HUMAN WORK CAPACITY UNDER COMBINED STRESS OF WORK AND HEAT

P. K. Nag, P. Bandyopadhyay, S. P. Ashtekar, D. Kothari, H. Desai, and A. Nag

National Institute of Occupational Health (Indian Council of Medical Research, Ahmedabad 380 016, India

The working capacity of young, healthy, unacclimatized men (N=11) was studied under long-duration (8 to 9 days) exposure to combined work and heat (dry and humid). The dry (Gr A, N=5) and humid (Gr B, N=6) groups were exposed to 41.3±0.6°C DB, 40–50% RH and 39.2±0.6°C DB, 70–80% RH, respectively, for all days of exposure. The experimental protocol was divided into: (i) direct determination of maximal oxygen uptake ($VO_2_{\text{max}}$) by stepped increases in bicycle ergometry everyday in the morning in the initial hours before exposure to heat, after which the recovery process of oxygen debt contraction was examined; and (ii) exposure to heat in a climatic chamber for 2 h where the subjects performed two spells of ergometric work (10 to 12 min each) at a relative intensity of 50±12 to 69±11% $VO_2_{\text{max}}$. The average heat exposure time for Gr A was higher (108±12 min) as compared to Gr B (95±10 min), but Gr B sustained a high heat load as reflected from the high deep-body temperature maintained during the exposure. The high body temperature load of Gr B had a significant effect on the cardiopulmonary capacity, indicating an upward trend in $VO_2_{\text{max}}$. This was statistically significant ($p<0.05$) for the first four days of exposure. Subjects of Gr B had a relatively higher working capacity compared to those in Gr A on all days. The $VO_2_{\text{max}}$ and analysis of the fractions of oxygen debt contraction (fast and slow component) indicated that the subjects showed a better training/heat acclimatization effect under hot, humid conditions.

Tropical heat represents one of the most pervasive circumstances under which teeming billions must live and work. Human adjustment to hot climate depends on a variety of conditions (e.g., degree and duration of exposure, type of physical activity performed, state of acclimatization and kind of environmental control

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measures available). It is understood that occasional exertion to high heat may be harmful with possible effects on health and work performance, however, the same exposure for a continuing period may result in different kinds of bodily adjustment and reactions. This exemplifies the enormous physiological and psychological potentials of human beings to acclimatize and combat environmental adversities. However, complete acclimatization to heat is rarely possible. Also, some argue that heat training may not be taken as an adequate substitute of heat acclimatization, and vice versa (Gisolfi, 1973; Avellini et al., 1982). This is primarily because of the differences in human physical characteristics, the level of physical fitness and the ability to work in heat (Mairianx and Malhaire, 1985; Barrett, 1991; Vassilis et al., 1973).

Since sustained heat exposure results in a degree of training or acclimatization (Inbar et al., 1981), it is likely that the state of acclimatization of a person may be reflected in cardiorespiratory and thermoregulatory capacities (Avellini et al., 1982; Davies, 1981). Aerobic physical training increases maximal oxygen uptake ($V_{O_2 max}$) (Haisman, 1988), which is conceived as the indicator of physical work capacity. It is possible that unacclimatized persons subjected to consecutive days of exposure at a highly effective heat load (i.e., the combined internal metabolic heat production due to physical activity and external heat load) may show changes in their cardiorespiratory responses. This study examines the changes in the working capacity of unacclimatized subjects under long-duration consecutive exposure to combined work and heat load in dry and humid environments.

