Physiology & Behavior 185 (2018) 23–30

Contents lists available at ScienceDirect

Physiology & Behavior

journal homepage: www.elsevier.com/locate/physbeh

Sleep on a high heat capacity mattress increases conductive body heat loss and slow wave sleep

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ARTICLE INFO

Keywords:
Distal and proximal skin temperatures
Core body temperature
Conductive heat transfer
High heat capacity mattress
Polysomnography
Slow wave sleep
Cyclic alternating pattern rate

ABSTRACT

Environmental temperature can strongly affect sleep. The habitual sleep phase is usually located between evening decline and morning rise of the circadian rhythm of core body temperature (CBT). However, the thermophysiological mechanisms promoting or disturbing sleep are not yet fully understood. The purpose of this study was to examine the effects of a high heat capacity mattress (HHCM) on CBT, skin temperatures and sleep in comparison to a conventional low heat capacity mattress (LHCM). Based on the higher heat capacity of HHCM an increase in conductive body heat loss enhances the nocturnal decline in CBT can be expected. Based on previous findings this may then be accompanied by an increase in slow wave sleep (SWS).

The mattresses were studied in a randomized single-blind crossover design in fifteen healthy young men (Age: 26.9 ± 2.1 yr, BMI: 22.2 ± 0.4 kg/m^2) by overnight in laboratory standard video-polysomnography in a temperature stabilized setting. CBT, room temperature, and skin and mattress surface temperatures were continuously recorded in order to get information about inner and outer body heat flow. Additionally, subjective sleep quality was estimated by visual analogue scale.

In comparison to LHCM sleep on HHCM exhibited a selective increase in SWS (16%, $p < 0.05$), increased subjective sleep quality and sleep stability [reduced cyclic alternating pattern (CAP) rate; 5.3%, $p < 0.01$]. Additionally, analyses of the sleep stages showed in the second part of the night a significant increase in SWS and a decrease in REMS. In addition, HHCM induced a greater reduction in CBT (maximally by − 0.28 °C), reduced the increase in proximal skin temperatures on the back (PROBA; maximally by − 0.98 °C), and delayed the increase in mattress surface temperature (maximal difference LHCM-HHCM: 6.12 °C). Thus, the CBT reduction can be explained by an increase in conductive heat loss to the mattress via proximal back skin regions. Regression analysis identified PROBA as the critical variable to predict inner conductive heat transfer from core to shell and SWS.

In conclusion, the study expands the previous findings that a steeper nocturnal decline in CBT increases SWS and subjective sleep quality, whereas inner conductive heat transfer could be identified as the crucial thermophysiological variable, and not CBT.

1. Introduction

It is common knowledge that a comfortable environment positively influences quality of sleep. Positive factors favoring initiation and maintenance of human sleep are darkness, a quiet setting, a supine body position, a familiar environment and a comfortable ambient temperature.

It has been shown that habitual sleep is closely related to the circadian rhythm of core body temperature (CBT), which is a resultant of the relationship between heat production and heat loss [1,2]. Sleep onset usually coincides with the maximal rate of decline of CBT [3–5] initiated by increased skin blood flow, skin warming and body heat loss [6,7]. All the mentioned processes are not only governed by endogenous circadian clock(s) but also modulated by so-called masking effects [8]. For instance, the process of sleep initiation includes behaviors such as lying down, switching the lights off, relaxation of mind and muscles all increasing blood redistribution from the core to the shell (skin) and thereby declining CBT and increasing skin temperature (ST). The latter most pronounced in distal skin regions [6,7]. Under real life situation all these processes occur together and are all supportive

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https://doi.org/10.1016/j.physbeh.2017.12.014
Received 7 August 2017; Received in revised form 1 November 2017; Accepted 13 December 2017
Available online 13 December 2017
0031-9384/

for this mechanism. Besides investigations describing habitual sleep in relation to thermophysiology, many studies explored the possibility to thermally influence sleep via air temperature, bed clothes, or bathing before sleep [9–12]. However, this is rather a complex endeavor and studies applying these methods reported contradictory results [13,14]. One consistent finding was that ambient temperatures outside the thermal comfort zone disturbs initiation and/or maintenance of sleep and prevents a conclusive interpretation of thermal interventions on sleep [7,12,15]. It is therefore crucial to select an intervention that thermally affects the body only mildly, without provoking a counter-regulation and yet strong enough to trigger specific effects on sleep [13,14]. For this purpose we have chosen a strategy of slowly removing body heat via conductive heat transfer by means of a high heat capacity mattress (HHCM). In comparison to a conventional low heat capacity mattress (LHCM), a HHCM has a higher thermal capacity thanks to its much higher density of the surface layer (1006 kg/m^3 vs. 80 kg/m^3). This difference should lead to an enhanced overnight body heat loss and this mild "thermic intervention" could therefore be useful to test the hypothesis that reduced CBT during the night leads to increased slow wave sleep (SWS, = N3 sleep) [16–18].

The main aim of this study was to examine the effects of a HHCM vs. LHCM upon sleep in relation to their different thermic properties. Or more specifically, is CBT decline enhanced and SWS increased under gentle core body cooling on HHCM, as previously found with mild air-cooling during night sleep [14].

2. Method

2.1. Study subjects

After giving written informed consent, 28 male subjects, aged between 25 and 30 yr (BMI 19-25 kg/m^2), were screened by a board-certified sleep medicine physician. Exclusion criteria were major not stabilized medical illnesses, history of alcoholism, drug dependence or abuse, neurological disorders, head trauma and mental disorders according to the Diagnostic and Statistical Manual of Mental Disorders (DSM-V, American Psychiatric Association, 2013), Mini Mental State Examination score < 26, CNS active drugs assumption, excessive use of caffeine and/or smoke (respectively > 2 cups and 5 cigarettes per day).

All volunteers without history for sleep disorders and normal sleep-wake pattern (Morningness-Eveningness Questionnaire: "neither type" [19]) underwent an ambulatory polysomnography (PSG) and a long term sleep-wake monitoring evaluated in order to exclude respectively sleep disorders (i.e. insomnia, motor and/or respiratory sleep related disorders) and assess habitual duration and sleep period. Ambulatory PSG was performed using a portable monitoring device (Embletta MPR PG with ST + Proxy module, Natus Medical Inc., Pleasanton, CA, US) monitoring four EEG channels (C3, C4, O1, O2), two electrooculogram channels, chin and anterior tibialis electromyogram, airflow (nasal-cannula), respiratory effort (thoracic and abdominal), oxygen saturation and cardiac frequency, body position, and snoring.

