Air change rates during sleep in Danish bedrooms

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Abstract. The ongoing project 'Bedroom Ventilation and Sleep Quality' investigates the effects of bedroom ventilation on sleep quality and next-day cognitive performance. As part of the project, 84 bedrooms in the Greater Copenhagen area of Denmark were inspected during the 2020 heating season. In the first week, participants slept under environmental conditions that they typically experienced during sleep; in the second week, they slept with the interventions made by opening/closing either the door, or window, or both. As an essential part of the study, the CO2 concentration in bedrooms was continuously measured. The bedroom window and door status during sleep were obtained the following morning via sleep diary. The air change rates per hour (ACHs) in bedrooms were estimated using the occupant-produced CO2 concentration decay method. Mechanical ventilation was rarely installed in bedrooms; extract ventilation in the bathroom and kitchen was predominant. Participants typically slept with both bedroom window and door closed. The median ACH was 0.40 h^{-1} during sleep under habitual conditions. Opening either the window or door increased bedroom ACH during sleep, but window opening led to better ventilation than the door opening, which was verified by the intervention. These results suggest that the ventilation in most bedrooms is currently insufficient compared with the ventilation requirements prescribed by limited standards, highlighting the urgency to look at its impact on sleep quality and improve bedroom ventilation.

Keywords. Bedroom Ventilation, Air change rate, Airing behaviour, Residential buildings, Sleep
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1. Introduction

Sleep is essential for our health and well-being by enabling human bodies to function well. Previous studies have shown that inadequate ventilation in bedrooms adversely affects sleep quality [1–3], which in turn increases the risk of a series of health-related diseases, such as obesity and chronic diseases [4], etc., and reduces the next-day cognitive performance [3,5].

In light of the difficulties in ventilation rate measurements on-site, for example, air mixing indoors and methods limitations, CO_2 concentration during sleep is typically measured in most studies as a proxy of ventilation in bedrooms, as summarized by Akimoto et al. [6]. Limited studies attempted to characterize bedroom ventilation by measuring the air change rate using the tracer gas method as summarized by Sekhar et al. [7]. They found that the mean air change rate (ACH) varied largely from 0.2 to 4.9 h^{-1}. A large number of surveyed bedrooms did not meet the ventilation requirements stipulated by ASHRAE and European Standards [8][9].

Buildings worldwide are being built tightly due to the energy crisis. Consequently, the ventilation rates in dwellings are reduced, especially in areas where the central heating system is installed. Occupants generally sleep with the bedroom door and window closed in these areas during the heating season, further decreasing the bedroom ventilation during sleep.

This study is part of a large field investigation on the effects of bedroom ventilation on sleep quality and next-day cognitive performance conducted in the Greater Copenhagen area of Denmark during the heating season in 2020. This paper presents the results of the estimated ACHs using the occupant-produced CO_2 concentration decay method to provide an overview of the actual bedroom ventilation and characterize how occupants' airing behaviours affect ACHs during sleep. Other measurements will be reported separately.

2. Method

A cross-sectional field study was conducted from September to December 2020 in the Greater Copenhagen area of Denmark. Eighty-four participants were recruited based on the answers to a recruitment questionnaire, which collected the information on candidates, characteristics of bedrooms and dwellings, and sleep quality over the past month prior to participating in this study. Participants could choose to take part in either one-week or two-week measurements: only weekdays (Monday evening to Friday morning) were considered. The participants were asked to sleep under their habitual sleep conditions in the first week; in the second week, they were instructed to make interventions by opening or closing the bedroom door, or window, or both at night. Among them, 64 participated in two-week measurements.

The CO_2 concentration was measured continuously in bedrooms at an interval of 5 min. Sixteen measuring units, each comprising a CO_2 sensor (GMW90R, Vaisala Corp., Finland) and a data logger (HOBO UX120-006M, Onset Computer Corp., USA), were used in the present study. The measuring range of the sensor was 0-5000 ppm with an accuracy of ±30 ppm + 2% of reading. The air temperature and relative humidity were recorded simultaneously. The CO_2 sensor was calibrated prior to the study.

