Abstract Effects of sleep deprivation and season on thermoregulation during 60 min. of leg-bathing (water temperature of 42°C, air temperature of 30°C, and relative humidity of 70%) were studied in eight men who completed all 4 experiments for normal sleep and sleep deprivation in summer and winter. Rectal temperature ($T_{re}$), skin temperature, total body sweating rate ($M_{sw-t}$), local sweating rate on the back ($M_{sw-back}$) and forearm ($M_{sw-forearm}$), and skin blood flow on the back ($SBF_{back}$) and forearm ($SBF_{forearm}$) were measured. The changes in $T_{re}$ ($\Delta T_{re}$) were smaller ($P<0.05$) for sleep deprivation than for normal sleep regardless of the season. This decrease in $\Delta T_{re}$ was significant only in summer ($P<0.05$). Mean skin temperature ($\bar{T}_{sk}$) was higher ($P<0.05$) for sleep deprivation than for normal sleep regardless of the season. $M_{sw-t}$ was smaller ($P<0.05$) for sleep deprivation than for normal sleep regardless of the season, although $M_{sw-back}$ and $M_{sw-forearm}$ were similar. $SBF_{back}$ and $SBF_{forearm}$ tended to be higher for sleep deprivation than normal sleep. The sensitivity of $SBF$ to $T_{re}$ was higher ($P<0.05$) for sleep deprivation than for normal sleep. These data indicate that seasonal differences in thermoregulation were small because of morning time. Sleep deprivation increased dry heat loss and restrained $T_{re}$ rise, in spite of decreased sweating rate. J. Physiol Anthropol Appl Human Sci 22 (6): 273–278, 2003 http://www.jstage.jst.go.jp/en/

Keywords: sleep deprivation, thermoregulation, seasonality, sweating, skin blood flow

Introduction

Sleep disturbance caused by irregular sleep habits, shift work and rapid travel to a different time zone could occur to anyone in the present day. Some researchers, therefore, have reported on how sleep-deprived humans manage thermoregulation. Most of these studies have reported small effects of one-night sleep deprivation on thermoregulation. The findings on thermoregulatory responses, however, were inconsistent. Several investigators reported lower body temperature in a neutral environment after a sleep-deprived night (Kolka et al. 1988; Landis et al. 1998; Opstad et al. 1991), while others showed increased body temperature (Bamezai et al. 1992; Fiorica et al. 1968) and still others showed no change in body temperature (Dewasmes et al. 1992; Knauth et al. 1978; Martin et al. 1984; Savourey et al. 1994; Sawka et al. 1984).

In addition, some studies reported the effect of sleep deprivation on thermoregulation during exercise. Sweating and blood flow responses to exercise from sleep loss were found lacking. In experiments conducted at about 3:00 pm in the summer, Sawka et al. (1984) reported that there was no change due to sleep loss in the threshold for sweating to begin, but that the gradient of sweating versus body temperature was reduced. A different study performed at about 11:00 am in the winter, on the other hand, found a higher threshold for sweating to begin and no change in the gradient of sweating versus body temperature (Dewasmes et al. 1992). Another study at about 3:00 pm in the summer showed a lower body temperature at the onset of skin blood flow and a smaller slope of skin blood flow versus body temperature (Kolka et al. 1988).

