Building and Environment 99 (2016) 252–259

Contents lists available at ScienceDirect

Building and Environment

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

Ten questions concerning thermal environment and sleep quality

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ARTICLE INFO

Article history:
Received 10 December 2015
Received in revised form
19 January 2016
Accepted 20 January 2016
Available online 22 January 2016

Keywords:
Thermal comfort
Indoor air temperature
Air flow
Thermal environment
Sleeping environment
Sleep quality
Sleeping people

ABSTRACT

People spend about one third of their lives sleeping. Sleep is essential for the recovery of the body from both physical and psychological fatigue suffered throughout the day, the refreshment of mind, and the restoration of energy for maintenance of bodily functions. Current thermal comfort theories and standards are mainly concerned with people in waking state. However, many problems regarding thermal environment are found within a few field surveys in bedrooms, pushing out the need to investigate thermal environment and thermal comfort for sleeping people. In this paper, the questions concerning the measurement and evaluation of human sleep quality, the correlation between thermal regulation system and sleep regulation, and the characteristics of night-time space cooling load etc. are answered. The evidences illustrating the effects of thermal parameters on human sleep quality are also provided, in an attempt to shed light on the thermal comfort requirements of sleeping people.

1. Introduction

People spend about one third of their lives sleeping. Sleep is essential for the recovery of the body from both physical and psychological fatigue suffered throughout the day, the refreshment of mind, and the restoration of energy for maintenance of bodily functions [1]. Poor sleep quality impaires cognitive performance in older adults [2], and impacts brain function related to reward processing, risk-taking, and cognition in adolescents [3]. Disturbed nocturnal sleep also has consequential effects on health, increasing the risk of obesity, type 2 diabetes and cardiovascular disease [4,5].

Many factors, such as health states, emotional states, bedding conditions, and thermal environments affect sleep quality, with thermal environment being one of the most important factors [6,7]. The issues of thermal comfort in office buildings in different climates have been studied by several researchers and are well documented in the scientific literature [8]. However, the definition of sleep thermal comfort and the relationship between sleep efficiency and sleep thermal environment have not been well-established in current literature. While there are many studies on thermal environment implication to psychological and physiological responses during sleep, most are in relation to medical conditions or necessities, such as sleep deprivation thermal regulatory changes [9] or military/performance athlete needs [10]. The studies from sleep medicine could offer great help to study thermal comfort in sleeping environments, but due to their different focus they usually cover extreme temperatures which rarely occur at typical sleeping environment and they also lack information on thermal comfort and covering insulation. There have been a few researches on sleeping thermal environment and thermal comfort of sleeping people. In this paper, the questions concerning the measurement and evaluation of human sleep quality, the correlation between thermal regulation system and sleep regulation, and the characteristics of night-time space cooling load etc., are answered. The evidences illustrating the effects of thermal parameters on human sleep quality are also provided, in an attempt to shed light on the thermal comfort requirements of sleeping people.

2. Ten questions concerning thermal environment and sleep quality

2.1. *What are the characteristics of normal human sleep?*

Answer: Normal human sleep is comprised of two states—rapid eye movement (REM) and non-REM (NREM) sleep—that alternate cyclically across a sleep episode [11,12].

NREM sleep includes a variably synchronous cortical electroencephalogram (EEG) (including sleep spindles, K-complexes, and

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http://dx.doi.org/10.1016/j.buildenv.2016.01.017
0360-1323/

slow waves) associated with low muscle tonus and minimal psychological activity; the REM sleep EEG is desynchronized, muscles are atonic, and dreaming is typical. NREM sleep is conventionally subdivided into three stages (stages N1, N2, and N3) defined along one measurement axis, the EEG. The nightly pattern of sleep in adults sleeping on a regular schedule includes several reliable characteristics: 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. The stage N3 sleep is characterized by slow wave activity (brain waves of frequency 0.5 Hz–2 Hz), thus is referred to as slow wave sleep (SWS) or deep sleep. NREM sleep and REM sleep alternate through the night, with an approximately 90-min cycle.

Generally, following statements can be made regarding sleep in the normal young adults who live on a conventional sleep-wake schedule and who do not have sleep complaints:

- SWS predominates in the first third of the night and is linked to the initiation of sleep and the length of time awake [13].
- REM sleep predominates in the last third of the night and is linked to the circadian rhythm of body temperature [14,15].
- Wakefulness in sleep usually accounts for less than 5% of the night.
- NREM sleep is usually 75%–80% of sleep.
- REM sleep is usually 20%–25% of sleep, occurring in four to six discrete episodes.

