Thermal environment and sleep quality

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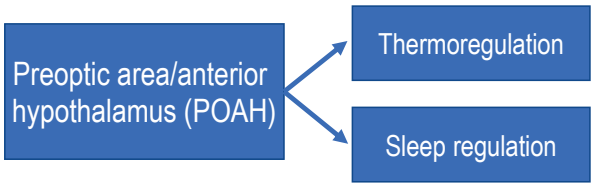
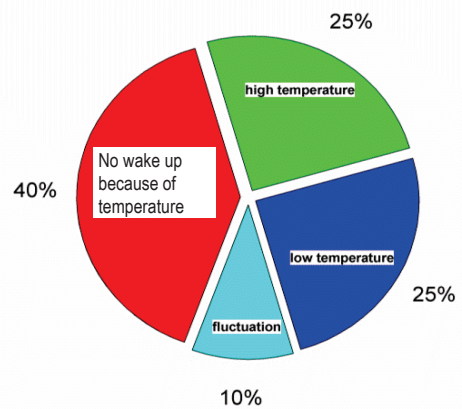
饮 水 思 源 • 爱 国 荣 校

1. Why thermal environment

- **Sleep quality should be affected by thermal environment**
  - ✓ POAH regulate both heat loss and sleep activity
- **Many problems were found in bedrooms**
  - ✓ Stuffy air, high CO_2 concentration, thermal discomfort…





(Lin & Deng. 2006, Energy Build)

2. Indoor temperature and sleep

- **Temperatures deviated from thermal neutral decreased sleep quality**

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Experimental study on thermal comfort of sleeping people at different air temperatures

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ABSTRACT

Current thermal comfort theories and standards are mainly concerned with people in waking state. The effects of air temperature on sleep quality and thermal comfort of sleeping people were investigated in this study by experimenting on human subjects. Sleep quality was evaluated by subjective questionnaires performed in the morning as well as electroencephalogram (EEG) signals, which were continuously recorded during the all-night sleep period. Subjective assessments on thermal comfort were performed both before and after sleep. Analysis on EEG signals indicated that the subjects took longer time to fall asleep and experienced shorter period of slow wave sleep (SWS) when the room temperatures moderately deviated from neutral. Consistently, they reported poorer subjective sleep quality in such conditions. The returned subjective questionnaires on thermal comfort from subjects reflected that the thermal comfort temperature was higher in sleep compared with that in waking state. Their skin temperatures were increased with air temperature and fluctuated during the sleeping period. In view of the distinctive requirements from waking people, it makes sense to study the thermal comfort of sleeping people. The results also have practical implications on energy savings in bedrooms.

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1. Introduction

1.1. Thermal environment and sleep quality

Sleep is essential for the body to recover from both physical and psychological fatigue suffered throughout the day and restore energy to maintain bodily functions [1]. Normal human sleep is comprised of two states — rapid eye movement (REM) and non-REM (NREM) sleep — that alternate cyclically across a sleep episode. Sleep begins in NREM and progresses through deeper NREM stages (stages N2 and N3) before the first episode of REM sleep occurs approximately 80–100 min later [2]. The stage N3 sleep is characterized by slow wave activity (brain waves of frequency 0.5 Hz–2 Hz), thus is referred as slow wave sleep (SWS) or deep sleep and is of vital importance to both body and mind. Studies with humans showed that poor sleep quality impaired cognitive performance in older adults [3], and impacted brain function related to reward processing, risk-taking, and cognition in adolescents [4]. Disturbed nocturnal sleep was also related to various adverse health problems, increasing the risk of cardiovascular disease and death [5].

Thermal environment could be one of the most important factors that affect human sleep. Very high or low air temperatures decreased SWS sleep, and increased the frequency and duration of wakefulness [6,7]. Moreover, thermoregulatory systems were shown to be strongly linked to the mechanisms regulating sleep [8–10]. The thermoregulatory control center, the preoptic — anterior — hypothalamus (POAH), also regulated sleep. It had been demonstrated in kangaroo and rat that peripheral thermal stimulation was capable of stimulating warm-sensitive neurons in the POAH, which in turn could promote sleep [11]. Therefore, providing a thermally comfortable sleeping environment is important for sleep maintenance and contributes positively to human health and their daytime activities.