Some reasons for these different findings are that thermoregulatory responses show large individual differences and sensitivity to many other factors, in addition to the small effect of sleep deprivation itself. Different exercise intensity, environmental temperatures, time of day, and seasons among the above reports could account for the inconsistencies. It is well known that in a normal sleep state the body temperature keeps circadian rhythm, and thermoregulatory responses to heat stress show diurnal variation (Aoki et al. 1995, 1997, 1998a,b; Stephenson et al. 1983; Tayefeh et al. 1998; Tsurutani-Midorikawa 1981). The seasonality of circadian rhythm is confirmed by higher rectal temperature in summer than in winter and earlier shift of decrease phase of
rectal temperature during nighttime in summer than in winter (Honma et al. 1992). Therefore, diurnal variation of thermoregulatory responses is affected also by seasonal changes in body-temperature circadian rhythm (Tsurutani-Midorikawa 1981). Besides, thermoregulatory responses to heat stress are seasonally changed because of humans’ advanced ability to adapt to heat or cold according to the season (Hori et al. 1993; Inoue et al. 1995; Shiraishi et al. 1990; Tsurutani-Midorikawa 1981). However, there are fewer studies observing thermoregulation effected by sleep deprivation on a seasonal basis. This study, therefore, investigated the effects of sleep deprivation on thermoregulation during leg-bathing at rest in a hot environment in two different seasons.

**Methods**

**Subjects**

Eight healthy young adult male students [23.2±2.0 (SD) yr of age] participated in this study. They were informed of the study’s purpose, its schedule, any known risks, and their right to terminate the experiment. This study was approved by the Human Ethics Committee of the Department of Ergonomics of the Kyushu Institute of Design.

Their biometric characteristics are shown in Table 1. Body surface area was calculated from height and weight according to the methods of Fujimoto & Watanabe (1969). Body fat was automatically calculated using a bioelectrical impedance analysis and a digital weight scale (TBF-546, Tanita Co. Ltd., Japan). Skinfold thickness was measured by a subcutaneous adipose tissue caliper (Meikosha Co. Ltd., Japan). No significant differences in these characteristics of the subjects were observed between summer and winter.

**Procedure**

The experiments were conducted four times per subject: one normal sleep test and one sleep deprivation test in September and the same tests in March when the subjects were naturally acclimatized to heat or cold. The subjects were asked to keep regular hours from about a week before participation until the series of experiments. The normal sleep test and sleep deprivation test in each season were performed in random order at intervals of over 2–3 days for each subject.

Each subject arose at 7:00 am at his residence and spent the day normally for all experiments. Then the subject stayed at our laboratory through the night beginning at 11:00 pm, in rooms judged suitable for the experimental requirements of either normal sleep or sleep deprivation. Rooms were controlled at air temperature ($T_a$) of 27°C, and the subjects were dressed in shorts and short-sleeved tops. Heat exposure testing started from 7:00 am of the next morning, after each subject either got up at 6:30 am in the lab or was deprived of sleep for 24 h. All subjects were dressed only in shorts and rested in a thermo-neutral room ($T_a=27^\circ$C) for 30 min. After moving to a hot room ($T_a=30^\circ$C, relative humidity 70%), they sat for 70 min and then had both lower legs immersed for the last 60 min with water maintained at a temperature of 42°C.

The subjects for the normal sleep test were prohibited from taking food and water from 11:30 pm until the end of the experiment in the next morning. The subjects for sleep deprivation, however, were permitted to take a little confectionery and water until 3 hours before each experiment.

**Measurements**

Rectal temperature ($T_r$) was continuously measured with a rectal thermistor probe (Nikkiso-YSI Co. Ltd., Japan) inserted 12 cm beyond the anal sphincter during the experiments. Skin temperatures were continuously measured at seven sites by thermistors (Nikkiso-YSI Co. Ltd., Japan) taped on the skin [forehead ($T_f$), chest ($T_c$), back ($T_b$), forearm ($T_{bf}$), hand ($T_h$), thigh ($T_{th}$), and foot ($T_f$)], then mean skin temperature ($\bar{T}_{sk}$) was calculated from the following equation by Sasaki (1981): 

$$\bar{T}_{sk} = 0.07(T_f) + 0.18(T_c) + 0.17(T_b) + 0.15(T_{bf}) + 0.05(T_h) + 0.25(T_h) + 0.13(T_f)$$

These temperature data was gathered in a data logger (LT8A, Gram Co. Ltd., Japan) every minute.

