Breathing Better: Evaluating the Impact of Personalized Ventilation in Daycare Baby Beds

Hailin Zheng*, Marcel Loomans, Shalika Walker, Zhijian Wang, Wim Zeiler

Eindhoven University of Technology, Eindhoven, the Netherlands
**Corresponding author: h.zheng1@tue.nl*
Presenting author: underline First & Last name

ABSTRACT

Daycare centers (DCCs) are pivotal in early childhood development, serving as a primary indoor environment for young children. A notable feature of DCCs, especially in the Netherlands, is the use of semi-enclosed baby beds for children aged 0-4 years. These beds provide safety and comfort but pose challenges in maintaining healthy air quality due to their enclosed design, which is critical given infants' vulnerability to pollutants and extended daytime sleep. Prior research has indicated the need to improve the air quality in these beds, and suggested using personalized ventilation (PV) as a potential solution.

Therefore, the current study builds on this by examining the effectiveness of PV in semi-enclosed baby beds, addressing limitations of earlier research such as fixed air supply rates directed towards the wall side. Utilizing a full-scale bedroom setup with a breathing thermal baby model, it evaluated the impact of three PV airflow directions (wall-side, head-side, cover-side), five ventilation rates (21, 37, 55, 65, 75 m^3/h), and three sleep positions (supine, lateral-to-corridor, and lateral-to-wall) on bed-level air quality. For comparative purposes, a control scenario employing the MV (mixing ventilation) strategy at the ventilation rate of 55 m^3/h was also examined. The experimental setup, including 23 CO_2 sensors, provided an in-depth analysis of CO_2 levels at various scales, with 34 experimental cases conducted across different ventilation modes, airflow directions, rates, and sleeping positions.

The results re-confirmed the superior effectiveness of PV in mitigating exposure of metabolic CO_2 emissions over the conventional MV strategy under the same ventilation rates. Moreover, the study noted that increased ventilation rates typically corresponded with lower CO_2 levels, although the optimal rate varied depending on the specific PV strategy and sleeping position. Notably, the PV head-side strategy consistently recorded the lowest inhaled CO_2 concentrations, highlighting its capability in effectively removing metabolic CO_2 emissions.

In conclusion, this research underscores the crucial role of PV in improving air quality in DCC baby beds. It demonstrates PV's ability to optimize air quality at lower rates, suggesting energy efficiency benefits. These insights are vital for developing customized ventilation solutions in daycare environments, and advancing the understanding of bed-level air quality optimization using diverse PV strategies.

KEYWORDS

Daycare Center; Indoor Air Quality; Personalized Ventilation; Inhaled Air Quality; Semi-enclosed Baby Bed.

1 INTRODUCTION

Daycare centers (DCCs) are the first educational programs for the social development of young children (infants and toddlers) prior to primary school ages, serving as the indoor environments to which they are most exposed, aside from their homes [1]. Naptimes for young children are key daily activities distinguishing DCCs from other educational facilities like schools [2], with many featuring densely populated bedrooms to accommodate this [3-6]. A notable solution for these accommodations is the semi-enclosed baby bunk bed (see **Figure 1b**), designed for 0-4-year-olds in DCCs [7]. There are three key features of this bed: safety features that prevent infant falls, a sheltered design that provides psychological comfort, and its compact size that allows for easy placement in small spaces. These features contribute to its global popularity. Notably, over 95,000 units are utilized in Dutch DCCs across more than 9,000 locations [7].

As the main occupants in DCCs, infants and toddlers are especially vulnerable to air pollutants due to their rapid and incomplete physiological development. Also, in semi-enclosed sleeping environments, young children are not able to actively control their surroundings as they are under the asleep state. Even worse, the source-proximity effect may become dominant in the bed-level environment. For example, the bed-level concentrations of volatile organic compounds (VOCs) from bedding materials can be significantly higher than in the bulk room air [8-10]. All of these factors point to the need for the investigation of ventilation conditions inside the semi-enclosed baby beds.

However, the current literature on this subject is scant. There is an existing study [11] where CO_2 dispersion and inhalation from a breathing thermal baby model in a semi-enclosed bed was investigated under standard room-level mixing ventilation. The findings concluded inadequate ventilation conditions at the bed level. Building on this, a subsequent study [12] explored the effectiveness of three ventilation strategies—mixing ventilation (MV), displacement ventilation (DV), and personalized ventilation (PV)—in improving air quality at the bed level. Employing a full-scale setup of a typical Dutch DCC bedroom [13], the study assessed ventilation performance through CO_2 dispersion and inhalation metrics, demonstrating PV's superior ability to reduce inhaled CO_2 concentrations compared to MV and DV. However, this study limited its scope to limited air supply rates and a singular direction of air supply (specifically, a PV setup directed only towards the wall side), leaving the effectiveness of bed-level ventilation under varied air supply directions and volumes unexplored.

The current study, therefore, aims to bridge this research gap by thoroughly investigating the effectiveness of PV setups inside semi-enclosed baby beds. It aims to study the effect of three variables: different PV airflow directions, ventilation rates, and sleeping positions. In terms of novelty, this study is the first, in a full-scale setup, to research the ventilation effectiveness of different PV configurations inside the semi-enclosed baby beds under a controlled indoor environment.

