Pilot study on the application of bedside personalized ventilation to sleeping people
Li Lan a, Zhiwei Lian a,*, Xin Zhou a, Chanjuan Sun a, Hongyuan Huang b, Yanbing Lin b, Jiangmin Zhao a
a Department of Architecture, School of Naval Architecture, Ocean & Civil Engineering, Shanghai Jiao Tong University, Shanghai 200240, China
b The Third Shanghai People’s Hospital, Shanghai 201900, China

Article info
Article history:
Received 13 March 2013
Received in revised form 2 May 2013
Accepted 18 May 2013

Keywords:
Bedside personalized ventilation
Sleep
Sleep quality
Health
Indoor air quality
Thermal comfort

A B S T R A C T
A bedside personalized ventilation (PV) was proposed to be used in the bedroom. An experiment with human subjects was performed to ascertain whether there are any negative consequences if applying this PV to sleeping people. Thirty-six subjects slept in the thermal neutral bedrooms with or without the bedside PV for a whole night in a winter season, while their physiological parameters and body movement were continuously measured. The autonomic cardiac measurements showed that the power of very low frequency (VLF) component and the low/high frequency (LF/HF) ratio of the subjects significantly decreased when the PV was turned on, although no significant change in sleep quality (measured with questionnaire and actigraphy) was found. They perceived to be cooler and their skin temperature decreased when they slept with PV, even if the supplying air temperature of PV was slightly higher than that of the background environment. The present study implies that the bedside PV could be used as a potential ventilation principle for sleeping people.

1. Introduction
People spend about 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 [1,2]. The indoor environmental parameters including air temperature, relative humidity and indoor air quality (IAQ) etc. could significantly affect sleep quality. Air temperatures that are higher or lower than the neutral temperature decrease slow wave sleep (SWS) and rapid eye movement (REM) sleep, and increase the frequency and duration of wakefulness [3,4]. Moreover, our study found that sleeping people had different thermal comfort requirements from waking people [5]. Combined with high humidity, humid heat exposure during night sleep increases wakefulness and decreases SWS, REM and melatonin secretion, probably through thermoregulatory mechanisms [6,7]. Elevated air flow has been found to be able to reduce the heat load and facilitate sleep in a warm humid condition [8]. Although there was no clear evidence to substantiate that sleeping duration decreased with increasing levels of CO2, the findings did suggest that high levels of CO2 may hinder the duration of sleep [9]. For awaking people, studies have found that poor air quality or increased CO2 concentration causes sick building syndrome (SBS) symptoms such as increased prevalence of headache, decreased ability to think clearly, etc. [10,11].

Many problems were found regarding the current situation of IAQ and thermal environment in bedrooms in the field surveys. The study in Korea shows that people were exposed to too low or high air temperatures and high CO2 concentration etc., when asleep [12]. Similar results were found in high-rise residences in Hong Kong that most people felt stuffy because of poor IAQ, and that approximately 60% of the respondents had experience of waking up during sleep because they felt either cold or warm even if air-conditioners were turned on in their bedrooms [13]. Measurement in the bedrooms of 500 Danish children show that 23% of the rooms experienced at least a 20-min period during the night when the CO2 concentration was above 2000 ppm and 6% of the rooms experienced concentrations above 3000 ppm [14]. Sehar found that in Singapore the overnight build-up of CO2 level in a bedroom served by a split system air-conditioning unit can be as high as 2900 ppm, due to lack of ventilation [15]. At present most Chinese homes with forced air conditioning have no mechanical supply of outdoor air.

Personalized ventilation (PV) systems may be served as a method to improve thermal comfort and IAQ in bedrooms, due to
their relatively good performance in local thermal environment and air quality control [16–18]. 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. Pan et al. probably are the pioneers who reported the energy saving performance of a novel bed-based task/ambient conditioning (TAC) system that supplied air with two symmetrically placed plenums on both sides of a mattress bed; their study demonstrated that the use of the bed-based TAC system could achieve energy saving, compared with the use of a full volume air conditioning system [19]. However, to the best of our knowledge, there is no report covering the effects of TAC or PV on sleeping people.

