Effects of airing behaviours on bedroom air pollutants during sleep

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Abstract. Higher ventilation rates were verified to have a positive impact on indoor air quality and therefore benefit sleep quality. However, how does ventilation influence bedroom air quality if the outdoor air quality is poor? Whilst ventilation helps to reduce indoor pollution it inadvertently brings outdoor pollution indoors, such as NO_2, which is from vehicular emission. In this study, we collected the info of window and door status during sleep and measured carbon dioxide (CO_2), nitrogen dioxide (NO_2), volatile organic compounds (VOCs) and particulate matter ($PM_{2.5}$ and PM_{10}) among 38 bedrooms while occupants were sleeping during nights. Meanwhile, the air change rate (ACR) was calculated. The experiments were conducted in the heating season (September to December 2020) in the capital region of Denmark. The median values were 981.8 ppm (mean CO_2 level during sleep), 0.6 h^{-1} (ACR), 3.4 $\mu g \cdot m^{-3}$ (NO_2), 166.2 $\mu g \cdot m^{-3}$ (VOCs), 11.0 $\mu g \cdot m^{-3}$ (PM_{10}) and 2.8 $\mu g \cdot m^{-3}$ ($PM_{2.5}$). CO_2 levels were positively correlated with VOCs levels, whereas negatively correlated with NO_2 levels in bedrooms. ACR was also negatively correlated with VOCs. CO_2 levels were significantly higher whereas NO_2 levels were lower with both window and door closed compared to them with either window or door open. With higher ventilation rates, while occupants would be less exposed to indoor pollution of VOCs, they would be increasingly exposed to NO_2. Future studies of bedroom ventilation and sleep quality should consider outdoor air quality.

Keywords. pollutant, indoor air quality, CO_2, air change rate, NO_2, VOCs, PM, window, door.
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1. Introduction

Indoor air quality (IAQ) is influential to sleep quality among human beings [1-9]. Subjective assessment of bedroom IAQ or measurement of CO_2 (only as a marker of ventilation) is typically considered as the criteria of IAQ for the majority of the studies regarding the association between bedroom IAQ and sleep quality. A recent study reviewed 15 studies with 133,695 subjects involving the association between ambient air pollutants and sleep quality. That epidemiological and experimental evidence underlines that exposure to ambient air pollutants, such as nitrogen dioxide (NO_2), particulate matter (PM_{10} and $PM_{2.5}$, particles with a diameter below 10 and 2.5 μm, respectively), might have detrimental effects on sleep quality [10]. Nevertheless, these air pollutants were generally not considered when it comes to the effects of IAQ on sleep quality. There are also limited studies involving how ventilation impacts bedroom IAQ.

Mattress dust, mattress foam and covers, pillows, and bed frames can emit a variety of volatile organic compounds (VOCs), which are also essential to understand the occupant exposure on them during sleep [11].

Canha et al. (2021) [12] reviewed bedroom IAQ in real-life conditions based on 22 articles from 2003 to

2020. 77% of the studies reported CO_2 levels, followed by $PM_{2.5}$ and PM_{10}, while only 18% of the studies reported volatile organic compounds (VOCs) or other air pollutants. 86% of studies reported $PM_{2.5}$ levels higher than the air quality guideline of the World Health Organisation (WHO, 2010) of 10 $\mu g \cdot m^{-3}$. However, no specific info regarding NO_2 levels in bedrooms was reported by previous studies.

Canha et al. (2017) also assessed the IAQ during sleep under different ventilation patterns. The highest levels of CO_2, VOCs, PM_{10} and $PM_{2.5}$ were found under the ventilation setting with door and window closed in summer in Portugal. The other 3 scenarios of natural ventilation in the bedroom were either window or door open [13].

The present study aimed to examine four air pollutants (NO_2, VOCs, PM_{10} and $PM_{2.5}$) and the impact of ventilation on bedroom IAQ. A marker of ventilation – CO_2, air change rate and "window and door status" during sleep were parameters or factors of ventilation in this study.