2.2. Why is thermal environment one of the most important factors that affect human sleep?

Answer: The thermoregulatory control center, known as the preoptic–anterior–hypothalamus (POAH), also regulates sleep. Even at the cellular level, there is an overlap in neurons sensitive to heat and neurons changing their firing pattern preceding and during sleep. These findings may explain the association between heat loss and preparedness to sleep observed in human sleep.

First described three-quarters of a century ago, the phenomenon that the onset of sleep is accompanied by vasodilation indicates the close linkage between thermoregulation and sleep [16]. Kräuchi et al. (1999) demonstrated that sleep onset latency correlated best with the amount of heat dissipation preceding sleep [17]. The parallel between sleep and heat loss is not surprising since the major brain region that drives heat loss (i.e., the POAH) is also of crucial importance in sleep regulation. von Economo proposed that sleep was regulated by opposing wake-promoting and sleep-promoting mechanisms localized in the hypothalamus [18]. The existence of such sleep-promoting mechanism in the POAH has been confirmed by later studies [19]. POAH contains populations of warm-sensitive and cold-sensitive neurons (WSNs and CSNs), which constitute 20–25% of neurons in these areas in vivo [20]. The activation of POAH WSNs (or deactivation of CSNs) is necessary and sufficient for control of NREM sleep [19,21]. The activity of WSNs is positively correlated with local or peripheral temperature. Mild to moderate ambient temperature elevation increases coincident sleep as well as subsequent sleep in rat [22,23]. Therefore, providing a thermal comfortable sleeping environment is important for sleep maintenance. Another important aspect to consider is that the thermoregulatory response during sleep differs depending on sleep stages [7]. Sensitivity to hot or cold stimulation is reduced during REM sleep compared to NREM sleep [24,25]. Sweat rate is lower in stages N1 and N2 of NREM than in slow-wave sleep (SWS), and the lowest in REM sleep [26], which consequently decreases evaporative heat dissipation and heat tolerance in REM sleep [7].

2.3. How to evaluate sleep quality in indoor environmental quality study?

Answer: Human sleep quality can be evaluated subjectively with questionnaires, and objectively using the recording of electrooculogram (EOG) for eye movements, electromyogram (EMG) for chin muscle tension, and electroencephalogram (EEG) for brain wave. The measurements of EMG, EOG, and EEG provide the basic information requisite for classifying sleep state and examining sleep processes.

The American Academy of Sleep Medicine (AASM) published a standardized manual for conducting these measurements, and made recommendations for recording, scoring, and summarizing the sleep stages [27]. The EEG, EOG, and EMG can be summarized according to such scoring criteria as sleep stages N1, N2, N3, and REM. The scoring criteria depend upon EEG bandwidth activity (delta, theta, alpha, and beta), EEG events (vertex sharp waves, sleep spindles, and K complexes), eye movement activity (slow and rapid eye movements), and the level of muscle tone. Stage N3 is characterized by high-amplitude slow-wave activity. Stage N2 contains sleep spindles and K complexes. Stage N1 has low-amplitude, mixed-frequency background, possibly slow eye movements, and vertex sharp waves. If rapid eye movements accompany the low-amplitude, mixed-frequency EEG, and skeletal muscle tone is low, rapid eye movement (REM) sleep is present [28].

The subjective assessments are usually divided into two types. One type is the examination of the sleep quality or habits in the previous days or months to determine the existence of sleep disturbances [29,30]. The other is daily evaluation, which is applied to assess the sleep quality of the previous night [31]. Although performing subjective evaluations is convenient, the perception of comfort of the subject is apt to be influenced by emotional or psychological stress. As to the sleeping thermal environment, the insulation level and style (covered or not) and the body posture (lying or seated) adopted when the subjective assessment is made would greatly affect thermoregulation and subjective perception. For example, when the body posture changes from upright to supine, skin blood flow is strongly promoted, and the distal and proximal skin temperatures increase [32], which then increase heat loss and decrease thermal sensation.

2.4. Whether the current thermal comfort standards and practices in air conditioning are applicable for sleeping people?

Answer: Many problems regarding thermal environment are found within a few field surveys in bedrooms, indicating that the current thermal comfort theories and standards, which are mainly concerned with people in waking state, are not applicable for sleeping people.