Evaluation of habitual sleep times, sleep onset latency, amount of sleep and sleep efficiency was accomplished by wrist actigraphy for 2 weeks (ActiGraph wGT3X and ActiLife + Sleep software, ActiGraph, Pensacola, FL, US) in addition to sleep logs.

Following evaluation visit and instrumental screening 13 subjects were excluded (5 at evaluation visit, 6 with sleep related breathing and/or movement disorders, 2 because of high variability of sleep period. Fifteen subjects fulfilled the entire study criteria and finished the study without any complaints.

2.2. Design

The mattresses were studied in a randomized single-blind crossover design at the Sleep Disorder Center, Department of Neurosciences, University of Turin, Italy. After an adaptation night in the sleep laboratory on a conventional low heat capacity mattress, each subject slept for two further nights on different mattress types with an interval of one week, randomly starting either with HHCM or LHCM. The study has been approved by the local university ethics committee.

2.3. Mattress properties

HHCM used in this study is coated by a polyurethane high heat capacity layer (Technogel, Italia S.R.L., Vicenza, Italy) on the top of foam layers underneath, whereas the LHCM is constituted of 100% foam. Both mattress sizes were 90 × 200 × 25 cm. The difference in thermal behavior of HHCM and LHCM is related to different density of the top 2 cm of the surface layer (HHCM: 1006 kg/m^3, LHCM: 80 kg/m^3) and hence to the different specific heat capacity in the temperature range studied 23–35 °C (HHCM: about 47 kJ/°C; LHCM: about 5.4 kJ/°C for the top 2 cm of the mattresses). In order to exclude possible effects of different covers the same cover type (bi-elastic non-quilted textile with a weight of 600 g/m^2) was used throughout the entire study.

2.4. Temperature measurements

In order to measure room, skin and mattress temperatures wireless temperature sensors were used (DS 1922L, Thermochron iButtons®; Maxim, Dallas, USA; resolution 0.0625 °C; sampling rate: 1 value per minute). All subjects received the same iButton for each site in both mattress conditions. The temperature sensors were fixed to the skin and mattresses with thin air-permeable adhesive surgical tape (Fixomull®; Beiersdorf, Hamburg, Germany). Air temperature was registered using an iButton in a mesh net bag installed at the wall in the sleep room. In total 18 temperature sensors were placed on the left and right site of the body on the following skin regions: ankle (inner side, between talus and Achilles' tendon), thigh (in the middle inner side of quadriceps), calf (in the middle inner side laterally of tibia), palmar sites of ring finger, wrist and middle of forearm, and infraclavicular region, and one temperature sensor was placed on the sternum. On the back skin temperatures were measured on left and right side of shoulder and one sensor on the spinal cross. Mean value of ankles, calves, thighs, right fingers, wrists and forearms was defined as mean distal ST (DIS), while mean proximal skin temperature is constituted by the average of infraclavicular regions, sternum, and back shoulders and spinal cross. Proximal frontal ST (PROFR) was averaged by ST of infraclavicular regions and sternum and proximal back ST (PROBA) by back shoulders and spinal cross. In contrast to PROBA, PROFR is not influenced by contact with the mattresses. None of the subjects lost a ST probe. In order to record mattress temperatures five temperature sensors were placed on the mattresses (3 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). CBT was recorded using a telemetric, ingestible capsule sensor system (VitalSense Core Temperature Capsule, Hidalgo Ltd., Cambridge, UK; sampling rate: 4 values per minute, later averaged in 1-min-bins).

2.5. Sleep recordings in the lab

Video PSG was performed by Comet XL Lab-based PSG (Grass Telefactor, Astro-Med Inc., West Warwick, RI 02893 U.S.A.) using four EEG channels (C3, C4, O1, O2), two electro-oculogram channels (right and left outer canthus), chin electromyogram, heart rate, oxygen saturation, and body position. Room temperature was kept at approximately 23 °C within a range of ± 0.5 °C and relative humidity between 45% and 55%. The subjects wore the laboratory standard cotton nightclothes and were covered by a cotton sheet during lights-off phase. PSGs were blindly scored by a sleep technician and interpreted by a sleep medicine–certified physician by using standard scoring procedures. PSG variables included time spent in stages N1, N2, N3 (= slow

wave sleep, SWS), rapid eye movement sleep (REMS), total sleep time, sleep efficiency, arousal index and wake time after sleep onset [20]. Sleep onset latency was defined as the time interval between lights off and the appearance of the first epoch of any sleep stage [20]. Cyclic Alternating Pattern (CAP) scoring was based on the rules defined by Terzano et al. [21]. Microstructural variables were: CAP rate, and number, type and distribution across sleep stages of A phases (A1, A2, A3) expressed as percentage value and index per entire night. All of these variables were manually scored using Hypnolab 1.2 sleep software analysis (SWS Soft, Italy).

In the morning after PSG, subjects rated their global comfort feeling during the previous night on a 100 mm-visual analogue scale (0 mm = extremely uncomfortable, 100 mm = extremely comfortable).

2.6. 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 [22]. Group data are expressed as mean ± SEM. ANOVA, paired *t*-test, were performed using StatisticaTM 6 software package (StatSoft, Tulsa, OK, USA). Multiple regression analyses were calculated using the computing environment R (R Core Team, 2015. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL; http://www.R-project.org/). The package 'lme' was used to perform linear mixed effect models with subjects (intercept) and slopes as random effects and predictor variables as fixed effect. In order to adjust for serial dependencies an autoregressive AR (1) process was included to the model. For more details in statistics see description of the results in RESULTS section. The level of significance was set at $p < 0.05$.

3. Results

3.1. Temperatures

In comparison to LHCM, sleep on HHCM significantly reduced CBT (top graph in Fig. 1, Table 1). The 8 h-mean value was significantly reduced by 0.163 ± 0.035 °C [main effect: LHCM vs. HHCM, $F(1,14) = 35.93$, $p = 0.0001$; Table 1]. The reduction developed steadily, was most pronounced in the middle (− 0.28 °C 5 h after lights off) and disappeared at the end of the sleep phase leading to a significant interaction term [TIME × MATTRESS, $F(14,47) = 2.427$, $p < 0.0001$]. The first significant difference in CBT between LHCM and HHCM appeared 70 min after lights off.

