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Original Article

ORIGINAL ARTICLE

Effects of sleep on a high-heat capacity mattress on sleep stages, EEG power spectra, cardiac interbeat intervals and body temperatures in healthy middle-aged men‡

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Abstract

Study Objectives: This study deals with the question whether a slow (non-disturbing) reduction of core body temperature (CBT) during sleep increases sleep stage N3 and EEG slow wave energy (SWE) and leads to a slowing of heart rate in humans.

Participants: Thirty-two healthy male subjects with a mean ± SD age 46 ± 4 years and body mass index 25.2 ± 1.8 kg/m^2.

Methods: A high-heat capacity mattress (HM) was used to lower body temperatures in sleep and was compared to a conventional low-heat capacity mattress (LM) in a double-blinded fashion. Polysomnography was performed accompanied by measurements of skin-, core body- and mattress surface-temperatures, and heart rate. EEG power spectral analyses were carried out using Fast Fourier Transform. Interbeat intervals were derived from the electrocardiogram.

Results: The HM led to a larger decline in CBT, mediated through higher heat conduction from the core via the proximal back skin onto the mattress together with reduced heart rate. These effects occurred together with a significant increase in sleep stage N3 and standardized slow wave energy (sSWE, 0.791–4.297 Hz) accumulated in NREM sleep. In the 2nd half of the night sSWE increase was significantly correlated with body temperature changes, for example with CBT decline in the same phase.

Conclusions: A HM subtly decreases CBT, leading to an increased amount of sleep stage N3 and of sSWE, as well as a slowing of heart rate.

Statement of Significance

Based on a previous investigation [1] using the same mattress types, we carried out in more detail this first double-blinded study in healthy middle-aged men of the effect of body cooling during sleep via a high-heat capacity mattress (HM). Similar to the previous study, significant decreases in core body and proximal back skin temperatures were observed in HM, together with more sleep stage N3. Additionally, heart rate was significantly slowed down indicating reduced heat production. Spectral analyses showed an increase mainly in standardized EEG slow-wave energy (sSWE) accumulated during NREM sleep, which was correlated with the observed temperature effects. Taken together, subtle conductive cooling of the body through a HM increases sleep stage N3, sSWE, and slowing of heart rate.

Key words: EEG slow wave energy; slow wave sleep; core body and proximal back skin temperatures; conductive body heat loss; high-heat capacity mattress

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Introduction

In all species sleep is a state of rest and recovery combining a number of complex physiological processes, ultimately resulting in a reduction of metabolism, body heat content, and hence of core body temperature (CBT) [2–5]. Habitual sleep occurs in a close phase relationship to the circadian rhythm of CBT, which is a resultant of heat production and heat loss (predominantly via warm distal skin region) governed by endogenous circadian clock(s) [2, 5, 6].

It has long been hypothesized that the circadian pattern of CBT is not only causally linked to maximal propensity of sleep initiation [7, 8] but also to EEG slow wave activity (SWA)—the faster and steeper the decline in CBT, the higher the SWA [9]. However, many studies have challenged this latter relationship. So-called forced desynchrony studies have conclusively demonstrated the nearly complete independence of SWA of circadian phase and of changes in CBT in humans [10, 11]. In contrast, it has been widely confirmed that sleep initiation leads to increased skin temperature (body heat loss), which in turn facilitates CBT decline at sleep onset [2]. In addition to the endogenous circadian rhythm, masking effects modulate the overt CBT pattern. For example lying down, switching the lights off, relaxation of mind and muscles, as well as bedclothes and room temperature are factors promoting not only sleep initiation but also redistribution of blood from the core to the shell (skin). The result is an increased skin temperature, most pronounced in distal skin regions leading to the subsequent reduction in CBT [12]. Slow-wave sleep (=sleep stage N3), and hence SWA occur most frequently in the first sleep cycles, and sleep initiation is involuntarily coupled with a decrease in CBT [13, 14], yet it is not fully understood how the two physiological processes are intertwined. However, is seems clear that the brain receives information on skin temperatures from vasodilatated or vasoconstricted skin regions, which are indicative for sleep-permissive and wake-promoting conditions, respectively [15].

Earlier research in this field attempting to influence CBT during sleep by manipulation of environmental thermal influence factors, for example ambient air temperature (AIRT), was limited because the application of the intervention can disturb sleep and cause adverse reactions [2, 6, 16]. It was found that such interventions require remaining within a thermal comfort zone of ambient AIRT to avoid disturbing regular sleep [17, 18]. Kräuchi et al. recently investigated the effect of a high-heat capacity mattress (HM) as an example of a reliable thermal intervention on sleep in healthy young men [1]. When compared to a common low-heat capacity mattress (LM), HM showed a larger decrease in CBT in sleep, which was mediated by increased heat conduction from the body core to the skin and subsequently to the mattress. The increase in internal heat conductance was found to be significantly associated with an increased amount of sleep stage N3 in HM compared with LM. However, heart rate analysis (an indirect measure for heat production) and spectral analysis of the EEG-signal (the classical approach for quantitative analysis of sleep homeostasis) were not performed in that study [1]; both analyses would have been important for a comprehensive interpretation of the findings. Based on the previous results, this study aimed to investigate the complex physiological processes in more depth. To better understand how CBT is related to N3 sleep and related changes in EEG spectral power, a HM-based thermal intervention was used. Besides that, the effects of body cooling during sleep on heart activity, as well as the relationships between changes in body temperatures and EEG spectral power were analyzed.