2 METHODS

2.1 A full-scale bedroom setup and a breathing thermal baby model

In this follow-up study, the same full-scale bedroom setup (see **Figure 1**) and the breathing thermal baby model (BTBM) (see **Figure 2**) were utilized, as described in the previous studies [11, 12]. Briefly, a field survey of 17 Dutch DCCs (including 68 bedrooms) informed the experimental design, capturing essential data on bedroom features, bed density, ventilation specifics, and typical occupant characteristics [13]. This led to constructing a 4.2m x 2.7m x 2.5m bedroom setup, featuring six baby bunk beds with used mattresses from a participating DCC, arranged in a bilateral layout that mirrors one of the common configurations (38%) found in the survey. The constructed bedroom, made of plastic films and wooden frames, is placed in a climate-controlled chamber to ensure an adiabatic environment, isolating the experiment from external temperature influences.

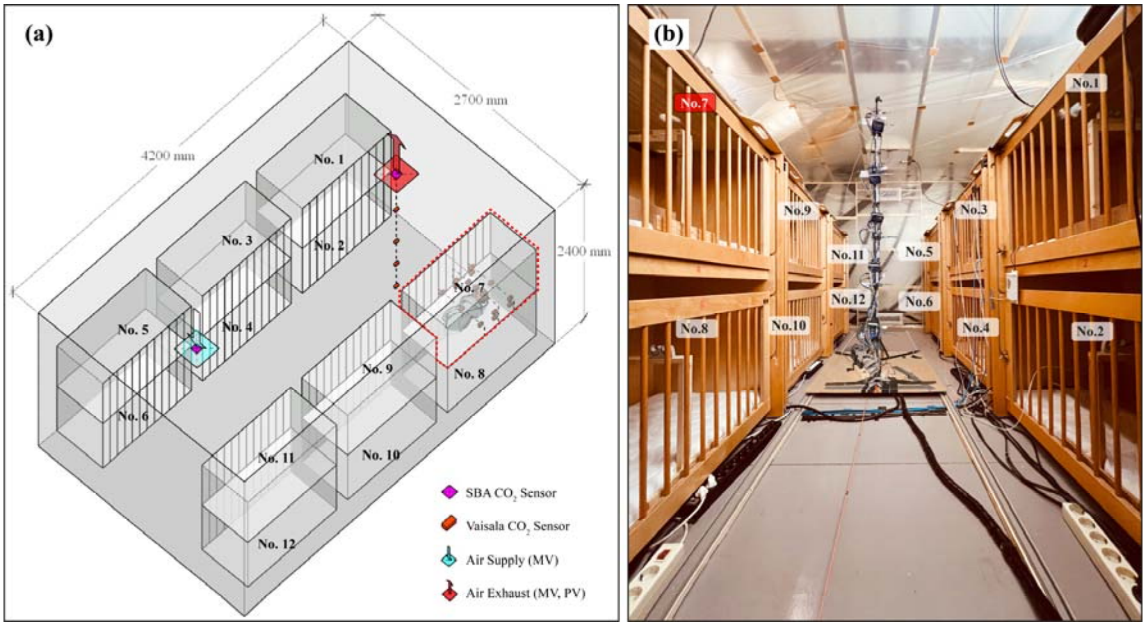

Figure 1: Experimental setup. **(a)** Axonometric schematic of the full-scale bedroom, including 12 beds (from No.1 to No.12) and sensor placement. **(b)** A picture of the on-site bedroom.

In terms of the BTBM, it was developed to mimic the sleeping body of a baby, generating heat and simulating breathing patterns. This model, representing a 30-month-old infant, featured a torso wrapped in an electric heating layer to produce a heat output of 45 W/m^2, matching the average metabolic rate of sleeping toddlers [14, 15]. An infrared image (see **Figure 2**) confirmed the BTBM's surface temperature at around 36.5 □, aligning with real toddler skin temperatures during sleep [16]. The BTBM's breathing mechanism comprised inhalation and exhalation systems, alternating through a digital timer controlling two valves. Both systems simulated realistic tidal volumes (123 ml), with exhalation and inhalation facilitated by simplified mouth and nose pathways. The exhaled airflow, mixed to achieve a CO_2 concentration of around 50000 ppm [17, 18], was delivered through the mouth, angled towards the chest to replicate natural breathing in sleep. Inhalation was similarly directed, with CO_2 levels continuously monitored by a Vaisala sensor (for the specification, see **Section 2.1**). The study simulated a 30-month-old's respiration rate at 30 breaths per minute [19], with each breath cycle consisting of 1-second inhalation and 1-second exhalation.