ST revealed a differentiated picture. With respect to LHCM HHCM slightly decreased the 8 h–mean value of DIS by − 0.24 ± 0.115 °C [main effect: LHCM vs. HHCM, $F(1,14) = 4.457$, $p = 0.0532$; Fig. 1; Table 1], however, PROBA was significantly reduced by − 0.74 ± 0.170 °C [main effect: LHCM vs. HHCM, $F(1,14) = 18.69$, $p = 0.0007$; Fig. 1, Table 1]. The first significant difference in PROBA between LHCM and HHCM appeared 30 min after lights off. In contrast, frontal proximal ST (PROFR), DPG and finger-forearm ST gradient (data not shown) revealed no significant differences between HHCM and LHCM (Fig. 1, Table 1).

Clear differences were found between LHCM and HHCM in the time courses of mattress surface temperature (bottom graph in Fig. 1, Table 1) [main effect LHCM-HHCM: 3.079 ± 0.246, $F(1,14) = 156.7$, $p < 0.0001$]. Compared with LHCM HHCM distinctly delayed the increase of mattress temperature, whereas LHCM reached a constant surface temperature already about 1 h after lights off. First significant difference between LHCM and HHCM were found 10 min after lights off [significant interaction term, TIME x MATTRESS, $F(1,47) = 156.7$, $p < 0.0001$].

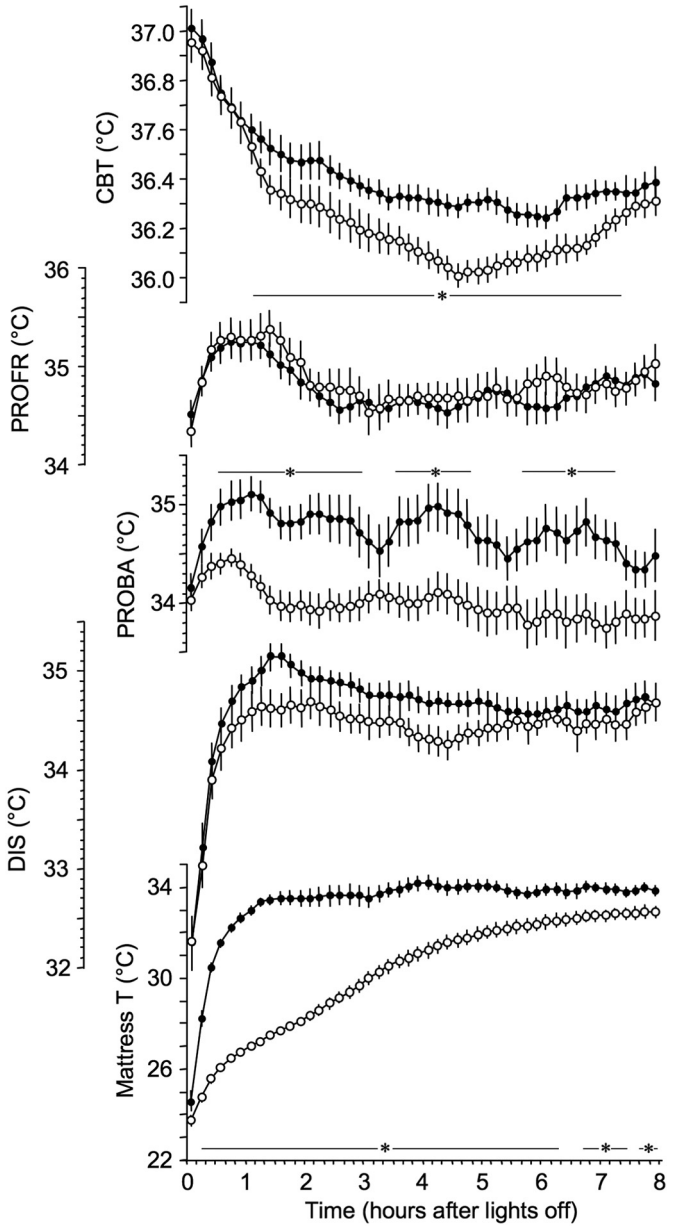

Fig. 1. From top to down: time courses (mean ± sem, N = 15 subjects; 10 min-bins) of core body temperature (CBT), proximal frontal (chest) skin temperature (PROFR), proximal back skin temperature (PROBA), distal skin temperature (DIS) and mattress surface temperature (Mattress T) during 8 h sleep phase for the two mattress types (low heat capacity, LHCM: black dots; high heat capacity, HHCM: open dots). *$p < 0.05$. Note: Mattress surface temperature showed the fastest effect, followed by PROBA and CBT – no significant effects between LHCM and HHCM were found for PROFR and DIS.

3.2. Sleep composition, sleep onset latency, sleep efficiency and CAP rate

The individual lights off times in the sleep lab matched the subject's habitual bedtimes (23:15 ± 20 min). The results of total night sleep analysis are summarized in Tables 1 & 2. In comparison to LHCM HHCM increased sleep stage N3 (time in sleep stage N3 as % of total sleep time) from 23.1 to 26.8% corresponding to an increase of 16% ($p < 0.05$). All other sleep parameter did not reach statistical significance indicating a selective effect of the mattresses on N3 sleep. Furthermore, the independence of sleep stage N3 and time awake after sleep onset was demonstrated by a non-significant correlation of their LHCM-HHCM differences per night (regression coefficient: 0.0105 ± 0.0133, N = 15, n.s.).

In Fig. 2 the time courses of N3 sleep and REMS are shown for the

Table 1
Summary of the LHCM and HHCM mean values of temperature (°C, 8 h-means) and sleep variables (7.5 h-means) (main effect, 2-way-ANOVA for repeated measures).

	LHCM		HHCM	
	Mean	Sem	Mean	Sem
CBT	36.420	0.037**	36.256	0.043#
DIS	34.641	0.098	34.399	0.104
PROFR	34.849	0.099	34.783	0.092
PROBA	34.736	0.142**	34.001	0.142
MATTRESS	33.318	0.206**	30.239	0.228#
DPG	− 0.176	0.102	− 0.025	0.107
N3 (min/10 min)	2.19	0.15	2.40	0.16#
REM (min/10 min)	1.94	0.12	1.67	0.14

LHCM: low heat capacity mattress, HHCM: high heat capacity mattress, CBT: core body temperature, DIS: distal skin temperature, PROFR: proximal frontal skin temperature, PROBA: proximal back skin temperature, DPG: DIS-mean proximal skin temperature gradient (data not shown), MATTRESS: mattress surface temperature (Fig. 1); N3: non-REMS sleep stage 3, REMS: REMS sleep (Fig. 2). (main effect MATTRESS: **p < 0.001, see Results)
Only CBT, MATTRESS and N3 sleep revealed significant interaction terms (TIME × MATTRESS, #p ≤ 0.01, see Results).

