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Publication date:
2021

Document Version
Publisher's PDF, also known as Version of record

Link back to DTU Orbit

Citation (APA):
Fan, X., Sakamoto, M., Shao, H., Kuga, K., Lan, L., Ito, K., & Wargocki, P. (2021). *Can human CO_2 emission rates staying awake be used staying asleep?*. Paper presented at Healthy Buildings Europe 2021, Oslo, Norway.

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Can human CO_2 emission rates staying awake be used staying asleep?

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INTRODUCTION

Indoor air quality (IAQ) has been imposed to negatively affect humans, not only the comfort and work performance staying awake (Wargocki, 1999; Zhang *et al.*, 2017a, b) but also sleep quality during sleep and its consequence on next-day work performance (Strøm-Tejsen *et al.*, 2016; Xu *et al.*, 2020). Therefore, sufficient ventilation needs to be secured and has far-reaching implications for occupants' health. However, we should note that ventilation ensures good IAQ at the cost of energy consumption. The ventilation rate (VR) should then be determined precisely and reasonably.

Currently, the required VR can be calculated for most buildings using CO_2 concentration by a mass-balance equation under a steady-state (ASHRAE Standard 62.1-2016, 2016). This estimation entails the knowledge of human CER. Persily and De Jonge proposed a new approach to estimate CER based on understanding human metabolism and exercise physiology (Persily and de Jonge, 2017). Previous studies have also shown that increasing temperature from 22°C to 26 °C didn't significantly influence CER (Bivolarova et al., 2019; Markov et al., 2021). Decreased IAQ significantly reduced CER by ca. 13% (Bakó-Biró et al., 2005). While most of these data are for people staying awake. There is minimal information on CER from sleeping people. Whether the CER from awake people can be used for sleeping people is still unknown, even it is reasonable to speculate that this is not the case as CER is a function of physical activity level (Yang *et al.*, 2020). People's physical activity level should be lower during sleep than staying awake as humans remain still for on average 7-8 hours during sleep. But this lacks evidence to support it.

The objective of the present study was to experimentally determine the human CER during sleep and compare it with that of humans staying awake.

METHODS

Eleven healthy subjects were recruited (height: 1.67±0.08 m; weight: 60.4±5.4 kg; age: 28.3±4.1 (y), BMI: 21.6±1.4 kg/m²). They were asked to sleep for four nights in a specially constructed capsule (net volume: 1.911 m³) located in a climatic chamber under three conditions (**Table 1**). The sleeping capsule was designed to create a confined and well-sealed space with its own ventilation devices. The first night was for adaption to eliminate the potential bias of an unfamiliar sleep environment. Subjects were asked to self-adjust their pajamas until thermal neutral at 23 °C and then wear the same pajamas during the whole experimental period. The physiological reactions and subjective responses were collected. The sleep quality was measured objectively and subjectively. The chemical emissions during sleep were also monitored. Subjects were also asked to complete the cognitive tests before and after sleep to examine the changes in work performance. These results will be presented elsewhere. The CER was estimated using a mass-balance equation (1) after the CO_2 concentration reached steady-state.

$$CER = Q * (C_{in} - C_{out})/1000 \quad (1)$$

Where Q: ventilation rate (m³/h); C_{in}: mean CO_2 concentration (ppm); C_{out}: ambient mean CO_2 concentration (ppm).

The obtained data were first tested for normality using Shapiro-Wilk's test. Normally distributed data were subjected to analysis of variance in a repeated measures design. The differences induced by various conditions were tested by post hoc analysis using the Bonferroni test. Non-normally distributed data were analyzed using Friedman's analysis of variance and the Wilcoxon Signed-Ranks test to examine the effects of conditions on humans. The statistical analysis was done with SPSS 22.0. The significance level was set at P=0.05 (2-tail).

RESULTS & DISCUSSION

The physical parameters describing the sleep environment quality in the capsule are summarized in **Table 1**. The measured temperature and CO_2 concentration were maintained in the intended levels, and the measured air temperature did not exceed 0.3 °C compared with the designed group. The deviation between the measured CO_2 concentration and the intended CO_2 level was within 30 ppm. The relative humidity was not controlled but still in the comfortable zone(Arundel *et al.*, 1986).

Table 1. Physical measurements in the capsule (Mean±SD) at different conditions.

Planned conditions		Measured parameters		
T (°C)	CO2 concentration (ppm)	T (°C)	CO2 concentration (ppm)	Relative humidity (%)
24	800	23.7±0.2	771±34	48±2
24	1700	24.0±0.2	1671±121	57±3
28	800	28.0±0.2	795±75	40±3

Figure 1 dedicates the calculated CER and its variation at three conditions. The measured CER was on averaged 11.16 L/h per person, ranging from 9.87 to 13.04 L/h per person at the reference condition of T24P800. Compared with reference condition, when decreasing IAQ indicated as increased CO_2 concentration from 800 to 1700 ppm, the mean CER reduced slightly to 10.51 L/h per person in the range of 7.14 to 13.80 L/h per person. The mean CER increased slightly (mean:11.43 L/h per person, range: 8.82-14.58 L/h per person) when the temperature increased from 24 °C to 28 °C. However, no significant differences in CER were observed, either increasing temperature or decreased IAQ indicated by increased CO_2 concentration. The CER for sleeping people can be thus obtained by averaging the values among three conditions. The CER during sleep is 11.04±1.43 L/h per person.