2. Method

2.1 Experimental design

Field measurements of bedroom environmental parameters were conducted from September to December 2020 in the capital region of Denmark. The monthly average outdoor temperature in the capital region of Denmark during the experiment period was 15.1 °C (3.5 – 26.9 °C) September, 11.2 °C (1.6 – 18.6 °C) October, 8.1 °C (-1.4 – 17.2 °C) November, and 4.8 °C (-4.5 – 9.4 °C) December [14].

2.2 Measurements

Bedroom environmental parameters were measured using an instrument box that was delivered to the participants on Sundays during the experiment period along with, the instructions and a consent form. The instrument box contained the devices of FLOW (Plume Labs, France) and GMW22 (Vaisala, Finland) and the sleep tracker. The participants were asked to place the box about one meter away from the head at the same height as the bed during sleep.

The concentrations of air pollutants were determined by FLOW, an inexpensive (< $200) personal air pollution device that tracks air quality in its immediate surroundings. In 60-second intervals, FLOW provides an estimate of the major air pollutants NO_2, VOCs, PM_{10} and $PM_{2.5}$. According to the manufacturer, the tests obtained by the reference devices in laboratory conditions point to the coefficients of correlation in the range 84% to 99% for NO_2, 68% to 72% range for VOCs, 87% to 95% for PM_{10} and 92% to 97% for $PM_{2.5}$. CO_2 concentrations were measured by GMW22.

Bedtime and wake-up time was recorded by the sleep tracker of Fitbit Alta. Fitbit, which determines awakenings and sleep stages based on movement and cardiac sensors [15], was reported to have good agreement with polysomnography, a gold standard to measure sleep quality, in differentiating wakefulness from sleep [16].

The participants were asked not to enter the bedroom for at least half an hour the next morning after leaving and keep the windows and door the same status as they were sleeping since air change rates (ACRs) would be calculated by the CO_2 decay in the morning.

In addition, the window and door status of "open" and "closed" during sleep was asked to be recorded the second morning of sleep.

2.3 Statistical analysis

Mean levels of the environmental parameters during sleep were calculated based on bedtime and wake-up time.

The Mann-Whitney *U* test was used to analyse the difference of environmental parameters between the different window and door status. Spearman's correlation coefficients were used to analyse the correlations between any two of the variables.

Statistical analyses and plots were performed by using "scipy" and "matplotlib" packages in Python (version 3.7.3). All analyses were considered statistically significant when the *p*-value was less than 0.05 (2-tailed).

3. Results & discussion

The levels of environmental parameters of 38 bedrooms were measured. The results are represented from three parts, which are bedroom ventilation, bedroom air pollutant, and correlation of bedroom ventilation and air pollutants. Statistical descriptions of the parameters and their levels between window and door status are displayed.

3.1 Bedroom ventilation and airing behaviours

Tab. 1 shows the statistical description of mean CO_2 level and air change rate (ACR) during sleep. The median CO_2 level during sleep was 981.8 ppm with an interquartile range (IQR) between 638.0 and 1547.6 ppm. The median ACR during sleep was 0.6 h^{-1} (IQR, 0.3 – 1.5 h^{-1}).

CEN standard specifies total ventilation (including infiltration) of 0.6 h^{-1} (CO_2 level of 1250 ppm) and 2.0 h^{-1} (1000 ppm) for whole dwellings and bedrooms, respectively, for Category (Cat.) II [8], which is the normal level used for operation and design [17]. However, the majority of the bedrooms did not achieve the required ACR, and CO_2 levels of more than half of the bedrooms exceeded 1000 ppm. Overall, IAQ in bedrooms based on CO_2 levels or ACR during sleep was generally poor.

Tab. 1 – Statistical description of CO_2 and air change rate (ACR) during sleep.

	Mean	Std.	min	Percentile 25th	Percentile 50th	Percentile 75th	max
Mean CO_2 (ppm)	1305.3	942.4	427.5	638.0	981.8	1547.6	4803.7
ACR (h^{-1})	1.1	1.3	0.1	0.3	0.6	1.5	4.9

Regarding bedroom airing behaviours during sleep, 31.6% of the participants slept with both window and door closed, while 68.4% slept with either window or door open. Fig. 1 and Fig. 2 show the mean CO_2 levels and air change rate (ACR) of two "window and door status" during sleep. As expected, mean CO_2 levels during sleep were significantly higher with window and door closed, compared to them with either window or door open. However, no significant difference between the two "window and door status" was found, although the ACRs were generally higher with either window or door open.