Each bedroom was installed with one unit. The unit was placed at a similar height of the bed and one meter away from the head region when participants lay down. Participants reported the status of the bedroom door and window via an online sleep diary in the morning, which they were asked to fill out twice, two weekdays' morning of each week.

The ACH was estimated for every weekday night by measuring the decay of the human-produced CO_2 concentration after the participants left the bedrooms assuming that the ACH did not change if the bedroom door and window status were kept the same as the previous night. Participants were asked not to make any changes to the bedroom window and door after waking up and to avoid re-entering the bedrooms at least within 30 min. after leaving to allow the decay of CO_2 concentration to be built up. The outdoor CO_2 concentration throughout the measuring period was not recorded. Instead, the mean value at a steady-state during daytime when the bedrooms were not occupied was used. Otherwise the outdoor CO_2 concentration was assumed to be 420 ppm as used by the previous study to estimate the ventilation rate under different CO_2 levels [10]

3. Results and Discussions

Fig. 1 shows the cumulative probability of estimated ACHs in bedrooms during habitual sleep conditions. The median ACH was 0.40 h^{-1}, ranging from 0.03 h^{-1} to 19.25 h^{-1}, similar to the value measured in 500 children's bedrooms of Denmark [11].

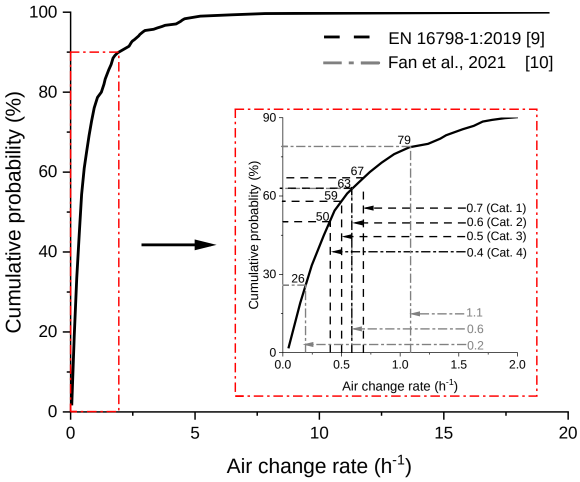

Fig. 1 – Cumulative probability plots of estimated ACHs in bedrooms during habitual sleep conditions. Bedroom ventilation stipulated by EN 16798-1 [9] and recommended by Fan et al. [10] are also presented.

Sekhar et al. reviewed 17 international and national standards and building regulations on ventilation requirements for bedrooms and found that most existing standards do not prescribe specific ventilation requirements for bedrooms; the requirements for bedroom ventilation is simply the application of ventilation requirements for the whole dwellings [7]. Among others, the European standard specifies the total ventilation (including infiltration) of 0.4, 0.5, 0.6, 0.7 h^{-1} for Categories 4 to 1 respectively for entire dwellings [9]. These values are used for benchmarking in the present study.

Half surveyed bedrooms had an ACH lower than 0.4 h^{-1} during sleep, the minimum ventilation requirement stipulated by EN 16798-1 [9]. If an ACH of 0.7 h^{-1} is used as the criterion for bedroom ventilation, 79% of bedrooms did not comply with the ventilation requirement.

Based on the tentative relationship between bedroom ventilation (indicated by CO_2 levels) and sleep quality established by Sekhar et al. [7], Fan et al. recommended the bedroom ventilation rates considering the adverse effects on sleep quality assuming that the CO_2 emission rate during sleep was

11.0 L/h per person [10]. To avoid sleep disturbance, the ventilation rate in bedrooms should be >10 L/s per person, corresponding to a CO_2 level of < 800 ppm. A ventilation rate of < 10 L/s per person may affect sleep; < 5 L/s per person, corresponding to a CO_2 level of >1150 ppm, will affect sleep; <1.5 L/s per person, corresponding to a CO_2 level of >2600 ppm, will affect both sleep quality and next-day cognitive performance. The corresponding ACH was estimated to be 1.1, 0.6, and 0.2 h^{-1} (the median bedroom volume and occupancy during sleep were 32 m^3 and one person in the present study). 79% of bedrooms had an ACH < 1.1 h^{-1} suggesting that occupants sleeping in these bedrooms may suffer from sleep disturbance; 26% was lower than 0.2 h^{-1} indicating that both sleep quality and next-day cognitive performance of occupants sleeping in these bedrooms might be affected already. These results highlight the urgency of improving bedroom ventilation and the importance of investigating its effects on sleep quality.