Table 2
Summary of entire night sleep stage analysis (macrostructure sleep analysis).

	LHCM		HHCM	
	Mean	Sem	Mean	Sem
N1 (%)	3.57	0.67	4.23	0.78
N2 (%)	51.40	1.68	49.06	2.23
N3 (SWS, %)	23.09	1.46*	26.80	1.85
REMS (%)	22.13	1.19	20.12	1.21
TST (min)	439.13	4.46	422.80	9.93
SOL (min)	11.87	2.44	9.70	1.59
WASO (min)	35.11	4.68	54.63	11.05
SE (%)	93.09	0.99	89.15	2.14
AI	10.42	0.92	11.52	1.09

TST: total sleep time (min); N1, N2, N3: non-REMS sleep stage 1, 2, 3 (% of TST); SWS: slow wave sleep; REMS: REMS sleep (% of TST); WASO: wake after sleep onset; SOL: sleep onset latency; SE: sleep efficiency (%); AI: arousal index (#/h). *p = 0.031, t = 2.40, all other comparisons n.s., paired t-test. Note: Compared to LHCM N3 sleep is selectively increased in condition HHCM.

time span with complete data for all 15 subjects (7.5 h after lights off). The statistical analyses (ANOVA for repeated measures) revealed a significant interaction term for N3 sleep [TIME × MATTRESS, $F(14,44) = 1.600$, $p = 0.010$] but not for REMS. In comparison to LHCM HHCM induced higher levels of N3 sleep in the third and fourth cycle (both $p < 0.05$, Fig. 2). It is interesting to note that HHCM induced more regular and distinct sleep cycles in both N3 sleep and REMS, and in both conditions N3 sleep and REMS exhibit inverse patterns. This was confirmed by linear mixed effect model analysis using predictors (e.g. TIME, REMS LHCM-HHCM -values) as fixed effect, and subjects (intercept) and slopes as random effects. Serial dependencies were adjusted by including an autoregressive AR(1) process to the model. In order to adjust for non-stationarity of the time series residuals to linear fitting were extracted (TIME as fixed effect) and taken for the final regression analysis to predict N3 sleep by REMS. N3 sleep was significantly associated with REMS within each condition with negative regression coefficients (HHCM: N3 sleep vs. REMS, − 0.144 ± 0.043, $p < 0.0001$; LHCM: N3 sleep vs. REMS, − 0.114 ± 0.040, $p < 0.005$). Using the same procedure the time course of mattress induced effects (HHCM-LHCM values) exhibit also an inverse pattern between REMS vs. N3 sleep with similar regression coefficient (− 0.108 ± 0.038, $p < 0.005$).

Furthermore, cumulative sum calculation of the data provided a more robust comparison of individual fluctuating time series with

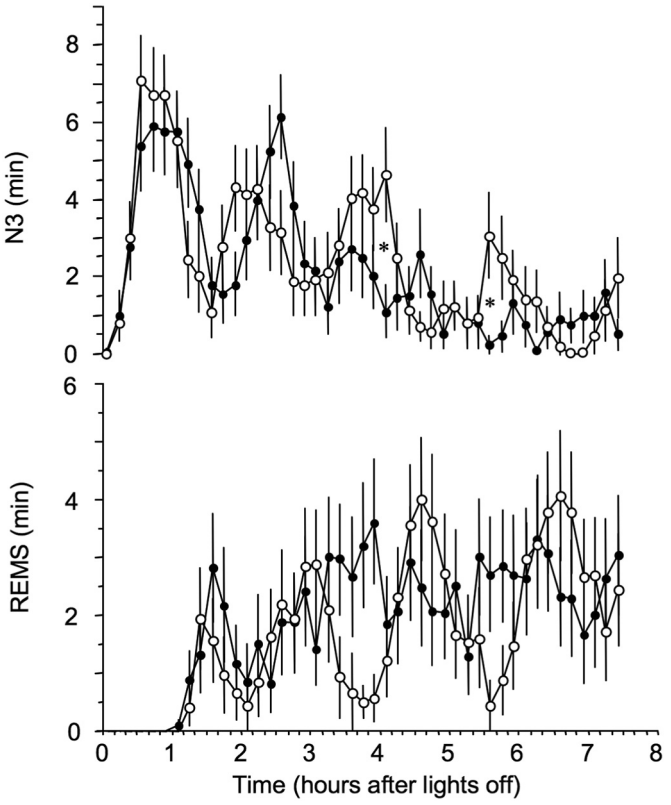

Fig. 2. From top to down: time courses (mean ± sem, N = 15 subjects; 10 min-bins) of sleep stage N3 (slow wave sleep) and REMS during the first 7.5 h of sleep for the two mattress types (LHCM: black dots, HHCM: open dots). Lights off at 0 h. Note: In comparison to LHCM HHCM exhibits more regular and more pronounced sleep cycles over the entire night and higher N3 values in the second part of the night. *p < 0.05, see RESULTS and Fig. 3.

respect to LHCM and HHCM. Fig. 3 (the two lower panels) shows no significant changes between LHCM and HHCM during the first part of the night (0–190 min after lights off). However, in the second part (190–450 min) HHCM in relation to LHCM significantly increased cumsum N3 and decreased cumsum REMS, respectively, confirming and corroborating the previous analysis (further details see below).

Microstructure analyses provide additional findings (Table 3). In comparison to LHCM CAP rate was significantly reduced by sleep on HHCM (LHCM: 30.7 ± 3.6% vs. HHCM: 25.4 ± 3.5%; $p < 0.01$). The reduction in CAP rate was reflected in a similar decrease of A1 and A2 subtypes index, without changes of A1, A2, A3 percentages.

Subjective sleep comfort was assessed using a 100 mm comfort evaluation scale. In comparison to LHCM sleep on HHCM was as slightly, but significantly, better estimated (HHCM: 78 ± 4 mm vs. LHCM: 74 ± 5 mm; $p < 0.05$).