1.2. Thermal comfort in sleep environment

Current thermal comfort theories and standards such as ANSI/ASHRAE 55-2010 [12] are primarily concerned with people in waking state although people spend a third of their lives sleeping. For office workers, the most occupied rooms are bedrooms when at home. Serving as a main technique to improve thermal comfort,

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Investigation of sleep quality under different temperatures based on subjective and physiological measurements

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This study investigated sleep quality at different indoor temperatures (17°C, 20°C, and 23°C [62.6°F, 68.0°F and 73.4°F]) via subjective and physiological methods by evaluating the thermal comfort and sleep quality before and after sleep. Electroencephalograms were also obtained, and skin temperatures were measured throughout the entire sleep cycle. The quantitative powers of each electroencephalogram frequency rhythm were calculated, and the duration of every sleep stage was determined. Both results show that the ambient temperature has a significant effect on sleep quality. The subjective results show that 20°C (68.0°F) was the most comfortable temperature for the waking state and 23°C (73.4°F) was the most satisfactory temperature for sleeping. The objective results show that at 23°C (73.4°F), the relative power of the sleep δ band was the highest, the duration of sleep onset latency was the shortest, and the slow-wave sleep was the longest. All these results were highly consistent, indicating that sleep quality was highest at 23°C (73.4°F). The higher thermal comfort temperature in sleep compared with that in the waking time may be due to the lower mean skin temperature during sleep.

Introduction

People spend one-third of their lives sleeping. Sleep is essential to help the body recover from both physical and psychological fatigue suffered throughout the day and helps restore energy to maintain bodily functions (Foreman and Wykle 1995). A comfortable sleep is also necessary for high productivity during daytime.

Sleep quality is affected by many factors, such as health states, emotional states, bedding conditions, and ambient environments, with ambient temperature being one of the most important factors (Zhang and Wing 2006). Two types of studies on thermal sleep comfort have been previously reported. The first type was conducted in an experimental sleep chamber with the beddings kept constant. Using this paradigm, a study on preschool children found that 22.2°C (72.0°F) was the best sleeping condition, and any deviation from that temperature resulted in a shortened total sleep time (Shinn 1932). Macpherson and Muncery (1962) reported that sleep quality was reduced when temperatures exceeded 24°C (75.2°F). Another study (Candas et al. 1979) found that at ambient temperatures of either 19°C or 22°C (66.2°F or 71.6°F), the microclimate temperature measured inside the sleeping covers was constant at 29.6°C (85.3°F). In an investigation of women sleeping with covers during winter (Sewitch et al. 1986), comfortable temperatures were found to range from 20°C to 22.2°C (68.0°F to 72.0°F). In the study conducted in a sleeping chamber in winter

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Li Pan is PhD student. **Zhiwei Lian** is Professor. **Li Lan** is Postdoctoral Scholar.

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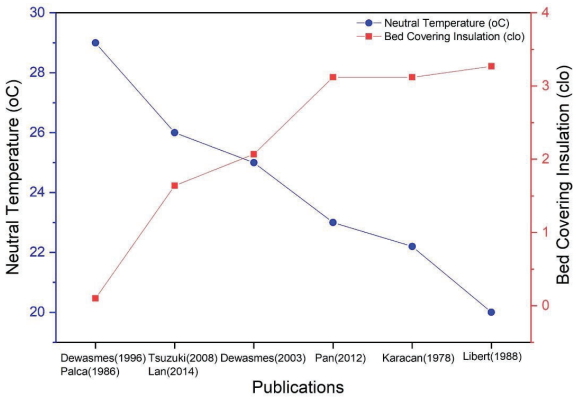

2. Indoor temperature and sleep

- **A slightly raised indoor temperature reduced sleep quality**

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ORIGINAL ARTICLE

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Experimental study of the negative effects of raised bedroom temperature and reduced ventilation on the sleep quality of elderly subjects