Nowadays, the use of air-conditioning is increasing remarkably, to maintain comfortable indoor thermal environments not only in workplaces at daytime, but also in sleeping spaces at night-time such as bedrooms of residences, guest rooms in hotels and wards in hospitals, at night-time. However, the current thermal comfort standards do not either differentiate the recommended design values for sleeping and waking people (EN 15251) [33], or exclude the application in sleeping or bed rest (ANSI/ASHRAE 55–2010) [34]. Sekhar and Goh (2011) measured the indoor air temperature of 12 air-conditioned bedrooms in summer and found that the mean temperature ranged from 22.5 °C to 25.5 °C [35]. Another field monitoring of 10 air-conditioned bedrooms in summer showed that the overnight mean indoor air temperature varied between 22.6 °C and 24.2 °C [36]. These measured results show that the air temperature of bedrooms was within the generally recommended limits of air-conditioning rooms [37]. On the other hand, the survey showed that approximately 60% of the 554 respondents experienced waking up during sleep because of thermal discomfort even with their air conditioners in operation [38]. Our study showed that the subjects felt warmer at pre-sleep waking state than slept at the same ambient temperature environment (Table 1) [39,40]. The above results suggest that sleeping people have distinctive requirements on thermal comfort from waking people.

2.5. Compared with waking people, what are the effects of moderate heat on human sleep quality?

Answer: Human sleep quality is sensitive to even mild change of air temperature; the thermal comfortable temperature is higher for sleep compared with that at pre-sleep waking state.

Indoor air temperatures deviating from the thermal neutral temperature (29 °C) have been shown to increase wakefulness and decrease REM and SWS in semi-nude subjects. However, these results are based on semi-nude subjects and ignore the effects of bed covers and clothing which are generally used in real-life situations. When typical season coverings were used, the results show that the subjects took longer time to fall asleep and experienced shorter SWS as the indoor air temperature moderately deviated from the neutral temperatures (26 °C in summer and 23 °C in winter) (Figs. 1–3) [39,40]. Thus, it is believed that thermoregulatory changes provide an additional signal to the brain regions that regulate sleep and wakefulness [41]. Within the limited research on thermal environment and sleep quality, there are few studies evaluate thermal comfort during sleep, thus the causal relationship between thermal comfort and sleep cannot be developed yet. Some physiological parameters such as skin temperature and heart rate variability are found to be related to thermal comfort in waking people [42,43]. Measurements of these indicators concurrently along with sleep to monitor human thermal comfort state are needed in future researches.

Compared with pre-sleep waking, our studies observed higher thermal comfort temperature when the subjects were sleeping, using their typical insulation level (Table 1). In the winter experiment, the subjects reported that 20 °C was the most comfortable temperature at the pre-sleep waking state, but when slept with typical covering their measured sleep quality was higher (higher relative power of the sleep delta band, shorter duration of sleep onset latency, and longer slow-wave sleep) at 23 °C. In the summer experiment the subjects felt thermally neutral at 23 °C and slightly warm at 26 °C at pre-sleep waking state, while they recalled it to be uncomfortably cool at 23 °C and slightly cool at 26 °C for sleep. Similar results were reported by Kumar et al. that, when exposed to ambient temperatures ranging from 18 °C to 36 °C, the rats preferred to stay at 27 °C when they were allowed to select their own ambient temperature, but maximum sleep was recorded when the rats were maintained at 30 °C [44]. In real life, people usually set their sleeping thermal environment based on their thermal sensation at pre-sleep waking state. A field measurement in Singapore showed that for all the 12 air-conditioned bedrooms, the indoor air temperatures were as low as 21 °C and were lower than 26 °C during most time of the night [35], implying that the indoor