3.3. Relationships between sleep and body temperature changes

At first glance there is no obvious association between the time courses of N3 sleep or REMS within both conditions for any of the temperature variables shown in Fig. 1. Similarly, visual inspection of mattress -induced effects (LHCM-HHCM -difference, Figs. 1 and 2) gives the impression that nightly modulation of N3 sleep and REMS are not closely related to changes in temperature variables. This visual impression has been confirmed by regression analyses. Short-term changes during the night were analyzed in a similar way as described above for comparison between LHCM-HHCM -difference in N3 sleep and REMS using residuals to linear regression lines in mixed effect model analysis. No significant short-term associations were found between any of the temperature variables and N3 sleep or REMS (e.g. CBT-PROBA vs. N3

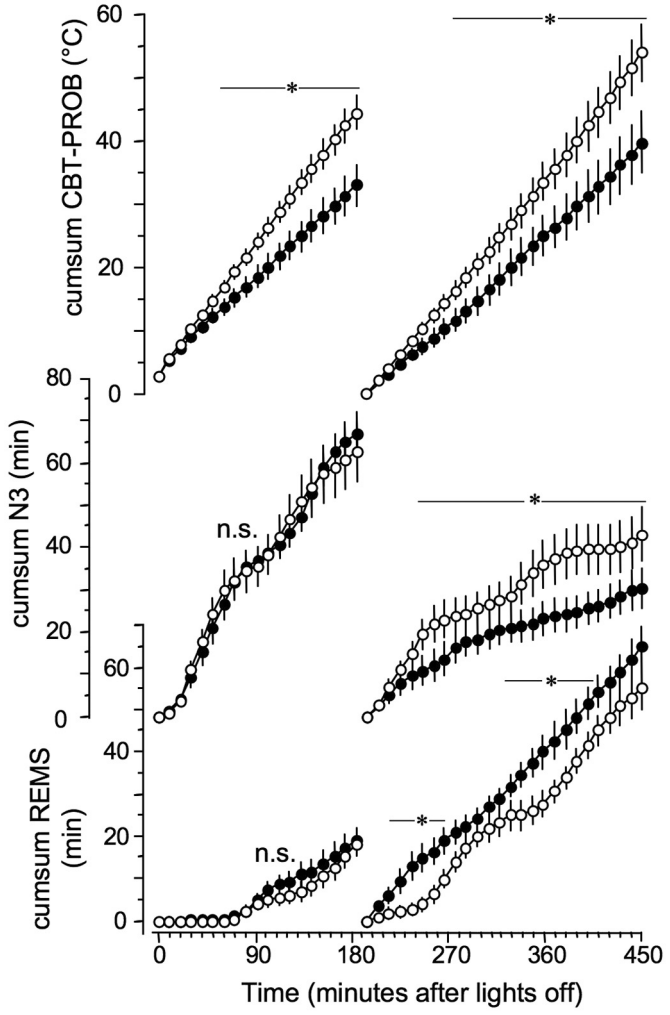

Fig. 3. Time courses of cumulative sum (cumsum) of CBT-PROBA, N3 sleep and REMS for LHCM (black dots) and HHCM (open dots) are shown for the first 190 min (left panel) and from 190 to 450 min (mean ± sem, N = 15 subjects; 10 min-bins, Lights off at 0 h). Note 1: In contrast to CBT-PROBA N3 sleep and REMS showed selectively in the second part of the night significant differences between LHCM and HHCM. Note 2: cumsum N3 and cumsum REMS exhibit inverse effects.

Table 3
Summary of entire night sleep Cyclic Alternating Pattern (CAP) analysis (microstructure sleep analysis).

	LHCM		HHCM	
	Mean	Sem	Mean	Sem
CAP rate (%)	30.7	3.6*	25.4	3.5
A1 index (#/hr)	30.1	3.8*	24.5	3.6
A2 index (#/hr)	4.6	0.5*	3.3	0.4
A3 index (#/hr)	0.2	0.1	0.2	0.6
A1% of total A	83.4	2.8	83.3	2.8
A2% of total A	15.5	2.2	15.3	2.5
A3% of total A	1.1	0.6	1.0	0.4

A1–A3 represent subtypes of CAP sequences (see Discussion).
For explanation of abbreviations see Method section.
CAP rate = % CAP time of non-REM sleep time.
* $p < 0.01$, all other comparisons n.s., paired *t*-test.

sleep, regression coefficient: 0.0132 ± 0.0288, n.s.). However, a division of the data in a first and second part of the night episode, in addition to cumsum analyses ('area under the curve'), revealed interesting relationships between N3 sleep and CBT-PROBA. During the first 190 min of the night (more or less the duration of the first two sleep cycles; Fig. 3 left panel) significant increases in cumsum CBT-PROBA were found after 70 min but no differences in cumsum N3 and REMS. These lead at the end of the first part of the night to non-significant correlations of sleep stage N3 or REMS with any of the temperature variable (Table 4).

Table 4
Results of regression analyses of different temperature variables on N3 sleep.

Temperature variable	Time segment 180–190 min		Time segment 440–450	
	Regr.coeff. ± sem	p-Value	Regr.coeff. ± sem	p-Value
CBT	0.1078 ± 0.2021	n.s.	0.0355 ± 0.3552	n.s.
PROBA	−0.0022 ± 0.0706	n.s.	−0.0830 ± 0.0250	0.0056
CBT-PROBA	0.0151 ± 0.0705	n.s.	0.0833 ± 0.0249	0.0053
PROFR	0.1495 ± 0.1452	n.s.	0.1072 ± 0.0736	n.s.
MATTRESS	−0.0082 ± 0.0415	n.s.	0.0105 ± 0.0266	n.s.

For regression analyses cumulative sum values were taken at the end of the first and second part of the night (= last 10 min time segments; N = 15 data pairs of LHCM-HHCM differences, see Fig. 3). CBT = core body temperature; PROBA = proximal back skin temperature; CBT-PROBA = core body temperature-proximal back skin temperature gradient; PROFR = proximal frontal skin temperature; MATTRESS = mattress surface temperature; regr.coeff. = regression coefficient. Note: Only CBT-PROBA and PROBA, and only in the second part of the night, exhibit significant correlations with N3 sleep.

In contrast, in the second part of the night (190-450 min after lights off) significant changes between LHCM and HHCM were found in cumsum N3 sleep and REMS (Fig. 3 right panel the two lowest graphs) and also in cumsum CBT-PROBA (compared to LHCM significant increases in HHCM were found; Fig. 3 right panel top graph). In addition, a significant linear correlation between sleep stage N3 and CBT-PROBA accumulation of LHCM-HHCM –differences were found at end of the night (right panel last 10 min values, Fig. 3 & Table 4). Furthermore, nearly identical results were found with PROBA instead of CBT-PROBA, but all other temperature variables didn't reveal significant associations with N3 sleep (Table 4). Similar analyses with REMS as predicted variable showed no significant correlations with any of the temperature variables ($p > 0.1$).