The total body sweating rate ($M_{sw}$) was determined using the change in nude body weight (Mettler ID2, Switzerland) from before to after the experiment. The local sweating rate on the back and forearm ($M_{sw-back}$, $M_{sw-forearm}$, respectively) was continuously measured by sweat-measuring equipment employing a ventilated capsule and a hygrometer (AMU-100II, K&S Co. Ltd., Japan). Dry nitrogen gas was pumped into closed capsules (1 cm$^2$) on the skin at a rate of 0.3 L min$^{-1}$ and the humidity of the gas in the capsules was measured. The data on local sweating were gathered every second by a computer (Gateway, Japan) during the experiment, and the onset time for sweating was determined by direct observation. Skin blood flow on the back and forearm ($SBF_{back}$, $SBF_{forearm}$ respectively) was continuously measured every second by a laser Doppler flowmetry (FLO-C1, Omega wave Co. Ltd., Japan). Metabolic heat production ($\dot{M}$) was calculated by oxygen uptake analyzed

| Table 1 Characteristics of the subjects (n=8) in each season. BSA indicates body surface area. |
|---|---|---|
| | Summer | Winter |
| | Mean | SD | Mean | SD |
| Height (cm) | 166.4 | 5.0 | 166.3 | 5.0 |
| Weight (kg) | 65.1 | 8.7 | 64.4 | 7.9 |
| BSA (m$^2$) | 1.74 | 0.12 | 1.73 | 0.12 |
| %Fat (%) | 22.0 | 4.1 | 23.2 | 4.2 |
| Skinfold Thickness (mm) | Back | 18.1 | 8.0 | 17.2 | 6.8 |
| | Upperarm | 12.4 | 4.6 | 9.8 | 1.6 |
| | Chest | 13.8 | 6.3 | 7.8 | 1.7 |
| | Abdomen | 10.2 | 5.3 | 10.1 | 2.2 |
| | Thigh | 11.1 | 3.1 | 10.6 | 3.1 |
by gas analyzer (AE-300S, Minato Co. Ltd., Japan) from gas samples collected by a Douglas bag for 5 min before and at the end of the experiment.

Statistics

The data was analyzed with repeated-measures analysis of variance (ANOVA) incorporating seasons (summer and winter), sleep states (normal sleep and sleep deprivation), and time (every 5 min) as factors using VisualStat for Windows Version 4.5 software. Through ANOVA, Scheffé’s post hoc comparisons were used to assess significant main effects or interactions. Statistical significance was set at \( P < 0.05 \).

Results

Thermoregulatory responses in a thermo-neutral environment before the heat test are presented in Table 2. No significant differences between seasons and sleep states were found, except for significantly higher \( T_{\text{sk}} \) in summer than in winter for both sleep states \( (P<0.05) \).

Figure 1 presents \( T_{\text{re}} \) and the changes in \( T_{\text{re}} \) \((\Delta T_{\text{re}})\) during leg-bathing for normal sleep and sleep deprivation states in summer and winter. \( T_{\text{re}} \) during leg-bathing showed a significant interaction among seasons, sleep states, and time \((P<0.01)\). However, post hoc comparisons did not provide any significant differences between sleep states and seasons compared at the same time. Post hoc comparisons for significant interaction between sleep states and time in \( \Delta T_{\text{re}} \) \((P<0.01) \) verified smaller \( \Delta T_{\text{re}} \) for sleep deprivation than normal sleep at 50 and 55 min \((P<0.05)\) regardless of the season. Besides, significant interaction among seasons, sleep states, and time in \( \Delta T_{\text{re}} \) \((P<0.05) \) was showed by significantly smaller \( \Delta T_{\text{re}} \) in summer for sleep deprivation than normal sleep at the final 10 min of leg-bathing \((P<0.05)\). Figure 2 shows \( T_{\text{sk}} \) during leg-bathing for normal sleep and sleep deprivation states in summer and winter. ANOVA showed a significant interaction between sleep states and time \((P<0.001)\) and among seasons, sleep states, and time \((P<0.001)\). Significantly higher \( T_{\text{sk}} \) for sleep deprivation than for normal sleep including the seasonal factor \((P<0.05)\) was verified from the interaction between sleep states and time.

