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Article type : Original Article

Local body cooling to improve sleep quality and thermal comfort in a hot environment

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Abstract

The effects of local body cooling on thermal comfort and sleep quality in a hot environment were investigated in an experiment with 16 male subjects. Sleep quality was evaluated subjectively, using questionnaires completed in the morning, and objectively, by analysis of electroencephalogram (EEG) signals that were continuously monitored during the sleeping

This article has been accepted for publication and undergone full peer review but has not been through the copyediting, typesetting, pagination and proofreading process, which may lead to differences between this version and the Version of Record. Please cite this article as doi: 10.1111/ina.12428

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period. Compared with *no cooling*, the largest improvement in thermal comfort and sleep quality was observed when the back and head (neck) were both cooled at a room temperature of 32°C. *Back cooling* alone also improved thermal comfort and sleep quality, although the effects were less than when cooling *both back and head (neck)*. Mean sleep efficiency was improved from 84.6% in the *no cooling* condition to 95.3% and 92.8%, respectively, in these conditions, indicating good sleep quality. *Head (neck) cooling* alone slightly improved thermal comfort and subjective sleep quality and increased Stage N3 sleep, but did not otherwise improve sleep quality. The results show that local cooling applied to large body sections (back and head) could effectively maintain good sleep and improve thermal comfort in a hot environment.

Keywords:

Local body cooling; sleep; sleep quality; thermal comfort; bedroom; physiological parameters

Practical implications

Providing a thermally comfortable sleeping environment is important for sleep quality and this contributes positively to human health and the performance of daytime activities. This study shows that local cooling applied to the back and head (neck) sections of sleeping subjects was effective in maintaining good sleep in a hot environment. The results provide the basis for researchers and engineers to develop new local body cooling strategies in hot sleeping environments and to efficiently control the use of energy in the bed micro-environment.

1. Introduction

People spend about one third of their lives sleeping and good sleep is important for their health and daytime activities: poor sleep quality impairs cognitive performance in older adults, and impacts brain function related to reward processing, risk-taking, and cognition in

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adolescents [1, 2]. Disturbed nocturnal sleep also has consequential effects on health, increasing the risk of obesity, Type 2 diabetes and cardiovascular disease [3, 4]. The thermoregulatory system and the sleep regulating mechanisms have been shown to be strongly linked in humans [5, 6], and this was later confirmed by many studies that show high or low air temperatures, even moderately different from the neutral temperature, could significantly decrease sleep quality [7-10]. However, in many areas with long and hot summers, indoor air temperatures are very high. For example, in southern China the indoor air temperature was found to be higher than 34°C in natural ventilated buildings during the summer season [11]. A survey in Indonesia found that the indoor air temperatures were higher than 32°C in naturally ventilated residential buildings [12]. Global warming that leads to higher temperatures will create still hotter indoor conditions. Attention is now being paid to how climate change may degrade the indoor thermal environment in buildings [13]. It has been reported that heat-related deaths correlate, not just with daytime temperature, but also with night-time temperatures. The highest risk factor for heat-related death is a bedroom located on the second floor without air conditioning [14]. A study in 79 households in Greenland showed that in summer 19% of all bedroom temperature were above 26°C although the outside temperatures averaged no more than 9.5°C [15].

Full air conditioning may be one of the easiest ways to improve thermal environment. However, large amounts of cool air (often recirculated room air, for residential buildings) must be supplied to maintain indoor temperatures at acceptable levels in the entire building (including unoccupied areas), leading to increased energy consumption [16]. Thus, especially in areas with hot summers, the long summer period and the correspondingly long operation time make energy consumption for air-conditioning in residential buildings, hotels, and hospitals an increasingly important contributor to total energy consumption. For example, electricity use for air-conditioning in residential buildings accounted for about 7.8% of the total electricity use in Hong Kong [17]. On the other hand, air conditioning is not always available. For economic reasons or living habits, many people live in naturally ventilated houses in areas with hot summer although the resulting indoor thermal environment is poor [11, 12, 18]. It has been suggested that local ventilation and comfort systems might be promising alternatives to

