Effects of Humid Heat Exposure on Human Sleep Stages and Body Temperature.

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Summary: The objective of this study was to confirm the effect of humid heat exposure on sleep stages and body temperature. Seven healthy male volunteers with a mean age of 22.7±1.63, served as the subjects. The experiments were carried out under four different conditions of room temperature and relative humidity: 29°C RH 50% (29/50), 29°C RH 75% (29/75), 35°C RH 50% (35/50), and 35°C RH 75% (35/75). The subjects wearing only shorts slept from 23:00 to 7:00 on a bed, which was covered with a 100% cotton sheet. EEG, EOG, and mental EMG were recorded through the night. Rectal temperature (Tr) and skin temperature were measured continuously. The 35/75 condition caused more wake and a lower sleep efficiency index (SEI) and stage S3+S4 than 29/50 and 29/75. Stage REM and stage 3 were significantly decreased at 35/75 than at 29/50 and 35/50. Tr was maintained at a higher level at 35/75 than under the other conditions. Mean skin temperature was higher at 35/50 and 35/75 than at 29/50 and 29/75. These results suggest that humid heat exposure during night sleep increases the thermal load to supress the sleep-evoked Tr decrease, stage 3, SWS, and REM, and increase wakefulness.
Key words: Humidity; ambient temperature; sleep stages; body temperature

INTRODUCTION

THE EFFECT OF HIGH AMBIENT TEMPERATURE (Ta) on sleep stages has been well studied. In humans, Ta, which is higher than the thermal neutral temperature, decreases slow wave sleep (SWS) and REM.[1] The changes in sleep parameters do not show any adaptation under continuous heat exposure, whereas the thermoregulatory response shows accumulation.[2] The involvement of thermoregulatory drive on sleep regulation is considered to be the reason for these effects. However, it is not yet known whether or not these effects depend on humidity. In most of the previous studies, humidity was maintained below RH 60% or was uncontrolled, although it is one of the most important factors complicating the prediction of heat stress.[3]

In wake subjects, the effect of humidity on various physiological functions is observed mainly at a high Ta. In humid heat exposure, increments in subjective discomfort, rectal temperature, plasma cortisol concentration,[4] and heart rate[5] were observed, while at the same Ta with low humidity, rectal temperature and plasma cortisol concentration did not increase and was well tolerated subjectively.[4] These previous results suggest that the thermoregulatory response in high Ta may involve humidity. This can be due to the increased vapor pressure that reduced heat loss by decreasing evaporative sweat efficiency.[6] In comparison to many studies during wake, only a few studies have focused on these effects during sleep. Sleep was perceived as poor by subjects[7] as the Ta and humidity increased. The humid heat exposure resulted in an increase in the wake stage and decrease in SWS and REM compared with neutral and dry conditions.[8] In these studies, it is not clear whether or not these results were due to the effect of Ta or humidity or both and as the subjects used bedding, the effect of bedding cannot be ruled out. Furthermore, most of these studies did not measure body temperature. The aim of the present study was to confirm the effect of humid heat exposure on sleep stages and body temperature.

METHOD

Subjects

Seven male volunteers served as the subjects. The physical characteristics were age 22.7±1.63 yrs; height 172.5±3.25 cm; weight 62.0±3.27 kg; and body surface area 1.69±0.05m^2. They were informed about the protocol, and they provided their written consent. Physical examinations, morningness and eveningness questionnaire,[9] a questionnaire about sleep, and psychological tests were administered prior to the experiment and the results showed that the subjects were physically and mentally healthy. All the subjects lived in the Kanto area of Japan

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Table 1. Sleep parameters under four conditions.

	29/50	29/75	35/50	35/75
Total duration of (min)				
Sleep onset	11.5± 5.8	11.9± 8.3	11.8±10.2	13.3± 9.9
Stage W	32.5±13.4	52.1±41.1	76.8±54.3	123.5±52.5 ab
Stage 1	33.9± 8.0	34.5±10.8	49.3±16.4	64.4±25.0
Stage 2	207.2±17.2	204.6±27.0	181.0±47.3	172.9±50.8
Stage 3	41.1± 9.6	32.7±10.7	34.9±17.8	16.7± 9.6 ac
Stage 4	40.8±15.5	36.4±16.6	26.8±10.3	21.8±16.0
SWS	81.9±18.1	73.4±15.6	61.7±27.3	38.5±20.3 ab
REM	105.5±18.2	89.0±31.1	96.0±16.0	63.6±11.6 ac
MT[1)]	2.6± 1.3	0.9± 1.0	2.9± 3.7	1.4± 1.5
TST[2)]	428.7±17.3	415.7±46.5	388.1±56.9	339.5±51.3
EMA[3)]	5.6± 8.7	0.0± 0.0	0.5± 0.9	3.1± 4.8
SEI (%)[4)]	92.6± 2.6	88.7± 8.7	82.9±11.4	73.1±11.0 ab

