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Effects of humid heat exposure on sleep, thermoregulation, melatonin, and microclimate

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Abstract

Nine healthy young male volunteers were recruited to participate in a study involving three non-consecutive nights of polysomnographically and thermoregulatory measured sleep. Nightly urine samples were assayed for the melatonin metabolite 6-sulfatoxymelatonin (aMT6s). Experimental conditions were 26°C 50% RH (26/50) and 32°C 80% RH (32/80), where the subjects wore pyjamas with cotton blanket. Rectal temperature (T_{re}) did not decrease during nocturnal sleep at 32/80. The duration of wakefulness and stage 1 sleep increased significantly at 32/80 compared to 26/50. Stage 2 and 4 sleeps were significantly shorter at 32/80 than at 26/50. Although there was no significant difference in urinary aMT6s between 32/80 and 26/50($n = 6$), the melatonin metabolite secretion tended to be lower at 32/80 than at 26/50 in accordance with the decrease in sleep efficiency index. Heart rate and sweat rate were significantly higher at 32/80 than at 26/50. The acute decrease in melatonin secretion during nocturnal sleep may be related to reduce sleep efficiency through thermoregulatory mechanisms.

Keywords: Sleep; Melatonin; Rectal temperature; Sweat rate; Microclimate; Humid heat

1. Introduction

Sleep induces core body temperature decrease (Barrett et al., 1993). Core body temperature decreases in accordance with nocturnal increase in melatonin, which precedes greater heat loss due to the increase in peripheral skin temperatures (Krauchi et al., 2000). Melatonin is widely known to have hypothermic effects (Carman et al., 1976; Strassman et al., 1991). Moreover, melatonin has relationships with sleep onset latency and sleepiness (Krauchi et al., 1999, 2000), and improves the quality and efficiency of sleep in elderly insomniacs (Garfinkel et al., 1995; Haimov et al., 1995; Hughes et al., 1998). These effects on sleep may result from the hypothermic effects of melatonin and the ensuing thermoregulatory response. However, it has not been established that melatonin affects sleep directly. While previous experimental evidence indicates that temperature as well as light may influence the endogenous production of melatonin in animals (Underwood and Calban, 1987; Firth and Kennaway, 1989; Stokkan et al., 1991; Ulrich et al., 1973/1974), no data are available for humans (Cagnacci, 1996). In a study in which young adults were heated with electric blankets during the latter half of the sleep period, although sleep efficiency decreased, there was no significant difference in melatonin secretion between heating and control groups. (Fletcher et al., 1999) That is, nocturnal melatonin secretion remained unaffected by the heating produced by the electric blanket. No other significant relationships

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between melatonin secretion and polysomnographic (PSG) sleep parameters were observed in either elderly insomniacs or good sleepers (Lushington et al., 1999; Lushington et al., 2000). These results may indicate that melatonin secretion is not affected by sleep efficiency. However, the hypothermic effects of melatonin administration were ineffective in subjects who were awake while subjected to extreme heat (McLellan et al., 2000). Environmental signals other than light may be involved in the regulation of pineal melatonin synthesis. Melatonin synthesis may be affected by endogenous conditions, since melatonin is a hormone. The aims of our study were to investigate the effects of temperature on sleep, thermoregulation and melatonin secretion during nocturnal sleep.

2. Method

2.1. Subjects

Nine male volunteers served as subjects. The physical characteristics of the subjects were as follows: age 25 ± 3.8 years; height 171.2 ± 4.5 cm; weight 62.5 ± 6.9 kg; and body surface area $1.68 \pm 0.09\,m^2$. Each subject provided written consent after being informed of the study protocol. Physical examinations, morningness and eveningness questionnaire (Horne and Ostberg, 1976), a sleep questionnaire, and psychological tests were administered prior to the study. The results indicated that all subjects were physically and mentally sound.

2.2. Conditions and procedure

The experiments were carried out from August to September using two climate chambers. The two chambers were partitioned by a wall and a door and controlled separately. The subjects were asked to rest for 2 h in the first chamber before being permitted to sleep under conditions consisting of air temperature (T_a) and relative humidity (RH) maintained at 26°C and RH 50% (ambient partial vapor pressure (P_a) of 12.6 Torr), respectively. Following this resting period, the subjects moved to the second chamber and slept under two environmental variations: a near neutral climate ($T_a = 26°C$, RH = 50%, $P_a = 12.6$ Torr; 26/50), and a warm and humid climate ($T_a = 32°C$, RH = 80%, $P_a = 28.5$ Torr; 32/80). The T_a and RH were stable and never exceeded $\pm 0.5°C$, $\pm 3\%$ from the set T_a and RH levels. The subjects slept wearing briefs, short pants, and short sleeve pyjamas (100% cotton) on a bed covered with a bed sheet (100% cotton) and a blanket (100% cotton). Clothing insulation was estimated to be 0.4 clo. The subjects experienced 350 lx lighting at their eye level through the frosted ceiling under fluorescent lamps from 20:30 to lights off. After the lights off, the subjects were left in the darkness (<3 lx) during the entire sleeping period.