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full air conditioning [19]. Several solutions of this kind have already been reported in the literature and some of them have been implemented in office buildings [16]. Personalized ventilation (PV) is one of the solutions that supply clean air close to the breathing zone of the user [20]. Studies show that PV improves occupants' health (reduces sick building syndrome and eye symptoms), perceived air quality, thermal comfort, and work performance [21, 22], and reduces energy consumption [23, 24]. A personalized exhaust system with diffusers in the seat head-rest has been shown to improve inhaled air quality and reduce exposure to airborne infection in aircraft cabins [25, 26]. Several studies have investigated the use of local cooling systems in a warm environment. Melikov et al (2013) found that local convective and radiant cooling of the upper body in a warm environment (28°C, 50%RH) improved thermal comfort compared to a reference condition without cooling [27]. Zhang et al (2007) showed that a cooled seat could increase the 90% satisfied range of room temperature by 2.3°C above the neutral point [28]. By using phase-change materials (PCM) in a cooling vest, an occupants' whole-body thermal sensation and skin-wetness sensations were improved at an air temperature of 34°C [29]. Pallubinsky et al. (2016) reported that local cooling of the face alone and face and underarms combined were effective ways to improve thermal sensation and increase thermal comfort in a warm environment [19]. Moreover, studies indicate that there are regional differences in the thermal comfort response to thermal stimuli. Nakamura et al (2008; 2013) reported that the limb and extremities are less influential for producing thermal comfort than the trunk areas; during mild heat exposure, facial and neck cooling was judged the most comfortable [30, 31]. Based on their influence on whole-body sensation, Zhang (2003) reported that the most influential body parts are back, chest, and pelvis [32]. Studies have confirmed that a large amount of heat can be lost from the head [33, 34], and that cooling the head is an effective way to reduce thermal stress while awake [33, 35].

Considering the immobility of occupants during a sleeping period, local comfort systems may be quite suitable in the sleeping environment. However, few studies have investigated the effects of local cooling or warming on sleep. The present authors proposed a bedside personalized ventilation system and observed slightly positive effects of this system on sleep quality [36, 37], although under warmer conditions convective local cooling may cause

discomfort due to the pressure of the airflow. Okamoto-Mizuno et al (2003) investigated the effects of a cooling pillow filled with gel on human sleep stages and body temperature [38]. They observed no significant change in sleep parameters although the whole-body sweat rate had been decreased by using the cooling pillow during sleep in a hot humid environment. The temperature of the pillow did not remain constant: it increased from 16°C to 28°C after 8h exposure. Moreover, it seems probable that the low temperature of the pillow in the initial phase would have caused some thermal discomfort.

In the present study, the effects of local cooling on sleep quality in a hot environment were investigated experimentally. Local cooling was applied to the upper back and head (together with the neck) because cooling of these parts has been shown to be effective in improving the thermal comfort of subjects who were awake [30-34, 35]. The lower body sections were not cooled since people are most comfortable with warm feet [32] and warm feet have been shown to promote the rapid onset of sleep [39]. Wyndham observed that the daytime temperature for comfort (26.6°C) was higher than the night-time comfort temperature (24.7°C) in the hot humid tropics of Australia when air conditioning was not yet available [40]. Lower air velocities at night could have been a possible explanation, but another reason could be that when we lie on a mattress, about 50 % of the body surface is rendered ineffective for heat loss by convection, radiation and evaporation.

2. Method

2.1 Subjects

Sixteen males (20-29 year old, Mean \pm SD: 23.5 \pm 1.9 years; BMI: 18.8-24.9 kg/m², Mean \pm SD: 21.8 \pm 2.0) without sleep disorders gave their informed consent to participate in this study. Background information was obtained by using the Pittsburgh Sleep Quality Index (PSQI) questionnaire, which assesses sleep quality and disturbances over a 1-month time interval [41]. If a candidate had a PSQI global score >5 , which is suggestive of a significant sleep disturbance, he was excluded. The subjects were non-smokers and were not taking any

medication. They were asked to avoid alcohol, caffeine, and intense physical activity from the evening of the day before the experiment. Their emotional state was investigated with the Profile Of Mood States Short Form (POMS-SF) on arrival for each experimental session [42]. No significant difference in the mood states of each subject was observed between experimental days. The subjects were instructed to wear the same short-sleeved nightshirt in all exposure. At night, they slept on a mattress bed with no bed covers, with an estimated insulation level (including clothing) of 1.28 clo. With this clothing level, the neutral temperature for sleep was predicted to be 28°C. This study was approved by the University ethics committee.