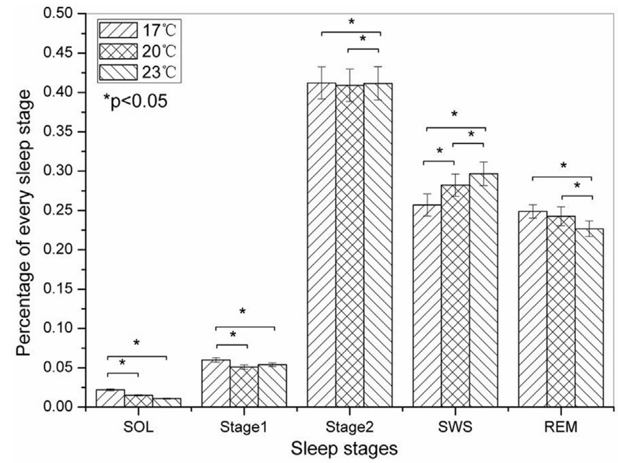

Fig. 1. Time percentages of every sleep stage for the entire night at different temperatures (error bars represent the standard deviation, SD). SOL-sleep onset latency; SWS-slow wave sleep. Eight subjects (four males and four females; age: 21.0 ± 2.0 years; height: 175.5 ± 10.5 cm; weight: 50 ± 25 kg) with a repeated measures design were exposed to the three thermal conditions [40].

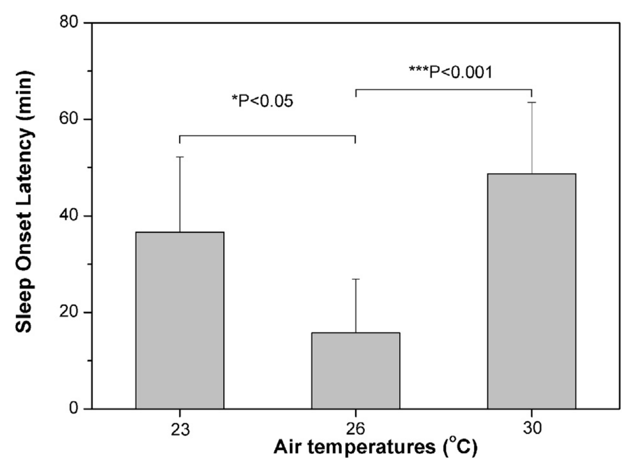

Fig. 2. Average of duration of sleep onset latency (SOL) in the three conditions (error bars represent the standard deviation, STD). Eighteen subjects (nine males and nine females; age: 23.3 ± 1.8 years; height: 171.8 ± 10.5 cm; weight: 58.1 ± 9.7 kg) with a repeated measures design were exposed to the three thermal conditions [39].

Table 1
Thermal sensation assessed before and during sleeping at different thermal conditions (mean ± STD) [39,40].

Exposure time in the chamber		Waking state (before sleep)	Sleeping state (recall after sleep)	P_{time}
Summer condition	23 °C	−0.13 ± 0.72	−1.31 ± 0.95	<0.01[a]
	26 °C	0.40 ± 0.74	−0.60 ± 0.83	<0.01[a]
	30 °C	1.39 ± 0.61	1.28 ± 0.89	ns
	$P_{temperature}$	<0.001[a]	<0.001[a]	
Winter condition	17 °C	−0.43 ± 0.53	−0.57 ± 0.79	ns
	20 °C	0.25 ± 0.46	−0.25 ± 0.71	<0.05[a]
	23 °C	0.75 ± 0.46	0.37 ± 0.52	<0.05[a]
	$P_{temperature}$	<0.001[a]	<0.05[a]	

[a] Significant differences ($P < 0.05$) between conditions observed.

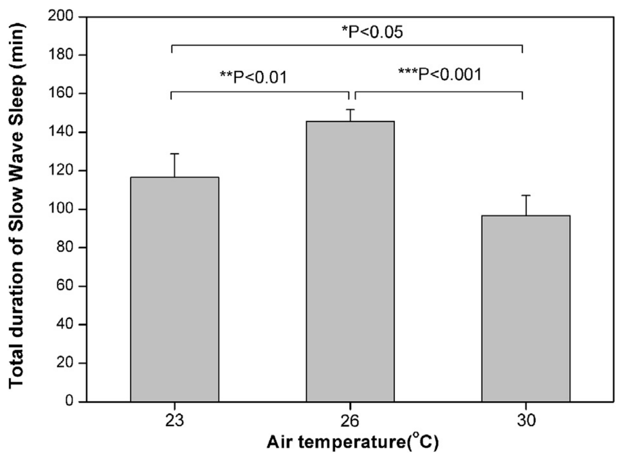

Fig. 3. Average of duration of slow wave sleep (SWS) in the three conditions (error bars represent the standard deviation, STD). Eighteen subjects (nine males and nine females; age: 23.3 ± 1.8 years; height: 171.8 ± 10.5 cm; weight: 58.1 ± 9.7 kg) with a repeated measures design were exposed to the three thermal conditions [39].

temperatures are usually kept to be unnecessarily low with air conditioner in summer. Being asleep differs from being awake by the inability of the person to consciously change their thermal environment, such as turning on a fan, or putting on or taking off clothing. Thus, direct copy of the theories from waking people could oversimplify and misunderstand the thermal comfort requirements of sleeping people.