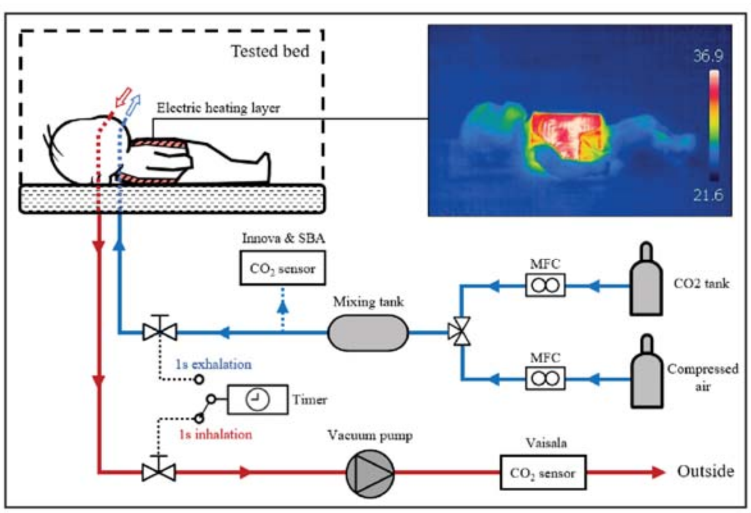

Figure 2: A schematic of the thermal and breathing simulation system of a baby model (BTBM), adapted from the prior study [11].

2.2 Instrumentation's specifications and placement

To evaluate bed-level and room-level ventilation, CO_2 was used as a tracer gas. 25 CO_2 sensors were placed at strategic locations to measure exhaled, inhaled, and dispersed CO_2 levels at bed and bedroom level. Four types of CO_2 measurement devices were deployed due to specific requirements for measurement range, conditions, and accuracy:

(1) An Innova Photoacoustic Gas Monitor setup, with a reported accuracy of ±1.5%, used at a ca. 42-second measurement interval to verify exhaled air CO_2 concentration at 50000 ppm (see **Figure 2**) and measure real-time room air exchange rates through SF6 gas dosing.

(2) Three SBA-5 CO_2 gas analyzers, accurate within 1% of span concentration, monitored CO_2 levels at 1-second interval in the air ducts to assess the supply and exhaust air quality (see **Figure 1a**), as well as the exhaled air (see **Figure 2**).

(3) 21 Vaisala CO_2 Probes provided 1-second readings within the room and inside a bed, capturing CO_2 distribution at various heights, as well as for the exhaled air measurement (see **Figure 2** and **Figure 3).** The accuracy of Vaisala was documented as ±40 ppm in the range of 0-3000 ppm, ±2% of reading in the range of 3000-10000 ppm, and ±3.5% of reading in the range of 10000-30000 ppm.

Before the experiments, all sensors underwent factory and laboratory calibrations to ensure accuracy, followed by a cross-calibration process to align readings across the different devices. This calibration confirmed an overall measurement uncertainty of 50 ppm.

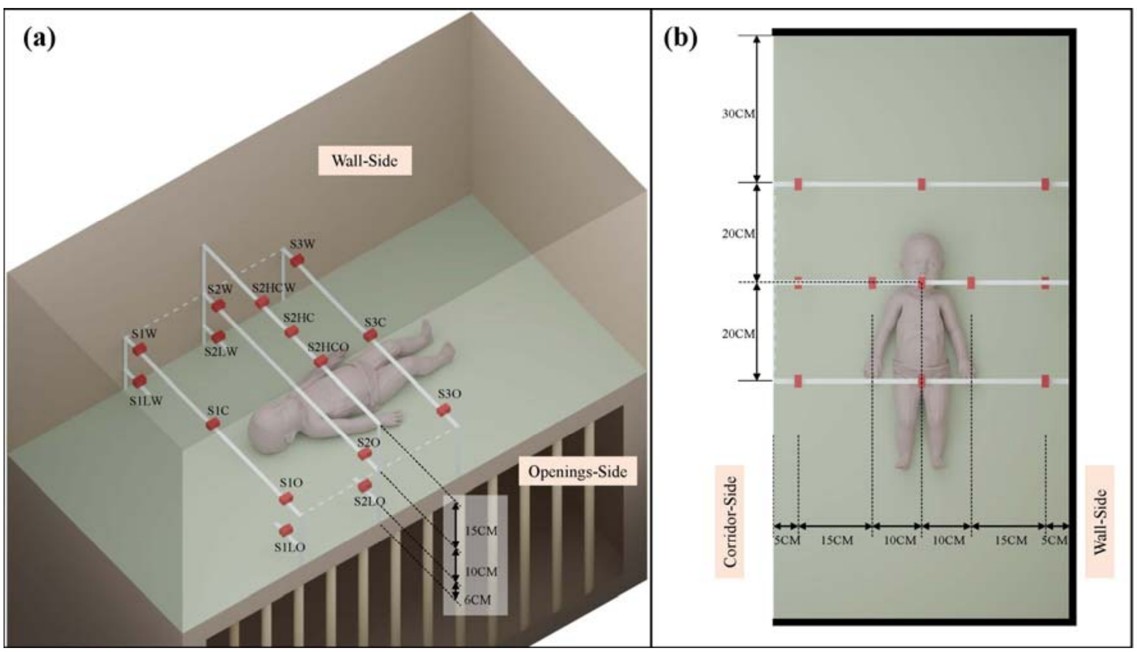

Figure 3: Experimental setup. **(a)** Axonometric schematic of the full-scale bedroom, including 12 beds (from No.1 to No.12) and sensor placement. **(b)** A picture of the on-site bedroom.