4. Discussion

The main outcome of the study is that in comparison to a conventional low heat capacity mattress (LHCM) subjects sleeping on a high heat capacity mattress (HHCM) significantly reduced core body temperature (CBT), proximal skin temperatures on the back (PROBA) and mattress surface temperature, and significantly increased sleep stage N3. Regression analyses revealed a significant relationship selectively between increased CBT-PROBA (and reduced PROBA) with enhanced sleep stage N3.

4.1. Temperatures

Decades ago diverse publications claimed a causal relationship between CBT decline and increased SWS [16,18,23,24]. Unfortunately, very often masking-effects, like for instance time of lying down, time of day; elapsed time awake, were not carefully controlled which precludes a final conclusion [7]. In the present study all these mentioned masking effects were strictly controlled and kept constant during the two randomly applied mattresses (LHCM vs. HHCM).

Additionally, many thermal interventions trigger thermoregulatory counter effects, which in turn affect sleep by increased arousals. For example, sleep after bathing at low temperatures or exposure to cold environmental air temperature induces distal vasoconstriction and delays sleep onset with succeeding rebound sleep and increased SWS [7]. The present study shows that the intervention of two different mattress conditions was not too strong as thermoregulatory counter effects were not observed, as shown by measurements of CBT, skin temperatures and

mattress surface temperatures, which allow conclusions about internal and external body heat flow.

As previously described [9] an increase in all ST occurred immediately after switching the lights off and lying down, but body temperature differences between LHCM and HHCM developed with a time lag (Fig. 1). Significant differences between LHCM and HHCM occurred when the thermoregulatory two compartments system (core and shell) was transformed into one, which was completed about 1 h after light off [6]. In comparison to LHCM, sleep on HHCM showed a slower increase of mattress surface temperature leading to a persistently increased external temperature gradient and hence to increased heat uptake by HHCM, which is in accordance with the higher heat capacity of this mattress. Significant differences between LHCM and HHCM surface temperatures occurred around 10 min after lights off and maximum differences of about 6 °C 1 h after lights off. Furthermore, analyses of ST exhibited a differentiated picture. PROFR and DIS showed minor changes whereas PROBA exhibited significant large effects of mattress, reflecting the probability of the different skin regions to be in contact with the mattress during sleep. These findings indicate that the mattresses did not induce different vasomotor effects providing therefore physiological evidence of thermal comfort during the entire night. Compared with LHCM HHCM reduced PROBA 30 min after lights off by about 0.70 °C, a finding which can be plausible explained by contact with the cooler HHCM. Finally, the time courses of CBT were significantly different between LHCM and HHCM. HHCM induced a stronger reduction of CBT off maximally by 0.28 °C about 5 h after light with no obvious changes in the phase of CBT minimum during sleep. Moreover, the occurred rank order in both the amount of temperature reductions and the velocity of cooling rate increasing from CBT, PROBA to mattress surface temperature provides strong evidence of an increased conductive body heat loss during sleep on HHCM. It can be assumed that HHCM takes up more heat from the body thanks the higher heat capacity than LHCM, leading to lower PROBA, and finally to reduced CBT. In other words PROBA seems to represent the crucial skin temperature determining conductive body heat loss by increasing internal temperature gradient (CBT-PROBA). I.e. the changes in CBT in relation to PROBA are relatively small and therefore of less importance to determine CBT-PROBA. In contrast, no indications for increased convective heat loss mechanisms could be found (e.g. warm extremities).

4.2. Sleep analyses

In comparison to LHCM, sleep on HHCM induced a specific increase in SWS (percentage of N3 sleep) indicating that the increase was not achieved at the cost of one single other sleep stage. In the first part of night (mainly the first two sleep cycles) no differences between the mattresses were observed in N3 sleep, sleep onset latency and time awake after sleep onset. This indicates that the increase of N3 sleep occurred in the second part is not due to sleep deprivation and/or to reduced amounts of N3 sleep during the first part. Additionally, subjective sleep comfort estimation was better on HHCM than LHCM.

Detailed analyses of the time course of N3 sleep in relation REMS disclosed interesting findings.

In a first step the time courses of N3 sleep and REMS were analyzed in 10 min intervals showing the well-known cyclic patterns with nightly decline and increase in N3 sleep and REMS, respectively (Fig. 2). Compared to LHCM HHCM amplified the alternating cyclicity of N3 sleep and REMS leading to significant increased N3 sleep in the third and fourth sleep cycle. REMS exhibited similar but non-significant inverse changes in relation to N3 sleep. Nevertheless, linear regression analysis revealed significant negative association between N3 sleep and REMS within both conditions (LHCM, HHCM) but also between the LHCM-HHCM differences with similar regression coefficients.

In a second step the previous analyses were corroborated by the more robust cumsum analysis, which reduced the intraindividual variability. Selectively in the second part of the night (190-450 min after lights off) higher accumulation of N3 sleep was found in condition HHCM than LHCM and inversely sleep stage REMS accumulated less during the same time span. This finding could indicate that the two mattress conditions affected N3 sleep and REMS not independently. The question remaining is why are consistent changes in sleep characteristics only found in the second part of sleep? It is well described that in the first and or second non-REMS cycle amount of SWS and EEG slow wave activity are at high values and decline thereafter [25]. Conversely REMS increases in the second part of the night [25]. Therefore, it could be that both the increase in N3 sleep and the decrease in REMS become more evident in the second part of the night when N3 sleep and REMS are at higher and lower levels, respectively (related comments see Conclusions -section below).

Previous studies have also shown an inverse regulation of N3 sleep and REMS after a mild cooling intervention. A slow reduction of environmental air temperature by 2 °C during the night increased SWS and reduced REMS in parallel to a decrease in CBT and leg skin temperature [14]. The authors concluded that lowering and delaying of the minimum of nocturnal CBT increases SWS, probably by an increase of dry heat loss. Our study confirmed and extended this conclusion to a conductive pathway of body heat loss, suggesting that body heat loss by mild cooling could be in general a crucial factor for SWS increase. However, the parallel occurrence of changes in physiological variables is only the first step to evidence a causal link between them (see below).

