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Body Heat Balance of a Man with Deficient Sweat Rate Subjected to Physical Work in a Hot Environment

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The dynamics of physiological stress and thermal balance were investigated in men subjected to endogenous and exogenous heat loads. The study was conducted using the thermometric method. Substantial differences in the dynamics of the tested parameters and their quantitative characteristics were observed in 1 out of 8 participants. In this article, the observed differences are rationalized in terms of the deficient sweat rate mechanism. It is pointed out that it is indispensable to address these cases in work safety regulations.

thermoregulation heat balance exercise heat exposure

1. INTRODUCTION

During work in a hot environment, sweat evaporation is the most effective way for internal heat loss. Convection and radiation require the temperature gradient to be effective. The driving force for sweat loss by evaporation is a gradient in absolute humidity. Therefore, the only limitation for heat loss by evaporation is high relative humidity.

Sweat secretion is a physiological process under strong neurohormonal control, whereas sweat evaporation from skin surface is a physical process,

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which can be precisely defined by a physical equation. This makes it possible to evaluate the risk of hyperthermia in hygienic standards. There are two standards based on the evaporation rate as a factor in evaluating the risk of thermal shock: Standard No. ISO 7243:1989 (International Organization for Standardization [ISO], 1989b), based on the theoretical model of the exchange of heat in the wet bulb globe temperature index (WBGT), and Standard No. ISO 7933:1989 (ISO, 1989a) about the analytical determination and interpretation of the thermal stress, based on the Required Sweat Rate Index.

In both of these standards thermal shock risk is calculated from basic environmental parameters such as air temperature, humidity, mean radiant temperature, air velocity, and clothing insulation. Metabolic rate is commonly evaluated by theoretical calculation, it is not, therefore, an indicator of the physiological capability for heat tolerance. Under these circumstances, even in conditions described in the standards as safe, sweat rate deficiencies, which are dependent on physiological processes create a potential risk of thermal shock. A case of low heat tolerance was found during studies carried out in the controlled environment of a climatic chamber. A possible explanation of the observed low heat tolerance is discussed in this paper.

2. METHODS

Studies of thermal balance in men subjected to physical work under controlled hot conditions (endo- and exothermal load) were conducted in a climatic chamber. Eight young healthy male volunteers performed exercise on a Monark bicycle ergometer Monark (Figure 1). Before the experiment, all participants had been medically examined and given instruction how to maintain proper body hydration during the experiment.

The volunteers wore lightweight briefs and shoes (clo = 0.01). The experiment involved 1-hr bicycle exercise at approximately $1/3\,\dot{V}_{O_2max}$ (50 W) at ambient temperature 37 °C (T_a), and the mean radiant temperature 60 °C ($\bar{T}_r$). These temperatures were measured with an accuracy of 0.1 °C. The relative humidity was kept constant at 40% and the air velocity at about 0.6 m·s^{-1}.

During the pre-exercise rest and recovery period the participants were at ambient temperature 26 °C outside the climatic chamber. The experimental conditions are presented in Figure 1.

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HOT CONDITIONS (SW T_a = 36.6 °C (±0.05)$_{req}$ = 300 W•m^{-2})
$\bar{T}_r$ = 59.6 °C
V_a = 0.58 m•s^{-1} (±0.01)
P = 2200 P_a (±5)
W = 50 W (~1/3 $\dot{V}_{O_2max}$)
I_{cl} = 0.01 clo

REST (15 min) **PHYSICAL EXERCISE** (60 min) **RECOVERY** (30 min)

THERMO NEUTRAL CONDITIONS (PMV = 0.9)
T_a = 26 °C (±0.1)
$\bar{T}_r$ = 23 °C
V_a = 0.1 m•s^{-1} (±0.01)
P = 599 P_a (±10)
I_{cl} = 0.01 clo

AGE (yr) ± *SD*	HEIGHT (cm) ± *SD*	WEIGHT (kg) ± *SD*	AREA, DuBois (m^2) ± *SD*
23 ± 2	177 ± 2	73.3 ± 8.9	1.9 ± 0.1

Figure 1. Experimental arrangement: Thermal balance in a man under combined (endogenous and exogenous) heat load was investigated in a climatic chamber, using the thermometric method.