Unlike the bed-based TAC that ventilates the whole body, we proposed to use a bedside PV system (Fig. 1) that directly supplies fresh and cool/warm air to the head and face of sleeping people. Studies on awaking people found that cooling the head is more effective in reducing thermal stress than cooling any other part of the body [20,21]. Desruelle and Candas demonstrate that, combining with cool air breathing, face skin cooling effectively caused a reduction in heat strain [22]. The study of Okamoto-Mizuno et al. reveals that the use of cooling pillow helped to decrease the whole-body sweat rate during sleep under humid heat conditions [23]. The Krauchi et al.’s report is another important reason why we preferred the bedside PV system; their study indicates that foot skin temperature is important for good sleep, and it has to be kept comparatively higher to promote the rapid onset of sleep [24]. However, great caution should be paid when applying this bedside PV to human subjects, because the continuous ventilation time could be very long (up to 7 h or more throughout the sleeping period) and most sleeping people are defenseless with respect to their immediate environment. In this study we carried out an experiment with human subjects cautiously at thermal neural environments, mainly aiming to ascertain whether the bedside PV would cause any negative consequences to the sleeping people if it was used for a whole night time.

2. Methods

2.1. Bedside PV for sleeping people

Fig. 1 shows the sketch map of this bedside PV system. The air terminal device, i.e. the cylindroid movable panel (CMP) will supply clean air directly to the breathing zone of the sleeping people meanwhile cool/warm the face skin, under the individual control. The CMP is mounted on a movable arm-duct, which allows the position of the CMP to the sleeping people and the direction of supplying air to be changed by the individuals. Each PV also offers occupants the possibility to adjust the flow rate and temperature of personalized air. The clean air zone may change, depending on the position and direction of CMP as well as the parameters of supplied air.

2.2. Approach and facility

The experiment was carried out from December to next January in two identical bedrooms of a residential building in Shanghai (Fig. 2); the two bedrooms were equipped with the same type of bedside PV and their background temperature and humidity were centrally air-conditioned by radiant ceiling panel system and a local upward supplied fresh air (supply inlet A as shown in Fig. 2) with a constant ventilation rate of 10 L/s. The outdoor air supplied by the PV was conditioned independent of the background environment by another air handling system; the air temperature and humidity were accurately controlled. Two sleeping conditions were investigated, i.e., condition 1 (C1) – the bedside PV was turned off, and condition 2 (C2) – the bedside PV was turned on, supplying a...
fresh air of 24 °C with a velocity of 0.15 m/s when arrived at the surface of subject’s face. This set of PV supplying parameter was chosen from 12 combinations of temperature and velocity that were assessed by another 8 subjects in the pre-experiment. The background environment of C1 and C2 was kept to be a similar thermal neutral environment. The noise level (occupants slept in the room) was 30 dB(A) and increased to about 35 dB(A) when the bedside PV was turned on.

The background temperature and humidity were measured with data logger at two positions, i.e., the middle of the bed head and bed end, both at a height of 0.4 m above the bed. The data logger has a built-in temperature (range: −20 to 70 °C, accuracy: ±0.7 °C) and humidity (range: 0−95%, accuracy: ±5%) sensors. When the PV was turned on, the air temperature and velocity near the face area of the subject (at a height of 0.2 m above the bed) were measured (UAS1100, range: 0.15−1.0 m/s, accuracy: ±5% of measured value). All of the instruments had been calibrated.

2.3. Subjects

Thirty-six subjects (18 males; 6−72 year old, mean ± SD: 35.08 ± 24.75 years) were recruited for this experiment based on the following criteria: having no complaints relevant to sleep, absence of chronic diseases, asthma, allergy and hay fever. The information was obtained from a questionnaire distributed during recruitment; none was examined medically. Three age groups were classified in this study: 6–14 years (children, 12 subjects and 6 females), 20–55 years (young and middle-aged, 12 subjects and 6 females), and over 60 years (elderly, 12 subjects and 6 females). The subjects were exposed to the two conditions in a balanced order, i.e., half of the subjects participated C1 first and half of them participated C2 first. All protocols were approved by the university’s ethics committee and conformed to the guidelines contained within the Declaration of Helsinki. Verbal and written informed consent was obtained from subjects before they participated in the experiment.