Window and door opening significantly affect bedroom ventilation [12–14]. According to the habitual airing behaviours, the sample size obtained can be categorized into four different scenarios of natural ventilation in bedrooms: (1) Scenario 1, Window Closed and Door Closed; (2) Scenario 2, Window Closed and Door Open; (3) Scenario 3, Window Open and Door Closed; and (4) Scenario 4, Window Open and Door Open.

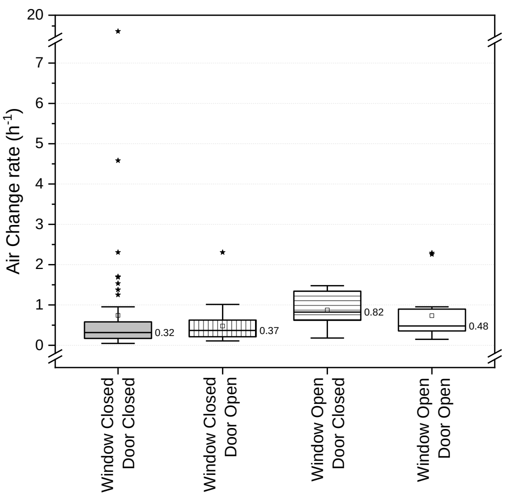

Fig. 2 – Estimated ACHs in different scenarios during the habitual sleep conditions.

Fig. 2 presents the estimated ACHs at different scenarios during the habitual sleep conditions. The lowest ACHs during sleep were found for Scenario 1 with a median value of 0.32 h^{-1} in Scenario 1; while the highest ACHs were observed for Scenario 3 with a median value of 0.82 h^{-1}. Window and door opening improved the bedroom ventilation, as expected. In contrast, the median ACH was 0.48 h^{-1} at Scenario 4 during sleep, which is in between Scenario 2 and 3. Similar results were observed under Scenario 2 and 3 but not Scenario 4 [12]. The plausible explanation for this divergence would be the opposite air movement directions from the window and the door. Further studies are necessary to investigate it.

We estimated the ventilation type in surveyed bedrooms using the information about the air terminals and trickle vents collected by the recruitment questionnaire. Bedrooms with air terminals were considered to have a fully balanced mechanical ventilation system. Bedrooms with trickle vents and exhaust air terminals in the bathroom or kitchen were considered to have mechanical ventilation with exhaust only. Bedrooms with other cases were considered to be ventilated naturally.

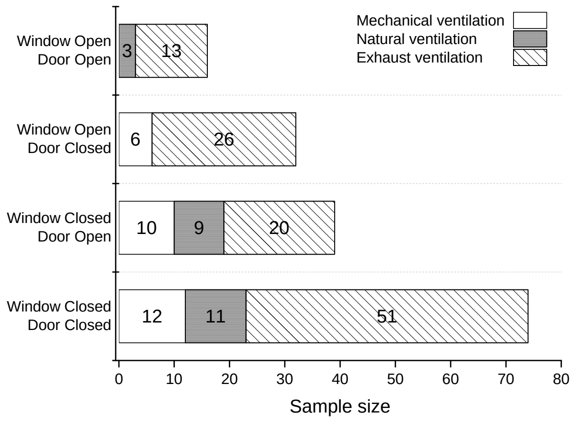

Fig. 3 – The distribution of sample size in terms of the ventilation system of the surveyed bedrooms in different scenarios. The sample size is larger than the number of occupants as more than one sample came from one participant.