[1)]moving time, [2)]early morning awake, [3)]total sleep time, [4)]sleep efficiency index: SEI=TST/Time in bed
a=differs from 29/50, b=differs from 29/75, c=differs from 35/50 by at least P<0.05 by post-hoc test (Fisher's PLSD).

and had not experienced living in a hot climate prior to the experiment.

Conditions and Procedure

The experiment was carried out from August to September (the outside temperature and relative humidity ranged from 27 to 31°C, 70 to 80%, respectively) using two climate chambers. Two chambers were partitioned by a wall and a door and were controlled separately. The subjects rested two hours and fifteen minutes in the first chamber before sleep with the air temperature (Ta) and relative humidity (RH) maintained at 29°C, RH 50% (ambient vapour pressure (Pa) of 15.0 Torr) respectively. After this acclimation period, the subjects moved to a second chamber and slept under four environmental variations: a neutral and dry climate (Ta=29°C, RH=50%, Pa=15.0Torr), a neutral and humid climate (Ta=29°C, RH=75%, Pa=22.5Torr), a hot and dry climate (Ta=35°C, RH=50%, Pa=21.0Torr), and a hot and humid climate (Ta=35°C, RH=75%, Pa=31.6Torr). The Ta and RH changes were stable and never exceeded ±0.5°C, ±3% from the set Ta and RH levels. The subjects slept wearing only shorts on a bed covered with a bed sheet (100% cotton). The mattresses were dried with a drying machine (FD-6PR, National) for 1.5 hr from 9:00 A.M. to maintain a stable mattress condition.

The subjects entered the first chamber at 20:30 and the electrodes were attached after measuring the body weight. They were asked to rest sitting on a chair. At 22:45, the subjects moved to the second chamber and were asked to sleep from 23:00 P.M. to 7:00 A.M. The polysomnographic recordings, rectal temperature (Tr), and skin temperatures were measured continuously. The subjects slept five nights, the first night of which was an adaptation night. The subjects were not informed of the order of the four conditions from the second night which were set at random. There was at least a two to three-day interval during the four experimental nights. The subjects were asked to sleep and wake on a regular schedule and keep a sleep diary from one week before until the end of the entire experimental period.

Physiological Measurements

EEG (F3-A2, C3-A2, C4-A1, O1-A2), EOG, and mental EMG were recorded using an 18 channel EEG machine (EEG-4317, Nihon-Kohden). Sleep recordings were scored visually every 30 seconds based on the standard manual of Reftschaffen and Kales.[10] Rectal temperature (Tr) was continuously measured by a thermister probe (Data collector AM7003, Anritu) inserted 10 cm beyond the anus at the time interval of 30 seconds. Local skin temperatures were continuously measured at the time interval of thirty seconds using a thermister (Data collector AM7003, Anritu). Thermisters were attached to the skin surface according to Ramanathan's[11] location: arm, chest, thigh, leg, and foot. Mean weighted skin temperature (Ts) was calculated according to Ramanthan.[11] Whole body weight loss was measured before and after the sleep record-

Table 2. Percentage of time in minutes for each sleep stage in first to fourth NREM/REM sleep cycle.