2.4. Measurements

The following measurements were performed in this experiment.

2.4.1. Subjective questionnaires

Every morning the subjects reported their subjective perception of sleep quality on six items, i.e., calmness of sleep, ease of falling asleep, ease of awakening, freshness after awakening, satisfaction about sleep and sufficient sleep [25]. The former five items are five-graded response alternatives with higher score (from 1 to 5) indicating better sleep quality, and the last one required just saying “yes” or “no”. A 7-point scale (−3−cold, −2−cool, −1−slightly cool, 0-neutral, 1−slightly warm, 2-warm, 3-hot) was used to register thermal sensation. Thermal comfort was casted on a 6-point scale (−3−very uncomfortable, −2−uncomfortable, −1−slightly uncomfortable, 1−slightly comfortable, 2-comfortable, 3−very comfortable). Similar questionnaires were used in the two conditions, except that the subjects had to assess whether the temperature and velocity of PV supplying air is too high both on a 5-point scale (−2−low, −1−slightly low, 0−just right, 1−slightly high, 2−high) before and after sleep if the PV was turned on. After two nights’ exposure, they also assessed whether the sleeping environment is more favorable when the PV was turned on, compared to without PV.

2.4.2. Actigraphy

Actigraphy is a method used to study sleep-wake patterns and circadian rhythms by assessing movement, most commonly of the wrist [26]. In this study the whole night actigraphic data were collected at 30-s intervals by Actiwatch (Actiwatch 2, Respironics, USA) worn on the nondominant wrist. Five sleep statistics were calculated based on the actigraphic data, including sleep time — total time scored as sleep (min), sleep onset latency — period of time between bed time and sleep start (min), snoring time — time between end of sleep and get up time, (min), sleep efficiency — percentage of time in bed actually spent sleeping (%), and wake after sleep onset (WASO) — the time in a sleep interval scored as wake (min).

2.4.3. Electrocardiogram (ECG)

Spectral analysis of heart rate variability (HRV) has been demonstrated as a sensitive noninvasive technique to evaluate cardiac autonomic function during sleep [27]. In this experiment the cardiac signal was recorded throughout the night by a PowerLab 8/30 system (AD Instruments, Australia) at a samprae rate of 500 Hz. After the recorded ECG data were visually inspected for rejecting artifacts, power spectral analysis was performed at repeated ectopic-free intervals of 5 min for the whole night sleep course by the software of Chart for Windows (ChartTM 5, AD Instruments, Australia). Three frequency bands could be derived from the spectral analysis of HRV, including the very low frequency (VLF, 0.02−0.05 Hz) component which is related to neurohumoral and thermal regulatory influences over heart rate, the low frequency (LF, 0.05−0.15 Hz) which is related to a mixture of sympathetic and parasympathetic modulation, and the high frequency (HF, 0.15−0.4 Hz) component which is primarily related to parasympathetic (vagal) activity [28,29]. The following parameters were then evaluated: the heart rate per minute, the power of VLF, LF and HF components, and the LF/HF ratio which reflects the sympathovagal balance [30]. Due to the limited recording device, the cardiac signal of 18 subjects was recorded. The ECG data of children were invalid and excluded from analysis, due to their frequent movement during sleep. Then the ECG data of 12 adults were analyzed.

2.4.4. Skin temperature

The skin temperature of 7 points (including forehead, chest, posterior forearm, hand, anterior thigh, anterior calf and foot) were continuously measured with a platinum film resistance system developed by our research team [31]. All resistances (accuracy: ±0.1 °C) were linked to a multi-channel data acquisition system that automatically collected data with a sampling interval of 10 s. Mean skin temperature was calculated as the sum of local skin temperatures and their respective weight factors according to the seven-point method [32].