2.6. What are the effects of humid heat exposure on human sleep?

Answer: Humid heat exposure during night sleep increases heart rate, sweat rate and thermal load that suppresses slow wave sleep and increases wakefulness.

The effects of humidity on thermal comfort become critical at high ambient temperature because evaporation (the most pronounced heat loss mechanism in the condition) is compromised in such condition. Experimental study showed that humid heat exposure during night sleep increased the thermal load, which thus suppressed SWS, REM sleep, and rectal temperature decline, and increased wakefulness in human [45]. Tsuzuki et al. (2004) observed higher heart rate and sweat rate, and lower melatonin metabolite secretion in sleeping people at humid heat than at neutral, and they suggested that the acute decrease in melatonin secretion may be related to reduced sleep efficiency [46]. The effects of partial humid heat exposure applied at different segments of sleep on sleep stages and body temperature were examined. Humid heat exposure in the initial or the later sleep segment reduced thermal load as compared to full-night humid heat exposure [47]. While humid heat exposure during the initial segment of sleep was more disruptive to sleep stage distribution, rectal temperature decline, and maintenance of clothing microclimate temperature than the same exposure during the later sleep segments [48]. So it is suggested that if air conditioning use is limited in daily life, it should be used during the initial segment of sleep to remove humid heat exposure.

Humid heat may affect sleep through homeostatic pathway possibly interfering with adenosine accumulation in basal forebrain and thereby affecting NREM sleep switch point [49]. It may also have a circadian element by interfering with thermo-regulatory feedback loop and/or by affecting skin temperature change input to sleep regulation.

2.7. What are the thermal neutral temperatures in sleeping thermal environment?

Answer: There is a fairly large range of thermal neutral temperature, indicating that a well-agreed explicit thermal neutral temperature has not been established.

Thermal neutral temperature depends on thermal factors such as humidity, air velocity, and mean radiant temperature, and human factors such as metabolic rate and clothing insulation. Table 2 summarizes the different thermal neutral temperatures for sleep reported in the published experimental studies [39,40,50–58]. The temperatures vary between 20 and 29 °C; such variation is possibly attributed to the different levels of covering insulation used in these studies. When the subjects were covered with bedding, thermal neutral temperatures of 20–26 °C were selected, and the thermal neutral temperature of 29 °C was mainly selected for subjects slept without covering. The thermal neutral temperature also varies with season, usually lower in winter. A well-agreed explicit thermal neutral temperature cannot be determined based on these experiments, because many of them are medical research and their findings are all specific to the selected conditions for sleep. Much more studies in sleeping thermal environment that involve typical season covering and measure all of the physical parameters more fully are needed, it is then possible to establish the summer and winter thermal comfort zone for sleep. It should be noted that, a same thermal neutral temperature of 26 °C was determined in the two studies that used typical summer covering [39,58].

2.8. Are there any gender differences in sleeping thermal comfort?

Answer: Females usually have poorer sleep quality and prefer a higher ambient temperature during sleep than males do.

Gender differences in thermal regulation and thermal comfort were observed in human at awakening. When exposed to heat stress, females sweat less than males in either dry or humid conditions, as the sweat glands of females are not as productive as those of males [59]. Compared with males, the cold/warm receptors in the females' skin are more sensitive, the brain receives information and gives instructions more rapidly [60], and then the skin temperature would change more rapidly to the environmental thermal changes. Accordingly, females appeared to be more sensitive to the ambient temperature [61]. Gender difference in sleeping comfort at different air temperatures was investigated with human subjects [62]. The experimental results showed that females would prefer a higher ambient temperature during sleep than the males. The finger skin temperature and finger blood flow of females were not only lower but also more sensitive to air temperature than those of males (Fig. 4, Fig. 5). The gender differences in preferred sleeping temperature could therefore be related to these physiological characteristics. Both subjective evaluations and EEG signal found better sleep quality in males under the same temperatures compared to females [62]. Many other studies also show that in general, females report a poorer sleep quality and have an increased risk for insomnia than do males [63]. Age-matched sleep bears great similarity in males and females; however, females might have slightly better preserved stage N3 sleep with advancing age [28].