The subjects entered the first chamber at 20:30 and donned pyjamas after measurements of body weight. Electrodes were attached while the subjects remained seated in a chair. At 22:45, the subjects moved to the second chamber and lay down on the bed, on top of the cotton sheet. After completing the last questionnaire before falling sleep, the subjects were allowed to sleep from 23:00 to 7:00. PSG recordings, rectal temperatures (T_{re}), skin temperatures, microclimate temperatures, and humidity inside the pyjamas were measured continuously. The subjects slept for three non-consecutive nights, the first night of which was an adaptation night and the subjects slept at 26/50. The subjects were not informed of the order of the two conditions which of the two climate conditions would be in effect for the second night, and were assigned to the two conditions at random. There was at least a 2–3-day interval between the two nights on which their sleep was actually monitored. The subjects were asked to sleep and wake on a regular schedule and to keep a sleep diary from 1 week before the study until the end of the entire study period.

2.3. Physiological measurements

EEG (C3-A2, C4-A1, O1-A2), EOG and mental EMG were recorded using a 14-channel EEG machine (EEG-4317, Nihon-Kohden, Japan). Sleep recordings were scored visually every 30 s based on the standard manual of Rechtshaffen and Kales, (1968). Rectal temperatures (T_{re}) were measured continuously at intervals of 30 s with a thermistor probe (ITP010-11, Nikkiso-YSI, Japan) inserted 12 cm beyond the anus. Local skin temperatures were continuously measured at 30 s-intervals using a thermistor probe (ITP10-12, Nikkiso-YSI, Japan) which was attached to each skin surface at the forehead, chest, arm, thigh, leg, and foot. Temperatures were measured and recorded by loggers (LT-8A or LT-8B, Gram Corp., Japan) through thermistor probe. Humidities were measured and recorded by loggers (LT-8B with LT-HM4, Gram Corp., Japan) with a semiconductor relative humidity sensor (CHS-APS, TDK, Japan). Mean skin temperatures (T_{sk}) were calculated according to Ramanathan (1964). The microclimate temperature and humidity inside the pyjamas were measured at 30-s intervals with a thermistor probe and semiconductor relative humidity sensors. A thermistor probe and a humidity sensor were placed on a 5-mm-thick heatproof board, which was placed on the skin of the chest area under the pyjamas. Overall body mass was measured before and after the sleep recording sessions, without pyjamas, using a sensitive platform balance (ID3S, Mettler). Overall body

weight loss was calculated from the two measurements of body mass taken before falling asleep and upon waking. Subjects were required to collect a urine sample after each sleep period. All urine volume produced between 20:30 and 07:00 was collected, and an aliquot was stored at −20°C in a refrigerator until all experiments were completed. All samples were assayed together to determined concentrations of the urinary melatonin metabolite 6-sulfatoxymelatonin (aMT6s). The concentration of aMT6s was determined by an adapted method using the Bhulmann Melatonin radioimmunoassay (RIA) kit, which measures melatonin by a double-antibody RIA based on the Kennaway G280 anti-melatonin antibody in the SRL Laboratory (Tokyo, Japan). The analytic sensitivity of this assay was 0.5 pg/ml and intra- and inter-assay variances were 4.3% and 7.5%, respectively. Melatonin secretion was calculated from the total urine volume and the concentration of aMT6s of the urine sample.

2.4. Statistical analysis

Before statistical analysis, melatonin output and sleep onset latency were log transformed. Two-tailed paired *t*-test was used to analyze the effects of simulated climate conditions on sleep parameters, overall weight loss, and melatonin secretion. Two-way ANOVA (condition × time) for repeated measures was used to test local skin temperatures, T_{sk}, T_{re}, microclimate temperature and humidity, and heart rate through the night. A two-tailed paired *t*-test was conducted to evaluate differences in time course between the two conditions. All references to differences in the results section were significant at $P<0.05$ or better unless specially stated otherwise.