Table 3 shows \( M_{\text{sw-t}} \) final \( M_{\text{sw-back}} \) final \( M_{\text{sw-forearm}} \) threshold \( T_{\text{re}} \) for the sweating, and final \( M \) for normal sleep and sleep deprivation states in summer and winter. The \( M_{\text{sw-t}} \) for sleep deprivation was significantly smaller \((P<0.05)\) than that for normal sleep, including the seasonal factor. \( M_{\text{sw-back}} \), \( M_{\text{sw-forearm}} \) threshold \( T_{\text{re}} \) for the sweating and \( M \) showed no significant main effect or interaction with the factors of season, sleep state, or time. Figure 3 shows \( SBF_{\text{back}} \) and \( SBF_{\text{forearm}} \) during leg-bathing for normal sleep and sleep deprivation states in summer and winter. Significant interaction between sleep states and time was verified in \( SBF_{\text{back}} \) \((P<0.01)\) and \( SBF_{\text{forearm}} \) \((P<0.001)\). \( SBF_{\text{back}} \) and \( SBF_{\text{forearm}} \) showed a tendency to be higher for sleep deprivation than for normal sleep during leg-bathing in both seasons. However, there were no significant

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**Table 2** Rectal temperature \((T_{\text{re}})\), mean skin temperature \((T_{\text{sk}})\), and metabolic heat production \((M)\) observed in a thermo-neutral room.

<table>
<thead>
<tr>
<th></th>
<th>Normal Sleep</th>
<th>Sleep deprivation</th>
<th>Normal Sleep</th>
<th>Sleep deprivation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Summer</td>
<td>(36.59\pm0.32)</td>
<td>(36.84\pm0.40)</td>
<td>(36.70\pm0.42)</td>
<td>(36.69\pm0.23)</td>
</tr>
<tr>
<td>Winter</td>
<td>(33.15\pm0.26)</td>
<td>(33.15\pm0.34)</td>
<td>(32.81\pm0.30)</td>
<td>(32.89\pm0.37)</td>
</tr>
</tbody>
</table>

Mean\(\pm SD\) \((n=8)\)

* Significant difference between seasons assessed from main effect of the seasonal factor, \(P<0.05\).
differences between sleep states and time in the post hoc comparison.

Figure 4 shows the direct linear relationship of $T_{re}$ to $SBF_{sw-forearm}$ for normal sleep and sleep deprivation states in summer and winter. Significant differences in the slopes of $T_{re}$ vs $SBF_{sw-forearm}$ ($F_{(3,236)}=2.70 \ P<0.05$) showed a steeper slope for sleep deprivation than for normal sleep in winter ($P<0.05$) and a similar tendency in summer ($P<0.06$).

**Discussion**

Repeatedly of heat exposure and exercise in a hot environment gradually induce earlier sweating (lower threshold body temperature for sweating), greater sweating rate, smaller body temperature rise and smaller heart rate rise during heat exposure. These phenomena are known as short-term heat acclimation (Lind et al. 1963). Similarly, transient acclimatization in summer appears in Japanese with exposure to a clear change of seasons. This is recognized as one type of short-term heat acclimation. Thermoregulation to the same given heat stress in summer and winter induced changes similar to short-term heat acclimation (Hori et al. 1993; Inoue et al. 1995; Shiraishi et al. 1990; Tsurutani-Midorikawa 1981). In this study, a higher $\bar{T}_{sk}$ in summer than in winter was assessed in the neutral environment room before