2.9. Whether air flow could be used to improve thermal comfort in sleeping environment?

Answer: Personalized ventilation (PV) system including bedside PV system and bed-based task/ambient conditioning (TAC) system with very low velocity could be applied to sleeping people to

Table 2
Different thermal neutral temperatures adopted in studies.

Literature	Thermal neutral temperature (°C)	Covering level	Season	Thermal parameters
Libert et al., 1988 [50]	20	Two cotton sheets and one wool blanket, pyjamas	Spring	Indoor air temperature
Macpherson, 1973 [51]	22–24	Not reported	Summer	Indoor air temperature
Karacan et al., 1978 [52]	22.2	Sleeping apparel, a light sheet or an ordinary blanket	Not reported	Indoor air temperature
Haskell et al., 1981 [53]	29	Naked	Not reported	Indoor air temperature
Sewitch et al., 1986 [54]	20–22	Clothed (details were not reported)	Not reported	Indoor air temperature
Dewasmes et al., 1996 [55]	29	Naked	Not reported	Indoor air temperature
Dewasmes et al., 2003 [56]	25	Cotton tee-shirt and pajama pants, one cotton sheet and one wool blanket	Not reported	Indoor air temperature
Palca, 1986 [57]	29	Naked	Not reported	Indoor air temperature
Pan et al., 2012 [40]	23	Full-sleeved sleepwear, quilt (3.12 clo)	Winter	Indoor air temperature
Lan et al., 2014 [39]	26	Short-sleeved sleepwear, thin blanket (1.64 clo)	Summer	Indoor air temperature
Tsuzuki et al., 2008 [58]	26	Short pyjamas (0.22 clo), one cotton sheet and one cotton blanket	Summer	Indoor air temperature

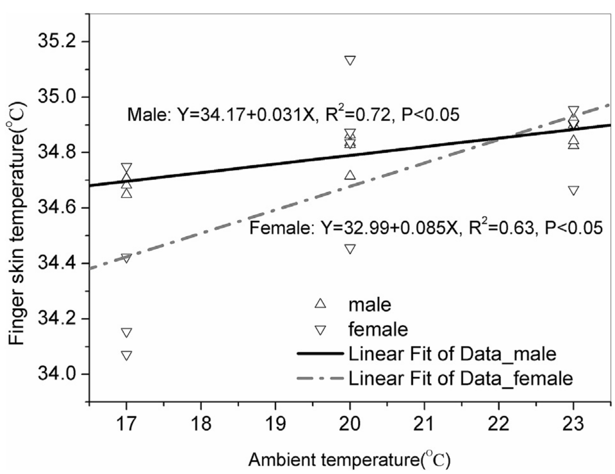

Fig. 4. Gender differences in finger temperature at different sleeping temperatures. Eight subjects (four males and four females; age: 21.0 ± 2.0 years; height: 175.5 ± 10.5 cm; weight: 50 ± 25 kg) with a repeated measures design were exposed to the three thermal conditions [62].

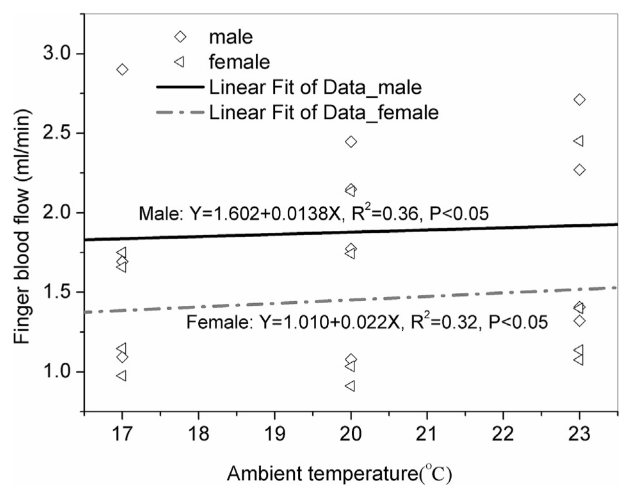

Fig. 5. Gender differences in finger blood flow at different sleeping temperatures. Eight subjects (age: 21.0 ± 2.0 years; height: 175.5 ± 10.5 cm; weight: 50 ± 25 kg) with a repeated measures design were exposed to the three thermal conditions [62].

achieve energy saving while still maintaining thermal comfort near the bed.