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Abstract

This study investigated the effects of air temperature and ventilation on the sleep quality of elderly subjects and elucidated the mechanisms involved. Sixteen subjects aged over 65 years old were exposed to four conditions in a 2 × 2 design: air temperatures of 27°C and 30°C (with a ceiling fan in operation at 30°C) and two ventilation conditions (with and without mechanical ventilation) in experimental bedrooms. Their electroencephalogram, electrooculogram, chin electromyogram, electrocardiogram, respiration, oxygen saturation, and wrist skin temperature were measured continuously during sleep. Saliva samples were collected, and blood pressure was measured both before and after sleep. The results showed that at the temperature of 30°C, the total sleep time, sleep efficiency, and duration of REM sleep of the elderly decreased by 26.3 min, 5.5%, and 5.3 min, respectively, and time awake increased by 27.0 min, in comparison with 27°C, indicating that the sleep quality of the elderly is very vulnerable to heat exposure. Even a small heat load led to an overactive sympathetic nervous system and increased wrist skin temperature, which reduced sleep quality. Improving the ventilation increased the duration of deep sleep and REM sleep by 10.3 min and 3.7 min, respectively. Higher pollutant concentrations affected the respiration and autonomous nervous systems to reduce sleep quality. The benefits of improved thermal environment and ventilation on sleep quality were found to be additive. Good ventilation and the avoidance of raised temperatures in the bedroom are thus both important for the sleep quality of the elderly.

KEYWORDS
elderly, raised temperature, sleep quality, sleeping conditions, ventilation

1 | INTRODUCTION

Aging populations are a world-wide concern. The Chinese demographic statistics announced in March 2021 showed that the percentage of the population 60 years old or more in China was 18.7% (260 million). People experience many physiological and psychological changes in old age, including a decrease in sleep quality and quantity and altered sleep structure.[1] Sleep disturbance of about 50% has been observed among the elderly in many countries.[2–7] Sleep disturbance is detrimental to both the physical and mental

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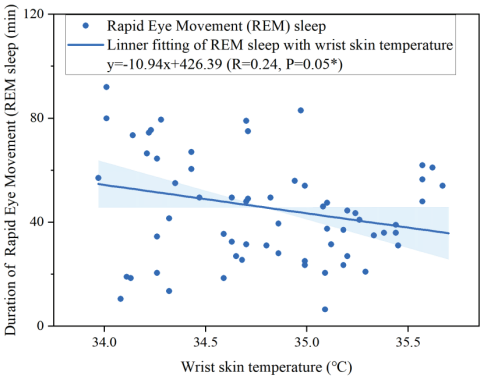
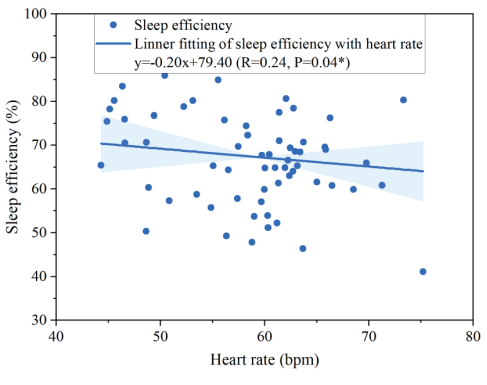
Physiological responses	T27/MV	T27/NMV	T30/MV	T30/NMV	Temperature effects F	p	f
Wrist skin temperature (°C)	34.7 ± 0.5	34.7 ± 0.5	34.8 ± 0.5	34.9 ± 0.5	6.36	0.02*	0.67
Heart rate (bpm)	58.6 ± 7.4	58.5 ± 7.4	59.3 ± 7.4	59.2 ± 7.8	6.38	0.02*	0.67
PNN_{50} (%)	14.9 ± 17.3	13.8 ± 16.7	11.4 ± 13.9	11.3 ± 12.0	3.69	0.07	0.50





2. Indoor temperature and sleep

- **Air temperature was the dominant factor influencing sleep quality in summer Shanghai**

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Association of bedroom environment with the sleep quality of elderly subjects in summer: A field measurement in Shanghai, China