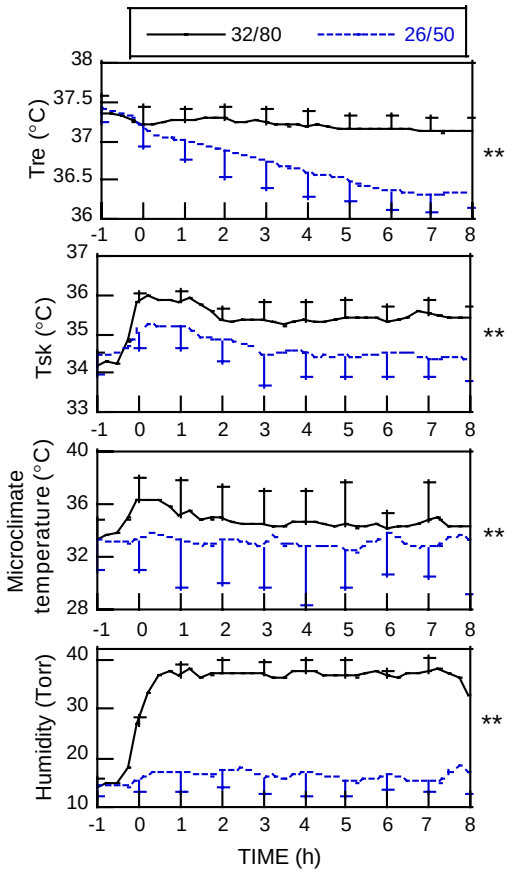

Fig. 1. Time courses of average rectal temperature (T_{re}), mean skin temperature (T_{sk}), microclimate temperature and humidity during 8 h night sleep under 26/50 (- - -) and 32/80 conditions (—). Values are means with SD ($n=9$). (**) represents statistically significant difference at $P<0.01$.

3. Results

3.1. Body temperature, microclimate, and sweat loss

Fig. 1 shows the changes in T_{re}, T_{sk}, microclimate temperature, and vapor pressure recorded under the two experimental climate conditions plotted against time. T_{re} was significantly higher at 32/80 than that at 26/50 ($F_{1,16}=32.48$; $P<0.0001$). T_{sk} was also significantly higher at 32/80 than at 26/50 ($F_{1,16}=31.14$; $P<0.0001$). A significant difference between the conditions in local T_{sk} was observed in all measured locations: the forehead ($F_{1,16}=25.92$; $P<0.0006$), arm ($F_{1,16}=18.54$; $P=0.0005$), thigh ($F_{1,16}=15.97$; $P<0.001$), calf ($F_{1,16}$)$=22.6$; $P<0.0002$), and foot ($F_{1,16}=32.13$; $P<0.0001$). Parameters at all of these locations were higher at 32/80 than at 26/50, except for the chest ($F_{1,16}=4.32$; $P=0.05$). Microclimate temperature and vapor pressure inside pajamas were significantly higher at 32/80 than at 26/50 ($F_{1,13}=13.41$; $P<0.0029$; $F_{1,13}=589.87$; $P<0.0001$).

The heart rate showed the effect of interactions with climate conditions over time ($F_{32,480}=1.77$; $P<0.0063$). Heart rates were significantly higher at 32/80 than at 26/50 when monitored from 3 h after sleep onset until time of waking.

Overall sweat losses were 65.4 (9.9) g/m^2 at 32/80 and 34.5 (8.9) g/m^2 at 26/50, respectively. Overall sweat losses at 32/80 were significantly greater than at 26/50 ($P<0.001$).

3.2. Sleep parameters

Table 1 shows the average (SD) for each sleep parameter at 26/50 and 32/80. For the onset latency of each sleep stage, no significant differences were found between the two sets of conditions. With respect to the

Table 1
Sleep parameters under the two conditions

	26/50	32/80
Total duration of time (%)		
Wake	3.69 (1.87)	20.43 (17.13)*
Stage 1	8.76 (4.24)	11.81 (5.91)*
Stage 2	47.01 (9.89)	37.43 (12.95)*
Stage 3	6.68 (9.89)	5.77 (4.26)
Stage 4	9.46 (5.20)	5.39 (5.46)*
Stages 3+4	16.13 (8.59)	11.16 (9.32)
REM	21.36 (4.97)	17.77 (5.83)
MT[a]	0.02 (0.05)	0.07 (0.08)*
SEI[b]	93.28 (3.40)	78.16 (17.98)*

*$P<0.05$.
[a] Moving time.
[b] Sleep efficiency index.

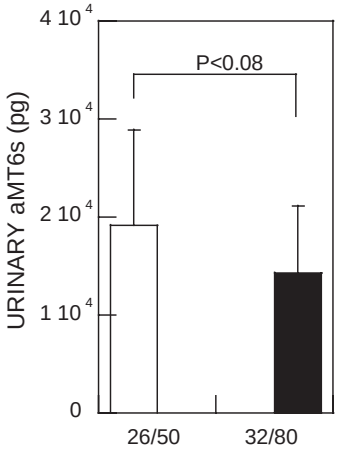

Fig. 2. Urinary aMT6s during nocturnal sleep under 26/50 and 32/80 condition. Values are means with SD ($n = 6$).

duration of each sleep stage, periods of wakefulness and stage 1 sleep increased significantly at 32/80 compared to 26/50 ($P<0.02$, 0.04). Stage 2 and 4 sleeps were significantly shorter at 32/80 than at 26/50 ($P<0.03$, 0.03). The sleep efficiency index (SEI) fell significantly at 32/80 compared to 26/50 ($P<0.04$), while MT was significantly higher at 32/80 than at 26/50 ($P<0.04$).