Airflow is an effective way to increase heat loss—an ongoing process during sleep and wakefulness in daily life. Tsuzuki et al. reported that airflow reduced the duration of wakefulness by decreasing rectal temperature, skin temperature, and body-mass loss in a warm humid condition [58]. Personalized ventilation (PV) systems may serve as a method to improve thermal comfort and indoor air quality (IAQ) in bedrooms, due to their relatively good performance in local thermal environment and air quality control [64]. The current investigations or applications of PV are mainly for awaking people, but not for sleeping people, although the immobility of the latter and the relatively small occupied space are the favorable conditions for the use of PV. It has been reported that use of PV could provide better local environment for patients in bed in hospital rooms [65,66]. Theoretical analysis demonstrated that the use of a bed-based task/ambient conditioning system that supplied air with two symmetrically placed plenums on both sides of a mattress bed could achieve energy saving, compared with the use of a full volume air conditioning system [67]. Studies on waking people found that cooling the head is more effective in reducing thermal stress than cooling any other part of the body [68,69]. Therefore, a bedside PV system (Fig. 6) that directly supplies fresh and cool/warm air to the head and face of sleeping people was proposed [70]. Experiments with human subjects were performed in winter and summer season to investigate the effects of this beside PV system on thermal comfort and sleep quality of sleeping people, and the results imply that the bedside PV could be used as a potential ventilation principle for sleeping people [70,71]. For conditions with bedside PV system, the returned questionnaires from participants reflected the thermal comfort level and subjective sleep quality were relatively higher than condition without the PV system. Physiological tests results include heart rate and heart rate variability also indicated that a calmer and more comfortable sleep could be obtained with this system. Bedsides, PV system could provide a more obvious positive impact on children than

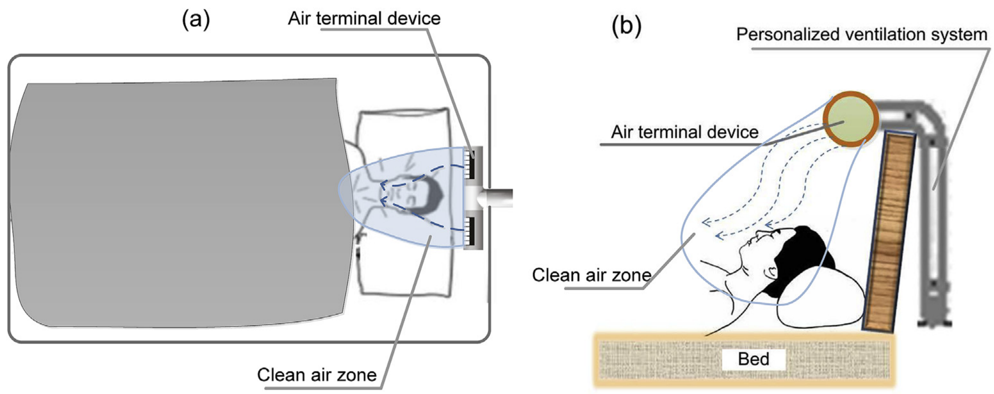

Fig. 6. (a) Overhead view and (b) side view of the bedside personalized ventilation (PV) system.

adults in sleep quality, and the impact on elderly subjects was not significant.

2.10. What are the night-time space cooling load characteristics in tropics and/or sub-tropics?

Answer: The total cooling load at night-time space peaks at the starting time of a nighttime air conditioning process, decreases rather rapidly in the next 2 hours and then decreases slowly afterwards, therefore a relatively smaller cooling capacity of an air conditioner for a bedroom could be offset by a relatively longer cool-down time.

The above results were obtained by simulating the night-time cooling load characteristics in bedrooms in a hypothetic high-rise model residential building in subtropical Hong Kong [72]. The results demonstrated that the cooling load characteristics in bedrooms at night-time operating mode are significantly different from those at daytime operating mode. At night-time, the cooling load due to the heat stored inside building envelope and furniture, which is accumulated over a non-air conditioning period if air-conditioning is not operated at daytime, dominates the total cooling load, in particular at the earlier hours of a night-time air conditioning process. For the whole duration of night-time operation, building envelope load dominates the total cooling load, followed by ventilation load, occupancy load, electric equipment load, and lighting load, respectively. Furthermore, since no solar heat gain is virtually present at night-time, orientation influences less on the total cooling load at night-time than at day-time.