Methods

Study population

Thirty-two healthy male subjects with a mean ± SD age 46 ± 4 years and body mass index (BMI) 25.2 ± 1.8 kg/m^2 were included in the study. The study was approved by the local Ethics Committee (application number: EA1/316/15) of the University Hospital, Charité - Universitätsmedizin Berlin, and subjects gave their written consent for participation. All subjects were normal sleepers and had no signs of any sleep disturbances. Exclusion criteria were acute or chronic illness, use of hypnotic agents or other medications influencing the sleep–wake-regulation, known sleep disorders, chronic drug- or alcohol abuse or dependence, or participation in other clinical–pharmacological trials in the past 4 weeks prior to the exam. Inclusion of subjects was performed by a sleep medicine specialist in clinical consult up to 4 weeks prior to study participation.

Study design

The study was designed as a randomized double-blinded crossover trial to compare the HM to a standard LM by performing polysomnography (PSG), CBT, skin, mattress, and ambient AIRT measurements in parallel. All recordings were performed under constant laboratory conditions. Each subject was randomized to either one measurement night on HM, followed by a 1-week wash-out period, followed by another measurement night on LM, or vice versa.

Mattress properties

The HM consists of a foam core coated with a polyurethane high-heat capacity material (Technogel, Italia S.R.L., Vicenza, Italy). The LM consists of 100% foam material. Both mattresses had the same size 90 × 200 × 25 cm. The different thermal properties are due to differences in material density of the top 2 cm, with a higher material density leading to a higher heat capacity in the temperature range studied, which was 23–35°C. (HM: 47 kJ/°C; LM: 5.4 kJ/°C for the mattress surface (top 2 cm). The same bed covers (bi-elastic non-quilted textile, 600 g/m^2) and pillows were used in order to exclude possible confounding effects.

Temperature measurements

Temperature recordings were carried out similarly to a previous study as described in Kräuchi et al. in 2018 [1]. CBT was measured using an ingestible, telemetric capsule sensor (VitalSense Core Temperature Capsule, Hidalgo Ltd., Cambridge, UK) using a resolution of 0.01°C and a sampling rate of 4/min. CBT, skin, room, and mattress temperatures were measured using wireless temperature sensors (“iButton” DS 1922L, Thermochron iButtons; Maxim, Dallas) using a resolution of 0.0625°C and a sampling rate of 1/min; for validation studies see [19, 20]. iButtons for skin temperature measurement were placed on the back of both shoulders and on the spinal cross between them.

In addition, five iButtons were placed on the mattresses as follows: three sensors in a row 60 cm from the top, 15 cm distance between sensors and 30 cm to the edges, a fourth sensor in the middle 20 cm below the first row, and the fifth sensor 20 cm below the fourth. The sleep technicians and caregivers of the study subjects were blind with respect to the mattress type; the mattress sensor placement was performed by other personnel. AIRT was recorded by an iButton located on the bedside table. The iButtons were adhered on the skin and mattresses by a thin air-permeable adhesive surgical tape (Fixomull; Beiersdorf, Hamburg, Germany). In order to control for inter-device variance, for every measurement position the same iButton was used in all subjects. In order to investigate conductive heat loss from the body core to the mattress, CBT, proximal back skin temperatures (PRO) and mattress surface temperatures (MAT) were evaluated. PRO was calculated as the mean of the three back skin temperatures and MAT as the mean of the five mattress temperatures, thereby reducing skin temperature changes caused by the body's turning during sleep. According to the subjects, none were "stomach sleepers".

PSG recordings and scoring

Subjects underwent PSG recordings using the EMBLA N7000 system (Embla Inc., Broomfield, CO) according to American Academy of Sleep Medicine (AASM) guidelines [21]. Recorded data included electrophysiological signals EEG, EOG, and EMG for sleep evaluation and one electrocardiogram (ECG) lead as well as leg movements, airflow, body position, actigraphy, RIP thoracic and abdominal movements, and pulse oximetry (SpO_2). A total of six unipolar EEG-derivations derived from the 10–20-system were recorded, along with two channels electro-oculogram (bilateral epicanthus), and two channels of electromyogram on the chin (*M. Mentalis*) and the leg (*M. Tibialis*). ECG was derived from precordial chest leads, body position from the PSG system and blood oxygen saturation from the digital probe. Room temperature was controlled by an air conditioner and kept stable at est. 23°C. Recordings were monitored throughout the night by trained personnel and the presence and quality of all signals was checked at least every hour. PSG recordings were evaluated and scored by a certified sleep technician according to the AASM criteria [21] blinded to the type of mattress used during PSG. This person had no knowledge about other variables, for example of subject's mattress temperature. Resulting variables of sleep scoring were absolute time of sleep stages N1, N2, N3, and R, as well as total sleep time (TST), sleep efficiency (SE), sleep onset latency to sleep stage N2 and wake time after sleep onset (WASO).

EEG spectral data processing and analysis

EEG spectral analysis was performed on a central-to-contralateral EEG derivation (C3:A2) from PSG data between "Lights Off" and "Lights On" conditions using the RemLogic software (ver. 3.4, Embla Inc., Broomfield, CO). Spectral power in 0.390625 Hz frequency-bins was calculated for every 30-s epoch of sleep staging by Fast Fourier Transform using a 512-point window with 50% overlap. In order to reduce unspecific artifacts in absolute spectral power, for example resulting from deviations of the electrode positions and hence in electrode capacitance, spectral power density of each frequency-bin was standardized to total power density between 0.391 and 35.156 Hz (=100%). From that, standardized spectral power density values were accumulated over NREM (sleep stage N1–3) sleep epochs (=standardized EEG energy) for the 1st and 2nd half of the night. Subsequently, the spectra were subdivided in specific spectral bands (averaged frequency bins within a band width). Definition of spectral bands: delta 0.781–4.297 Hz (N = 9 frequency bins), theta 4.297–7.813 Hz (N = 9 frequency bins), alpha 7.813–12.500Hz (N = 12 frequency bins), sigma 12.500–15.234 Hz (N = 7 frequency bins), beta 15.234–30.078 Hz (N = 38 frequency bins), gamma: 30.078–35.156 Hz (N = 13 frequency bins). Based on previous findings [17, 18, 22], standardized EEG energy in the delta-band (=standardized slow wave energy, sSWE) was considered as the primary spectral measure for this study. To illustrate this with a hypothetical example, if all sleep epochs in the second half of the night would be rated as NREM sleep, and the entire EEG energy would be located in the delta range (0.781–4.297 Hz) then sSWE would equal 100%.