The distribution of sample size based on the bedroom ventilation system is shown in Fig. 3. Most ACHs were estimated from bedrooms only with exhaust ventilation; only a few bedrooms were installed with a fully balanced mechanical ventilation system. The choice of opening or closing the window or door seems to be independent of the bedroom ventilation system.

It can also be seen that most samples were from bedrooms in Scenario 1; only a few samples were from bedrooms in Scenario 4; as expected. This study was conducted in wintertime in Denmark when the outdoor temperature was lower. Occupants prefer to avoid air draught and keep the bedroom warm during sleep by closing both the window and door, resulting in poor ventilation. More attention should be paid to bedroom ventilation during sleep, especially in these areas with central heating systems in winter. The sample size from the bedrooms with the door open was similar to those with the window open.

The locations of the surveyed bedrooms were deduced from postcodes collected from the recruitment questionnaire. The distribution of the sample size based on the locations is shown in Fig. 4. Most samples in the present study were from bedrooms located in suburban regions. There was only a small number of samples from bedrooms located in urban regions. The composition of the sample size in each Scenario was similar.

Both the characteristics of the ventilation system in surveyed bedrooms and information on the airing behaviour during sleep explain the observed low ACHs during sleep under habitual conditions in the present study.

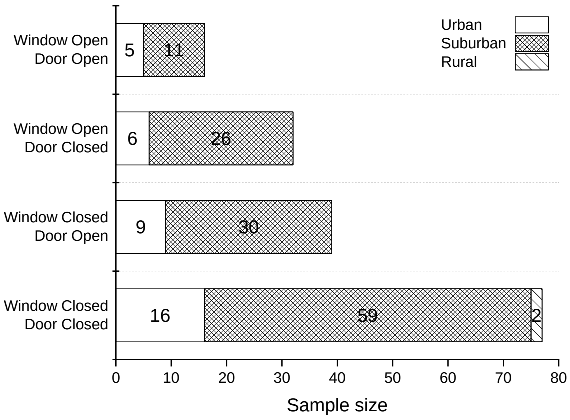

Fig. 4 – The sample size distribution in terms of the locations of the surveyed bedrooms in different scenarios. The sample size is large than the number of occupants as more than one sample came from one participant. The areas of the bedrooms with the first two numbers of postcodes 25 or below are regarded as urban regions; suburban regions refer to the areas with the first two numbers of postcodes 26-31, 34-36, 40, 50-52, 70, 80-82, and 90-92; and the other areas in the Capital Region of Denmark are rural.

The ACHs obtained from two-week measurements with the interventions are depicted in Fig. 5. This analysis is a within-subject comparison. The median ACHs were approx. 0.3 h^{-1} in Scenario 1 during sleep, which was similar to 0.32 h^{-1} measured during habitual sleep conditions. The median ACHs increased from 0.27 h^{-1} to 0.39 h^{-1} in Scenario 2. When opening the window only, the median ACHs increased from 0.32 h^{-1} to 1.14 h^{-1}. The median ACHs were only increased by 27% when opening both the window and door, which was similar to the estimated value under the conditions with the door open.

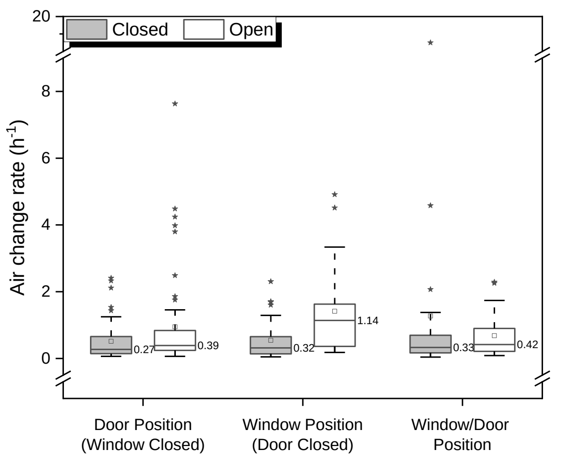

Fig. 5 – Estimated ACHs before and after interventions made by opening or closing either the door, or window, or both.