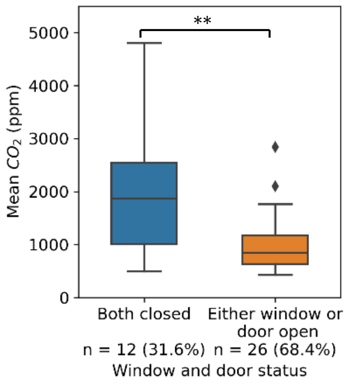

Fig. 1 – Mean CO_2 levels between two "window and door status" during sleep. ** *p*-value < 0.01.

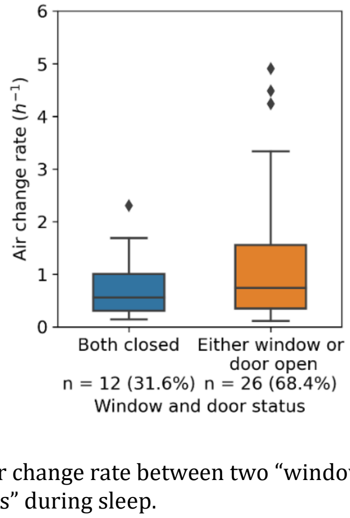

Fig. 2 – Air change rate between two "window and door status" during sleep.

3.2 Bedroom air pollutants

Tab. 2 shows the statistical description of bedroom pollutants during sleep. The median NO_2, VOCs, PM_{10} and $PM_{2.5}$ levels during sleep were 3.4 ppb (IQR, 1.7 – 7.1 ppb), 166.2 ppb (146.7 – 204.0 ppb), 11.0 µg·m^{-3} (7.1 – 36.4 µg·m^{-3}) and 2.8 µg·m^{-3} (2.3 – 7.1 µg·m^{-3}), respectively.

The WHO (2021) reported recommended a long-term $PM_{2.5}$ air quality guideline (AQG) level of no more than 5 µg·m^{-3}, PM_{10} no more than 15 µg·m^{-3}, and NO_2 no more than 10 ppb [18]. The WHO did not recommend AQG value for VOCs, while a previous study reported the reference value was 600 ppb from the Portuguese air quality standard [12]. Based on these standards, the NO_2, VOCs, PM_{10} and $PM_{2.5}$ levels were acceptable in the majority, all, more than half of the bedrooms, respectively.

Tab. 2 – Statistical description of bedroom pollutants during sleep.

	Mean	Std. Dev.	min	Percentile 25th	Percentile 50th	Percentile 75th	max
NO_2 (ppb)	5.7	5.9	0.2	1.7	3.4	7.1	30.2
VOCs (ppb)	187.7	80.9	84.1	146.7	166.2	204.0	445.9
PM_{10} (µg·m^{-3})	24.5	26.0	3.9	7.1	11.0	36.4	99.4
$PM_{2.5}$ (µg·m^{-3})	5.0	4.0	2.0	2.3	2.8	7.1	19.5

VOCs, volatile organic compounds; PM, particulate matter.

Fig. 3 shows the mean levels of four air pollutants. Only NO_2 levels were significantly different between the two "window and door status". Higher concentration with either window or door open point to the significant influence of outdoor or indoor sources other than the bedroom (e.g. kitchen or garage). The median values of mean VOCs, PM_{10} and $PM_{2.5}$ with window and door closed was slightly higher compared with it with either window or door open. However, the difference was not statistically significant.

Opening doors or windows had an effect on CO_2 levels indicating that there was an improved dilution, whereas VOCs, PM_{10} and $PM_{2.5}$ were not significantly different between the two window and door status since the dilution could be due to outdoor air or air from other parts of the dwellings having lower CO_2 levels than bedrooms at night. This and other mixed factors influencing the effects of window and door status on air pollutants levels would be one of the reasons why no significant differences of VOCs, PM_{10} and $PM_{2.5}$ levels between the window and door status were shown in Fig. 3.