ECG-based heart rate analysis

Heart rate analysis was derived from single ECG (lead II) recordings according to the Task Force on HRV Standards [23] using the Embla software of the PSG system (*RemLogic* ver. 3.4, Embla Inc., Broomfield, CO) as described previously [24]. In brief, for data preprocessing and artifact rejection, interbeat intervals (IBI) less than 500 ms and more than 1700 ms, as well as abnormal beats, for example wide QRS complexes were excluded. A minimum of 10 IBI was used to include an epoch. Finally, visual inspection of the ECG time-series was performed as human quality control. One-minute mean values of IBI were calculated from data between "Lights Off" and "Lights On" conditions and used for further statistical analysis.

Statistical analyses

Time courses were statistically tested by analyses of variance for repeated-measures (ANOVA) using Huynh–Feldt correction; however, reported are original degrees of freedom. For alpha correction of multiple post hoc comparisons, Curran–Everett method was used [25]. Group data are expressed as mean ± SEM. ANOVA, multiple regression analyses and paired t-tests were performed using StatisticaTM 6 software package (StatSoft, Tulsa, OK). The level of significance was set at $p < 0.05$.

Results

Temperatures and heart rate

Directly after lights off MAT, PRO, and IBI increased rapidly in both conditions and CBT declined to a minimum after 1–2 h. The most pronounced temperature differences between LM and HM were found in the time courses of MAT (bottom graph in Figure 1, Table 1) [main effect LM vs. HM: 2.73 ± 0.19°C; $F(1,31) = 197.8$, $p < 0.0001$]. Compared to LM, HM delayed the increase of MAT, whereas LM reached a constant surface temperature about 3 h after lights off. The first significant difference between LM and HM was already found in the first 10 min interval after lights off [significant interaction term, TIME × "mattress condition" (COND), $F(31,47) = 165.1$, $p < 0.0001$], the last significant

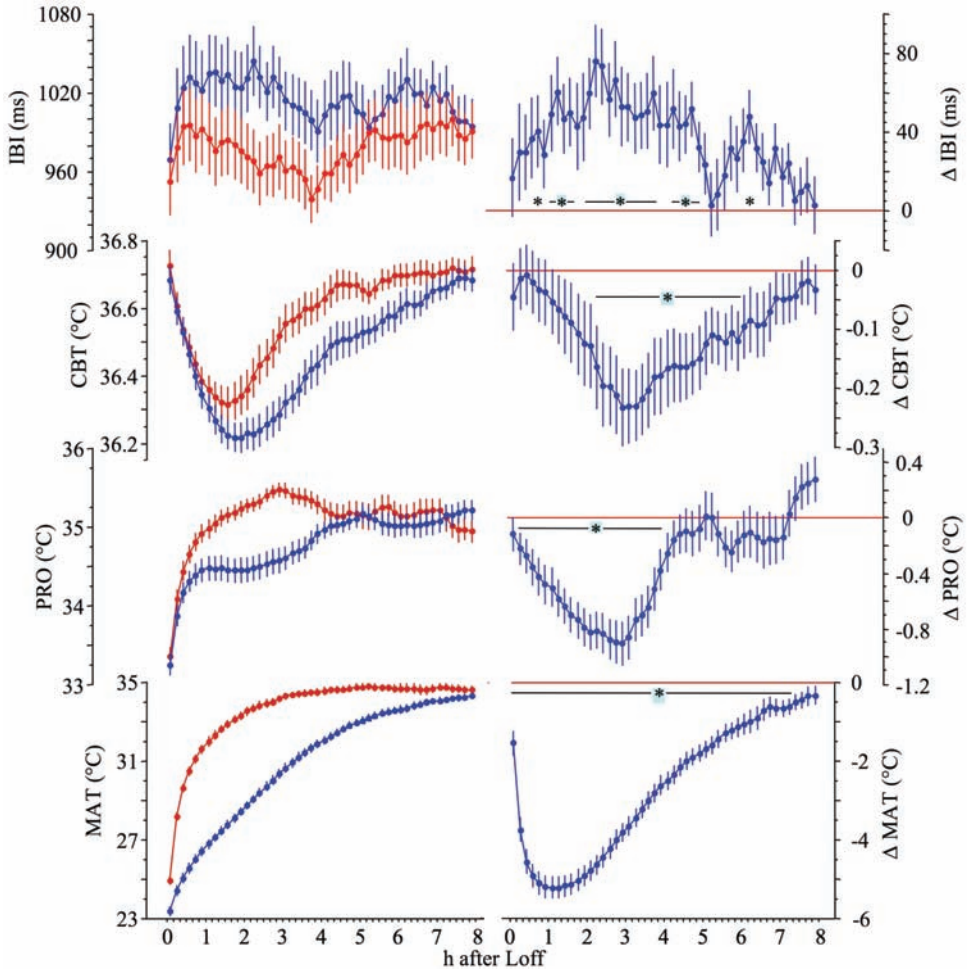

Figure 1. Time courses of temperatures and ECG interbeat intervals. From top to bottom, left panel: shown are time courses (mean ± SEM, N = 32 men; 10 min-interval) of interbeat intervals (IBI), core body temperature (CBT), proximal back skin temperature (PRO), and mattress surface temperature (MAT) during 8 h-sleep phase for the two mattress conditions (low-heat capacity mattress, LM: red curves; high-heat capacity mattress, HM: blue curves). Right panel: time course (mean ± SEM, N = 32 men; 10 min-interval) of the differences between HM and LM (blue curve). The red line at zero indicates LM values. *p at least <0.05, adjusted for alpha errors for multiple tests, FDR correction, Curran–Everett (2000) 25. Note: Mattress surface temperature showed the fastest and biggest changes, followed by PRO and CBT, indicating body heat loss via a conductive way to the mattress.