These results from the intervention part verify the observations from the habitual sleep conditions. The findings of the present study suggest that opening either the door, or the window, or both increases the ACH. However, the open window leads to better ventilation than the open door, as may be expected. Similar results were found by Mishra et al.[13]. It is worth noting that opening both window and door in the present study did not further improve the ventilation in bedrooms compared with only opening the window or door. A follow-up study is necessary to investigate the reasons behind that and the optimal conditions to increase the bedroom ventilation by opening both.

4. Limitation

This study was conducted during the heating season in Denmark, where the outdoor temperature in winter is low. The airing behaviour of participants during sleep may be different in other seasons, resulting in different ventilation. More future studies are needed to investigate it further.

The ACH was estimated by the decay of human metabolically produced CO_2 concentration. Its accuracy depends on the CO_2 measurement, elapsed time for decay, and air mixing in bedrooms. In addition, if the window and door status after sleep is the same as they are during sleep, it is also crucial to estimate the ventilation rate during sleep precisely by the CO_2 decay after sleep. The outdoor CO_2 level was not measured throughout the entire measuring period in the present study. We also did not check the air mixing. It would be useful to monitor the outdoor CO_2 concentration simultaneously and deploy more sensors at the different locations in bedrooms. Besides, we asked participants not to re-enter their bedroom within 30 min. after leaving it, which may lead to large uncertainty of the ACH estimation due to the limited data points available as the CO_2 concentration was registered every five min., especially at the high ventilation conditions where the decay would be quickly established. A more extended decay period could contribute to a more accurate estimation of the ACH.

The ACHs estimated in the present study are the total airflow into the bedroom, including airflows from adjacent spaces, especially when the bedroom door was open as an intervention. In light of no CO_2 measurements conducted in the adjacent spaces, especially outside the bedroom door, we assumed that the CO_2 concentration in the air supplied into bedrooms from adjacent spaces was equal to that in the outdoor air.

Even though we identified the ventilation systems of surveyed bedrooms based on the information about the air terminals and trickle vents, we did not check if they were operated appropriately throughout the entire measuring period. The previous study has shown that the ACH can be further enhanced by operating the exhaust ventilation system when opening the door in bedrooms [15]. In the present study, we did not observe that. It may be because the extraction systems were not in operation during sleep. It would be helpful to check the operations of the ventilation systems in bedrooms during sleep in future studies to investigate the bedroom ventilation with different ventilation systems installed.

5. Conclusions

This work estimated the ACHs in bedrooms during sleep and explored how bedroom window and door opening affects ventilation. Extract ventilation was predominant in surveyed bedrooms; only a few had mechanical ventilation installed. Most participants slept with both the window and door closed. There was only a small number of participants who kept the bedroom window or door open during sleep, even less with both the window and door open. During habitual sleep conditions, the median ACH was 0.40 h^{-1}, ranging from 0.03 h^{-1} to 19.25 h^{-1}. Bedroom ventilation with closed door and window resulted in the lowest ACH, but window or door opening increased bedroom ACH, and window opening led to better ventilation than the door opening. This was verified by the results from intervention. The median ACH increased from 0.27 h^{-1} to 0.39 h^{-1} by only opening the door and from 0.32 h^{-1} to 1.14 h^{-1} by only opening the window. However, both window and door opening only slightly increased ventilation from 0.33 h^{-1} to 0.42 h^{-1}. During habitual sleep settings, half the surveyed bedrooms did not meet the minimum ventilation requirement prescribed by European Standard; 79% of bedrooms had an ACH of <1.1 h^{-1}, including 26% lower than 0.2 h^{-1}. Future studies are required to investigate whether the sleep quality is disturbed after sleeping under the insufficiently ventilated bedrooms and how window and door opening will affect the bedroom ventilation and sleep quality.

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Data Statement

The datasets generated during and/or analysed the current study are not publicly available but are/will be available by contacting the first author upon reasonable request.