2.2 Approach and facility

The experiment was carried out from August to September, 2016, in Shanghai in two identical and adjacent sleep chambers that were equipped with the same type of air conditioner. Four experimental conditions were investigated, i.e., Condition 1: both back and head (neck) were cooled; Condition 2: back was cooled; Condition 3: head (neck) was cooled; and Condition 4: no local cooling. The room temperature was set to 32°C in Condition 1, as both back and head were cooled, and to 31°C in other three conditions. Local cooling was achieved by using a commercial hypothermic blanket (90cm×50cm) with cellular tubes in which water flowed slowly, covered with thermally conductive soft sheet (Figure 1a). This blanket is usually used in hospital for cryotherapy, to help patients recover from surgery. Based on thermal comfort votes obtained in a brief pilot experiment, water with a temperature of 28°C was supplied to the blanket. The blanket was fastened to the surface of pillow to cool the head and neck of the subject when asleep, and was fastened to the bed to cool the back, as shown in Figure 1b.

The subjects were randomly assigned to four groups and each group was exposed to the four experimental conditions in a Latin-square design, balanced for order of presentation. There was a 2- to 3-day interval between any two experimental nights. During each exposure in the chamber, electroencephalogram (EEG) for brain wave, electrooculogram (EOG) for eye movements and electromyogram (EMG) for chin muscle tension were continuously monitored, to obtain the basic information required for quantifying sleep quality. The subjects reported sleep quality after waking and thermal comfort both before going to bed and after getting up.

A low noise level (30 dB(A) when subjects slept in the room) was maintained under all conditions. The background air temperature and relative humidity were recorded by placing a data logger at each of two positions: the middle of the bed head and the bed end, both at a height of 0.4m above the bed. The data logger (TR-76Ui, T&D corporation) had a built-in temperature sensor (range: 0°C-55°C, accuracy: $\pm 0.5^\circ\text{C}$), a humidity sensor (range: 10-95%, accuracy: $\pm 5\%$) and a CO₂ sensor (range: 0-9999ppm, accuracy: $\pm 50\text{ppm} + 5\%$ of reading at 5000ppm or less). The air velocity was measured at the same positions with an air flow sensor (UAS1100, Degree Controls Inc., range: 0.15-1.0 m/s, accuracy: $\pm 5\%$ of reading). The instantaneous values of air temperature, relative humidity, CO₂ concentration and air velocity were recorded at intervals of 1 minute.

2.3 Measurements

2.3.1 Physiological measurements

EEG (F4-M1, C4-M1, O2-M1, F3-M2, C3-M2, O1-M2), bilateral EOG, and chin EMG were recorded using a portable polysomnographic sleep recording system (Somté 32 PSG, Compumedics, Australian) [43]. The EEG, EOG and EMG of a nocturnal sleep period is characterized by alternating periods of non-rapid-eye movement (NREM) sleep, subdivided into three (N1, N2 and N3) stages, and rapid-eye movement (REM) sleep. Sleep stages were visually scored every 30 seconds based on the *2007 AASM Manual for the Scoring of Sleep and Associated Events* [44]. Table 1 shows definitions for the most commonly used parameters

derived from sleep staging. Lower SE, longer SOL or WASO, lower duration of N3 or R stage, and larger NOA are all indicators of poorer sleep quality.

The skin temperatures of the back and neck were measured at 8 s intervals using PyroButtons (Pyrobutton-L; Dallas, TX, USA) with an accuracy of $\pm 0.2^{\circ}\text{C}$ from -40°C to $+85^{\circ}\text{C}$ and a 0.0625°C resolution. The sensor side, with a protruding edge, of the PyroButton was fixed onto the skin with adhesive tape. The validity of using such wireless sensors to measure skin temperature has been validated in previous studies [45, 46].