2.3 PV setup and experimental conditions

The PV setup (see **Figure 4b**), featuring an air supply interface measuring 45 x 40 cm (length*height), is designed to deliver a consistent distribution of airflow across its surface. The setup allows for adjustable ventilation rates by modulating the power supplied to the unit, facilitating a tailored approach to study the impact of different airflows on the bed-level ventilation performance.

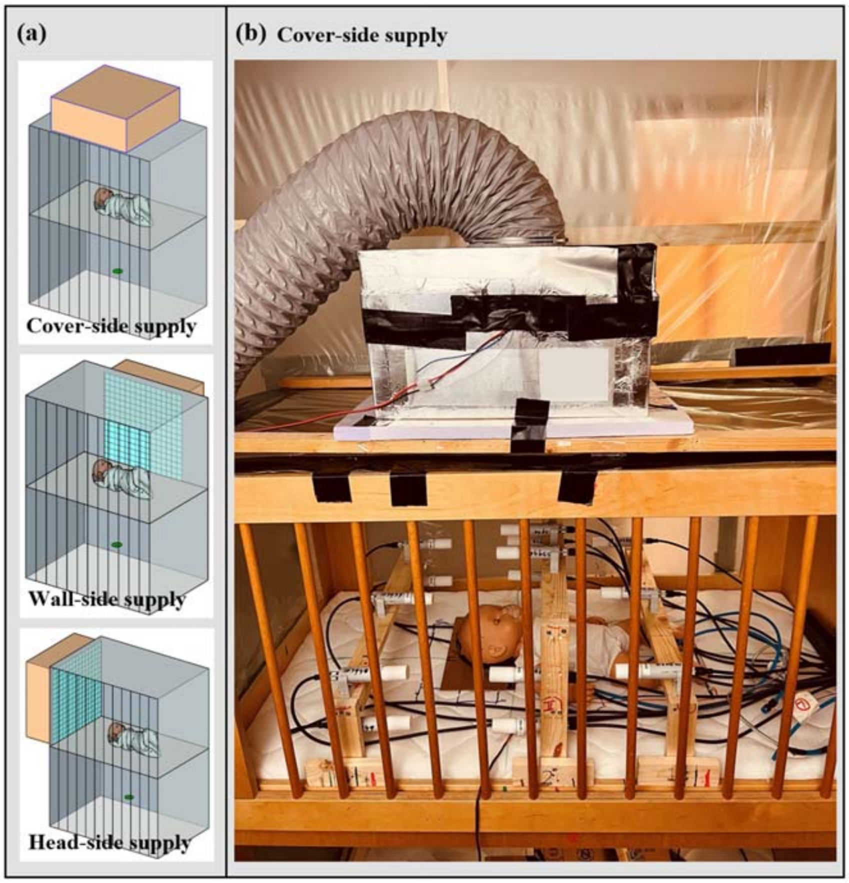

Figure 4: Experimental setup. **(a)** Axonometric schematic of the full-scale bedroom, including 12 beds (from No.1 to No.12) and sensor placement. **(b)** A picture of the on-site bedroom.

Table 1: Overview of 34 experiments categorized by combinations of experimental conditions.

Ventilation Mode	PV Location Placed	Ventilation Rate	Sleep Position	Test Run Time *
MV	-	55 m^3/h	Supine	1
		55 m^3/h	Lateral-to-Wall	1
		55 m^3/h	Lateral-to-Corridor	2
PV	Wall-side	55 m^3/h	Supine	1
		55 m^3/h	Lateral-to-Wall	1
		55 m^3/h	Lateral-to-Corridor	1
	Head-side	27, 37, 55 m^3/h	Supine	2
		21, 37, 55, 65, 75 m^3/h	Lateral-to-Wall	2
		55 m^3/h	Lateral-to-Corridor	1
	Cover-side	21, 37, 55, 65, 75 m^3/h	Supine	2
		21, 37, 55, 65, 75 m^3/h	Lateral-to-Wall	2
		55, 65, 75 m^3/h	Lateral-to-Corridor	2

Notes: * In the scenario described as 'MV' (Mixing Ventilation), the indicated ventilation rate was solely provided by a single ceiling air supply diffuser (see **Figure 1a**), while in the 'PV' (Personalized Ventilation) case, the supply of air was exclusively provided through the PV setup (see **Figure 2**). The 'Test Run Time' column in this table primarily indicates the number of experimental runs conducted under a specific ventilation rate of 55 m^3/h for each sleeping position and ventilation mode combination. For ventilation rates other than 55 m^3/h (as listed under the 'PV Location Placed' category), each experimental condition was tested only once.

Notably, the baby model was positioned in the No.7 bed (see **Figure 1**). This choice was necessitated by the dimensions of the PV setup, which could not be accommodated in the smaller space of other beds inside the climate chamber.