2.5. Procedure

Every night two subjects participated in the experiment and slept in the two bedrooms (but with the same sleeping condition), respectively. The experiment was completed in 36 days. During sleep, the subjects wore full-slip sleepwear and were covered by quilt; the resistance of the covering materials including the clothing was estimated to be 3.27 clo [33]. The detailed procedure of each experimental session is shown in Fig. 3. After arriving at the apartment, the subjects rested in their bedrooms for 30 min. Then they washed up and changed their clothes, and the physiological parameters (ECG and skin temperature) probes were applied; this process lasted 45 min. Next the subjects filled out questionnaires on thermal sensation and comfort. Theirs perception on PV supplying air were assessed twice when the PV was turned on, i.e., 12 min and 2 min before lights off, respectively. Then the lights were turned off and the actigraphic data, ECG and skin temperature were continuously measured throughout the night till the next
morning. After getting up, the subjects assessed sleep quality and PV supplying air (if it was turned on) on questionnaires. The subjects went to bed at their normal time and got up when they wished. The exact time of going to bed and getting up were record by the experimenters.

2.6. Statistical analysis

The SPSS 13.0 (SPSS Inc., Chicago, IL, USA) program was used to make the statistical analysis considering gender and age as between-subject factors. The measured data were subject to analysis of variance in a repeated measures design. LSD Post hoc analysis was applied if necessary. The significance level was set to be 0.05 (P ≤ 0.05).

3. Results

Table 1 shows the physical parameters describing the indoor environment in the bedrooms as well as the local environment near the subject’s face (if the PV was turned on). The background temperature and humidity in the bedroom were similar under both conditions. When the PV was turned on, a low velocity of 0.15 m/s was kept and the temperature near the subject’s face was 1 °C higher than that of the background environment; the local temperature and velocity did not deviate from the intended levels.

About half subjects felt slightly warm and the others felt thermal neutral when they slept in the bedroom of 23 °C with a 3.27 clo covering; the use of PV significantly cooled down their thermal sensation (Table 2). No significant difference in thermal comfort was found between the two conditions. No other significant between-subjects effects (age and gender) or interaction effects were found. Compared with no PV, 75% subjects assessed that it was more favorable, and 12.5% subjects assessed that it was less favorable to turn on PV during their sleep period; the other 12.5% voted that there was no difference.

Most subjects perceived that the supplying temperature and velocity of PV were just right no matter before or after sleep; very few of them felt that the supplying velocity was slightly high (Fig. 4a and b). No subject except one (aged 70 years old) who complained that there was a little noise when the PV was turned on.

The subjects assessed that they had good sleep when the PV was or was not used; no significant difference in subjective sleep quality was found between the two conditions (Table 3). At both conditions, there were two children complained that they did not have sufficient sleep. Compared with males, the female subjects were easier to wake up in the morning (4.06 ± 0.72 versus 3.53 ± 1.03, P < 0.05), felt fresher after wake up (4.22 ± 0.77 versus 3.69 ± 0.96, P < 0.05), and expressed higher satisfaction to their sleep (4.28 ± 0.44 versus 3.92 ± 0.88, P < 0.05). The elderly were easier to wake up in the morning than the young and middle-aged group (4.21 ± 0.83 versus 3.46 ± 0.83, P < 0.05). No other significant between-subjects effects (age and gender) or interaction effects were found.

Based on the continuous measurement of body movement with Actiwatch, the five parameters of sleep quality were calculated. No significant difference in the five sleep quality parameters was found between the two conditions (Table 4). Compared with subjects younger than 60, the subjects aged above 60 have shorter sleep onset latency (4.0 ± 6.8 min versus 19.2 ± 17.3 min with young and middle-aged group, P < 0.01), but longer WOSA (146.0 ± 60.9 min versus 67.8 ± 44.1 min with children, P < 0.01; 146.0 ± 60.9 min versus 64.3 ± 43.5 min with young and middle-aged people, P < 0.01), and lower sleep efficiency (67.2 ± 10.2% versus 84.1 ± 8.6% with children, P < 0.01; 67.2 ± 10.2% versus 79.5 ± 12.0% with young and middle-aged people, P < 0.05). No other significant between-subjects effects (age and gender) or interaction effects were found on the above analyzed items.