The sleep microstructure analysis reveals further interesting findings allowing a deeper insight how the differences in N3 sleep and REMS pattern occurred. Among the various CAP parameters, CAP rate is the most extensively used for clinical purposes [26]. In general, CAP rate can be enhanced when sleep is disturbed by internal or external factors and its variation correlates with the subjective estimation of poor sleep quality [26]. In our study this relationship was confirmed, lower CAP rate and higher sleep quality was found in condition HHCM. High CAP rate is interpreted to express a condition of instability in vigilance level that translates the brain effort to preserve and regulate sleep macrostructure [27]. CAP subtype A1 are primarily involved in the build-up of N3 sleep and sleep consolidation, whereas subtypes A2 and A3 are closely related to the onset of REMS and arousability [27]. We observed that A1 and A2 similarly contribute to the global reduction of CAP rate (reduction of both A1 and A2 indexes without changes in A1 and A2 percentages). Intriguingly, similar results were occurred in patients with insomnia when compared before and after therapy [26]). However, all these interpretations remain on a hypothetical level and need to be challenged by further studies including detailed analyses of the time course during sleep (temporal association) of CAP rates, spectral analytic derivatives e.g. slow wave activity together with thermometric measures.

Concerning a comparison of different mattress types a previous study reported higher CAP rates during sleep on an innerspring mattress in relation to a foam mattress, however, no difference in sleep stages were found [28]. Unfortunately no thermometric measure was recorded preventing a detailed comparison with the presented findings.

4.3. Relationships between sleep and body temperature changes

To strengthen the argument that body temperature alterations exhibit causal effects on sleep stages regression analyses were performed between the time courses in mattress -evoked changes (LHCM-HHCM) of temperature and sleep stage variables. A previous study has reported that under baseline conditions time courses of CBT and skin temperatures show only a small, but parallel, modulation of CBT and ST in relation to sleep cycles [9]. However, short-term changes (e.g. sleep cycle) in LHCM-HHCM differences of N3 sleep and CBT-PROBA were not significantly associated. Significant correlations occurred only for overall integrated changes, and only for the second part of the night. Moreover, similar significant correlations of N3 sleep were found with

PROBA, but not with CBT, PROFR or mattress surface temperature. No such correlations were found with REMS.

The effect on N3 sleep and REMS suggests either that the increase in inner conductive heat transfer affects directly sleep inducing brain regions or indirectly via a feed back signal from reduced PROBA [13]. Regardless of the mechanism, the present findings are contrary to the hypothesis that a mere increase of in ST (about 0.4 °C), while not altering CBT, shifts sleep to deeper stages and suppresses nocturnal wakefulness [13]. One possible explanation of this discrepancy could lay in different protocol and experimental setting. In the present study the "thermal intervention" started with lying down, reached a maximum LHCM-HHCM value about in the middle of the night (e.g. CBT), whereas PROBA was more or less constantly reduced 30 min after lights off. The temporal effects on sleep stages were clearly different to the thermal changes, e.g. PROBA was clearly reduced before changes in sleep stages N3 and REMS occur. Conversely, based on the clear advance of thermophysiological effects in relation to sleep stage changes it seems to be rather unlikely that changes in sleep induced thermophysiological changes (Fig. 1–3). Therefore, it can be concluded that different time constants exists for changes in body temperatures and sleep stage, whereby the causal chain of thermal changes to alterations in sleep remains to be discovered.

4.4. Study limitations

The study sample size calculation was based on power analysis to detect differences in sleep stages. However, for a multivariate analysis a larger study sample would be necessary. Therefore, the performed regression analyses remain on a preliminary level. It is also important to keep in mind that some techniques and analyses applied in the present study could be improved. For instance, skin temperature recordings provide an indirect measure of skin blood flow and body heat loss. Therefore, it is necessary to confirm the present study findings by additional, more direct measurements of body heat loss, for instance by measuring thermal conductivity. No EEG spectral analysis was carried out preventing a final conclusion whether the observed changes in SWS are reflected in changes in EEG slow wave activity (delta-band).

The subjects were studied during November and December. In spite of the controlled room temperature at 23° the finding could be different in other seasons due to seasonal adaptation of the thermoregulatory system.

5. Conclusions

The present controlled laboratory study provides evidence that sleep characteristics can be influenced by the thermal property of the mattress. In comparison to a conventional LHCM sleep on the HHCM significantly reduced PROBA and CBT, and increased SWS and sleep continuity. Detailed analyses with respect to time courses of body and mattress surface temperatures clearly indicate that CBT reduction by HHCM was induced by conductive heat loss via back skin regions to the mattress. These findings are reminiscent of induction of daily torpor and energy conservation in certain animals [9] - of course, in a very weak form. In analogy, those animals loose heat also via a conductive way to the environment, reduce body surface temperature and CBT and enter torpor via non-REM sleep including SWS - during torpor mainly N3 sleep occurs and REMS is suppressed [29,30]. These animals reduce metabolic rate in parallel to heart rate [29,30]. Whether these changes occur also in humans during sleep on HHCM is presently under investigation. Furthermore, the temporal evolution of sleep stage N3 and REMS revealed inverse patterns with increased N3 sleep and decreased REMS selectively in the second part of the night. These time courses were clearly delayed with respect to the temperature changes. The changes in body temperatures and sleep characteristics seem to be linked. Regression analyses showed significant correlations between individual decrease in CBT-PROBA (and PROBA) and increase in N3 sleep (but not REMS) induced by HHCM in relation to LHCM. These findings indicate that changes in N3 sleep and REMS could be regulated in conjunction, whereas without further studies (e.g. nap study) and adequate analyses (e.g. path analysis) no final conclusions can be drawn about a possible causative mechanism chain (see study limitations). Notwithstanding, we hypothesize a link between increased inner conductive heat transfer and increased SWS and reduced REMS at least in the second part of the night sleep (usually between 3 and 7 a.m.). At this time of the night sleep pressure (i.e. SWA) is reduced after the first two sleep cycles and REMS propensity is at highest level due to coupling with the circadian CBT rhythm. This interpretation needs to be investigated in prospective studies, for example, comparing LHCM-HHCM differences at different circadian phases, for instance during an afternoon nap, when sleep pressure (SWA and SWS) and REMS propensity is lower than during habitual nocturnal sleep. Furthermore, future studies have also to show whether different subject groups with sleep disturbances (e.g. insomniacs, older persons) can benefit from sleep on HHCM.

Declaration of interest

The authors report no conflicts of interest; they alone are responsible for the content and writing of the paper.