2.3.2 Subjective questionnaires

The subjects reported their subjective perception of sleep quality on three 5-point scales including *the calmness of sleep*, *freshness after awakening*, and *satisfaction with sleep*; higher score indicates improved sleep quality [10]. A 7-point scale (-3-cold, -2-cool, -1-slightly cool, 0-neutral, 1-slightly warm, 2-warm, 3-hot) was used to report thermal sensation. Overall thermal comfort was reported on a 6-point scale (-2-very uncomfortable, -1-uncomfortable, -0.01-just uncomfortable, 0.01-just comfortable, 1-comfortable, 2-very comfortable).

2.4 Experimental procedures

The experimental procedures for an all-night sleep are shown in Figure 2. Subjects arrived at the waiting room (which was adjacent to their sleeping chambers and was maintained at 26°C) at 21:00, rested for 30 min in order to adapt thermally, wearing short-sleeved nightshirts (the estimated clothing value was 0.5 clo), and filled out the POMS questionnaire (Q1) for 10 min. The physiological parameter sensors were attached: this process lasted 40 minutes. The subjects then entered their sleeping chamber and after lying on the bed for 30 minutes, recorded their thermal sensation and thermal comfort votes (Q2), which took 10 minutes. Sleep could begin at 23:00 when the lights were turned off. The physiological parameters were

continuously measured throughout the night until subjects were woken up promptly in the next morning. The local cooling was supplied continuously while the subjects were lying on the bed. After getting up, subjects filled out the thermal comfort and sleep quality questionnaires (Q2, Q3) in their sleeping chamber. In addition to their perception of thermal comfort at that moment, they were also asked to recall their thermal sensation during the night.

2.5 Statistical analysis

The data were first tested for normality using Shapiro-Wilk's W test. Normally distributed data were subjected to analysis of variance in a repeated measures design and a Paired Samples T test. Not-normally distributed data were analyzed using Friedman's One-Way analysis of variance and the Wilcoxon Matched-Pairs Signed-Ranks test. The significance level was set to be 0.05 ($P < 0.05$).

3. Results

3.1 Physical environment parameters

Table 2 shows the measured air temperature, relative humidity and CO₂ concentration of the sleeping chamber in the four conditions. The air temperature did not deviate systematically from the designed level and the relative humidity varied within a narrow range.

3.2 Thermal sensation and thermal comfort

Compared with the three local cooling conditions, the subjects felt significantly warmer in the *no cooling* condition before sleep ($P < 0.05$) and during sleep (as recalled after getting up) ($P < 0.05$) (Table 3). They also felt significantly warmer in the *head (neck) cooling* condition than in the *back and head (neck) cooling* condition, although the air temperature was higher in

the latter condition. Most of them reported feeling thermally neutral when *back cooling* alone and *both back and head (neck) cooling* were applied.

The subjects were less comfortable in the *no cooling* condition than in the three local cooling conditions before sleep ($P<0.05$), and they perceived the *back and head (neck) cooling* condition to be the most thermally comfortable among the three local cooling conditions before sleep ($P<0.05$) (Table 3). After getting up they recalled that, compared to *no cooling*, the *back and head (neck) cooling* improved their thermal comfort ($P<0.05$); the *back cooling* and *head (neck) cooling* also improved thermal comfort, although the difference was not formally significant (Table 3).

3.3 Sleep quality

The subjects' scores on 'calmness of sleep' and 'satisfaction about sleep' were higher in the three local cooling conditions than in the *no cooling* condition; they also reported higher scores for 'calmness of sleep' in the *back and head (neck) cooling* than in the *back cooling* condition or the *head (neck) cooling* condition (Figure 3).