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Heart rate (HR), oxygen consumption ($\dot{V}_{O_2}$), and rectal (T_{re}), auditory canal (T_{ac}) and skin (T_{sk}) temperatures were measured every 5 min throughout the experiment (including the rest and recovery periods).

Oxygen consumption ($\dot{V}_{O_2}$) and the respiratory quotient (RQ) were measured using a Beckman (Germany) analyzer. Maximal oxygen consumption ($\dot{V}_{O_2 max}$) was calculated by the indirect Åstrand-Ryhming method (Åstrand & Ryhming, 1954), the metabolic heat production was calculated from the oxygen consumption according to Standard No. ISO 8996:1990 (ISO, 1990).

Body temperatures were measured with an accuracy of 0.15 °C using standard thermocouples. They were recorded on a 15-channel Ellab (Denmark) point recorder. Mean skin temperature was calculated with an 8-point formula according Standard No. ISO 9886:1992 (ISO, 1992), heart rate by measuring R-R intervals in the ECG.

Participants were weighed before and after the experiment with an accuracy of ±5 g on a Sartorius (Germany) platform scale. Clothes were also weighed before and after the experiment with the same accuracy. No dropping sweat was observed during our experiments and following Craig and Moffitt (1974), the efficiency of evaporative cooling was considered equal to 1.

The physical parameters of ambient air were measured according to Standard No. ISO 7726:1985 (ISO, 1985).

During the relative steady-state of body temperature, heat storage rate ($\dot{S}$) and net body heat load ($\dot{H}$) were determined and calculated from the heat balance equation according to Grucza (1983) and Vogt, Meyer, Candas, Libert, and Sagot (1983).

The increase in body heat content (body heat storage, ΔS_1, in kJ) was calculated from the rate of heat storage ($\dot{S}$), as defined by Jequier (1977). The increase in body heat content (body heat storage, ΔS_2, in kJ) was also determined and calculated from the calorimetric equation according to Gagge (1972), where the Stolwijk and Hardy (1966) equation is used to calculate the increase in mean body temperature.

The thermoregulation efficiency coefficient (TI) calculated according to Grucza's (1988) definition as a function of the increase in mean body temperature.

The Required Sweat Rate (SW_{req}) for evaluating the thermal load and permissible time of exposure, and the Predicted Mean Vote (PMV) index for evaluating the thermal sensation were all investigated according to international standards No. ISO 7933:1989 (ISO, 1989a) and ISO 7730:1993 (ISO, 1993).

The results for participant A were calculated and are presented separately in the paper. They are compared with the mean values of the remaining 7 participants.

3. RESULTS

The conditions during the experiment are shown in Figure 1. During the rest and recovery periods the value of the PMV index was 0.9, which classified these conditions as thermoneutral.

The value of SW_{req} during the exercise in the climatic chamber was 300 W/m^2. According to Standard No. ISO 7933:1989 (ISO, 1989a), this value characterizes hot conditions and determines the limit of work time (in this case, 2 hrs).

As shown in Figure 2, the net body heat load (i.e., heat received from the environment and muscular work) was similar (about 270 W/m^2) for all participants during the experiment. This also applied to the heat load of participant A (dotted line), who was under special scrutiny because of physiological signs of maladaptation to work in hot conditions.