Table 1. Summary of temperatures and ECG interbeat intervals

	Whole night			1st half	2nd half	
	LM	HM	HM–LM	HM–LM	HM–LM	TIME × COND
IBI (ms)	977.6 ± 21.4	1015.4 ± 22.0	37.8 ± 11.8*	49.2 ± 14.1*	24.3 ± 10.6*	*
CBT (°C)	36.58 ± 0.03	36.47 ± 0.03	–0.11 ± 0.04*	–0.13 ± 0.05*	–0.10 ± 0.04*	
PRO (°C)	35.09 ± 0.08	34.73 ± 0.10	–0.36 ± 0.09**	–0.66 ± 0.12**	–0.06 ± 0.10	**
MAT (°C)	33.65 ± 0.16	30.92 ± 0.16	–2.73 ± 0.19***	–4.22 ± 0.23***	–1.24 ± 0.19***	***
AIRT (°C)	20.50 ± 0.09	20.41 ± 0.02	–0.09 ± 0.10	–0.06 ± 0.10	–0.12 ± 0.10	

Mean ± SEM values (N = 32 men) of interbeat intervals (IBI) and temperatures for the whole, 1st and 2nd half of the night. CBT = core body temperature, PRO = proximal back skin temperature, MAT = mattress surface temperature, AIRT = air temperature, statistics: two-way ANOVA for repeated measures, main effects: COND (HM vs. LM), TIME (1st vs. 2nd half); interaction term: TIME × COND; HM–LM differences: *p < 0.02, **p < 0.001, ***p < 0.0001.

difference 40 min before lights on. The maximal difference in MAT was found 70 min after lights off (–5.25 ± 0.26°C).

PRO exhibited smaller effects than MAT. With respect to LM, HM decreased the 8 h-mean value by –0.36 ± 0.09°C [second graph from bottom in Figure 1; Table 1, main effect: LM vs. HM, $F(1,31) = 15.22$, p =0.0005]. The first significant difference in PRO between LM and HM occurred 20 min after lights off, the last one after 240 min [TIME × COND, $F(31,47) = 8.76$, $p < 0.0001$]. The maximal difference in PRO was found 3 h after lights off (–0.92 ± 0.15°C).

Compared to LM, sleep on HM induced a significantly stronger reduction in the 8 h-mean value of CBT [–0.11 ± 0.04°C; second top graph in Figure 1, Table 1; main effect: LM vs. HM, $F(1,31) = 7.26$, $p = 0.0113$]. The first significant difference in CBT

between LM and HM appeared 150 min after lights off, the last one 130 min before lights on significant interaction term [TIME × COND, $F(31,47) = 4.18$, $p < 0.005$]. The maximal difference in PRO occurred 3 h after lights off (–0.24 ± 0.06°C). Nearly identical AIRTs were recorded during both conditions (main effect: HM–LM –0.09 ± 0.10°C, n.s.; TIME × COND, n.s.). Taken together, the strongest and fastest temperature changes occurred in MAT followed by PRO, while CBT exhibited the smallest and slowest changes.

In comparison to LM, HM induced a significant increase in 8 h-mean value (=sleep phase) of IBI (Table 1). Significant increases in IBI occurred in all sleep stages including WASO (data not shown). Analysis of the 8 h-time courses disclosed significant differences between LM and HM changing over time (two-way ANOVA for repeated measures, TIME × COND: $F(47,1363) = 2.15$, $p < 0.02$) (top graph Figure 1). The first significant difference in IBI occurred 50 min after lights off, the last one 110 min before lights on, while the differences between LM and HM can mainly be noted in the 1st half of the night.

These findings were confirmed in separate two-way ANOVA for repeated measures including mean values of the first and second half of the night (significant interaction term TIME × COND; p at least <0.05; see Table 1 last two columns), showing significantly stronger mattress effects in the first half (0–240 min after lights off) than in the second half of the night (240–480 min after lights off).

Sleep structure

No significant differences occurred in sleep onset latency between LM and HM. Sleep stage analysis of the entire night revealed selectively significant findings for sleep stage N3 (Table 2). In comparison to LM, sleep on HM increased duration of sleep stage N3 by 11.4% ($p = 0.0268$), however, no significant differences occurred in %N3.

Analysis of the time course of N3 throughout the night revealed small increases per 10-min intervals in HM which accumulated to significant differences at the end of the night (Figure 2 lower panel) [two-way ANOVA for repeated measures; TIME × COND, $F(47,1457) = 2.916$, $p < 0.02$; see legend to Figure 2] even though no significant interaction term [TIME × COND, $F(47,1457) = 0.911$, n.s.] in the original data occurred (Figure 2 upper panel).