7. References

[1] L. Lan, Y. Sun, D.P. Wyon, P. Wargocki, Pilot study of the effects of ventilation and ventilation noise on sleep quality in the young and elderly, Indoor Air. 31 (2021) 2226–2238. https://doi.org/10.1111/ina.12861.

[2] X. Xu, Z. Lian, J. Shen, T. Cao, J. Zhu, X. Lin, K. Qing, W. Zhang, T. Zhang, Experimental study on sleep quality affected by carbon dioxide concentration, Indoor Air. (2020) 1–14. https://doi.org/10.1111/ina.12748.

[3] P. Strøm-Tejsen, D. Zukowska, P. Wargocki, D.P. Wyon, The effects of bedroom air quality on sleep and next-day performance, Indoor Air. 26 (2016) 679–686. https://doi.org/10.1111/ina.12254.

[4] M. Miller, F. Cappuccio, Inflammation, Sleep, Obesity and Cardiovascular Disease., Curr. Vasc. Pharmacol. 5 (2007) 93–102. https://doi.org/10.2174/157016107780368280.

[5] X. Fan, H. Shao, M. Sakamoto, K. Kuga, L. Lan, D.P. Wyon, K. Ito, M.P. Bivolarova, C. Liao, P. Wargocki, The effects of ventilation and temperature on sleep quality and next-day work performance : pilot measurements in a climate chamber, Build. Environ. 209 (2022) 108666. https://doi.org/10.1016/j.buildenv.2021.108666.

[6] M. Akimoto, C. Sekhar, M.P. Bivolarova, C. Liao, X. Fan, J. Laverge, L. Lan, P. Wargocki, Reviewing how bedroom ventilation affects IAQ and sleep quality, ASHRAE J. 63 (2021) 56–60.

[7] C. Sekhar, M. Akimoto, X. Fan, M. Bivolarova, C. Liao, L. Lan, P. Wargocki, Bedroom ventilation: Review of existing evidence and current standards, Build. Environ. 184 (2020) 107229. https://doi.org/10.1016/j.buildenv.2020.107229.

[8] ASHRAE 62.2, Ventilation and Acceptable Indoor Air Quality in Residential Buildings, (2019).

[9] EN 16798–1:2019, Energy performance of buildings – Ventilation for buildings – Part 1 : Indoor environmental input parameters for design and assessment of energy performance, (2019).

[10] X. Fan, M. Sakamoto, H. Shao, K. Kuga, K. Ito, L. Lan, P. Wargocki, Emission rate of carbon dioxide while sleeping, Indoor Air. 31 (2021) 2142–2157. https://doi.org/10.1111/ina.12911.

[11] G. Bekö, T. Lund, F. Nors, J. Toftum, G. Clausen, Ventilation rates in the bedrooms of 500 Danish children, Build. Environ. 45 (2010) 2289–2295. https://doi.org/10.1016/j.buildenv.2010.04.014.

[12] N. Canha, J. Lage, S. Candeias, C. Alves, S.M. Almeida, Indoor air quality during sleep under different ventilation patterns, Atmos. Pollut. Res. 8 (2017) 1132–1142. https://doi.org/10.1016/j.apr.2017.05.004.

[13] A.K. Mishra, A.M. van Ruitenbeek, M.G.L.C. Loomans, H.S.M. Kort, Window/door opening-mediated bedroom ventilation and its impact on sleep quality of healthy, young adults, Indoor Air. 28 (2018) 339–351. https://doi.org/10.1111/ina.12435.

[14] J. Few, C. Elwell, Open or Closed ? Use of Windows and Doors at Home : Ventilation Rates in Occupied Dwellings, in: ASHRAE Top. Conf. Proceedings. Am. Soc. Heating, Refrig. Air Cond. Eng. Inc., 2021: pp. 1–8.

[15] C. Sekhar, M. Bivolarova, M. Akimoto, P. Wargocki, Detailed characterization of bedroom ventilation during heating season in a naturally ventilated semi-detached house and a mechanically ventilated apartment, Sci. Technol. Built Environ. 27 (2020) 158–180. https://doi.org/10.1080/23744731.2020.1845019.