As shown in **Table 1**, the experimental design encompassed three supply airflow directions (cover-side, wall-side, head-side, also see **Figure 4a**), five ventilation rates (21, 37, 55, 65, 75 m^3/h), and three sleep positions (supine, lateral-to-corridor, and lateral-to-wall). It should be mentioned that the selection of the lowest ventilation rate (21 m^3/h) was based on the operational capacity of the PV setup with the lowest power, while the selection of the highest rates (75 m^3/h) was aimed at the supplied air velocity to be within 0.2 m/s for comfort considerations [20-22]. For comparative purposes, a control scenario employing mixing ventilation (MV) at the ventilation rate of 55 m^3/h was also examined.

2.4 Experimental procedure and data analysis

The experimental procedures, as followed the protocols established in the prior study [11], ensured that each measurement reached a steady state for accurate CO_2 quantification. Data analysis was processed using Python 3.8.8 with the following key steps:

(1) Measurements from various instruments were averaged into 1-minute averages using pandas' DataFrame.resample.mean method.
(2) Equilibrium in indoor air distribution was determined by analyzing sensor data over a 10-minute period for consistency using the Shapiro-Wilk test for normality and either one-way ANOVA or Kruskal-Wallis H Test for statistical differences, with a significance level of 0.05.
(3) Actual CO_2 concentration variations were isolated by subtracting the stable background supply air CO_2 level (average 418 ppm) from sensor readings.
(4) Experimental repeatability was checked by comparing the absolute difference in CO_2 concentrations between repeated tests to a 50 ppm threshold (the uncertainty of CO_2 measurements).
(5) Steady-state values for each sensor were calculated from 10-minute averages in each case.

3 RESULTS AND DISCUSSION

All tests showed no significant differences (p-value > 0.05) in CO_2 concentrations across the last 10-minute measurements, indicating that a steady state was reached in each case. The reproductivity test confirmed that the median of absolute differences in CO_2 concentrations between repeated cases for each sensor was below 50 ppm, demonstrating good experimental repeatability. Consequently, data from six repeated cases were averaged to represent a single case based on the steady-state data of each sensor.

3.1 Bed-level CO_2 spatial distribution

Figure 5 presents the CO_2 spatial distribution at bed level for all cases under ventilation rate of 55 m^3/h. The CO_2 distribution can be visually compared in four ventilation strategies and three different sleep positions. Two main aspects that are generally applicable to most cases in **Figure 5** are pointed out as follows:

(1) Under the same sleep position, the MV mode generally registered the highest CO_2 concentration around the baby model within the bed, compared to others three PV modes. This demonstrated that PV mode has better ventilation effectiveness to remove the metabolic CO_2 emissions from the semi-enclosed bed than MV mode.
(2) Under the same ventilation strategies, a significant difference in CO_2 spatial distribution inside the baby bed was observed among the three sleep positions investigated. This

confirms that the CO_2 distribution pattern within the breathing zone is affected by the babies' posture [11, 23].