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ABSTRACT

Sleep is essential for the health of elderly people, but few studies have made connection between their sleep quality and their bedroom environment. This study performed field measurements in Shanghai, China, to investigate the bedroom thermal environment and ventilation and their associations with the sleep quality of elderly subjects in summer. Forty-five elderly subjects participated in this study for six consecutive days. Their bedroom air temperature, relative humidity and CO_2 concentration were measured continuously and their sleep quality was objectively measured using a wrist-worn sleep tracker. Wrist skin temperature was measured continuously at night. Each morning after waking up the subjects assessed their sleep quality, recalled their thermal sensation, and recorded their bed covering, sleepwear and cooling/ventilation arrangements during that night. The results show that higher air temperature and CO_2 concentration were both negatively correlated with objective sleep quality. Air temperature was the key factor influencing objective sleep quality. When air temperature increased by 1 °C, sleep efficiency (SE) decreased by 0.7%, duration of Rapid Eye Movement (REM) sleep decreased by 2.1min, and time awake increased by 2.3min. The sleep quality of elderly subjects was more negatively affected by heat exposure than has been previously reported for younger subjects. As CO_2 concentration increased by 100 ppm, the Total Sleep Time (TST) decreased by 11min. The combined effects of air temperature, relative humidity and CO_2 concentration were analyzed: TST and duration of REM sleep were reduced at higher air temperature, relative humidity and CO_2 concentration.

1. Introduction

People spend about one-third of their lives asleep. Sleep is an important physiological process that enables the body to recover from physical and psychological fatigue [1]. Sleep consists of Non-Rapid Eye Movement (NREM) sleep and Rapid Eye Movement (REM) sleep. In general, NREM sleep comprises the three stages N1, N2 and N3. Sleep begins in NREM (usually stage N1) and progresses through deeper NREM stages (stages N2 and N3) before the first episode of REM sleep occurs in mature humans [2]. Deep sleep (stage N3) in NREM sleep can facilitate physical recovery, e.g., the removal of cellular debris from the brain [3]. REM sleep enables the memory to process and learn from daily experiences [4]. Metabolic rate and sensitivity to ambient temperature conditions all decrease during sleep; while skin temperature and core temperature change between sleep stages during each cycle [5]. When the thermoregulatory responses of the human body during sleep fail to compensate for warm and hot conditions, sleep disturbance may occur [6]. The thermal environment is therefore one of the more important factors affecting sleep quality [1]. Previous studies indicated that air temperatures higher than the neutral temperature for whole-body heat balance impair the sleep quality of young people, resulting in increased awakening, decreased total sleep time (TST), duration of deep sleep and REM sleep [7,8]. High humidity was reported to increase the negative effects of high air temperatures on sleep quality [9]. Poor ventilation, as indicated by a high CO_2 concentration in the bedroom, was shown to result in poorer sleep quality and cause sleep disturbance [10–17]. However, most of these studies were conducted in laboratories and the subjects were young adults.

Aging populations are a world-wide concern. The recent Chinese demographic statistics announced in March 2021 show that the percentage of the population 60 years old or more was 18.7% (260 million). A high incidence of sleep disturbance has been observed in 50% of the

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Objective sleep parameters	(26-32°C) B(Ta)^P	(36-88%) B(RH)^P	(400-2400ppm) B(CO_2)^P
Time in bed (min)	$-92.35^{0.12}$	$-38.07^{0.87}$	$-2.71^{0.49}$
Total sleep time (min)	$\mathbf{-86.59^{0.02}}$*	$-23.63^{0.56}$	$\mathbf{-1.65^{0.05}}$*
Sleep efficiency (%)	$\mathbf{-7.96^{0.01}}$**	$-2.55^{0.08}$	$-0.21^{0.10}$
Wake time (min)	$\mathbf{15.37^{0.04}}$*	$5.23^{0.13}$	$0.44^{0.23}$
REM sleep (min)	$\mathbf{-32.97^{0.04}}$*	$-14.40^{0.56}$	$-1.52^{0.21}$
Light sleep (min)	$\mathbf{-38.90^{0.02}}$*	$\mathbf{-11.85^{0.04}}$*	$\mathbf{-0.33^{0.03}}$*
Deep sleep (min)	$-27.34^{0.27}$	$-9.90^{0.44}$	$-1.01^{0.14}$

*P < 0.05; **P ≤ 0.01.