	29/50	29/75	35/50	35/75
Cycle 1				
Stage W	6.0±3.8	6.4±7.2	9.3±5.9	32.3±19.8[abc]
Stage 1	9.6±3.6	8.5±4.1	10.8±5.7	18.3±8.3
Stage 2	32.3±5.2	30.2±9.2	39.5±11.1	33.1±15.1
Stage 3	13.5±4.9	12.5±3.1	12.3±7.7	5.2±3.3
Stage 4	20.1±6.3	24.6±12.1	12.3±9.4[b]	3.0±3.0[ab]
SWS	33.6±9.2	37.1±14.2	24.6±13.9	8.2±6.0[abc]
REM	16.0±2.5	17.7±5.5	15.1±4.8	8.0±4.6[abc]
MT[1)]	0.6±0.3	0.1±0.2	0.7±1.0	0.1±0.2
Cycle 2				
Stage W	6.6±4.3	16.9±19.5	17.5±13.8	29.1±17.9
Stage 1	8.9±10.6	4.2±3.1	7.2±3.5	13.0±5.2
Stage 2	41.2±11.4	42.7±11.8	38.6±12.5	31.8±18.3
Stage 3	7.2±5.8	7.2±5.2	4.4±2.2	3.1±3.1
Stage 4	12.8±9.3	9.6±5.9	4.2±3.8	12.8±12.6
SWS	20.0±11.8	16.6±9.0	8.6±4.3	15.9±13.5
REM	22.9±6.0	21.3±9.2	27.6±11.0	9.6±3.3[ac]
MT	0.3±0.4	0.4±0.5	0.5±0.8	0.5±0.7
Cycle 3				
Stage W	6.2±4.8	7.3±3.1	18.7±13.8	27.0±9.0[ab]
Stage 1	7.4±4.2	5.0±2.4	8.3±4.0	11.7±7.1
Stage 2	50.6±7.4	47.4±9.6	42.5±17.8	34.1±11.6
Stage 3	8.7±9.9	3.4±3.9	3.4±2.6	0.7±1.0
Stage 4	1.5±2.6	3.1±4.4	0.8±1.4	0.5±0.7
SWS	10.2±11.6	6.5±7.4	4.2±3.5	1.2±1.7
REM	25.1±6.5	33.6±5.3	23.8±8.7	25.6±8.6
MT	0.6±0.7	0.3±0.3	2.1±3.2	0.4±0.5
Cycle 4				
Stage W	17.2±16.3	11.0±8.3	21.3±18.9	12.8±5.9
Stage 1	19.5±18.8	16.3±7.8	19.7±15.6	10.7±4.1
Stage 2	47.7±19.6	46.0±15.4	24.4±13.6	44.3±14.2
Stage 3	10.0±8.6	9.0±8.2	6.4±4.6	9.2±7.9
Stage 4	0.9±1.3	0.0±0.0	3.7±5.0	2.7±3.2
SWS	10.9±9.5	9.0±8.2	10.1±6.8	10.6±8.4
REM	25.6±16.5	17.8±12.0	24.4±10.8	21.3±16.4
MT	0.6±0.7	0.0±0.0	0.0±0.0	0.4±0.5

[1)]moving time
a=differs from 29/50, b=differs from 29/75, c=differs from 35/50 by at least $P<0.05$ by post-hoc test (Fisher's PLSD).

ing sessions using a sensitive platform balance (KCC150, Mettler). Whole-body sweat loss was calculated from the loss of weight before and after sleep.

Statistical Analysis

In order to test the statistical significance of the data, two-way ANOVA (Condition; 29/50, 29/75, 35/50, 35/75 and subjects) was used to analyze the effect of condition on sleep parameters, whole body weight loss, minimum Tr and maximum decrease in Tr. Two-way ANOVA (condition x time) for repeated measures was used to analyze local skin temperature, Ts and Tr change through the night. As the absolute humidity differed among the four conditions, the factors were not separated into temperature and humidity. Fisher's PLSD was applied for the post-hoc pairwise comparison. The level of significance was considered to be $p<0.05$.

RESULTS

Sleep Parameters

The average of each sleep parameter under the four conditions are shown in Table 1. In the onset of each sleep stage, no significant difference was observed among the conditions, although stage 3 and 4 tended to be delayed at 35/50 and 35/75 than at 29/50 and 29/75. Sleep efficiency index (SEI) differed significantly among the conditions ($F_{3,24}=3.17$; $p<0.05$) indicating remarkably less efficient sleep at 35/75. SEI decreased almost 20% at 35/75 than at 29/50 and 29/75. A significant difference among the conditions in the total duration of each sleep stage through the night was observed in stage wake ($F_{3,24}=3.07$; $p<0.05$), stage 3 ($F_{3,24}=3.08$; $p<0.05$), SWS (stage 3 + stage 4) ($F_{3,24}=3.37$; $p<0.05$), and REM ($F_{3,24}=3.27$; $P<0.05$). The amount of stage wake tended to increase at 29/75 and 35/50 than at 29/50, however no significant difference was observed. A significant increase in the amount of stage wake was observed at 35/75 compared to the 29/75 and 29/50 conditions which was almost four times that at 29/50. The amount of SWS significantly decreased to almost half the level at 35/75 than at 29/50 and 29/75. At 35/50, SWS did not significantly differ from that at 29/50 and 29/75. Stage 3 and REM significantly decreased at 35/75 compared with those at 29/50 and 35/50. The amount of stage 3 was almost half the level and REM decreased more than 40 min at 35/75 compared to 29/50 and 35/50.