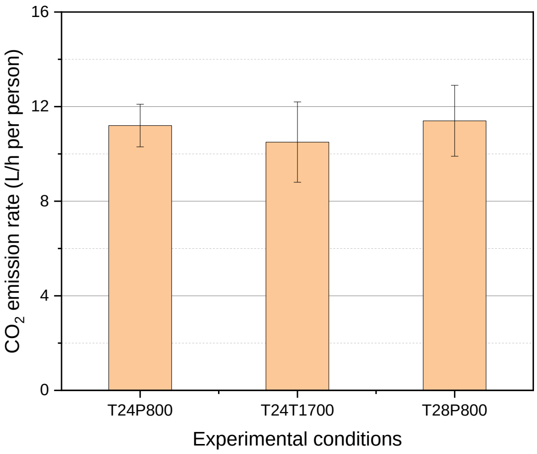

Figure 1. Estimated CO_2 emission rate across conditions. *Note: T24 represents the temperature of 24°C, and P800 represents a CO_2 concentration of 800 ppm.*

Two widely adopted equations from the published paper (Persily and de Jonge, 2017) and the standard (ASHRAE Standard 62.1, 2016) to calculate the CER were also used in the present study. The calculated CERs are shown in **Fig. 2**. The calculated human CERs during sleep are 10.1±1.1 L/h per person and 10.84 L/h per person by equations from Persily and Jonge (2017) and ASHRAE Standard 62.1 (2016), respectively. These CERs are similar to what was observed in the present study.

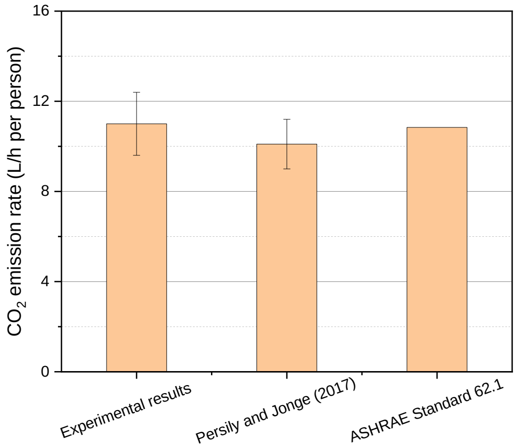

Figure 2. Comparison of CO_2 emission rate from the present study with standard and previous research.

Figure 3 depicts the differences in CER between sleep and awake people. Two different physical activity levels (Lying and light office work) were chosen to compare with. It can be seen that the calculated lowest CER is higher than the CER during sleep. The differences between them increase significantly as increased activity level. Therefore, CER from awake people cannot be used directly in sleeping people. VR is a function of CER, as shown in equation (1). The required VR in bedrooms should be lower than other functional areas in buildings. If the CER from awake people is used for sleeping people, the required VR would be overestimated, resulting in energy waste.

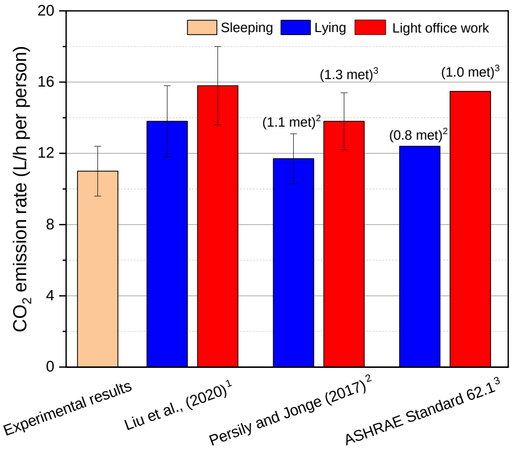

Figure 3. Comparison of CO_2 emission rate staying sleep with that of staying awake. [1] The CER is the average value of all reported CER at all office activity levels examined; [2] The physical activity level for lying; [3] Physical activity level for light office work.

Even there are no significant differences in CER at present experimental conditions; we can not conclude that the CER is not affected by increasing temperature or reducing IAQ as the changes in either temperature or IAQ may not enough to evoke the changes in CER. Alternatively, subjects could take off pajamas and/or sleep without quilt to copy with the thermal stress that may exist induced by increasing temperature. Further studies are necessary to explore this.

One limitation in the present study is that only 11 college-age healthy subjects participated in the experiment. Future studies are necessary to validate the current results with more subjects and different populations.

CONCLUSIONS

The measured CO_2 emission rate from sleeping people was 11.04±1.43 L/h per person, which is similar to what estimated by equations in the previous study and standard. Measured CO_2 emission rate did not change when increasing temperature from 24°C to 28 °C and reducing indoor air quality indicated by increasing CO_2 concentration from 700 ppm to 1700 ppm. The measured CO_2 emission rate during sleep is significantly lower compared with that of awake people.

ACKNOWLEDGEMENTS

This study was funded by the ASHRAE 1837 RP on Ventilation and Sleep Quality. Huiqi Shao, funded by China Scholarship Council (CSC), took part in the study during her study as a guest Ph.D. student at DTU. Xiaojun Fan would like to express gratitude to the CSC also for the generous support. The authors thank the subjects who volunteered for this study.

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