The results of PSG recording shows that the subjects altered their body position about 10 times during sleep when local cooling was applied. Table 4 summarized the sleep quality parameters and sleep stages calculated based on the EEG, EOG and EMG recording. The last column of Table 4 provides normative values (of sleep efficiency, sleep onset latency, and wake time after sleep onset) of good sleep quality [47-49]. The values of these parameters are age dependent, in general less REM and N3 sleep, more WASO and lower sleep efficiency with increasing age. Since this study only involved young male subjects, we compared our results with studies that had young people as their subjects. The subjects spent a longer time in sleep, had higher SE and lower NOA, and had shorter WASO in the *back and head (neck) cooling* condition than in the *no cooling* and the other two local cooling conditions. Compared with the *no cooling* condition, the SE was higher and the NOA and WASO were lower in the

back cooling condition, while no significant difference was found in the *head (neck) cooling* condition. The WASO was also lower in the *back cooling* condition than in the *head (neck) cooling* condition. As to the SOL, the subjects took a longer time to fall sleep in the *no cooling* condition than in the *back and head (neck) cooling* condition and the *head (neck) cooling* condition. The SE, SOL and WASO results show that the subjects slept very well when their back and neck were both cooled, as compared with the normative sleep values assumed in the literature.

Significant difference in the total durations of Stage N3 and REM sleep were found among the conditions (Table 4). The total duration of Stage N3 sleep was significantly lower in the *no cooling* condition than in the other three local cooling conditions. The duration of REM sleep was significantly higher in the *back and head (neck) cooling* condition than in the *head (neck) cooling* or *no cooling* condition. No significant differences in other sleep stages were observed between conditions.

Analysis of sleep stages was performed within each third of the night, which were of 160 min duration, to study the temporal effects of local cooling on sleep quality. Figure 4 shows the distribution of sleep stages for each third of the night. It may be seen that Stage N3 sleep was dominant in the first third of the night and that REM sleep was dominant in the last third of the night. In the central third of the night, the duration of Stage N1 sleep was lower and the duration of Stage N3 sleep was higher in the *back and head (neck) cooling* condition than in the other three conditions, and the duration of Stage N2 sleep was lower in the *no cooling* condition than in either the *back and head (neck) cooling* or *back cooling* condition. Significant differences in REM sleep duration were observed between the conditions in each third of the night. Compared with the other three conditions, the duration of REM sleep was slightly higher in the first third of the night and slightly lower in the second third of the night in the *back and head (neck) cooling* condition, although the absolute changes are relatively small. At the last

third of the night, the duration of REM sleep was much higher in the *back and head (neck) cooling* condition than in the *head (neck) cooling* or *no cooling* condition.

3.4 Skin temperature

Figure 5 shows the mean value of the back and the neck skin temperature throughout the night in the four conditions. It may be seen that local cooling on the back reduced the skin temperature by 1.5~2°C in the *both back and head (neck) cooling* condition and the *back cooling* condition, and similarly local cooling on the neck reduced the skin temperature by 1.5~2°C in the *both back and head (neck) cooling* condition and the *head (neck) cooling* condition.

4. Discussion

The most important result of this study is that local body cooling efficiently improved sleep quality and thermal comfort in a hot environment. Compared with the no local cooling condition, thermal sensation was reduced (Table 3), thermal comfort level was improved (Table 3), and sleep quality was significantly improved on several measures (longer total sleep time and Stage N3 duration, shorter sleep onset latency and wake time after sleep onset, higher sleep efficiency, and less number of awakenings) (Figure 3 and Table 4) when local cooling was applied to both back and head (neck) or back alone in the hot environment. The sleep efficiencies were increased by about 10% in these two conditions and attained a level characterized as “good sleep” in a thermally neutral environment [47, 48]. In the waking state, cooling the head has previously been shown to be effective in reducing thermal stress [33, 35]. However, in this study local cooling of the head (neck) alone was not enough to maintain efficient sleep (Table 4), although it reduced thermal sensation, increased thermal comfort slightly (Table 3) and increased subjective sleep quality (Figure 3) and duration of Stage N3 sleep (Table 4). Studies of waking people have previously found that thermal sensation is based on area summation [50, 51]. An increase in the area of skin exposed to warming/cooling results

in a decrease in the temperature threshold required to induce a thermal sensation [51-53]. In the present study, although local cooling reduced the skin temperature of the back and neck (Figure 5), due to its much smaller skin surface, head (neck) cooling was much less able to alleviate thermal stress compared to back cooling. The results suggest that for local cooling, it is crucial that a large enough area is cooled in order to reduce thermal stress and maintain good sleep. However, this does not suggest that it would be preferable to cool the whole body, because warm feet allow people to fall asleep rapidly [39]. The negative effect of thermal stress on sleep was confined to Stage N3 and REM sleep. This is in agreement with previous studies that found that heat stress reduced Stage N3 and REM sleep, but not the duration of stages N1 or N2 [7, 8, 48, 54].