3. Sleeping micro-environment

- **Conductive cooling on back and head maintained sleep quality at 32°C**

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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 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
bedroom, local body cooling, physiological parameters, sleep, sleep quality, thermal comfort

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 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 nighttime 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

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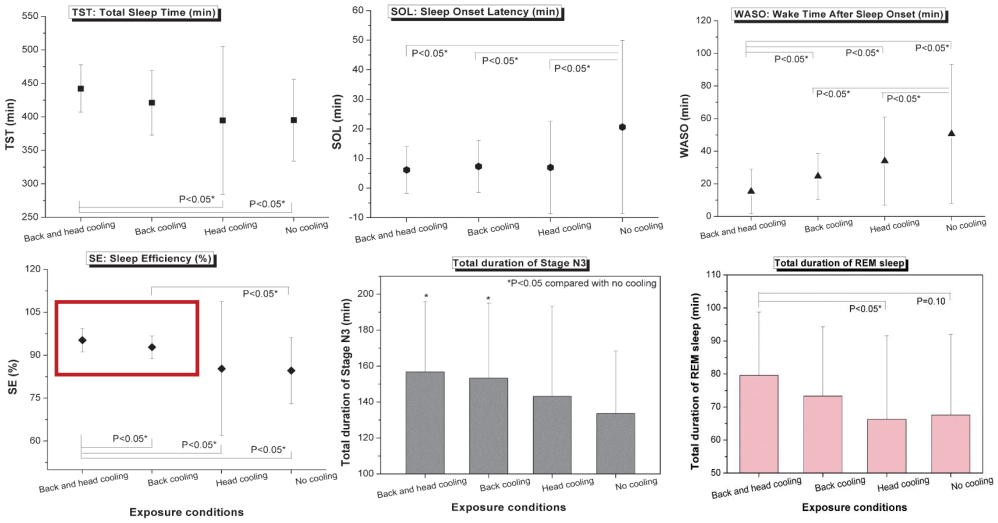

3. Sleeping micro-environment

- **Covering heating and mattress heating improved sleep quality at 7°C**

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Bed heating improves the sleep quality and health of the elderly who adapted to no heating in a cold environment

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ABSTRACT

Since aging is associated with a progressive decrease in thermoregulation, a cold bedroom environment may have negative effects on the sleep quality of the elderly. This study investigated the effects of two bed heating methods (covering heating and mattress heating), compared with no heating, on sleep quality of the elderly without sleep disorders in a cold environment. Twelve elderly who did not use any heating in daily life participated into this field intervention experiment, which was performed in their own bedrooms. Sleep quality was subjectively evaluated using questionnaires in the morning and objectively measured with a wristband which continuously monitored throughout the sleep period. Skin temperatures and blood pressure were measured. The subjects felt thermally comfortable when slept in all conditions. Compared with no heating, covering heating and mattress heating increased the total sleep time by 35.5 min and 20.3 min, and decreased the sleep onset latency by 13.3 min and 18.3 min. Compared with mattress heating and no heating, the covering heating decreased the wake after sleep onset by 28.7 min and 12.5 min, and increased the sleep efficiency by 2.8% and 5.7%. Both two heating methods increased the bed temperature and reduced the skin temperature gradient between the chest and calf. The systolic blood pressure measured in the morning was significantly lower in the covering heating than in no heating. These results suggest that, without changing thermal comfort, bed heating improved micro thermal environment, sleep quality and health of the elderly without sleep disorders in a cold environment.

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1. Introduction

In China, the number of the elderly is expected to account for 25% of the total population by 2030. Some physical and psychological changes, including decrease of sleep quality, greatly affect the health and life quality of the elderly [1,2]. Large population-based epidemiologic studies indicate that sleep complaints and sleep problems are common in the elderly [3–5]. Sleep disturbance increases the risk of heart disease, arthritis, obesity, and has negative effects on restorative and immune function, endocrine function, cardiovascular system and brain function in the elderly [1,6–10]. Thermal environment is one of the primary causes of sleep disturbance [11–16]. With biological ageing, many factors related to thermoregulation are impaired in the elderly [3,17]. Therefore, providing a thermally comfortable sleeping environment is critical for sleep maintenance and the health of the elderly.