**METHODS AND MATERIALS**

Eleven young healthy, motivated male volunteers from a small industrial sector participated in the study. This homogenous group of volunteers was divided into two groups for dry (Gr A, $N=5$) and humid (Gr B, $N=6$) heat exposure. Since identifying people by state of acclimatization is difficult, the unacclimatized subjects were selected to undergo a scheduled heat-exposure programme. The volunteers were subjected to an experimental protocol stretching over a period of eight to nine days of exposure. As a primary condition for selection of volunteers, the investigators ascertained, through interviews and cross references, the pattern of habitual physical activity and the subjects’ usual exposure to high heat. The climate of Ahmedabad City is very hot during the summer months (April–July), and the subjects are naturally exposed to high heat during these months. However, the experiments were undertaken during the months of October to February, and the subjects were naturally free from high environmental heat. For all practical purposes, the subjects were not acclimatized to heat prior to their introduction to the experimental protocol.

Following selection, the subjects were indoctrinated not to participate in any additional heavy activity and remain in sedentary activity outside of the experimental protocol. It was ascertained that the subjects had sufficient sleep and no alcohol
comfortable consumption during the days of the experiment. The subjects were asked to attend the laboratory in the morning every day at least 1 h before the commencement of the experiment, and each had undergone 30 min of rest (lying/sitting) in a comfortable environment (22–25°C dry-bulb (DB) temperature, 40–50% RH). The experimental protocol was divided into two parts:

(i) direct determination of maximal oxygen uptake ($VO_2_{max}$) as the measure of physical work capacity, done everyday in the initial hour before exposure to heat;

(ii) exposure to heat in a walk-in climatic chamber (Hotpack International, USA) for a duration of approximately 2 h every day for a period of eight to nine days.

For the two exposure groups, the temperature of the climatic chamber was maintained as follows:
- Group A, 41.3±0.6°C DB and 40–50% RH (dry heat);
- Group B, 39.2±0.6°C DB and 70–80% RH (humid heat).

The climatic conditions remained unchanged for all days of exposure. There was no forced-air ventilation source inside the chamber and the air movement recorded at different corners of the chamber was within the free convection range (below 0.3 m/s). During the 2 h exposure period, the subjects performed two spells of ergometric work of moderately heavy to heavy intensity (50±12 to 69±11% $VO_2_{max}$), each lasting 10 to 12 min. The deep-body temperatures of the subjects were continuously monitored during heat exposure. This was done with the help of a deep-body thermometer (Type NPT2, Deep Body Thermometers Ltd., UK) originally designed by the British Medical Research Council (Fox et al., 1973; Solman and Dalton, 1973).

In order to determine $VO_2_{max}$ the ergometric tests were also undertaken in the comfortable environment mentioned above. The subjects undertook step-increased bicycle ergometric work, with the braking load varying from 50 to 225 W at 60 rpm. The maximal loading of the subjects on different days varied within the range of 175 to 225 W. During and after the cessation of ergometric work, physiological responses were continuously monitored. The measurements included minute by minute recording of pulmonary ventilation using a calibrated KM respirometer and oxygen content of the expired air using a Syvron-Taylor (UK) paramagnetic oxygen analyzer. Heart rate changes were monitored by recording ECGs through a Beckman R612 Dynograph, a 4-channel storage oscilloscope and on-line storage of the analog signals in a Instrumentation Tape Recorder (HP 3964A) for subsequent retrieval and digitization. Also, an experienced observer constantly noted palpations using a stethoscope.

The criteria to establish $VO_2_{max}$ were one or more of the following: (i) heart rate reached the age-related maximum (i.e., 190 beats/min); (ii) oxygen consumption reached a high level and attained steady consumption with no further increase in oxygen uptake at the time of an increase in work load; and (iii) subjects expressed inability to continue cycling due to perceived physical exhaustion.
After the cessation of ergometric work, the subjects were continuously monitored to study the kinetics of oxygen uptake (NAG, 1984; HAGBERG et al., 1990; ARMON et al., 1991) during the period of recovery. There is an exponential decay pattern for oxygen debt contraction and replenishment of energy reserves. Physiological mechanisms such as alactoid and lactoid fractions of oxygen debt contraction (fast and slow components) have different rate constants, implying different recovery pattern associated with the corresponding physiological functions. In this contribution, an attempt was made to derive a mathematical relationship of the recovery process, which is considered as the superimposition of $n$-number of decay curves of different rate constants. An orthogonal polynomial gives the number of exponential components best fitted to $F_a$. The complex exponential functions were analyzed using Prony’s method of approximation in the form:

$$F_a = a_1 e^{-k_1 t} + a_2 e^{-k_2 t} + \cdots + a_n e^{-k_n t},$$

where $F_a$ (i.e., $VO_2$ values) are equally spaced at one-minute intervals. Each exponential term of the equation represents a decay curve. To simplify the physiological mechanism involved for $n$-number of curves, the recovery process was analyzed by taking two possible groups (fast and slow components), for which $n = 2$ is assigned;

$$F_a = a_1 e^{-k_1 t} + a_2 e^{-k_2 t}.$$

The detailed procedures to compute $e^{-kt}$ are available in HILDEBRAND (1956). Both $a_1$ and $a_2$ are determined by the method of least squares. Accordingly, the resultant total $O_2$ debt was fractionated for the $O_2$ debt fractions due to fast and slow processes, and the integrated area of the curve was measured to obtain the relative contribution of each factor.

**RESULTS AND DISCUSSIONS**

The physical characteristics of the subjects selected in the study are given in Table 1. As indicated from the age group and other characteristics, the subjects

<table>
<thead>
<tr>
<th>Group</th>
<th>Age (yrs)</th>
<th>Body height (cm)</th>
<th>Body weight (kg)</th>
<th>Body surface area (m²)</th>
<th>$VO_2_{max}$ (l/min)</th>
<th>Heart rate (beats/min)</th>
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<tbody>
<tr>
<td>A (Dry heat)</td>
<td>18 ± 1.1</td>
<td>157.3 ± 4.9</td>
<td>40.8 ± 18</td>
<td>1.36 ± 0.04</td>
<td>1.912 ± 0.15</td>
<td>193 ± 12</td>
</tr>
<tr>
<td>B (Humid heat)</td>
<td>19 ± 1.2</td>
<td>163.3 ± 4.3</td>
<td>43.9 ± 3.0</td>
<td>1.44 ± 0.58</td>
<td>2.130 ± 0.33</td>
<td>189 ± 5</td>
</tr>
</tbody>
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Values are means ± standard errors.
were homogeneous and belonged to similar socio-economic backgrounds. The average $VO_{2\text{max}}$ of the two groups of subjects, as recorded prior to introducing them to the heat exposure programme, had only a marginal difference, indicating that the difference in work capacity of the two groups was statistically insignificant.

Exposure to heat for the two groups of subjects was characteristically different in terms of the effective heat load. The ambient temperature conditions in which the groups (Gr A and Gr B) were exposed varied only within a narrow range, 41.3 ± 0.6 and 39.2 ± 0.6°C DB, respectively; Gr A subjects had exposure to ambient vapour pressure of 40–50% RH (dry heat), whereas Gr B subjects had exposure in the range of 70–80% RH (humid heat). These two climatic situations had a consequential influence on the subjects under long-duration exposure.

Figure 1 shows the average deep-body temperature attained by the subjects on different days of exposure. The humid group (Gr B) sustained a high heat load, as reflected from the high deep-body temperature maintained during exposure. The body temperature on the first day of exposure was 37.5 ± 0.09°C and on the eighth day, it was noted as 37.6 ± 0.08°C. On the other hand, the subjects in Gr A (dry heat) showed a consistently downward trend in deep-body temperature, from the first day of exposure (37.7 ± 0.06°C) through all subsequent days of exposure; that is, the difference in average deep-body temperature by the eighth day of exposure dropped 0.4°C as compared to the value recorded on the first day.