### Table 3

<table>
<thead>
<tr>
<th></th>
<th>Summer</th>
<th>Winter</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Normal sleep</td>
<td>Sleep deprivation</td>
</tr>
<tr>
<td>$M_{sw-t}$ (g·m$^{-2}$·h$^{-1}$)$^*$</td>
<td>211.72±33.61</td>
<td>179.57±52.01</td>
</tr>
<tr>
<td>$M_{sw-back}$ (mg·cm$^{-2}$·min$^{-1}$)</td>
<td>0.88±0.39</td>
<td>0.87±0.32</td>
</tr>
<tr>
<td>$M_{sw-forearm}$ (mg·cm$^{-2}$·min$^{-1}$)</td>
<td>0.84±0.26</td>
<td>0.92±0.29</td>
</tr>
<tr>
<td>Threshold $T_{re}$ for sweating (°C)</td>
<td>36.64±0.27</td>
<td>36.85±0.4</td>
</tr>
<tr>
<td>$M$ (W·m$^{-2}$)</td>
<td>37.71±8.27</td>
<td>34.53±7.32</td>
</tr>
</tbody>
</table>

Mean±SD (n=8)

* Significant differences between sleep conditions assessed from main effect of sleep factor, $P<0.05$. 

Fig. 3 Time courses of skin blood flow on the back ($SBF_{back}$) and on the forearm ($SBF_{forearm}$) during leg-bathing. Values are means and SD. $^*$ Significant main effect and interaction with ANOVA, $P<0.05$.

Fig. 4 Skin blood flow on the forearm ($SBF_{forearm}$) as function of rectal temperature ($T_{re}$) for normal sleep and sleep deprivation states in summer (NS-s, SD-s, respectively) and winter (NS-w, SD-w, respectively). $^*$ Significant differences between slopes for sleep states and seasons, $P<0.05$. 

(P$<0.05$) and a similar tendency in summer (P$<0.06$).
in the morning in this study. The appearance of seasonality on thermoregulation was restrained small (Tsurutani-Midorikawa 1981). This suggests that an difference between summer and winter in the morning is also temperature rise in the morning than at other hours, and the difference between summer and winter in the morning is also small (Tsurutani-Midorikawa 1981). This suggests that an appearance of seasonality on thermoregulation was restrained in the morning in this study.

The main findings during leg-bathing were a higher $\bar{T}_{sk}$ (Figure 2), smaller $M_{sw,t}$ (Table 3), and smaller $\Delta T_{re}$ (Figure 1) for sleep deprivation than for normal sleep in both seasons. In particular, the $\Delta T_{re}$ in summer was significantly smaller for sleep deprivation than for normal sleep. However, this $\Delta T_{re}$ was the only seasonality of the thermoregulatory response that was found. A higher $\bar{T}_{sk}$ for sleep deprivation during leg-bathing in this study was not in agreement with previous descriptions of no change in $\bar{T}_{sk}$ between sleep deprivation and normal sleep during exercise (Dewasmes et al. 1992; Kolka et al. 1988; Sawka et al. 1983). It was, however, in agreement with Opstad et al. (1991), who found a higher $\bar{T}_{sk}$ for sleep deprivation during exercise. Also, another study showed a higher $\bar{T}_{sk}$ for sleep deprivation in conjunction with cold stress (Sovourey et al. 1994). Besides, our study found a trend of higher $SBF$ for sleep deprivation during leg-bathing (Figure 3). These findings suggest that sleep deprivation may accelerate responses of dry heat dissipation.

The mechanism of the acceleration of dry heat dissipation by sleep deprivation is not clear, but it is considered that sleep itself might affect thermoregulatory responses. One of the effects of sleep (non-REM sleep) on thermoregulation is to decrease the core temperature by causing heat dissipation to increase at the beginning of sleep. Vice versa, it can be understood that non-REM sleep appears to prevent core temperature from rising (Inoue 1989). Therefore, when a person is deprived of sleep, his heat dissipation response may accelerate to decrease core temperature during night. Higher $\bar{T}_{sk}$ and $SBF$ during leg-bathing for sleep deprivation might be explained by this acceleration of heat dissipation.