In Hot Summer and Cold Winter (HSCW) area of China, in which region no central heating is provided, the averaged bedroom temperature in winter is as low as 12.7 °C [18]. The thermal environment is worse in the rural areas, as confirmed in a field survey in the bedrooms of thirty-nine elderly people in a rural area of this region [19]. The results show that the mean air temperature in the bedroom was 7.1 ± 2.3 °C, and about 50% of the respondents used local heating methods in cold winter, mainly the electric blankets.

Tokura et al. reported that the use of electric blankets inhibited the decrease of the rectal temperature of young people during sleep, exerting hygienical problems for normal sleep [20]. However, Okamoto et al. found that heating the lower body extremity of young people by electric blankets decreased the cold stress and maintained stability and thermoregulation during sleep [21]. The

Abbreviations: ADL, activities of daily living; BP, blood pressure (mmHg); DBP, diastolic blood pressure (mmHg); ES, effect size; RHi, relative humidity near the human side of the covering (%); RHm, relative humidity near the human side of the mattress (%); HSCW, hot summer and cold winter; MRHi, the mean bed relative humidity (%); MRT, the mean bed air temperature (°C); MST, mean skin temperature (°C); PSQI, Pittsburgh sleep quality index; REM, rapid-eye movement; SBP, systolic blood pressure (mmHg); SE, sleep efficiency (%); SOL, sleep onset latency (min); Ti, air temperature near the human side of the covering (°C); Tm, air temperature near the human side of the mattress (°C); TST, total sleep time (min); WASO, wake after sleep onset (min).

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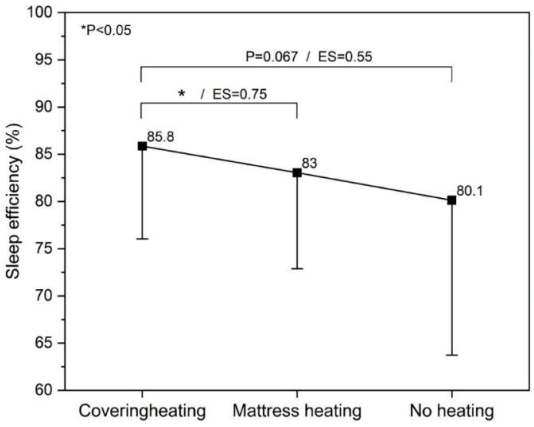
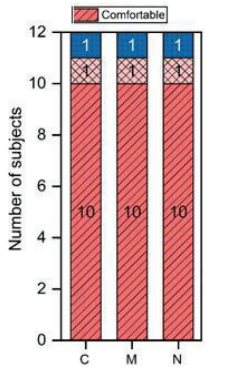
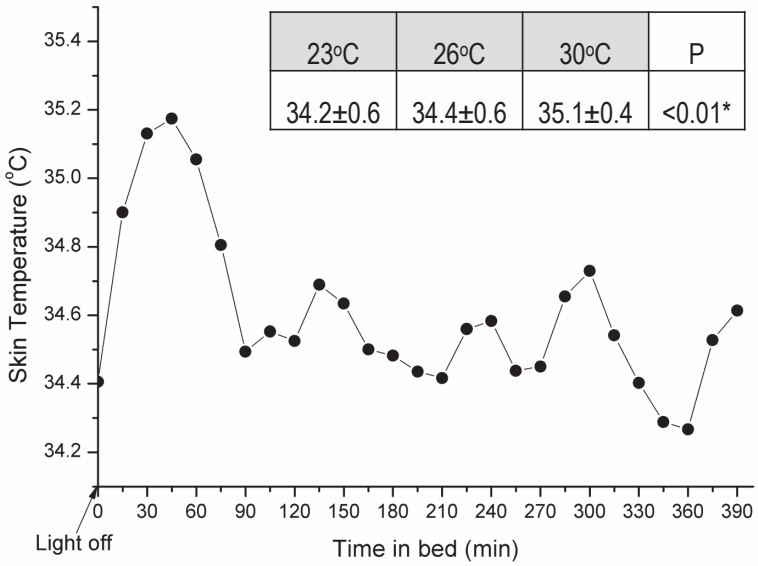