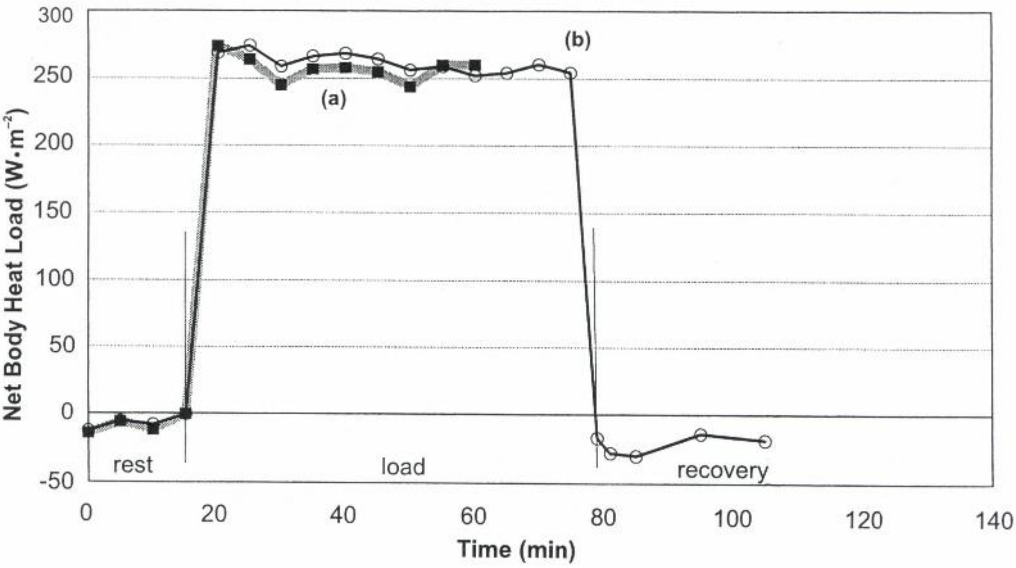

Figure 2. Time course of net body heat load: (a) value for an individual participant, (b) mean value for all participants ($\sigma / \sqrt{n} = 20$).

Although the physical and thermal loads were the same for all participants, the experiment had to be discontinued for participant A after 40 min of the exercise because his heart rate reached 180 beats/min and his rectal temperature reached 38.5 °C, the limits of the physiological values permitted for human experiments (Kenney, Levis, Anderson, & Kamon, 1986).

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Changes in heart rate (HR) and rectal temperature (T_{re}) during the experiment are presented in Figures 3 and 4. The mean values of the 7 participants and the values of the participant A are shown separately.

Both rectal temperature (T_{re}) and heart rate (HR) at rest of participant A are higher than those in the remaining group from the very beginning of the experiment. The increase in heart rate in the course of the experiment was 100 beats/min in participant A whereas the average for the group was 70 beats/min.

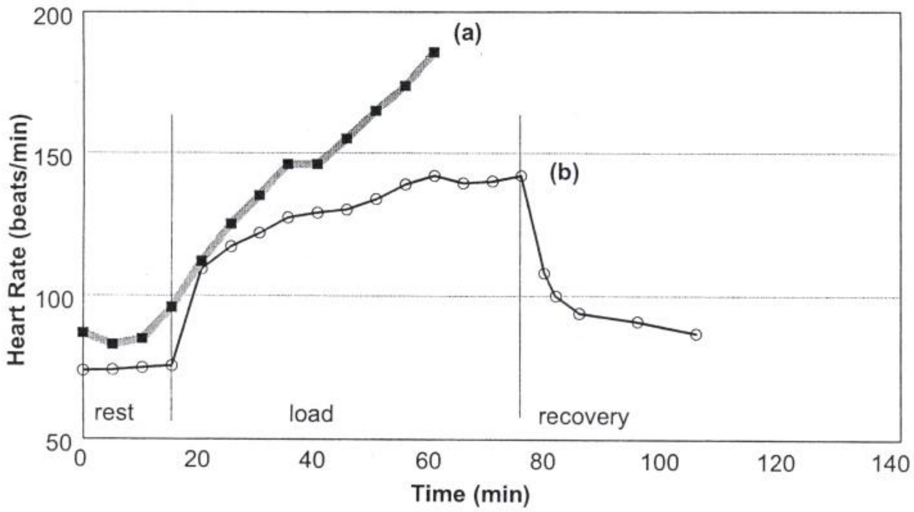

Figure 3. Time course of heart rate: (a) value for an individual participant, (b) mean value for all participants ($\sigma / \sqrt{n} = 6$).