Another cause might be the effect of differences in light conditions during night between sleep deprivation and normal sleep. Sleep is highly dependent on the light environment; it is directly affected by the arousal function of a light stimulus such as a bulb or seasonal change of day length. It is also indirectly affected by light through effects on circadian rhythm, body temperature, and autonomic nerve (Koyama 1998, Ohkawa et al. 1999). For sleep deprivation in this study, subjects spent the night in a light intensity of a few hundreds lux. These factors must be connected to the effects of sleep deprivation and seasonality on thermoregulation, although our data does not adequately explain this connection. Aoki et al. (2001a) reported that different light conditions during sleep deprivation did not affect cutaneous vascular conductance during exercise at the end of sleep deprivation. However, comparisons between sleep deprivation and normal sleep including the light factor are still not clear. Therefore, the effect of light conditions needs to be considered in further studies on sleep deprivation.

Improvement of cutaneous blood flow is reflected in threshold $T_{core}$ for onset of cutaneous blood flow and the slope of the relationship of cutaneous blood flow to $T_{core}$ (Nadel et al. 1974; Roberts et al. 1977). Aoki et al. (2001b) showed that a lower threshold $T_{core}$ for onset of cutaneous vasodilation in the morning is caused by the activity of the cutaneous vasodilator system, and that the smaller sensitivity (slope) of cutaneous vasodilation in the morning is caused by the response of vasoconstrictor nerves to heat stress. This study did not observe clear results for threshold $T_{core}$ of onset of cutaneous blood flow but found that the slope of cutaneous blood flow versus $T_{re}$ was steeper for sleep deprivation than for normal sleep in summer and winter (Figure 4). This suggests that the acceleration of dry heat dissipation may result from the effect of restrained activity on the vasoconstrictor nerve.

Sleep-deprived subjects were allowed water intake until 3 h before the experiment but subjects for normal sleep were deprived water from bed until the end of the experiment. This means that body fluid was less for normal sleep than for sleep deprivation when the experiments started. Since decrease of body fluid suppresses heat dissipation from cutaneous blood flow and sweating and induces body temperature rise (Morimoto 1990), it might be necessary to regard the effects of dehydration and plasma osmolarity rise for a study on sleep deprivation.

$M_{sw,t}$ was smaller for sleep deprivation than for normal sleep, although there were no differences between sleep states in $M_{forearm}$, $M_{back}$, and threshold $T_{re}$ for sweating to start (Table 3). This result for sleep deprivation agreed with decreased $M_{sw,t}$ during exercise in air temperature of 28°C (Sawka et al. 1983) but did not agree with increased $M_{sw,t}$ during exercise in air temperature of 35°C (Dewasmes et al. 1992). It might be considered that the increase in $M_{sw,t}$ for sleep deprivation was minimized because the air temperature of 30°C in this study, which is lower than skin temperature, was advantageous to dry heat dissipation, besides the role of sleep deprivation in accelerating dry heat dissipation. It might also be considered that $M_{sw,t}$ for sleep deprivation was effective enough to restrain $\Delta T_{re}$ for sleep deprivation.

In conclusion, this study indicated that seasonal differences on thermoregulation were small for both sleep deprivation and normal sleep, possibly because of the choice of morning as a testing time. Sleep deprivation increased dry heat dissipation and restrained $\Delta T_{re}$ in spite of decreased $M_{sw,t}$. These findings suggested that the increased dry heat dissipation might result from restrained vasoconstrictor nervous activity by sleep deprivation.
deprivation. It was confirmed that consideration of diurnal variation and seasonality on thermoregulation will continue to be important to clarify the effects of sleep deprivation.

References


Received: June 26, 2003
Accepted: September 18, 2003
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