Table 2: Summary of sleep stage analysis

	LM	HM	HM–LM
SOL (min)	19.84 ± 1.65	20.27.4 ± 2.41	0.42 ± 2.22
N1 (min)	65.13 ± 5.70	63.92 ± 6.10	–1.06 ± 4.71
N2 (min)	191.41 ± 6.51	196.89 ± 7.82	5.48 ± 7.06
N3 (min)	61.84 ± 4.47	68.92 ± 5.04	7.08 ± 3.05*
REM (min)	66.27 ± 4.93	67.94 ± 4.50	1.67 ± 4.74
WASO (min)	75.52 ± 7.71	61.31 ± 7.00	–14.20 ± 7.47
Total sleep time (min)	384.64 ± 8.00	398.41 ± 7.94	13.77 ± 8.36
Sleep efficiency (%)	80.13 ± 1.67	83.00 ± 1.65	2.87 ± 1.74
N1 (%)	16.98 ± 1.47	16.37 ± 1.62	–0.61 ± 1.26
N2 (%)	49.71 ± 1.29	49.12 ± 1.47	–0.59 ± 1.37
N3 (%)	16.32 ± 1.25	17.51 ± 1.44	1.19 ± 0.92
REM (%)	17.00 ± 1.17	17.00 ± 1.10	0.01 ± 1.10

Mean ± SEM, N = 32. SOL = sleep onset latency (statistic based on log-transformed values). WASO = wake after sleep onset. Sleep stages are given either in min/8 h-sleep phase, or in % of total sleep time. *$p = 0.0268$, paired t-test. In comparison to LM, HM exhibits selectively more sleep stage N3.

EEG spectral analysis

Based on the temperature findings (see above), EEG spectral analyses were performed separately for the first and second half of the night (cp. findings in ref. [1]). For both parts of the night no significant mattress effects were found on EEG power density values expressed as mean values per NREM-sleep epochs or as accumulated EEG energy in NREM-epochs (data not shown). Additionally, total EEG power density over the entire frequency range (0.391–35.1562 Hz) did also not significantly differ between the mattresses (1st half of the night, HM = 54.194 ± 8.981 $\mu V^2 \times 10^3$/Hz per30 s, LM = 45.703 ± 8.229 $\mu V^2 \times 10^3$/Hz per 30 s; 2nd half of the night, HM = 50.522 ± 6.202 $\mu V^2 \times 10^3$/Hz per 30 s, LM = 63.571 ± 17.243 $\mu V^2 \times 10^3$/Hz per 30 s. Two-way-ANOVA based on log-transformed values; main effects: main effects: COND (HM vs. LM), n.s.; TIME (1st vs. 2nd half of the night), $F(1,31) = 5.581$, $p = 0.0246$; interaction term: TIME × COND; n.s.).

Subsequently, in order to detect subtle redistribution of power densities within a spectrum, original power density values were standardized to total EEG power density and expressed as percentage of total power (see *Methods*). This calculation reduces intra-individual variances and enhances therefore the chance to detect changes within a spectrum, however bearing the disadvantage that only relative changes can be recognized. Afterwards, standardized EEG power density values were accumulated for NREM epochs (=standardized EEG energy) in both halves of the night. A significant percentage increase in accumulated standardized EEG energy (=standardized slow wave energy, sSWE) was found predominantly in the delta frequency range in the 2nd half of the night (Figure 3).

The increase of % sSWE (0.461 ± 0.130, Figure 3) corresponds to 115.9% increases expressed as % with respect to LM (=100%) (=retransformed HM – LM differences of log values, Figure 3 right panel). Statistics was calculated by two-way ANOVA for repeated measures using log transformed values; COND, $F(1,31)=5.995$, $p = 0.0202$; TIME, $F(1,31) = 41.302$, $p < 0.0001$; TIME × COND, $F(1,31) = 4.530$, $p = 0.0414$. To a lower extent, an increase in accumulated standardized EEG energy was also observed in the theta band and again only in the 2nd half of the night (HM – LM differences: 0.111 ± 0.038%, $p < 0.02$ paired t-test), however, TIME × COND did not reach statistical significance. All other frequency ranges (alpha, sigma, beta, and gamma range) also showed positive HM – LM differences (mean HM – LM differences >0% and <0.06%), but did not reach statistically significant values (data not shown). These results indicate that the mattress induced increase in standardized EEG energy is dependent on frequency and occurs predominantly in sSWE. Interestingly, the HM – LM difference in sSWE is correlated with sleep stage N2 and not with sleep stage N3 (2nd half of the night, correlations of HM – LM differences in N2 vs. sSWE, $r = 0.526$, $p = 0.0020$; N3 vs. sSWE, $r = –0.077$, n.s.).

Relationships between sleep and body temperature changes

A significant negative correlation ($r = –0.465$, $p = 0.0074$) was found between the mattress-induced changes (HM–LM) in PRO in the 1st half of the night with standardized EEG energy in the