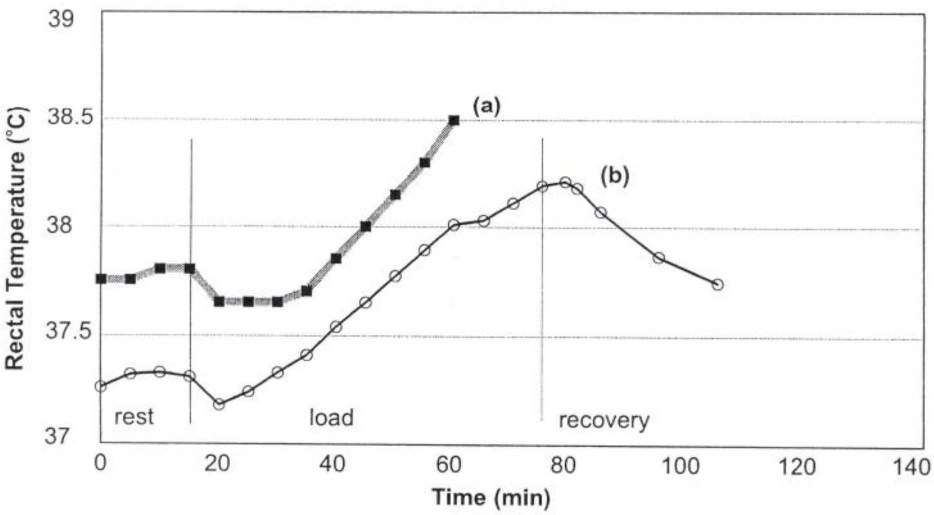

Figure 4. Time course of rectal temperature: (a) value for an individual participant, (b) mean value for all participants ($\sigma / \sqrt{n} = 0.1$).

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Rectal temperature (T_{re}) of participant A was 37.75 °C during the rest period and increased during the experiment by 1 °C more than the temperature of the rest of the group.

On the other hand, the sweat rate of participant A was threefold lower compared with the average sweat rate of the other 7 participants (Figure 5).

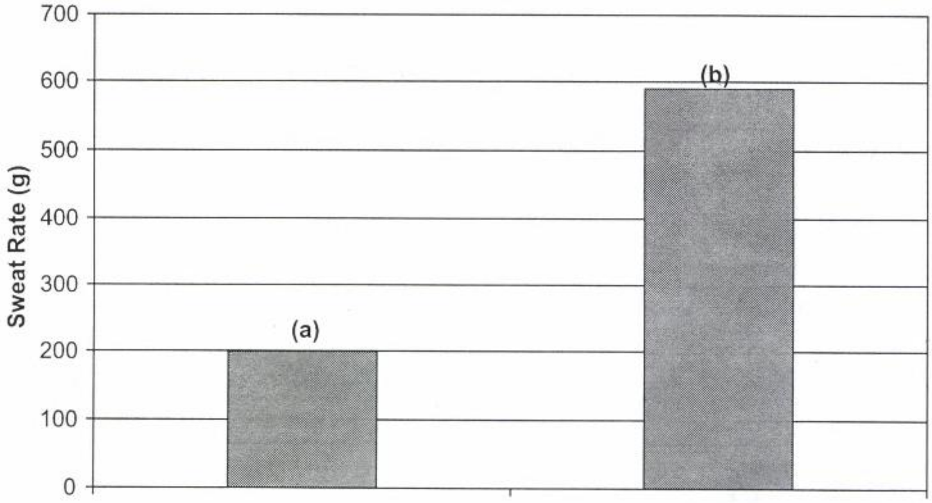

Figure 5. Sweat rate: (a) value for an individual participant, (b) mean value for all participants ($\sigma/\sqrt{n} = 25$).