Compared with back cooling, the subjects were more thermally comfortable and reported better sleep quality, and had higher sleep efficiency and shorter wake time after sleep onset in the back and head (neck) cooling condition (Figure 3, Table 4). It should be noted that the background air temperature in the back and head (neck) cooling condition was higher than that in the back cooling alone condition. The above results indicate that keeping the head and neck cool is also important for good sleep in a hot environment. Researchers have observed that thermal comfort votes are complaint-driven in people who are awake, that is, that overall thermal comfort is mainly determined by the minimum local comfort votes [32]. Both Kuno and Cabanac believe that it is the reduction or removal of thermal stress that creates pleasure [55, 56]. The head and neck have been shown to only moderately influence overall thermal sensation [32], and people usually prefer to maintain a cooler head and neck [31]. Many studies have confirmed the fact that a large amount of heat can be lost from the head [33, 34]. Moreover, head and neck are always in contact with the bed and the pillow while sleeping. Removing the local discomfort of the head and neck thus has a decisive impact and should have a high priority in achieving overall comfort while sleeping.

The results show that Stage N3 sleep predominated in the first third of the night and that REM sleep predominated in the last third (Figure 4), which is consistent with the general sleep patterns of normal young adults without sleep disorders [57]. Except for REM, sleep was not significantly affected during the first third of the night, suggesting that the subjects were

relatively less sensitive to the thermal environment during this period. Previous studies have found that, although not completely depressed, thermoregulation is reduced during REM sleep compared to other sleep stages [58, 59], which may explain why a significant change in REM sleep duration was observed in all three periods. The sweat rate has been shown to increase during Stage N3 sleep compared to other sleep stages [7] and the homeostatic sleep drive, which is predominant in the regulation of Stage N3 sleep, has been shown to be greatest at sleep onset and to facilitate sleep during the first half of the night [60]. Stage N3 sleep was maintained during the first third of the night in all conditions, but was reduced by thermal stress when the homeostatic sleep drive declined during the latter part of the night. The percentage of Stage N3 sleep observed in this study was higher than that of normal young adults as summarized by Carskadon and Dement (2011) [57]. The high ambient temperature could be one of the possible reasons for this, as it is hypothesized that the Stage N3 sleep induces brain and body cooling and provides several advantages, including lower energy use, reduced cerebral metabolism, protection of the brain against the sustained high temperature of wakefulness etc. [61]. However, more studies are needed to clarify whether this is so. We were aware of the risk that sweat evaporation would be inhibited by the very high vapour diffusion resistance of the cooling blanket, so one of the questions to which subjects were asked to respond was whether they had experienced any discomfort that was not covered by the thermal comfort scales. Had unevaporated sweat remained to any extent on the skin area subject to local contact cooling was thought likely would be reported here, but no discomfort related to sweating was reported by the subjects. Whether this was due to local suppression of sweating or to a generally low level of sweating was not determined in the present experiment.

The incidence of warm bedrooms in modern homes, even during a cool summer, is of concern, especially as there is a marked trend towards the adoption of even better insulation standards in new homes and the energy-efficient retrofitting of existing homes. Compared with full air conditioning, the use of local cooling has a large energy saving potential. Earlier human subject experiments identified 26°C as the thermally neutral temperature when participants slept with a light covering and wore a short-sleeved night shirt (with an estimated insulation value of 0.36 clo, as in the present experiment) [10, 47]. If they slept without covering, the

neutral temperature would increase to 28°C [62]. By using local cooling, the thermal comfortable temperatures increased to 31°C and 32°C in the present study. Moreover, the temperature of the water used for local cooling in the present study was as high as 28°C, so local cooling can be achieved with renewable energy sources and reduced energy cost. However, the amount of energy saving was not estimated: we did not perform an energy calculation or a simulation. This will form a part of our future research. Measurement (e.g. using thermal manikin) and analysis of heat transfer between the local cooling surface and the human body will be performed to determine the useful range of this local cooling system, as a function of the bedding and covering insulation value.