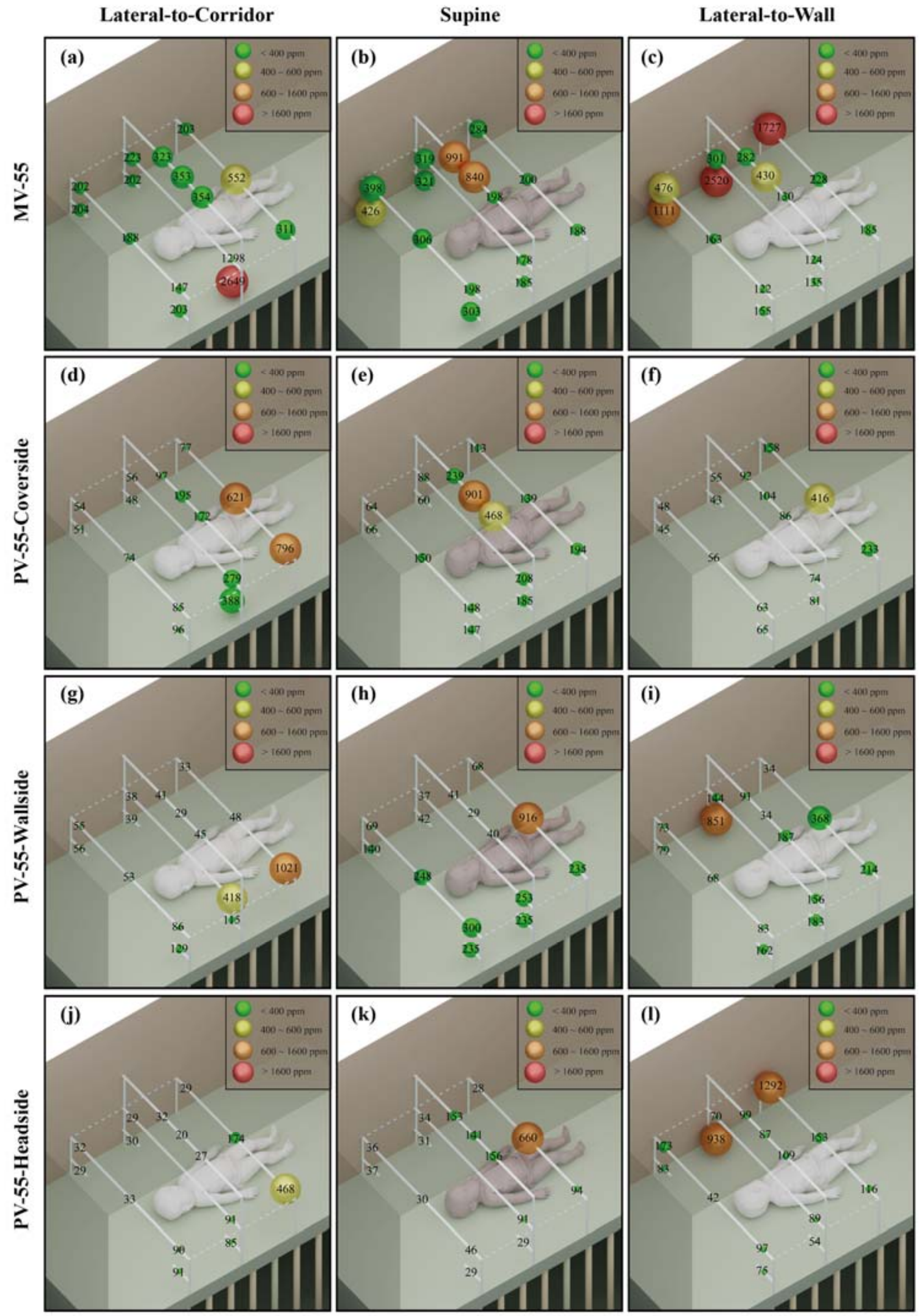

Figure 5: CO_2 dispersion (values above the background level: 418 ppm) inside the No.7 bed in all cases under the ventilation rates of 55 m^3/h.

3.2 Effect of different PV strategies

Results from **Figure 6** indicate CO_2 concentrations measurements at different locations, considering inhaled air, in-bed mean, and exhaust air at the same ventilation rate of 55 m3/h for the comparison of MV and the other three PV strategies. Key findings can be drawn from the figure:

(1) The exhaust air CO_2 concentrations were consistent across all strategies, underpinning the robustness of the experimental setup. This consistency is attributed to the same settings in CO_2 emission rates and ventilation rates, ensuring a stable baseline for comparison.
(2) MV resulted in the highest CO_2 levels in both inhaled and in-bed measurements compared to the PV strategies. Particularly for inhaled air, MV's values were noticeably elevated (up to 1392 ppm above the background level), suggesting that PV strategies are more effective in diluting CO_2 concentrations within the breathing zone over MV.
(3) PV head-side consistently recorded the lowest inhaled CO_2 concentrations across all positions, suggesting an enhanced capability for removing metabolic CO_2 emissions. Notably, in the lateral-to-wall position, PV head-side reduced inhaled CO_2 to as low as 53 ppm above the background level, demonstrating a better improvement in inhaled air quality compared to the other PV strategies.