Sources of funding

Technogel Italia S.R.L. (Vicenza, Italy) supported the study through an unconditional funding to Neuroscience Department of University of Torino (FE 3.04.24.62 & FS 7.07.0960), Italy.

Acknowledgments

We thank Andy Schötzau (eudox, Statistische Beratung, Malzgasse 9, Basel, Switzerland) for his advice in statistics.

References

[1] J. Aschoff, H. Biebach, A. Heise, T. Schmidt, Day night variation in heat balance, in: J.L. Monteith, L.F. Mount (Eds.), Heat Loss from Animals and Man, Butterworths, London, 1974, pp. 147–172.
[2] K. Krauchi, How is the circadian rhythm of core body temperature regulated? Clin. Auton. Res. 12 (2002) 147–149.
[3] S.S. Campbell, R.J. Broughton, Rapid decline in body temperature before sleep: fluffing the physiological pillow? Chronobiol. Int. 11 (1994) 126–131.
[4] J. Zulley, R. Wever, J. Aschoff, The dependence of onset and duration of sleep on the circadian rhythm of rectal temperature, Pflugers Arch. 391 (1981) 314–318.
[5] J. Zulley, R.A. Wever, Interaction between the sleep-wake cycle and the rhythm of rectal temperature, in: J. Aschoff, S. Daan, G. Groos (Eds.), Vertebrate Circadian Systems, Springer Verlag, Berlin, Heidelberg, 1982, pp. 253–261.
[6] K. Krauchi, The thermophysiological cascade leading to sleep initiation in relation to phase of entrainment, Sleep Med. Rev. 11 (2007) 439–451.
[7] K. Krauchi, T. Deboer, The interrelationship between sleep regulation and thermoregulation, Front Biosci (Landmark Ed). 15 (2010) 604–625.
[8] J. Aschoff, Exogenous and endogenous components in circadian rhythms, Cold Spring Harb. Symp. Quant. Biol. 25 (1960) 11–28.
[9] K. Kräuchi, T. Deboer, The interrelationship between sleep regulation and thermoregulation, Front Biosci (Landmark Ed). 15 (2010) 604–625.
[10] K. Okamoto, K. Nakabayashi, K. Mizuno, N. Okudaira, Effects of truss mattress upon sleep and bed climate, Appl. Hum. Sci. 17 (1998) 233–237.
[11] K. Okamoto-Mizuno, K. Mizuno, Effects of thermal environment on sleep and circadian rhythm, J. Physiol. Anthropol. 31 (2012) 14.
[12] E.J. Van Someren, Mechanisms and functions of coupling between sleep and temperature rhythms, Prog. Brain Res. 153 (2006) 309–324.
[13] R.J. Raymann, D.F. Swaab, E.J. Van Someren, Skin deep: enhanced sleep depth by cutaneous temperature manipulation, Brain 131 (2008) 500–513.
[14] F. Togo, S. Aizawa, J. Arai, S. Yoshikawa, T. Ishiwata, R.J. Shephard, et al., Influence on human sleep patterns of lowering and delaying the minimum core body temperature by slow changes in the thermal environment, Sleep 30 (2007) 797–802.
[15] K. Okamoto-Mizuno, K. Mizuno, S. Michie, A. Maeda, S. Iizuka, Effects of humid heat exposure on human sleep stages and body temperature, Sleep 22 (1999) 767–773.
[16] D. Sewitch, E.M.W. Kittrell, D.J. Kupfer, C.F. Reynolds, Body temperature and sleep architecture in response to a mild cold stress in women, Physiol. Behav. 36 (1986)

951–957.
[17] D. McGinty, R. Szymusiak, Keeping cool: a hypothesis about the mechanisms and functions of slow-wave sleep, Trends Neurosci. 13 (1990) 480–487.
[18] R.J. Berger, N.H. Phillips, Energy conservation and sleep, Behav. Brain Res. 69 (1995) 65–73.
[19] J.A. Horne, O. Ostberg, A self-assessment questionnaire to determine morningness-eveningness in human circadian rhythms, Int. J. Chronobiol. 4 (1976) 97–110.
[20] C. Iber, S. Ancoli-Israel, A.L. Chesson, F. Quan, AASM Manual for the Scoring of Sleep and Associated Events, American Academy of Sleep Medicine, Westchester, IL, 2007.
[21] M.G. Terzano, L. Parrino, A. Sherieri, R. Chervin, S. Chokroverty, C. Guilleminault, et al., Atlas, rules, and recording techniques for the scoring of cyclic alternating pattern (CAP) in human sleep, Sleep Med. 2 (2001) 537–553.
[22] D. Curran-Everett, Multiple comparisons: philosophies and illustrations, Am. J. Phys. Regul. Integr. Comp. Phys. 279 (2000) R1–8.
[23] D. McGinty, A. Metes, M.N. Alam, D. Megirian, D. Stewart, R. Szymusiak, Preoptic hypothalamic warming suppresses laryngeal dilator activity during sleep, Am. J. Phys. Regul. Integr. Comp. Phys. 286 (2004) R37–R1129.
[24] D.E. Sewitch, Slow wave sleep deficiancy insomnia: a problem in thermo-down-regulation at sleep onset, Psychophysiology 24 (1987) 200–215.
[25] D.P. Brunner, D.J. Dijk, A.A. Borbély, Repeated partial sleep deprivation progressively changes in EEG during sleep and wakefulness, Sleep 16 (1993) 100–113.
[26] L. Parrino, R. Ferri, O. Bruni, M.G. Terzano, Cyclic alternating pattern (CAP): the marker of sleep instability, Sleep Med. Rev. 16 (2012) 27–45.
[27] M.G. Terzano, L. Parrino, A. Smerieri, F. Carli, L. Nobili, S. Donadio, et al., CAP and arousals are involved in the homeostatic and ultradian sleep processes, J. Sleep Res. 14 (2005) 359–368.
[28] M.B. Scharf, R. Stover, M. McDannold, H. Kaye, D.V. Berkowitz, Comparative effects of sleep on a standard mattress to an experimental foam surface on sleep architecture and CAP rates, Sleep 20 (1997) 1197–1200.
[29] J.M. Walker, A. Garber, R.J. Berger, H.C. Heller, Sleep and estivation (shallow torpor): continuous processes of energy conservation, Science 204 (1979) 1098–1100.
[30] T. Deboer, Brain temperature dependent changes in the electroencephalogram power spectrum of humans and animals, J. Sleep Res. 7 (1998) 254–262.