Several field surveys have shown that bedrooms are poorly ventilated and that the indoor air quality in bedrooms is poorer than in other spaces in a residential building [15, 63]. The average CO₂ concentration was found to be higher in bedrooms where children sleep (either alone or with their parents) compared to bedrooms where only adults sleep [15]. A recent field study examined how bedroom air quality affects sleep and the results show that sleep quality and next-day work performance improved when the CO₂ level in the bedroom during of the night was reduced by improving the ventilation [64]. The result of the present study suggest that by supplying back and head (neck) cooling, night-time ventilation could be used in areas with hot summers. This will improve the indoor air quality in bedroom and sleep quality of occupants, compared to using split air conditioning to reduce the bedroom air temperature, as this would require a reduction in the ventilation rate. In China (especially in rural areas), natural ventilation is still the most frequent means of ventilation in residential buildings. Tong et al. (2016) reported that the aggregated energy saving potential of office buildings in 35 major Chinese cities was 112 GWh in 2015, even after allowing for a 43 GWh loss due to China's serious air pollution issue, especially in North China [65]. Considering that outdoor air temperatures and noise level are lower at night, night-time ventilation with appropriate filtration, may be expected to improve the thermal environment and the indoor air quality of bedrooms in summer.

5. Conclusions

By applying local conductive cooling to the back and/or head (neck) sections while sleeping, the skin temperature of the back and neck were reduced by 1.5~2°C and thermal comfort and sleep quality were improved, with the largest improvement in the *both back and head (neck) cooling* condition and the smallest in *the head (neck) cooling* condition. The mean sleep efficiency was improved from 84.6% in the *no cooling* condition to 95.3% and 92.8%, which is characteristic of very good sleep, in the *both back and head (neck) cooling* condition and the *back cooling* conditions, respectively, while *cooling the head (neck) alone* did not improve sleep efficiency. In summary, the present study shows that local cooling applied to the major body parts (back and head) that are in contact with the bed could effectively maintain very good sleep and improve night-time thermal comfort in hot environments.

6. Acknowledgments

This work was supported by the National Natural Science Foundation of China (No. 51478260 and 51238005). The authors would like to thank Professor David P Wyon at the Technical University of Denmark and Professor John Zhai at the University of Colorado at Boulder for their extensive comments on this paper. The authors also would like to thank the subjects who participated in the study.

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Figure 1 Hypothermic blanket made of cellular tube (a), as fastened to the bed for back and head (neck) cooling (b)

Figure 2 Experimental procedures for an all-night sleep

Figure 3 Subjective sleep quality in the four conditions (Error bars represent the standard deviation of mean, * $P < 0.05$)

Figure 4 Distribution of sleep stages in each third of the night

Figure 5 Mean value of back and neck skin temperature throughout the sleeping period

Table 1 Parameters derived from sleep staging

Parameter	Notation	Explanation
Lights out clock time	L-out	The clock time (in hh:mm) that the subject was instructed to allow himself or herself to fall asleep
Lights on clock time	L-on	The clock time (in hh:mm) that the subject was awakened
Total recording time	TRT	Elapsed time with lights out (in minutes)
Total sleep time	TST	Total time scored as sleep (in minutes)
Sleep efficiency	SE	Percentage of time in bed actually spent sleeping, i.e., TST as a percentage of TRT (%)
Sleep onset latency	SOL	Elapsed time from lights out to the first occurrence of Stage N1 sleep (the start of sleep) (in minutes)
Sleep latency	SLAT	Elapsed time from lights out to the first occurrence of Stage N2, N3, or R (in minutes)
Wake time after sleep onset	WASO	Total time of wakefulness recorded from the start of sleep to lights on (in minutes)
Number of awakenings	NOA	Number of stage wake occurrences
Duration of each sleep stage	M1, M2, M3, MR	Minutes scored as N1, N2, N3, and REM (individually, in minutes)
Sleep stage percentages	P1, P2, P3, PR	Time scored as N1, N2, N3, and REM as a percentage of TST