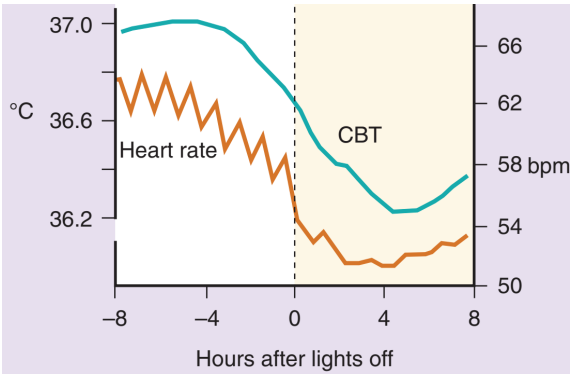
Thermal comfort voting

4. The importance of skin temperature

- **Mean skin temperature increases with air temperature and fluctuates during the entire sleep period**



23°C	26°C	30°C	P
34.2±0.6	34.4±0.6	35.1±0.4	<0.01*



4. The importance of skin temperature

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Mean skin temperature estimated from 3 measuring points can predict sleeping thermal sensation

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Sleep

ABSTRACT

Sensory input from the skin appears to be of crucial importance in the regulation of sleep but there has been limited research on human skin temperature during sleep. The present study was undertaken to validate calculation of the mean skin temperature (MST) of sleeping subjects from measurements at only three locations: forehead, chest, and foot, by means of an analysis of skin temperature data obtained from four human experiments that investigated the effects of thermal environment on the sleep quality and thermal comfort of a total of 64 sleeping subjects. The results show that skin temperatures were more evenly distributed across the body surface of sleeping subjects than they are when subjects are awake. The skin temperature of the forehead was highly correlated with thermal sensation in long-term measurements. MST values calculated using the three-point method were found to predict thermal sensation while sleeping better than those calculated using the normally accepted Hardy and Dubois's seven-point method. The validity, convenience and reliability of this approach, which also causes less sleep disturbance, makes it a suitable choice for obtaining estimates of mean skin temperature in sleep studies.

1. Introduction

Sleep is essential for the body to recover from both physical and psychological fatigue suffered throughout the day and is important for human health [1]. The thermal environment is one of the primary causes of sleep disturbance [2,3], which can also be caused by such factors as health, emotional state and bedding. Exposure to moderate heat or cold results in increased sleep onset latency and decreased slow wave sleep (SWS) [3]. Even mild heat exposure leads to significantly decreased sleep quality in older people [4]. Creating a thermally comfortable sleeping environment is thus an important research topic.

Input from the skin appears to be of crucial importance in the regulation of sleep [5]. Since the human skin forms the interface between the human body and the thermal environment, skin temperature provides essential information on heat loss from the human body. Moreover, when we feel warm or cool, we do not actually sense the air temperature, but rather the temperature of the thermoreceptors, most of which are located in the periphery of the body and in or around the great veins in the upper abdomen and thorax, as they send signals to the hypothalamus at the base of the brain when stimulated [6]. The hypothalamus will then trigger autonomic thermoregulation to help the human body maintain a constant central body temperature in a hot or cold environment. Skin temperature has been shown to have the same weighting as core temperature for predicting thermal sensation in uniform conditions [6]. Importantly, the hypothalamus not only controls thermoregulation, but also regulates sleep. It has been suggested that sleep is regulated by opposing wake-promoting and sleep promoting mechanisms located in the hypothalamus [5]. Skin warming induced by cutaneous vasodilation is likely to contribute to the activation of thermosensitive sleep-active neurons in the hypothalamus [7]. The effect of skin warming on sleep was confirmed in a human subject experiment, which showed that an experimentally induced but subtle increase in skin temperature, within the thermoneutral range, caused a decrease in sleep-onset latency [8]. Human subject experiments also found that mean skin temperature (MST) changed as a function of the thermal environment during the sleeping period [3,9,10]. These results suggest that skin temperature is of primary importance in assessing the thermoregulation and sleep regulation of sleeping subjects.