In order to observe the difference in sleep stage distribution according to the time course, the percentage of each sleep stage was calculated separately in each sleep cycle. The results are shown in Table 2. A significant difference among the conditions was observed in the first, second and third cycles. In the first cycle, stage wake ($F_{3,24}=5.14$; $p<0.01$), stage 4 ($F_{3,24}=5.62$; $p<0.01$), SWS (F3,24=5.98; $p<0.01$) and REM ($F_{3,24}=3.43$; $p<0.05$) showed significant differences among the conditions. Stage wake increased and stage 4, SWS and REM decreased at 35/75 compared to the other conditions. In the second cycle, a significant difference was observed in REM ($F_{3,24}=3.49$; $p<0.05$) and in the third cycle in stage wake ($F_{3,24}=3.80$; $p<0.05$). REM in the second cycle decreased at 35/75 compared to 29/50 and 35/50, and stage wake in the third cycle increased at 35/75 compared to 29/50 and 29/75. The main difference among the conditions was concentrated in the first cycle, which indicates that sleep was disturbed at 35/75 especially in the first part of the night.

Body Temperature and whole Body Sweat Loss

Figure 1 (above) shows the changes of Ts and Tr under the four conditions. Ts differed significantly among conditions ($F_{3,24}=40.83$; $p<0.001$), but no significant difference was observed in time and interaction. Ts was maintained at a 1–1.5ºC higher level through the night at 35/50 and 35/75 than at 29/50 and 29/75. No significant difference was observed between the two levels of relative humidity. Tr also differed significantly depending on the condition ($F_{3,24}=9.62$; $p<0.001$) and time ($F_{16,48}=40.62$; $p<0.001$). A significant difference was observed between 35/75 and the other conditions which indicates that Tr was maintained at

Table 3. Average and minimum level, maximum decrease of the rectal temperature under four conditions

	29/50	29/75	35/50	35/75
Average level (℃)	36.80± 0.38	36.90± 0.36	37.16± 0.19^{a}	37.47± 0.25^{abc}
Minimum level (℃)	36.49± 0.34	36.59± 0.28	36.91± 0.14^{ab}	37.32± 0.26^{abc}
Maximmun decrease (℃)	0.92± 0.23	0.92± 0.24	0.48± 0.16^{ab}	0.21± 0.14^{abc}

a=differs from 29/50, b=differs from 29/75, c=differs from 35/50 by at least P<0.05 by post-hoc test (Fisher's PLSD).

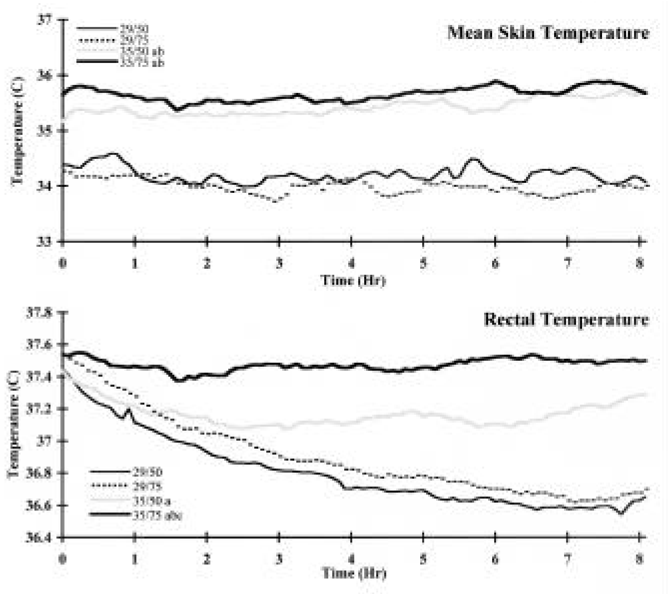

Fig 1—Changes of rectal temperature and mean skin temperature under four conditions in average of seven subjects. Each line represents the conditions: 29/50, 29/75, 35/50, 35/75.

a higher level as the temperature and humidity increased. A significant difference was not observed between the 29/50 and 29/75 conditions. The 29/50 and 29/75 conditions, under which Tr was maintained lowest, showed the greatest maximum decrease, whereas this decrease was almost 50% at 35/50 and 25% at 35/75 (Table 3). A significant difference was observed between all conditions except for 29/50 and 29/75. Minimum temperature was also highest at 35/75 compared to the other conditions.