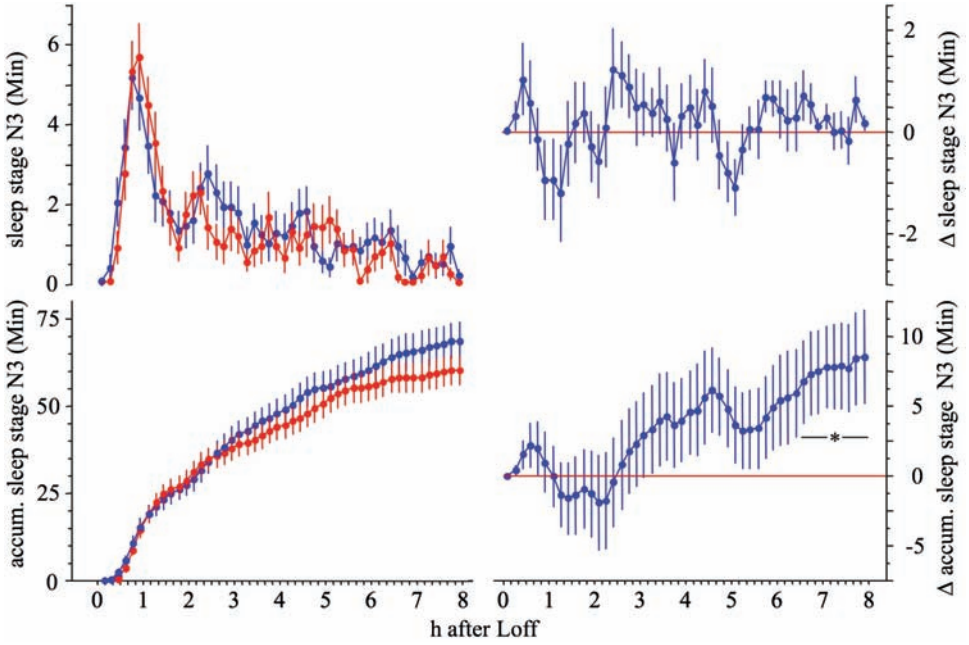

Figure 2. Time courses of sleep stage N3. In the left upper graph, the time course of sleep stage N3 is shown during the 8 h-night sleep phase for the two mattress types in 10 min-intervals (mean ± SEM, N = 32 subjects). Below, corresponding time courses of accumulated sleep stage N3 are presented (LM: red curves; HM: blue curves). The graphs in the right panel depict time courses of the differences between HM and LM (LM = 0, red line) for their corresponding left graphs. *$p < 0.05$, paired *t*-test. Note: In comparison to LM, HM exhibits higher accumulated N3 values, reaching statistical significance in last 90 min of the night.

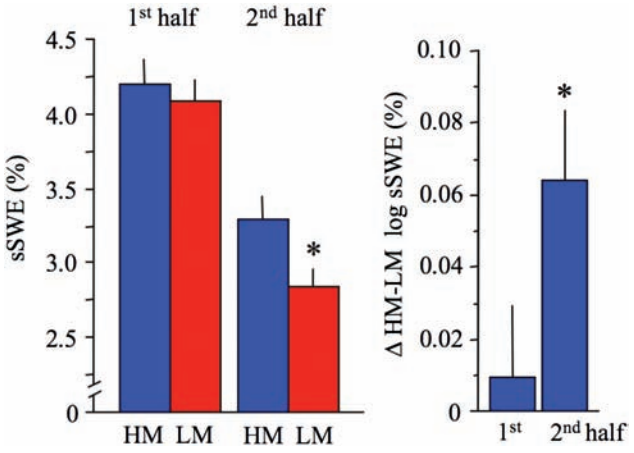

Figure 3. Mattress-induced effects on standardized slow wave energy. Left panel: mattress-induced effects on standardized EEG energy in the delta frequency range (0.781–4.297 Hz) (=standardized slow wave energy, sSWE) accumulated in NREM sleep during the 1st or 2nd half of the night. Right panel: difference between log-transformed values of sSWE in HM and LM for the 1st and 2nd half of the night. HM = high-heat capacity mattress, LM = low-heat capacity mattress. * $p < 0.05$, HM–LM differences; statistics see *Results* section. Mean ± SEM per 30 s; N = 32 healthy middle-aged men. Note: In comparison to LM, HM exhibits significant %-increased standardized EEG energy predominantly in the delta range (sSWE) in the 2nd half of the night indicating a relative slowing of the EEG activity in condition HM.

delta range (=standardized slow wave energy, sSWE) in the 2nd half of the night (Figure 4, left graph).

Among all tested variables PRO is the only variable showing this predictive association (backward stepwise regression analysis; PRO was extracted in three steps; tested predictor variables: PRO, CBT, MAT, IBI). When CBT–PRO (a measure for inner heat conductance from core to shell) was tested instead of PRO, a similar but positive correlation was found ($r = +0.445$, $p = 0.0108$). In contrast to these findings, only changes in CBT in the 2nd half of the night were associated with changes in sSWE in the same phase (Figure 4, right graph; $r = -0.458$, $p = 0.0085$; backward stepwise regression analysis; CBT was extracted in three steps; tested predictor variables: PRO, CBT, MAT, IBI). Correlations of body temperatures with sleep stages did not reveal statistical significance.

Discussion

This study in healthy middle-aged men confirms and extends previous findings in a smaller sample of young men using the same type of mattresses [1]. Compared to a conventional LM, sleep on a HM not only significantly reduced MAT and body temperatures (CBT and PRO), but also found significantly increased sleep stage N3, standardized EEG slow-wave energy in the delta range (sSWE) and cardiac IBI in HM over LM. These findings conclusively show that conductive body heat loss is associated with enhanced sleep stage N3 and sSWE and reduced heart rate, indicating physiological changes with potentially positive health effects [26–28].

Temperatures, heart rate

Differences between HM and LM in body temperatures developed continuously after lying down and switching the lights off with different temporal patterns. The strongest and fastest changes occurred in MAT followed by PRO, while CBT exhibited the smallest and slowest changes. These relationships can be explained by the fact that body contact with the mattress surface initiates body heat loss, leading to a reduction in PRO and CBT (Newton's law of