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Comparison of wrist skin temperature with mean skin temperature calculated with Hardy and Dubois's seven-point method while sleeping

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ABSTRACT

Wrist skin temperature has been validated to be sensitive to the thermal state of awake people, but its correlation with thermal state of sleeping people has not been investigated. In the present study four human subject experiments were performed on both young and elderly subjects in different seasons (winter, transition, summer). Their skin temperatures were continuously measured during the whole night sleep at wrist (WST) and at the normally accepted seven points (forehead, chest, posterior forearm, hand, anterior thigh, anterior calf, and foot) proposed by Hardy & Dubois. The WST was compared with the mean skin temperature (MST) calculated with Hardy & Dubois's seven-point method. The results show that the WST was moderately and positively correlated with MST, with the Pearson's R value ranged from 0.44 to 0.63. When comparing the variation of WST and MST throughout the whole-night sleep, the averaged maximum crossing correlation coefficient was 0.56 (Q1 = 0.4, Q3 = 0.7) and the lag time was on average −10.4 min (Q1 = −11.0, Q3 = 0.0 min), indicating that the WST was synchronically correlated with MST. Similar to MST, the WST could differentiate sleeping micro thermal environments which were created by different combinations of indoor temperature and bedding thermal insulation. These results suggest that the WST was linearly and synchronically correlated with the MST calculated using Hardy & Dubois's seven-point method. Thus, the skin temperature at wrist could provide information on thermal state of human body when people asleep, making it possible to measure skin temperature in field studies and to personally and energy efficiently control the thermal environment for sleep.
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1. Introduction

Sleep is a vital physiological process of the human body, and has a substantial impact on human health [1]. More and more studies have linked bedroom environment, especially thermal environment with sleep quality [2,3]. Exposure to moderate cold or heat resulted in increased sleep onset latency and decreased slow-wave sleep [3,4]. Mild heat exposure significantly contributed to increased wakefulness during sleep and reduced rapid eye movement sleep (REM) in older men [5]. Providing a thermally comfortable environment is thus essential to maintain sleep.

Different thermal mitigation facilities, such as air-conditioners and fans, are widely used while sleeping to maintain thermal comfort [6–8] by consuming a certain amount of energy [9]. The survey in Hong Kong showed that 68% of the respondents would leave their air conditioners on throughout their sleep and only 6.1% used their air conditioners for <2 h during sleep in summer [7]. However, many problems regarding thermal environment were still found in bedrooms in field surveys. Approximately 60% of the 554 respondents in Hong Kong experienced waking up during sleep because of thermal discomfort even with their air conditioners in operation. A study in South Korea showed that occupants were exposed to either too low or too high indoor temperatures when sleeping [10]. These evidences indicate that the current sleeping thermal environment control may not meet the thermal comfort need of sleeping people.

The sleeping environment is a unique environment, in which occupants are asleep and not awake as they are in any other indoor space. The sleeping micro thermal environment was significantly affected by the total insulation of the bedding systems [11]. By using different levels of bed coverings, a thermally comfortable environment for sleep has been observed when the air temperature changed from 17 °C to 29 °C. On the other hand, during sleep an individual occupies and thus requires less space for thermal control compared with other spaces, e.g. office. Therefore, in sleep-

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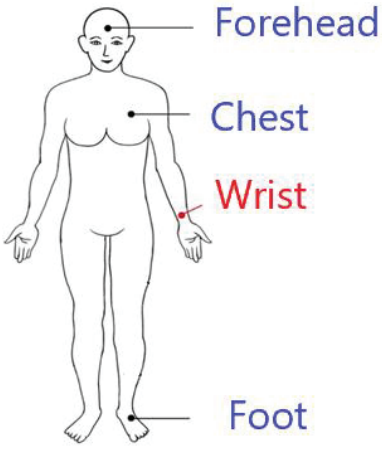

Summary

- Human sleep quality was sensitive to change of air temperature; temperatures moderately deviated from thermal neutral impaired sleep quality, while the neutral temperature is closely related to thermal insulation
- Sleep quality could be improved while energy saving was achieved when the air temperature cycled properly; more studies are needed to identify the optimum cycle
- Control bed micro-environment energy efficiently by using of local heating, cooling and/or ventilation system
- Skin temperature is a good index for predicting the thermal state of human body while sleeping

Thank you

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