The result of whole body sweat loss is shown in Figure 2 (below) Whole body sweat loss significantly differed among the conditions ($F_{3,24}$=108.8; p<0.001) and was higher at 35/50 and 35/75 than at 29/50 and 29/75. The value was two-fold greater at 35/50 and 35/75 compared to 29/50

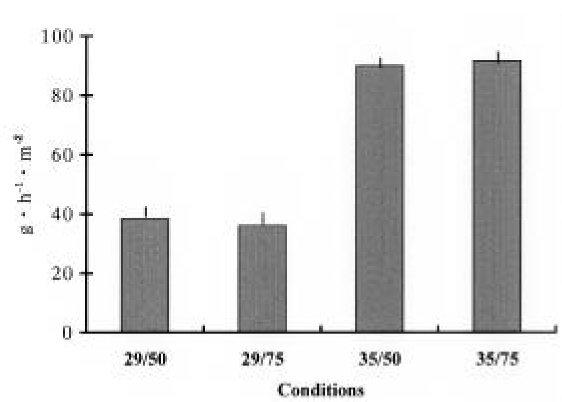

Fig 2—Whole body sweat loss calculated from body weight before and after sleep in average of seven subjects. The vertical line represents the standard deviation.

and 29/75. No significant difference was observed between the two humidity levels.

DISCUSSION

A significant difference in sleep parameters were observed mainly between the 35/75 and other conditions. Stage wake increased and stage 3, SWS, REM and SEI decreased significantly at 35/75 which shows inefficient sleep under this condition. The most notable finding was the decreased REM at 35/75 compared to 35/50 and 29/50. No significant difference between the 35/50 and 29/50 was in agreement with previous studies, which did not find any significant difference in REM among Ta of 29°C, 34°C, and 37°C,[1] 32~39.5°C,[12] and 20°C and 35°C using bedding[2] in which the relative humidity was maintained below 60%. REM generally decreases in a hot and cold environment, and this effect is greater as the Ta deviates from the thermoneutral zone.[1] This suggests that the increased thermal stress under the 35/75 condition may have caused the significant decrease in REM. A similar study on heat stress and sleep also found a significant decrease in REM with a heavy thermal load using an electric blanket with a 39°C air temperature inside the bedding.[13] The main reason for the increased thermal stress at 35/75 may be the highest Pa in this condition. In wake subjects under low Pa conditions, all the secreted sweat will be evaporated, whereas under high Pa conditions, the percentage of wetted skin surface increases[14] and eventually 0–10% of the sweat for evaporation will be lost due to dripping, hence the sweating evaporative efficiency decreases.[6] This decrease in sweat evaporative efficiency is related to percent skin wettedness, independent of the sweat rate.[15] It is possible that decreased evaporative sweat efficiency increased the thermal stress at 35/75. In animal studies, response to a thermoregulatory effect is suppressed or depressed in REM due to loss of thermosensitivity in the majority of hypothalamic preoptic neurones.[16] On the other hand, the thermosensitivity during REM in humans is not completely inactive,[17] however, the heat tolerance is reduced compared to SWS as a delayed onset of the sweating reduces the evaporative heat dissipation.[18] Considering that REM and thermoregulation are most likely mutually exclusive in animals as well as humans, REM may have decreased at 35/75 in order to maintain homeothermy. In kangaroo rats, REM periods show transitions when either the central or peripheral sensors indicate thermal stress.[19] In humans, the sweat gland response persists during sleep and there are multiple relationships between local influences and central drive during sleep.[20] If human sweat during sleep is regulated both by peripheral and central factors, it is most likely that skin wettedness has a relation with decreased REM. The increased thermal stress at 35/75 is also supported by the result that the stage wake increased, and SWS decreased at 35/75. Thermal response decreases during sleep compared to wake.[26] Stage wake probably increased in order to enable thermoregulation as this is the only stage which complies to a heavy thermal load as already suggested by Parmeggiani.[16] The increase in stage wake may have replaced SWS and this decrease in SWS may also reflect the thermoregulatory need.[21] However, the decrease was limited in the initial part of the sleep, thereby agreeding with a previous study.[13] This may indicate that increased demand for SWS due to sleep disturbance in the initial part of the sleep may have overcome the increased thermal stress later in the night.[13] During sleep at 35/75, there can be competition between sleep maintenance and the thermoregulatory system as the neuronal mechanism controlling sleep receives input from the hypothalamus and peripheral temperature receptors.[19]

