Figure 3.2) were compared. The subject had a consistent rise in sweating with higher environmental warmth. Since each litre of sweat evaporated from the skin surface represented 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 $E_{sk}$ corresponded to the trend of sweat loss, *i.e.*, up to 35.4°C ET (B) both sweat loss and $E_{sk}$ had a consistent rise with higher environmental warmth followed by shallowing of its effect.

This was further evident from the skin wettedness ratio (*Figure 3.3*), *i.e.*, the subject almost reached unity at 38, 39, and 40°C ET (B). These regulatory responses are controlled by the difference in water vapor pressure on the sweat wetted skin surface and 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.

*Fig. 3.1 Mean skin temperature and body core temperature in different hot environments.*
DISCUSSION

Human tolerance to work in heat depends on the degree of environmental exposure either to dry and humid heat, personal characteristics and the physical activity performed (Kamon et al. 1978; Montain et al. 1994; Davies 1981; Mairiaux and Malchaire 1985). The present study included a wide range of environmental conditions to determine their influence on thermoregulatory responses, with reference to limit of tolerance.

Fig. 3.2 Sweat loss and evaporation through skin (Esv) in hot environment.
Despite the workload being maintained constant in different exposures, the non-linear increase in metabolic demand (i.e., 42% VO$_2$ max at 32.3°C ET-B) raised to 65% VO$_2$ max at 39.0°C ET-B) observed may be attributed to the environmental effects on the cardio-respiratory system. This emphasizes that caution is needed in applying strict limits for prolonged work in high heat. The study showed that the total metabolic 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.

Fig. 3.3 Skin wettedness ratio and thermal sensation as predicted mean voting at different effective temperatures (ET-B).
Fig 3.4 Comparative analysis of tolerance time in different studies.

The average heart rate and $T_{cr}$ 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 uptake reached only to 65% of $VO_2_{max}$, such an increased cardiovascular load was probably a limiting factor to stop the exposure to heat. Also, the $T_{cr}$ reached over 39°C in high heat, e.g., 38, 39, and 40°C ET (B), showing non-steady state situations in $T_{cr}$ adjustment with narrow body temperature gradient for heat exchange (Nag et al. 1986; Pandolf and Goldman 1978). The high $T_{cr}$ might adversely affect the function of the motor centers, reduce the ability to
recruit motor units for the required work and decrease work motivation (Sen 1965).

![Graph showing the relationship between Body Core Temperature and Effective Temperature.](image)

**Fig. 3.5 Exponential pattern of tolerance time and build up of body core temperature with increase in effective temperature (ET-B). Cut-off levels of acceptable and tolerable limits of core temperature are shown.**

Different thermal strategies may be adopted to work in high heat, and the human responses are the joint adjustment of the cardiovascular and sweating responses (Davies 1993). The thermoregulatory responses (e.g., sweating and $E_{sk}$) obtained by in the study 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 supports this (ISO 7730, 1994). 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 may affect thermoregulation and result in a rise of $T_a$. This suggests that the subjects had both cardiovascular and thermoregulatory limitations, which was 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. (1954) 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). Leithead and Lind (1964) recommended the Oxford Index for all air movements, work rates and clothing. Wyndham et al. (1968) found that the inverse of the tolerance times in each environment were normally distributed, the variance being independent of the environment, and suggested the best fit weighing coefficients as $0.88 T_{wb} + 0.12 T_a$ for resting and $0.85 T_{wb} + 0.15 T_a$ for working subjects. WBGT has been widely used as a standard procedure for estimation of safe exposure time (NIOSH 1986).
Figure 3.4 shows the comparison of mean tolerance time against the WBGT, by different researchers and the data obtained in the present study. In most of the studies, tolerance time refers to voluntary ending of the exposure. The trend line of the present study closely resembled to those of Bell & Walters (1969), and McConnell & Yaglou (1925). The present study obtained the multiple regression line between $T_a$, $T_{wb}$ and tolerance time ($TT$, minute) as:

$$TT = 278.3 \cdot T_a - 2.9 \cdot T_{wb} \ (R^2 = 0.613, p<0.001)$$

Further, the $T_{cr}$ and tolerance time had statistically significant relationships with the environment. That is, when the maximum $T_{cr}$ had a linear build up, the tolerance time had an exponential decay with the increase in ET (B) (Figure 3.5). The regression equations are as follows:

$$T_{cr} = 32.8 + 0.17 \cdot ET (B) \ (r = 0.722, p<0.001); \text{ and}$$

$$TT = 3005 \cdot e^{-0.116 \cdot ET (B)} \ (r = 0.844, p<0.001)$$

The present study corroborated the earlier studies (Pandolf and Goldman 1978; Mairiaux and Malchaire 1985) that the $T_{cr}$ 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 $T_{cr}$ that is lethal to a human being, Bynum et al. 1978). However, it is difficult to identify heat intolerant persons to avoid possible placement in high heat, and the intolerants are usually the most vulnerable (Armstrong et al. 1990). Based on the present regression
analysis, one may arrive at the \( T_{cr} \) of 39°C and heat tolerance time of 45 min at 36.5°C ET (B). Accordingly, about \( T_{cr} \) and cardiorespiratory criteria, the exposure ranges may be grouped as acceptable, and/or tolerable limits, (i) acceptable at 38 to 38.2°C \( T_{cr} \) for a tolerance time of 80 to 85 min, and (ii) tolerable limit of short duration (40 to 45 min) at 39°C \( T_{cr} \), 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.

Further, the interaction of the physiological variables and heat stress and strain indices have been examined (Chapter 4) in order to predict human heat exposure limits under varying environmental conditions. Also, the applicability of the thermal indices is described.