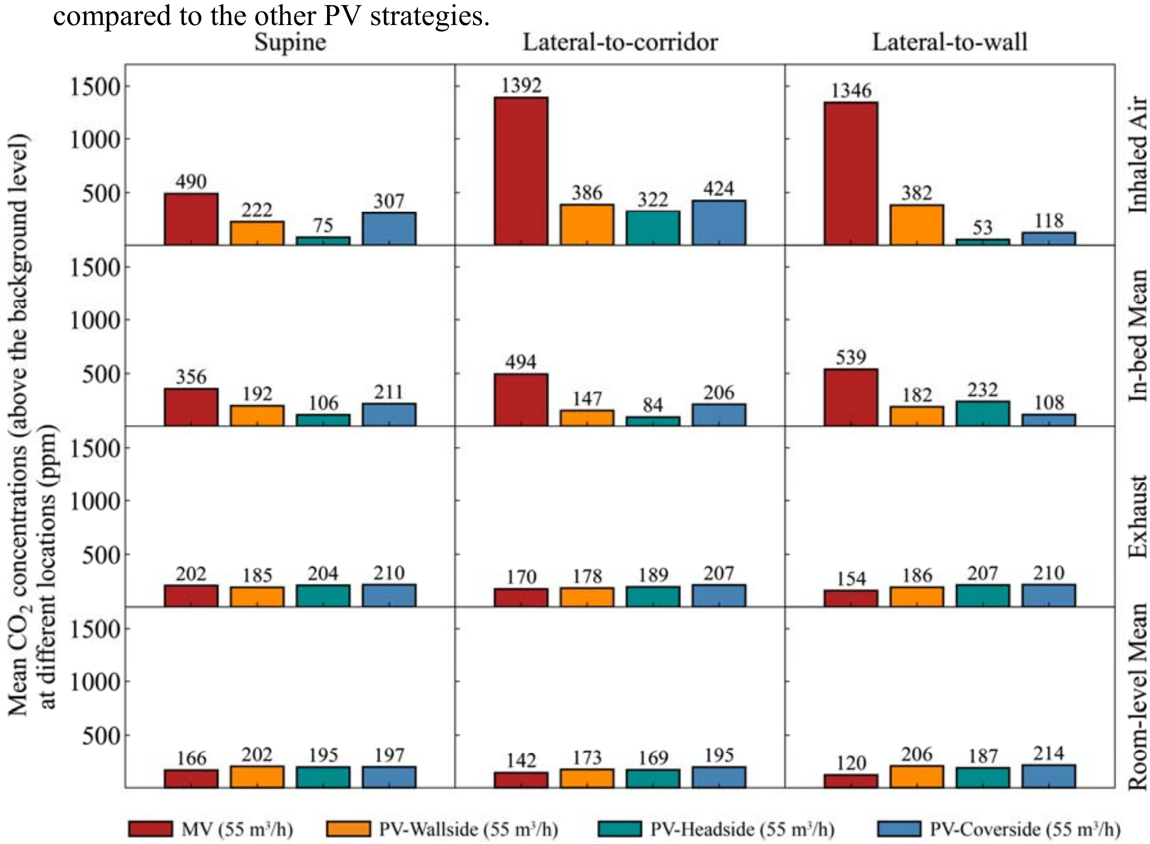

Figure 6: Comparative CO_2 concentrations (values above the background level: 418 ppm) across four different ventilation strategies and three sleep positions at a uniform ventilation rate of 55 m^3/h.

3.3 Effect of different ventilation rates

Additionally, **Figure 7** presents CO_2 concentration levels at two different locations for two PV strategies —PV head-side and PV cover-side— under varying ventilation rates (21, 37, 55, 65, 75 m^3/h) and three different sleeping positions, revealing that:
(1) Generally, increased ventilation rates correlate with lower CO_2 concentrations at different measurement points across different sleep positions and ventilation strategies.
(2) The PV head-side strategy tends to perform better at lower ventilation rates, while the PV-cover-side strategy requires higher rates to achieve similar dilution effects.
(3) However, the relationship is not linear, and some positions show a plateau or increase in CO_2 concentrations at higher ventilation rates, indicating that the optimal rate may vary by position and strategy.

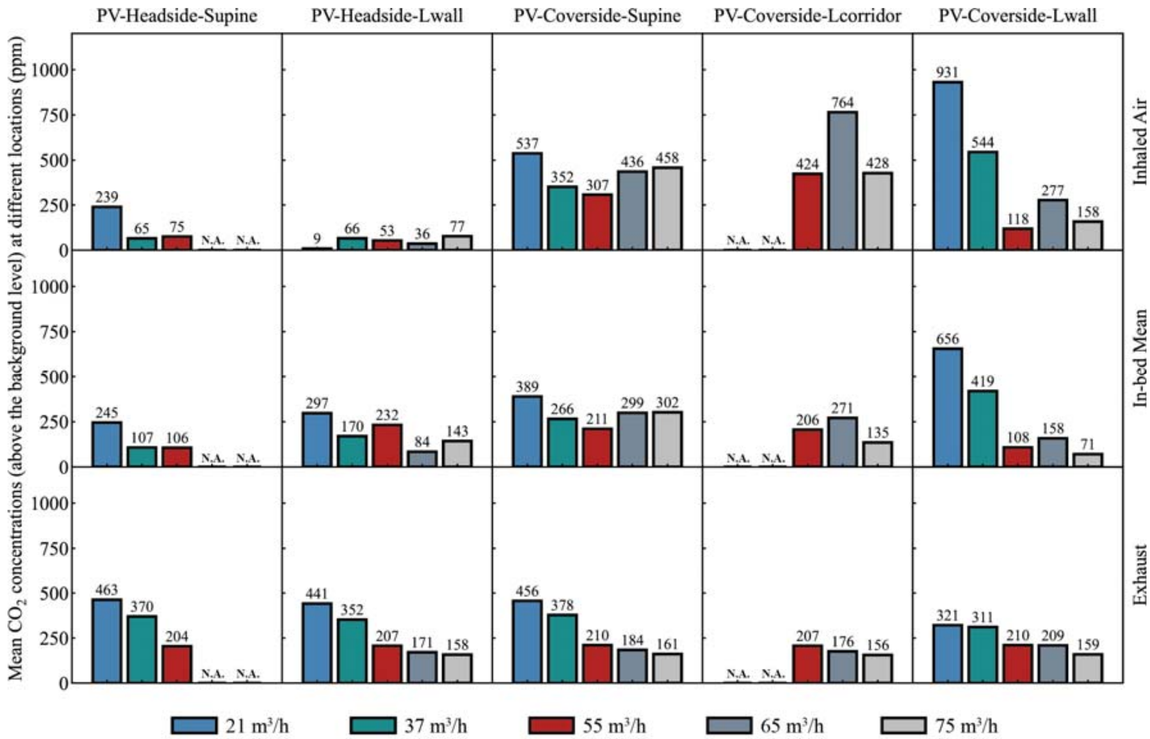

Figure 7: CO_2 concentrations (values above the background level: 418 ppm) at different measurement points (inhaled, in-bed, and exhaust air) for two ventilation strategies (PV head-side and PV cover-side) under three different sleeping positions and ventilation rate (21, 37, 55, 65, 75 m^3/h).