### Table 1

<table>
<thead>
<tr>
<th>Conditions</th>
<th>Without PV</th>
<th>With PV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Environment in the bedroom</td>
<td>Temperature (°C) 22.9 ± 0.8 22.9 ± 0.8</td>
<td>Humidity (%) 52 ± 3 43 ± 4</td>
</tr>
<tr>
<td>Local environment near PV</td>
<td>Temperature (°C) /</td>
<td>Velocity (m/s) / 0.14 ± 0.02</td>
</tr>
</tbody>
</table>

### Table 2

<table>
<thead>
<tr>
<th>Condition</th>
<th>C1</th>
<th>C212min</th>
<th>C22min</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.53 ± 0.05</td>
<td>0.23 ± 0.60</td>
<td>0.16 ± 0.52</td>
<td>0.04*</td>
</tr>
<tr>
<td>Thermal sensation</td>
<td>1.56 ± 1.00</td>
<td>1.73 ± 0.88</td>
<td>1.65 ± 0.84</td>
<td>0.76</td>
</tr>
<tr>
<td>Thermal comfort</td>
<td></td>
<td></td>
<td></td>
<td>0.41</td>
</tr>
</tbody>
</table>

*P < 0.05.

*C1-without PV, C212min, C22min = 12 min and 2 min before lights off at C2 (with PV) condition, respectively.*
The mean skin temperature averaged along the whole night sleep was analyzed; lower mean skin temperature was observed when the PV was turned on (34.8 ± 0.4°C without PV versus 34.6 ± 0.5°C with PV, P < 0.01). The mean skin temperatures of females are significantly higher than that of males (34.7 ± 0.5°C versus 34.5 ± 0.4°C, P < 0.05); no significant age effects or interaction effects on mean skin temperature were found. Fig. 5 shows the variation of mean skin temperature over the whole night. It can be seen that the subjects’ mean skin temperature was lower with PV compared with no PV throughout the night. Their mean skin temperature increased rapidly after lights off and peaked about 25 min later; after this period, their skin temperatures decreased gradually for about 30 min and then fluctuated with smaller variations.

Significant decreases of power in VLF band and LF/HF ratio were found when the bedside PV was turned on during the sleeping period (Fig. 6). The power in LF and HF bands also reduced when the PV was turned on, although no significant difference was found. No significant difference in heart rate were found between the two conditions (67.9 ± 7.4 BPM without PV, 66.9 ± 4.9 BPM with PV, P = 0.34). No other significant between-subjects effects (age and gender) or interaction effects on these HRV indexes were found.

4. Discussion

Poor sleep quality impairs cognitive performance in older adults [34], and more significantly, impacts brain function related to reward processing, risk-taking, and cognition in adolescents [35,36]. Disturbed nocturnal sleep has also been found to be related to various adverse health problems, increasing the risk of death from cardiovascular disease [37]. Therefore, providing a good sleeping environment is important for sleep maintenance as well as daytime activities and health status. However, the survey results indicate that both the thermal environment and IAQ of bedrooms are not good in many countries [12–15]. The need to improve sleeping environment quality was also expressed by the medical and indoor environmental quality (IEQ) experts in the questionnaire survey we performed prior to the above described experiment. Fifty Western medicine (WM) experts and 78 traditional Chinese medicine (TCM) experts from the hospitals and medical institutes in China, as well as 57 IEQ experts studied topics related to thermal comfort, indoor air quality and air distribution were approached; forty WM experts, 75 TCM experts and 52 IEQ experts