3.3. Melatonin secretion

Since melatonin samples for three of nine subjects in this experiment were lost, we drew on melatonin data for six subjects. No significant differences in aMT6s secretion were observed between 32/80 and 26/50, although aMT6s secretion in the urine tended to be lower at 32/80 than at 26/50 ($P<0.08$) (Fig. 2).

4. Discussion

There was no significant difference in urinary aMT6s between 32/80 and 26/50 during nocturnal sleep, and sleep-evoked rectal temperature decrease and sleep efficiency were suppressed. The suppressions of a sleep-evoked rectal temperature decrease and the deterioration in sleep parameters were consistent with previous heat exposure studies, which did not measure melatonin (Karacan et al., 1978; Haskell et al., 1981a; Haskell et al., 1981b; Okamoto-Mizuno et al., 1999). The melatonin metabolite secretion was not affected by temperature during nocturnal sleep. This finding was consistent with those of Strassman et al. (1991) and Fletcher et al. (1999). However, four of six subjects, whose aMT6s reduced in accordance with the decrease in SEI at 32/80 compared to 26/50 in the present study. The other two subjects' aMT6s hardly changed as well as less decrease of SEI at 32/80 compared to 26/50. There was no significant difference in melatonin secretion or minimum rectal temperatures between wakeful individuals in settings of dim light and individuals fast asleep in the dark (Strassman et al., 1991). When young adults were heated with an electric blanket during the latter half of the sleep period, although core temperatures increased slightly (0.18°C/3 h) and sleep efficiency decreased (5.5%), there was no significant difference in melatonin secretion between the heating and control groups (Fletcher et al., 1999). These earlier results showed that melatonin secretion was not dependent on sleep and was unaffected by heat. This discrepancy may be due to the degree of the heat load imposed on the body, since the subjects did not sweat and declines in rectal temperature were not completely suppressed. In addition, in the present study, heart rates and sweat rates were significantly higher at 32/80 than at 26/50. Some reports have indicated that human melatonin secretion appears to be controlled by the sympathetic nervous system, since propranolol blocks the nocturnal secretion of melatonin (Hanssen et al., 1977). The suppression of melatonin may be explained by sympathetic nervous activity related to thermoregulation. While rectal temperatures leading up to bedtime tended to decrease slightly, rectal temperatures upon sleep onset remained constant rather than declining when subjects slept under conditions of 32/80, even though melatonin was secreted. This result is consistent with studies in which melatonin administration failed to exert the hypothermic effects in subjects who were awake during conditions of extreme heat (McLellan et al., 2000). It may be that melatonin does not influence sudomotor response to heat stress.

The vasodilation of blood vessels in peripheral skin increases blood flow under conditions of humidity and heat, resulting in the diffusion of heat from the blood to the environment. The increase in peripheral skin

temperature was greater at 32/80 than at 26/50, although the increase in peripheral skin temperature of 32/80 did not shorten sleep onset latency in the present study. This result is inconsistent with previous studies of increases in peripheral skin temperature, which report shorter sleep onset latencies in cool environments (Krauchi et al., 2000).

The 32°C air temperature is the upper limit of the thermoneutral condition under low humidity conditions. However, a combination of air temperatures of 32°C and 28.5 Torr (80% RH) and clothing insulation creates a heat load and drives up microclimate temperature and humidity inside pajamas up to 36°C and 38 Torr (90% RH), most likely due to decreasing sweat evaporative efficiency. The subjects in most of the previous studies slept naked, since such studies sought to investigate the effects of air temperature on thermoregulation and sleep. Thus, these studies have reported an optimal sleep microclimate for humans of 34°C (Van Someren et al., 2002), just slightly above the thermoneutral range (28–33°C) (Golding and Yousef, 1989). While the microclimate temperature at 26/50 in the present study is consistent with this thermoneutral temperature range, conditions at 32/80 are above the optimal microclimate temperature. However, to the best knowledge of the authors, microclimate humidity has never been discussed, due to the difficulty of measuring the conditions in the small region between the body and clothing or bedding. In the present study, comfort may have been reduced in proportion to increasing humidity in this microclimate region.

In conclusion, sleep-evoked rectal temperature decrease was suppressed, sleep efficiency declined, and urinary melatonin tended to decrease when subjects were exposed to conditions of humidity and heat during nocturnal sleep. This was because the temperatures and humidity of the microclimate within the pajamas tended to be above ambient parameters. Clarification of the relationships between sleep, thermoregulation, and melatonin secretion as well as the involvement of the sympathetic nervous activity during sleep will require further research data.

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