The simulation results also showed that during most of the 9 hours sleep period, the total hourly space cooling load is only half or less than half of the peak load at the start of the period [72]. Therefore, the sizing of air conditioner for bedroom may be better based on the load at the later hours of, rather than the peak load at the beginning of a night-time air conditioning, with the smaller sized air conditioner starting operation adequately before occupancy [73]. The smaller sized air conditioner will lead to a minimum number of off-cycles, and consequently a minimized indoor air temperature and humidity swing, resulting in a high level of thermal comfort and operating energy efficiency.

3. Summary and conclusions

Much evidence supports that the current thermal comfort theories and standards, which are mainly concerned with people in waking state, are not appropriate for sleeping people, because the sleeping people have much different requirements for their thermal environment than the waking people. A well-agreed single thermal neutral temperature cannot be established, until more sleeping thermal comfort studies are performed involving typical season covering level and measuring physical parameters more fully. People usually sleep with bed coverings, especially in cold environment. Depending on mattress, covering, sleep wear and percentage of coverage, the total insulation of the bedding system varied greatly [74]. Thus, covering insulation is an important factor that affects indoor thermal neutral temperature for sleeping people. To accommodate individual difference and gender difference, people may use covering of different insulation level to achieve a thermal comfortable sleeping environment. Considering the effects of covering insulation, it would be interesting to study the bed thermal micro-environment around human body. The layer of air between the skin and inner surface of the clothing and covering, the clothing and covering itself and the layer of air separating the outer surface of the covering from the ambient environment form the bed mirco-environment [75]. Personal control of airflow interaction around a human body would have the potential to improve thermal comfort and inhaled air quality [75]. Preliminary studies on bed climate have been reported [76,77]. The relationships between the human body and the bed micro-environment and the ambient environment remain to be studied.

The thermoregulatory systems are strongly linked to the mechanisms regulating sleep, so it is hoped that temperature related interventions can alleviate sleep disturbances and be helpful to cure certain aspects of sleep problems in the general population. Following studies are needed to achieve these targets:

- Former studies suggest that human body possess different physiological and biochemical profiles during different periods of the night. Change in indoor environment that meet the varied thermal comfort requirements can probably improve human sleep quality. To what extent and in what way the thermal environment could be allowed to change need further investigation.
- Pilot studies showed that air flow could be applied to sleeping people to maintain thermal comfort while help to achieve energy saving. It has been confirmed in waking people that elevated air speed can be used to improve comfort beyond the maximum temperature limit within the comfort zone. However, it is not clear whether such effect is valid for sleeping people. Further studies are needed to confirm it.
- It has been indicated that cold exposure significantly changed cardiac autonomic activity during sleep, without affecting the sleep stages and subjective sensations [78]. Thus the impact of cold exposure may be greater than that of heat. Such adverse effects of cold exposure on health warrant further studies.

- Indoor air quality could be another important factor that affects sleep quality [79], but very few studies were reported in this aspect. Usually the indoor air quality can be closely linked to thermal environment, e.g., in the bedside PV system [70,71], or the interventions of open or close window. More studies are needed to investigate the impact of bedroom air quality on sleep, and maybe primarily of people with respiratory disease.

Author biography

Zhiwei Lian is a full professor and Li Lan is an associate Professor at Shanghai Jiao Tong University. They have conducted extensive laboratory experiments and field studies with human subjects, investigating the effect of different indoor environmental factors on health, sleep quality, comfort and productivity, and co-authored dozens of peer-review journal papers on thermal environment and human sleep quality. Professor Lian pioneered the research on thermal comfort and sleep environment by introducing the measurement of physiological parameters into the IEQ area to elucidate the physiological mechanisms involved, and he is the principal investigator of ten (including a Key Program) projects funded by the National Natural Science Foundation of China (NSFC). Dr Lan is the principal investigator of three undergoing projects on sleeping environment funded by the NSFC and the China Postdoctoral Science Foundation.

Acknowledgements

This work was financially supported by the National Natural Science Foundation of China (No. 51408260 and 51238005).

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