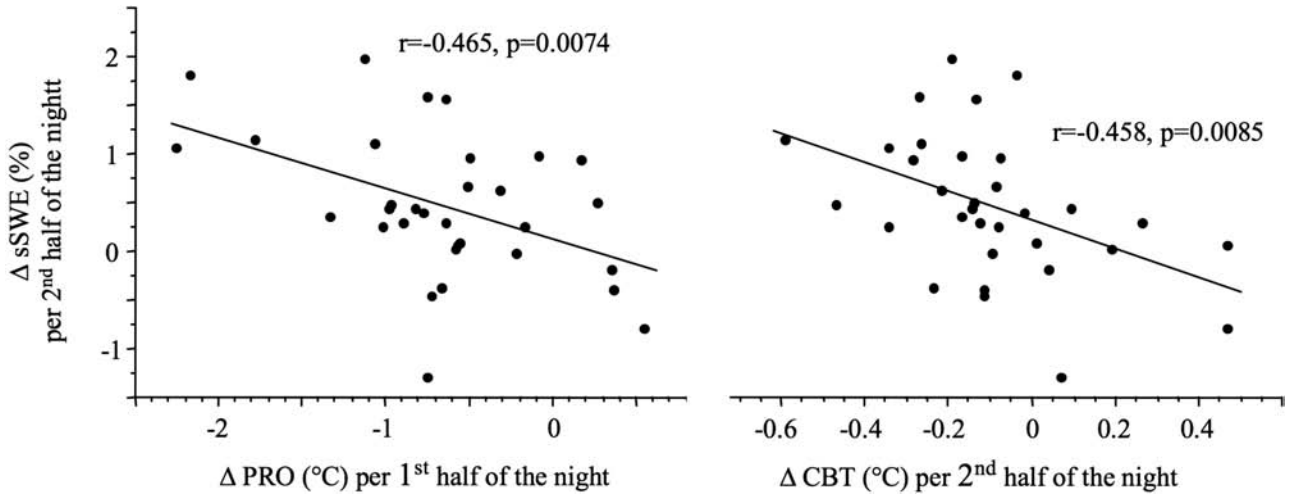

Figure 4. Relationship between body temperatures and standardized slow wave energy in the delta band. Regression analysis of mattress-induced changes (HM–LM) of PRO in the 1st half of the night and CBT in the 2nd half of the night with standardized slow wave energy (sSWE) in the 2nd half of the night. Right fig.: sSWE(HM–LM 2.half) = 0.3174 ± 0.1286–1.4813 ± 0.5255 × CBT(HM–LM 2.half) Shapiro–Wilk-test: W = 0.9798, n.s. indicating no violation of the assumption of a normal distribution of the residuals. Left fig.: sSWE(HM–LM 2.half) = 0.1162 ± 0.1679–0.5210 ± 0.1812 × PRO(HM–LM 1.half) Shapiro–Wilk-test: W = 0.9745, n.s. Note: Those subjects with a larger mattress-induced reduction in PRO in the 1st half of the night and a stronger decline in CBT in the 2nd half of the night exhibit larger increases of sSWE in the 2nd half.

cooling). However, in comparison to the previous study in healthy young men using the same mattress types [1], CBT and PRO exhibit shorter lasting hypothermic effects induced by HM, but also different time courses after lying down and switching the lights off. In another well-controlled study, similar differences in CBT after lying down and switching the lights off could be found between younger (20–30 years old) and older subjects (65–75 years old) [29]. Therefore, the age difference is likely to be responsible for the differences between the studies. No indications of increased convective heat loss mechanisms could be found (e.g. warm extremities, data not shown; see also ref. [1])—hands and feet are known to represent the major sites for vasomotor heat loss [2]. Thus, the findings of the current study are indicative of differences in passive body heat loss via a conductive way to the mattress.

In addition, IBI was increased in condition HM compared with LM, which is a further indication that no active thermoregulatory changes were induced. It is known that active body heat gain and heat loss mechanisms are energy consuming thermoregulatory processes, which would lead to higher metabolic rate (increased O_2-consumption) and heart rate (reduced IBI) [6, 30, 31]. In general, chemical processes are body temperature-dependent and therefore metabolic rate and heart activity slow with temperature decline. Moreover, a direct temperature sensitivity of the sinus node influences IBI immediately with changed body temperatures [32]. Whether only one or several of these mechanisms are responsible for the present study findings remains to be clarified. Further analyses of heart rate variability changes in sleep stages could lead to additional insights and are currently in preparation. A first analysis carried out for the entire night revealed significantly increased IBI during all sleep stages, including WASO, in the HM condition, indicating that heart rate is not slowed solely by increasing sleep stage N3.

Sleep stage analyses

HM compared to LM showed a selective increase in sleep stage N3. No differences in sleep onset latency, TST, SE, or WASO were found. These findings are similar to the predecessor study in healthy young men [1]. Compared to that study, which included only 15 young male subjects, sleep efficiencies were lower (80–83% vs. 89–93%), whereby not only the difference in age could be responsible for the discrepancy, but also the fact that no adaptation night was used in the present study. Independent of the difference in SE, the increase in sleep stage N3 was not achieved at the cost of one single other sleep stage. Time course analyses showed only small non-significant differences in sleep stage N3/10 min-intervals, however, accumulated over time, they amounted to significant increases in N3 at the end of the night in HM compared with LM (see Figure 2). In a very recent study, similar results were found in a comparison of two different mattress types (different materials than HM and LM) inducing different decline patterns in CBT and HR [18]. Unfortunately, no skin temperatures were recorded, which precludes a direct comparison with the present study. In contrast to the present study, the differences occurred in the 1st half of the night with parallel decline in CBT and heart rate and increase in sleep stage N3 and SWA, which could indicate that temporal localization of the effects are not strictly dependent on circadian phase or on the time elapsed in sleep. In another study by Togo et al. in 2007, a slow reduction of environmental AIRT during the night led to increased sleep stage N3, SWA, and IBI, and to reduced REMS in the 2nd half of the night in parallel to a decrease in CBT and leg skin temperature [17], however, again no proximal skin temperatures were measured, which would be necessary to estimate the pathway of body heat loss. Nevertheless, in spite of the temporal differences, the common effects of reduced CBT, increased sleep stage N3 and increased IBI were inducible by mild passive body cooling. Taken together, such mild passive body cooling, without disturbing counter regulations, could be induced physically either via increased conductive (e.g. by HM) or via increased convective (e.g. by cool air) body heat loss, and, as a consequence of body heat loss, sleep stage N3 could be increased. At first glance these findings contradict the results of a previous study [33] showing increased nocturnal slow wave sleep induced by 0.4°C increase in skin temperature without changing CBT. Yet, this discrepancy in changes in CBT might be