**Table 3**

<table>
<thead>
<tr>
<th></th>
<th>Mean ± SD Without PV</th>
<th>Mean ± SD With PV</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calmness of sleep</td>
<td>4.03 ± 0.91</td>
<td>3.97 ± 1.03</td>
<td>0.83</td>
</tr>
<tr>
<td>Ease of falling asleep</td>
<td>4.06 ± 0.86</td>
<td>4.06 ± 0.86</td>
<td>1.00</td>
</tr>
<tr>
<td>Ease of awakening</td>
<td>3.86 ± 0.83</td>
<td>3.72 ± 1.00</td>
<td>0.45</td>
</tr>
<tr>
<td>Freshness after awakening</td>
<td>4.03 ± 0.85</td>
<td>3.89 ± 0.95</td>
<td>0.51</td>
</tr>
<tr>
<td>Satisfaction about sleep</td>
<td>4.11 ± 0.52</td>
<td>4.08 ± 0.91</td>
<td>0.88</td>
</tr>
</tbody>
</table>

**Table 4**

<table>
<thead>
<tr>
<th></th>
<th>Mean ± SD Without PV</th>
<th>Mean ± SD With PV</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sleep efficiency (%)</td>
<td>78.85 ± 12.39</td>
<td>78.03 ± 11.66</td>
<td>0.87</td>
</tr>
<tr>
<td>Sleep onset latency (min)</td>
<td>12.00 ± 14.05</td>
<td>10.35 ± 14.94</td>
<td>0.94</td>
</tr>
<tr>
<td>Sleep time (min)</td>
<td>392.9 ± 72.1</td>
<td>391.5 ± 79.8</td>
<td>0.68</td>
</tr>
<tr>
<td>Snooze time (min)</td>
<td>13.8 ± 11.1</td>
<td>13.7 ± 13.1</td>
<td>0.69</td>
</tr>
<tr>
<td>WOSA (min)</td>
<td>78.9 ± 58.0</td>
<td>87.7 ± 55.9</td>
<td>0.66</td>
</tr>
</tbody>
</table>

Fig. 5. Variation of mean skin temperature throughout the night.
distributed. The WM experts expressed their opinion on the effects of PV on human respiratory, nervous, circulatory, and immune systems, and the TCM experts on human respiratory, nervous, and circulatory systems as well as the meridians dredging and qi-flow regulation. The latter are two important body functions in TCM theory that a vital energy or life force called qi-flow circulates in the body through a system of pathways called meridians; human health could be maintained when the qi-flow circulates smoothly through the meridians [38]. The IEQ experts expressed their opinion on the effects of PV on air distribution, indoor air quality, thermal comfort, and overall sleeping environment quality around the sleeping people. There were 52.8% WM experts thought that the use of PV could improve the health of respiratory system, and should have no effect on the nervous, circulatory and immune systems. Compared with WM experts, the TCM experts expressed even more positive attitude to the use of bedside PV. There were 65.7% and 71.0% TCM experts voted that the respiratory system and qi-flow regulation of the sleeping people could be improved. More than half TCM experts thought that the use of bedside PV could improve the function of circulatory system and meridians dredging. Almost all (98%) of the consulted IEQ experts thought that the air quality as well as the air distribution around the sleeping people would be better if the PV was used. More than 60% of them voted that the thermal comfort and overall sleeping environment quality could be improved by PV. In brief, most medical and IEQ experts support to apply this bedside PV in bedroom. Not until got these positive feedbacks from experts did we test the effects of PV on the human subjects, who confirmed that it was more favorable to turn on PV during their sleep period.

An important finding in this subjective experiment was that the LF/HF ratio significantly decreased when the PV was turned on during the sleeping period (Fig. 6). Our former studies have demonstrated that for the awaking people, their LF/HF ratio (reflects the sympathovagal balance) was higher when they stayed in uncomfortable cold or hot environment than in thermal comfort [48]. The latter are two important body functions in TCM theory that a vital energy or life force called qi-flow circulates in the body through a system of pathways called meridians; human health could be maintained when the qi-flow circulates smoothly through the meridians [38]. The IEQ experts expressed their opinion on the effects of PV on air distribution, indoor air quality, thermal comfort, and overall sleeping environment quality around the sleeping people. There were 52.8% WM experts thought that the use of PV could improve the health of respiratory system, and should have no effect on the nervous, circulatory and immune systems. Compared with WM experts, the TCM experts expressed even more positive attitude to the use of bedside PV. There were 65.7% and 71.0% TCM experts voted that the respiratory system and qi-flow regulation of the sleeping people could be improved. More than half TCM experts thought that the use of bedside PV could improve the function of circulatory system and meridians dredging. Almost all (98%) of the consulted IEQ experts thought that the air quality as well as the air distribution around the sleeping people would be better if the PV was used. More than 60% of them voted that the thermal comfort and overall sleeping environment quality could be improved by PV. In brief, most medical and IEQ experts support to apply this bedside PV in bedroom. Not until got these positive feedbacks from experts did we test the effects of PV on the human subjects, who confirmed that it was more favorable to turn on PV during their sleep period.