Although NO_2 levels were significantly higher with either window or door open, the levels were still below 10 ppb for most of the bedrooms.

Fig. 4 shows the mean NO_2 levels during sleep among different housing locations and "window and door status". The NO_2 level was significantly higher among bedrooms with either window or door open (urban, 6.8 ppb (4.0 – 13.3 ppb); rural, 5.5 ppb (2.7 – 8.9 ppb)), compared to the bedrooms located in rural areas with window and door closed (1.8 ppb (1.3 – 3.0 ppb)). Window and door status had a more dominant impact on NO_2 levels than housing areas.

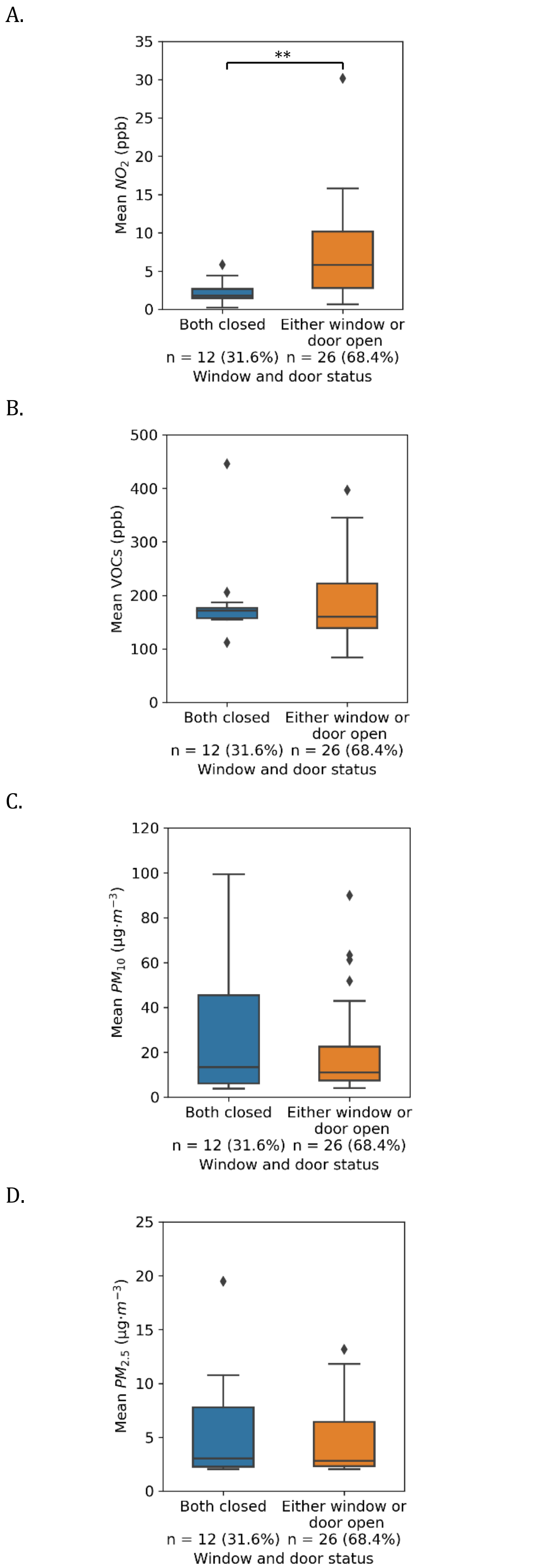

Fig. 3 – Mean levels of indoor pollutants during sleep between two "window and door status". A, NO_2; B, VOCs; C, PM_{10}; D, $PM_{2.5}$. NO_2, nitrogen dioxide; VOCs, volatile organic compounds; PM, particulate matter. ** p-value < 0.01.

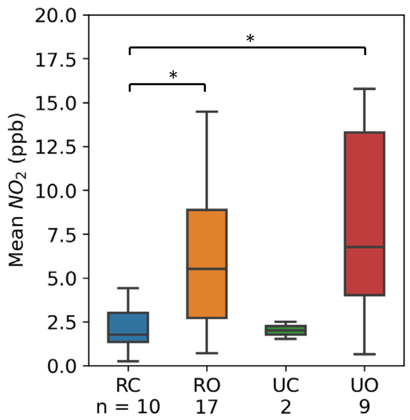

Fig. 4 – Mean NO_2 levels during sleep among different housing areas and "window and door status". RC, rural + window and door closed; RO, rural + either window or door open; UC, urban + window and door closed; UO, urban + either window or door open. ** p-value < 0.01.