4 CONCLUSIONS

Ventilation in semi-enclosed baby beds requires improvement, and fortunately, there are feasible solutions available. The study examined the effectiveness of personalized ventilation (PV) strategies within a semi-enclosed baby bed in a typical daycare center environment. This study confirms that PV can more efficiently enhance inhaled and bed-level air quality for young children compared to traditional ventilation methods. Using a detailed setup with varied airflow directions and rates, the PV head-side strategy proved to be most efficient at lower flow rates, optimizing inhaled air quality and suggesting potential for energy savings. The results also indicate that while increased PV ventilation rates typically improve bed-level air quality, the optimal ventilation rate is influenced by the specific strategy and sleeping position. This emphasizes the need for tailored ventilation solutions for infants in daycare centers.

5 ACKNOWLEDGEMENTS

Dr. Arjen de Jong from AirTulip is acknowledged for providing us with personalized ventilation setup from New York and assisting us in the experimental preparations. We are also grateful to the Building Physics and Services Laboratory team for their support.

6 REFERENCES

1. Zheng, H., et al., *Laboratory evaluation of low-cost air quality monitors and single sensors for monitoring typical indoor emission events in Dutch daycare centers.* Environment International, 2022. **166**: p. 107372.
2. Zhang, Y., P.K. Hopke, and C. Mandin, *Handbook of Indoor Air Quality*. 2022: Springer Nature Singapore Pte Ltd.

3. Basinska, M., M. Michalkiewicz, and K. Ratajczak, *Impact of physical and microbiological parameters on proper indoor air quality in nursery.* Environment International, 2019. **132**: p. 105098.
4. Roda, C., et al., *Assessment of indoor environment in Paris child day care centers.* Environ Res, 2011. **111**(8): p. 1010-7.
5. Sander, I., et al., *Allergen quantification in surface dust samples from German day care centers.* Journal of Toxicology and Environmental Health - Part A: Current Issues, 2016. **79**(22-23): p. 1094-1105.
6. Onishchenko, A., et al., *RADON MEASUREMENTS IN KINDERGARTENS IN URAL REGION (RUSSIA).* Radiation protection dosimetry, 2017. **177**(1-2): p. 112-115.
7. Capi Education BV. *Capi Education for Bed*. 2022; Available from: https://www.capi-education.com/?s=bed&post_type=product.
8. Boor, B.E., et al., *Human exposure to indoor air pollutants in sleep microenvironments: A literature review.* Building and Environment, 2017. **125**: p. 528-555.
9. Liang, Y. and Y. Xu, *Emission of phthalates and phthalate alternatives from vinyl flooring and crib mattress covers: The influence of temperature.* Environmental Science and Technology, 2014. **48**(24): p. 14228-14237.
10. Jr, E.J.F., et al., *Modeling indoor air concentrations near emission sources in imperfectly mixed rooms.* Journal of the Air & Waste Management Association, 1996. **46**(9): p. 861-868.
11. Zheng, H., et al., *Bed-level ventilation conditions in daycare centers.* Building and Environment, 2023: p. 110638.
12. Zheng, H., et al., *Bedroom ventilation performance in daycare centers under three typical ventilation strategies.* Building and Environment, 2023. **243**: p. 110634.
13. Wang, Z., et al. *A survey of indoor air quality conditions in bedrooms of Dutch daycare centers*. 18th Healthy Buildings Europe Conference 2023; Available from: https://pure.tue.nl/ws/portalfiles/portal/301657351/Wang_1312_A_1_.pdf.
14. Hull, D., et al., *Individual variation in sleeping metabolic rates in infants.* Archives of disease in childhood, 1996. **75**(4): p. 288-291.
15. Hull, D., et al., *Metabolic rate of sleeping infants.* Archives of disease in childhood, 1996. **75**(4): p. 282-287.
16. Garcia-Souto, M. and P. Dabnichki, *Core and local skin temperature: 3–24 months old toddlers and comparison to adults.* Building and Environment, 2016. **104**: p. 286-295.
17. Kierat, W., et al., *Towards enabling accurate measurements of CO2 exposure indoors.* Building and Environment, 2022. **213**: p. 108883.
18. ISO, *ISO 8996:2021-Ergonomics of the thermal environment — Determination of metabolic rate*. 2021, ISO.
19. Fleming, S., et al., *Normal ranges of heart rate and respiratory rate in children from birth to 18 years of age: a systematic review of observational studies.* Lancet, 2011. **377**(9770): p. 1011-8.
20. Dongmei, P., et al., *Air-conditioning for sleeping environments in tropics and/or sub-tropics – A review.* Energy, 2013. **51**: p. 18-26.
21. Zhu, S., W. Cai, and J.D. Spengler, *Control of sleep environment of an infant by wide-cover type personalized ventilation.* Energy and Buildings, 2016. **129**: p. 69-80.
22. Cao, G., et al., *A review of the performance of different ventilation and airflow distribution systems in buildings.* Building and Environment, 2014. **73**: p. 171-186.
23. Pantelic, J., et al., *Personal CO2 cloud: laboratory measurements of metabolic CO2 inhalation zone concentration and dispersion in a typical office desk setting.* Journal of Exposure Science & Environmental Epidemiology, 2020. **30**(2): p. 328-337.