An important finding in this subjective experiment was that the LF/HF ratio significantly decreased when the PV was turned on during the sleeping period (Fig. 6). Our former studies have demonstrated that for the awaking people, their LF/HF ratio (reflects the sympathovagal balance) was higher when they stayed in uncomfortable cold or hot environment than in thermal comfort [39,40]. Lavigne et al. found that the autonomic cardiac nervous system remains reactive to external sensory inputs during sleep [41]. Higher LF/HF ratio has been observed at REM sleep stage [27,42] and observed to be inverse coupling with os-cillations in the delta frequency band of brain wave, which reflects the depth of sleep [43,44]. Therefore, the lower LF/HF ratio should indicate that the subjects experienced more deep sleep, i.e., better sleep quality when the bedside PV was turned on. However, this result is not reflected in the questionnaire and actigraphy measurements, which did not find significant change in sleep quality between the two conditions. The reasons for this inconsistency are unclear at present. Future studies exploring other sleep quality assessment such as brain wave measurement are needed to validate it.

Similar to the results reported by Pan et al. [5,45], Kräuchi et al. [46] and Kräuchi [47], increase in skin temperature after lights off was observed; this increase may due to relaxation (withdrawal of the sympathetics vasoconstrictor tonus) [46,47]. The decreased metabolic rate after sleep onset is possibly one of the main causes of subsequent skin temperature decrease. In this experiment we found that the subjects’ mean skin temperature decreased and they perceived to be cooler with PV even if the supplying air temperature of PV (about 24 °C) was slightly higher than that of background environment (about 23 °C). This result may indicate that the bedside PV is more favorable to be used for cooling than for heating. However, great caution should be paid if lower temperature air is supplied because sleeping people are speculated to be more sensitive to draft. Although in this experiment the noise level did not exceed 35 dB, a level that had no effect on sleep quality [48], and there was only one elderly who complained about noise, PV terminals with lower noise level that had no effect on sleep quality [49,50] and measured, so it is unable to evaluate the effects of bedside PV on inhaled air quality. This experiment was not double blind so the subjects knew whether the PV was turned on or off, this may lead to bias of some subjective feelings, but it should affect the physiological parameters to a much less extent.

5. Conclusions

A bedside PV system that supplies fresh air to the breathing zone of sleeping people was applied to human subjects for a whole night sleep. The subjects perceived to be cooler and their skin temperature decreased when the bedside PV was turned on, even if the supplying air temperature of PV (about 24 °C) was slightly higher than that of the background environment (about 23 °C). Compared with no PV, the VLF power and the LF/HF ratio throughout the sleep significantly decreased when the PV was turned on, although no significant differences in subjective sleep quality and actigraphy measurement were found. The present results imply that the bedside PV could be used as a potential ventilation principle for sleeping people in the bedrooms. Future research should focus on (i) occupant’s response (including health, thermal comfort, and sleep quality) to PV in hot or cold environment; (ii) operation zone (supply temperature, velocity, turbulence, etc.) of bedside PV for sleeping people; and (iii) design of (e.g., lower noise) PV terminals that are better meet the requirements of sleeping people.

Fig. 6. Effects of bedside personalized ventilation on heart rate variability (HRV).
Acknowledgments

This work was supported by the National Natural Science Foundation of China (No. 51108260 and 51238005). The authors also would like to thank the experts and the subjects who actively participated in this study.

References