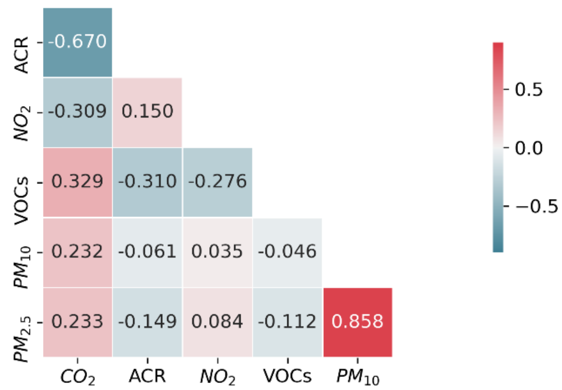

Fig. 5 – Spearman's correlation coefficients between any of the two parameters of bedroom ventilation (CO_2 and ACR) and air pollutants (NO_2, VOCs, PM_{10} and $PM_{2.5}$). ACR, air change rate; NO_2, nitrogen dioxide; VOCs, volatile organic compounds; PM, particulate matter.

3.3 Correlation of bedroom ventilation and air pollutants

Fig. 5 shows the correlation between any of the two parameters of bedroom ventilation and air pollutants. CO_2 levels were moderately correlated with ACR (p-value < 0.05) and weakly correlated with VOCs (p-value < 0.05) and NO_2 levels (p-value < 0.1). ACR was only weakly correlated with VOCs (p-value < 0.1).

PM_{10} and $PM_{2.5}$ levels were highly correlated (p-value < 0.05), while NO_2 and VOCs levels were weakly correlated (p-value < 0.1).

The correlations in Fig. 5 could be influenced by many other factors as well. For example, opening doors might not change $PM_{2.5}$, PM_{10} or VOCs if sources were other places than the bedroom. Estimation of ACR might have errors and could be inaccurate. This might explain some weak correlations.

CO_2 decay and the reference of ambient CO_2 levels were utilized to calculate ACR. However, there are uncertainties by this method since a mix of outdoor CO_2 levels and the other parts of the dwellings could be the reference instead of the ambient CO_2 levels. A more accurate method to calculate ACR should be used in future studies. Future studies should figure out the correlation between bedroom ACR and air pollutants by using a more accurate method.

Previous studies performed the association between bedroom ventilation (IAQ) and sleep quality mostly using CO_2 as a marker of ventilation [1-9]. However, that the relevant contaminants of VOCs and the other pollutants measured in the present study were only weakly or even not correlated with CO_2 levels in the present study stipulates that CO_2 is a poor marker of VOCs levels, as well as the other pollutants measured in this study.

3.4 Strengths and limitations

Although the present study reported the levels of four air pollutants in the occupants' bedrooms during sleep, this work was a relatively small study with only 38 bedrooms. The uncertainties of ACR could not be captured. Only roughly correlations were made and other factors were not adjusted. Ventilating bedrooms by opening windows or doors could be with outdoor air or the air coming from other parts of the dwellings, while it was uncertain. These limitations could influence the outcomes.

4. Conclusion

The levels of CO_2, air change rate (ACR), NO_2, VOCs, PM_{10} and $PM_{2.5}$ were measured in bedrooms during sleep in the heating season in Denmark. The infiltration of NO_2 into bedrooms is significant and thus it should be included in future research. CO_2 levels were only weakly correlated with VOCs levels in bedrooms during sleep, while not correlated with the other pollutants. ACRs were only correlated with VOCs in the present study.

Air pollutants potentially related to sleep quality, such as PM and NO_2, are necessary to be measured when it comes to the topic of bedroom IAQ (and its effects on sleep quality). Sleep parameters will be included in our future analyses and the results will be reported later.

5. Acknowledgement

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