In spite of the protocol for 2h exposure, all subjects could not complete the exposure duration. The average exposure duration for Gr A (108 ± 12 min) was relatively higher than that for Gr B (95 ± 10 min). However, the high body-temperature load in the latter group had a significant effect on the cardiorespiratory capacity.

Figure 2 shows the maximum oxygen uptake recorded on different days of exposure. The humid group had a relatively higher $VO_{2\text{max}}$ as compared to that recorded for Gr A. Gr B subjects showed a consistently upward trend in $VO_{2\text{max}}$.

![Fig. 1. Changes in deep-body temperature on consecutive days of heat exposure.](image-url)
for the first four days of exposure, and $V_{O_2}^{\text{max}}$ was comparatively higher than that for Gr A on all days. From an unpaired $t$-test of significance, this difference was found to be statistically significant ($p<0.05$). The higher work capacity of the humid group is indicative of a better form of bodily adjustment or acclimatization. A relatively lower level of work capacity in the last days of exposure might be the result of cumulative muscular fatigue. Changes in work capacity were evident in both groups, and this could also be explained from the trend in total oxygen deficit (Fig. 3). In case of Gr B, the oxygen deficit incurred during the work phase increased for the first four days and subsequently decreased to a significant extent ($p<0.001$). The oxygen deficit in Gr A was constant for the first four days of exposure. From the fourth day onwards, there was a gradual increase in total oxygen deficit, which was compensated during the recovery phase. The oxygen deficit reached a peak on
the sixth day, and maintained a high value on subsequent days as compared to those values noted on the first four days. The increase in oxygen deficit was also an indication of improvement in work capacity and acclimatization, which seemed to have been achieved relatively quickly in the case of Gr B (humid heat), but took a longer time in the case of Gr A (dry heat).

This observation was evident from the oxygen debt contraction as shown in Fig. 4. In Gr A, the oxygen debt remained steady with a marginal downward trend on different days of heat exposure; whereas in the case of the humid group, there was a noticeable increase in O₂ debt contraction. The fractions of oxygen debt contraction was resolved into two components (i.e., fast and slow components) representing alactoid and lactoid fractions of energy replenishment, as shown in Figs. 5 (Gr A) and 6 (Gr B).
Fig. 6. Fractions of oxygen debt contraction (fast and slow components of recovery) of humid-heat group (Gr B) on consecutive days of exposure.

Fig. 7. Slow component fraction of maximal oxygen debt on consecutive days of exposure.

The patterns of Figs. 5 and 6 indicate that the slow components were relatively predominant as compared to the fast component of oxygen debt contraction. Gr B (Fig. 6) showed a sharp rise in the slow component of the oxygen debt fraction from the fourth day onward, and the reverse was noted in the case of the fast component fraction. A comparison of the slow components of oxygen debt fraction in Gr A and Gr B is shown in Fig. 7.

This study suggests that human exposure to a combined load of work and heat causes strain on the energy delivery mechanism in a characteristic manner. A prolonged exposure to high heat influences one's working capacity and energy reserves. The design of the experiment was made in a manner that the possible influence of every-day exposure to combined heat and work was examined on the subsequent day prior to heat exposure. This allowed a day-to-day comparison of the same subject in dry (Gr A) as well as humid heat (Gr B). The study indicated
that the humid group (Gr B) had a relatively higher working capacity, which was found to be statistically significant ($p < 0.05$) up to four days of exposure, as compared to Gr A. The subjects of Gr A (dry heat), however, showed a marginal improvement in working capacity from the fifth to seventh day; but in all previous days, it seemed that the body maintained the initial level of working capacity. Since Gr A and Gr B were homogeneous in all respects, the relatively higher work capacity of Gr B may be attributed to a possible training/heat acclimatization effect under humid conditions. A humid environment indulges the cardiorespiratory system to considerably higher activity during consecutive exposures as compared to activity in a dry environment. The implication of a relatively higher cardiorespiratory load reflected some adjustment or heat acclimatization effect on working capacity.

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