Another factor which should be taken into account for decreased REM, SWS, and increased wake in 35/75 is the non-specific effect.[1] It is well studied that discomfort increases when Ta is higher than the thermal neutral zone and accompanies increased humidity.[4,22,23] Severe stress due to acute transient rise in temperature and humidity from 29/50 at the beginning of the sleep may have decreased SWS, REM and increased wake. The stress leads to reduction in stage 4 sleep duration, REM and increases transient awakening.[24] In continuous heat exposure,[2] where stress due to acute high temperature exposure was minimized, no significant decrease in SWS was observed while it significantly decreased in acute exposure.[1] As humid heat exposure was acute in the present study, we could not define whether or not our result was due to non-specific effect or thermal stress or both. Comparison of these results with continuous humid heat exposure may be one approach to clarify this issue. However, considering the fact that slight changes of Ta in the thermal neutral zone may affect the REM sleep cycle[25] and central thermoregulatory mechanisms are involved in the sleep stage distribution,[19] a non-specific effect may not be the only effect on the sleep stage changes.

Tr was maintained significantly higher at 35/75 and 35/50 compared with 29/50 and 29/75. This finding agrees with the previous result that Tr was maintained higher as the Ta increased.[27] The most noteworthy result was that Tr was higher at 35/75 than 35/50 although the Ta was the same. This result indicates that Tr during sleep is affected both by Ta and relative humidity and this effect appears to be limited to a higher Ta as we did not find any significant difference between the 29/50 and 29/75 conditions. The difference in Pa which decreases evaporative sweat efficiency may be the reason for the significant difference in Tr. In awake subjects, heat stress increases according to the combination of Ta and humidity. The effect on Tr level may be limited to a very high Ta and humidity.[15] In our study, the 35/75 condition clearly sustained a higher Tr compared to 35/50 although the Ta was much lower than in Candas's study. This may be due to the fact that thermal response decreases during sleep compared to the wake state[26] and was in agreement with a previous study which concluded that an increase of few degrees of Ta above the thermal neutral zone influenced the response in internal temperature during sleep.[28] It can be concluded that the effect of humid heat is much greater during the sleep than the wake state. The reason for a high Tr at 35/75 may also be related to the sleep parameters. At 35/75, sleep was disturbed mainly in the first sleep cycle where sleep-evoked Tr decrease mainly occurs.[29] It is well known that there is a lowering of the hypothalamic set temperature during sleep.[30] As the central thermoregulatory drive is involved in sleep stage distribution,[2] the high Pa at 35/75 may have disturbed sleep as well as the lowering of the set point temperature. In spite of this significant difference in Tr, whole body sweat loss did not show any significant difference between the 35/50 and 35/75 conditions, although it was significantly higher than at 29/50 and 29/75. As evaporative sweat efficiency decreases under high Pa conditions, sweat loss increases in order to avoid rectal and skin temperature increases in awake subjects.[6] However, this increase was not observed during sleep. It is most likely that the lower rate of evaporative sweat efficiency was maintained at 35/75 compared to 35/50. As the thermal stress during sleep was heavy at 35/75, it might have been difficult to induce efficient evaporation to avoid the Tr increase. Another possibility may be hidromeiosis, which is the sweat decline due to skin wettedness. Hidromeiosis is a local adaptive sweating mechanism in order to avoid hydration by decreasing the ineffective sweat rate and maintaining an evaporative sweat rate.[31,32] This mechanism might explain the same whole body sweat loss at 35/50 and 35/75.

In conclusion, humid heat exposure during sleep increases thermal load to supress the sleep-evoked Tr decrease, stage 3, SWS, and REM, and increase wakefulness. Although there is general agreement that the effect of cold is greater than heat on sleep stages,[1,16] our results indicates that heat also affects sleep when it is combined with high humidity. The heat stress during sleep should not be considered only in items of Ta but in combination with humidity.

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