the key to explain the findings. A reduction of both CBT and skin temperatures is indicative for body heat loss via a passive conductive way; however, an increase in skin temperatures is usually indicative for body heat loss via a convective way. It is well known, that all these temperatures (skin and CBTs) are sensed and conveyed to the central thermo- and sleep regulatory brain regions [15]. Therefore, it can be hypothesized that feed-back information on body heat loss via sensing CBT and skin temperatures is provided to these brain regions. In order to explain the results of all available findings, the previous hypothesis (see [15, 33]) would have to be modified accordingly.

EEG spectral analysis

EEG power density was analyzed using accumulated power density values in NREM sleep epochs over a certain time span (e.g. as time integral of SWA in the delta-range = slow wave energy, SWE) [34, 35]. SWE can be considered as the most sensitive EEG-measure to reflect responses to sleep homeostatic changes [22]. For example, it has been shown that the response of EEG energy in the delta and theta frequency range to sleep homeostatic changes (e.g. induced by sleep stage N3 deprivation) was accurately predictable from the EEG energy deficit [35]. In the present study, EEG energy has been affected without changing sleep duration, indicating an additional sleep-homeostasis independent pathway to affect EEG energy via subtle conductive heat loss. Within this context, it would be interesting to study the interaction between sleep deprivation and body cooling (i.e. recovery sleep after sleep deprivation on HM vs. LM). The outcome of such a study would give more insight about the inter-relationship between the influencing factors of SWE. In comparison to LM, sleep on HM significantly increased standardized EEG energy in the delta-range (sSWE). sSWE, the main spectral outcome of this study, is dependent on both the amount (duration) of NREM sleep (i.e. the definition of N3 includes a minimum amount and duration of slow waves) and SWA. The spectral analysis revealed that the mattresses did not significantly influence EEG power density (e.g. of SWA), but that it did significantly increase sleep stage N3, suggesting that the increase in sSWE has come about by extending NREM epochs. On the basis of these results alone, however, it cannot be concluded that the increase in sSWE can be explained solely by the increase in sleep stage N3, because sleep stage N2 was found to be the most influencing factor of sSWE, not sleep stage N3 (see results). Furthermore, the significant increase in sSWE in the 2nd half of the night could not have been achieved by redistribution of the standardized EEG energy from higher to lower frequency ranges, as all spectral frequency differences between HM and LM exhibited positive values in the second half of the night, even though not statistically significant. More detailed future studies are needed to solve this question.

Association between temperatures and sSWE

Due to the still relatively small number of subjects studied, only bivariate and relatively simple multivariable statistical analyses were performed. However, more complex statistics would be needed (such as e.g. path analyses) to conclusively analyze how body heat loss (mainly occurring in the 1st half of the night) induces sSWE changes (mainly occurring in the 2nd half of the night). This implies structure models including thermophysiological variables (e.g. changes in skin temperature, CBT, IBI) of the 1st and 2nd half of the night. Nevertheless, in a first step a backward stepwise regression analysis extracted changes in PRO in the 1st half of the night as the critical variable predicting changes in sSWE in the 2nd half of the night. A comparison of temperature changes in the 2nd half of the night with sSWE changes in the same phase revealed CBT as the crucial predictor variable. This would rather support the hypothesis that temperature changes could induce changes in EEG activity by slowing the rate of neurochemical processes [36]. It seems plausible and worthwhile to further explore their temporal relationships, for example whether the initial heat loss in the 1st half of the night affects the thermic status of the body in the 2nd half of the night.

The history of research of changes in body temperatures before and during sleep, and their effects on sleep (e.g. on distal and proximal skin temperatures, CBT) spans over several decades. Originally, these studies started with the observation that at the beginning of sleep, CBT declines together with the occurrence of NREM sleep. Later on, it could be shown that skin temperatures, most pronounced in distal skin regions, increased before sleep (sleep stage N2) occurs [2]. Therefore, thermoregulatory changes occur first, followed by initiation of sleep. However, sleep in turn also promotes thermoregulatory changes, indicating a feedback-loop system [5]. For example, during 8 h-night sleep, CBT is slowly reduced to about 0.3°C compared with a controlled wake episode at the same circadian time in a constant routine protocol that strictly controls for posture, as well as food and water intake [2, 3, 33]. Even though our study showed that the HM induced decline in CBT was associated with more sleep stage N3 and more sSWE, the interrelationship between the parameters remains to be further investigated.

Conclusion

In comparison to a LM, sleep on a HM subtly increased conductive body heat loss from core to skin and finally to the mattress. These changes developed slowly with maximal reduction in CBT 3 h after lights off. It has been shown that sleep expands the thermoregulatory inter-threshold-zone between the autonomic temperature defense mechanisms (e.g. metabolic heat production, evaporative heat loss) [2]. This expansion of the inter-threshold-zone could be the reason why the subjects slept undisturbed leading to a further decline of CBT during sleep. The subjects in this study, middle-aged men, showed an increase of sleep stage N3 and sSWE (indicating slowing of the EEG), and increased IBI during sleep on HM. Therefore, it can be concluded, that the strategy used in this study could be a promising approach for sleep management in people with suboptimal sleep or sleep complaints and should be investigated further in the future.

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