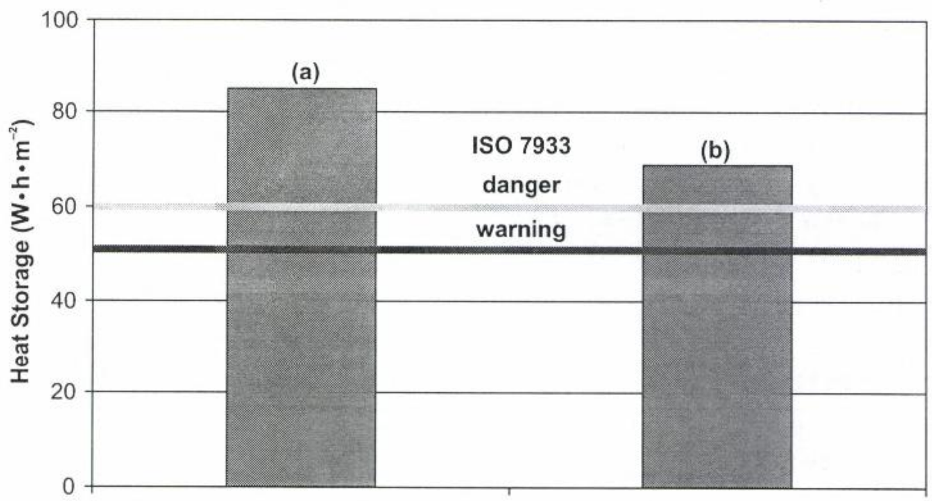

Figure 6. Heat storage compared to levels acceptable according to Standard No. ISO 7933:1989 (ISO, 1989a): (a) value for an individual participant, (b) mean value for all participants ($\sigma/\sqrt{n} = 8$).

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Participant A's heat storage calculated from the calorimetric equation was significantly higher than the mean value for the group (Figure 6). It is evident that the heat storage values for all participants were in the danger zone (according to the criterion described in Standard No. ISO 7933:1989 [ISO, 1989a]) but for participant A the heat storage level was especially high.

4. DISCUSSION

In the course of the experiment, rectal temperature of 7 participants showed a steady increase and heat storage reached the warning zone specified by Standard No. ISO 7933:1989 (ISO, 1989a). However, stabilization of heart rate and a relatively high level of sweat rate indicated an onset of adaptation processes. In such cases, low hyperthermia (such as observed in Figure 6) should last for a limited time, if sweat rate is effective in dissipating internal heat. So, the low sweat rate observed in the case of participant A may be responsible for thermal maladaptation. This maladaptation may cause large accumulation heat (Figure 6) and rapid increase in rectal temperature and heart rate without any stabilization in the course of the experiment.

It is difficult to determine unequivocally the mechanisms responsible sweat deficiency in this case.

Sweat rate change depends on various physiological factors: age, gender, region, individual differences, emotional conditions, and acclimation processes (Anderson & Kenney, 1987; Bar-Or, Lundegren, & Buskirk, 1969; Delamarche, Bittel, Lacour, & Flandrois, 1990; Drinkwater, Bedi, Loucks, & Horvath, 1982; Foster, Ellis, Dore, Exton-Smith, & Weiner, 1976; Fennell & Moore, 1973; Hellon & Lind, 1956; Hofler, 1968; Hori & Ihzuka, 1986; Kimura, Araki, Tohori, Tsuita, & Hori, 1983; Kuno, 1956; Shoenfeeld, Udassin, Shapiro, Ohri, & Sohar, 1978; Shvartz et al., 1979; Wagner, Robinson, Tzankoff, & Mario, 1972; Yousef, Dill, Vitez, Hillyard, & Goldman, 1984). Sweat rate is also strongly modified by various pathological disorders such as local (skin) and central diseases. Circulatory (mainly vasomotor) and hormonal disturbances (Behr, Hildebrandt, Koca, & Bruck, 1991; Bothorel, Heller, Grosshans, & Candas, 1992; Ferguson & Martin, 1991) as well as changes in the thermoregulation system may heavily influence the sweat rate. In such cases, sweat rate decreases when core temperature increases. On the other hand, excessive sweating is observed when core temperature decreases.

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The routine health examination before the experiment did not show any evidence of health disturbances of participant A. The only abnormality was the rectal temperature of 37.8 °C from the beginning of the experiment, which could be interpreted as a slight fever (the normal range is 36–37.8 °C). However, it is difficult to recognize the deficiencies of the sweat rate in thermoneutral conditions without any other pathological evidence. In such cases, only a test of sweat rate could show low efficiency of the thermoregulation processes, which can lead to hyperthermia during extreme load condition, such as physical load in hot conditions. Thus, a person with low sweat rate should not be exposed to external (environmental) or internal (work) thermal load.

Deficient sweat rate has not so far been addressed by any hygienic standards. The results of this study show that such a possibility should be considered during initial medical examinations. Therefore, it is proposed that hygienic standards should contain a provision that they concern only healthy men whose sweat rate is not deficient.

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