Table 2 Measured physical parameters (mean±std) in the sleeping chamber

	Air temperature (°C)	Relative humidity (%)	CO2 (ppm)
Back and head (neck) cooling	31.7±0.5	50.7±6.7	840±115
Back cooling	30.7±0.5	55.5±5.5	904±118
Head (neck) cooling	30.7±0.6	57.6±5.3	908±114
No cooling	30.7±0.5	56.4±6.7	885±143

Table 3 Thermal sensation and thermal comfort votes assessed before sleep and after getting up in the four conditions

	<i>C1</i>	<i>C2</i>	<i>C3</i>	<i>C4</i>	<i>P</i>
Thermal sensation [hot (3); warm (2); slightly warm (1); neutral (0); slightly cool (-1); cool (-2); cold (-3)]					
Before sleep (lying down)	0.20±0.62	0.31±0.56	0.62±0.47 ^{*a}	0.91±0.56 ^{*abc}	<0.01 ^{**}
Sleeping (recalled after getting up)	0.72±0.62	0.32±0.34	0.25±0.29	0.07±0.29 ^{*abc}	<0.01 ^{**}
Thermal comfort [very comfortable (2); comfortable (1); just comfortable (0.01); just uncomfortable (-0.01); uncomfortable (-1); very uncomfortable (-2)]					
Before sleep (lying down)	0.56±0.70	0.53±0.73 ^{*a}	0.83±0.72 ^{*a}	1.40±0.69 ^{*abc}	<0.01 ^{**}
Sleeping (recalled after getting up)	0.34±0.63	0.12±0.42	0.28±0.70	-0.06±0.49 ^{*a}	<0.05 [*]

‡C1- Back and head (neck) cooling, C2-Back cooling, C3-Head (neck) cooling, C4- No cooling.

*P<0.05, a-different from C1, b-different from C2, c-different from C3.

Table 4 Sleep quality parameters (mean±std) derived from EEG, EOG, and EMG recordings

Parameters [§]	Conditions [‡]				Normative values of good sleep
	C1	C2	C3	C4	
TST (min)	443.97±35.64	419.50±49.28 ^{*a}	411.28±55.27 ^{*a}	392.34±61.88 ^{*a}	/
SE (%)	95.28±4.22	92.8±4.07 ^{*a}	88.56±10.21 ^{*a}	84.16±11.74 ^{*ab}	90~96 [43,44]
SOL (min)	4.22±6.19	6.91±9.00	13.88±29.56	21.5±30 ^{*ab}	< 20 min [45]
WASO (min)	15.34±14.09	25.03±14.46	38.69±25.13 ^{*ab}	51.91±43.61 ^{*ab}	< 25 min [45]
NOA	10.88±5.30	15.31±8.36 ^{*a}	16.31±6.89 ^{*a}	18.50±7.05 ^{*a}	/
Total duration of (min)					
Light sleep (Stage N1+ N2)	204.34±44.89	192.63±41.15	191.56±36.32	192.56±43.01	/
Deep sleep (Stage N3)	157.97±40.24	153.16±43.26	150.38±36.69	132.16±35.64 ^{*abc}	/
REM	81.66±17.68	73.72±21.59	69.34±20.73	67.63±25.20	/
Percentage of (%)					
Light sleep (Stage N1+ N2)	45.89±8.80	46.00±8.63	46.67±6.95	49.28±8.51	/

Deep sleep (Stage N3)	35.73±9.19	36.50±9.34	36.52±7.37	33.85±8.34	/
REM	18.38±3.78	17.52±4.46	16.83±4.44	16.86±5.29	/

‡C1- Back and head (neck) cooling, C2-Back and head (neck) cooling, C3-Head (neck) cooling, C4- No cooling.

§Notation of the parameters are explained in Table 1.

*P<0.05, a-different from C1, b-different from C2, c-different from C3.







