Infection Risk between Patients and Healthcare Staff with Mixing and Attachment Ventilation Systems in a Double-bed Patient Room

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SUMMARY
This study investigates the effectiveness of different air distribution methods in reducing airborne infection risk in a double-bed patient room. Full-scale chamber experiments were conducted under a heat gain of 17 W/m² with airflow rates of 40 L/s and 80 L/s, using sulfur hexafluoride (SF_6) tracer gas released from a thermal breathing manikin to simulate exhaled aerosols. Mixing ventilation, exposed-side attachment ventilation, and infected-side attachment ventilation were compared. At 80 L/s, infected-side attachment ventilation achieved 29.6% and 28.3% higher average dilution ratios than mixing ventilation and exposed-side attachment ventilation, respectively, while no significant differences were observed at 40 L/s. Infection probability was lower for patients in the exposed area, with reductions of up to 23.1 percentage points. Infected-side attachment ventilation provided the lowest infection probability, indicating its effectiveness in high-exposure zones. Overall, higher airflow rates enhanced infection risk reduction, with spatial variations becoming more pronounced at 80 L/s.

KEYWORDS
Infection risk, patient room, air distribution, chamber study, tracer gas

1 INTRODUCTION

Hospital environments face a high risk of person-to-person infection transmission in highly occupied spaces, particularly following outbreaks of respiratory diseases (Li et al., 2022; Danesh Yazdi et al., 2022). During clinical activities such as general nursing (e.g., bed making, admission interviews, and wound care), particle mass concentrations may increase significantly in local areas between healthcare staff and patients due to close contact and verbal communication (Furåker, 2009). In addition, healthcare staff may act as vectors and introduce virus-laden particles into patient rooms during daily routines (Huttunen and Syrjänen, 2014). Therefore, it is necessary to implement effective protective measures to safeguard vulnerable patients from external pollutants within local microenvironments.

Ventilation is a critical method for preventing the transmission of pathogens and has been emphasized in worldwide guidelines (R3 Nordic, 2024; ASHRAE, 2021). Mixing ventilation (MV) is widely applied in patient rooms because it is easy to implement in practice. Moreover, MV generally produces a more uniform indoor environment by enhancing the mixing of air, resulting in relatively even temperature and contaminant distributions within the occupied zone (Dao et al., 2022). As a result, air quality across the room is often comparable to exhaust conditions because heating and cooling loads are effectively extracted (Zhao et al., 2024).

In previous studies, novel air distribution solutions have also been investigated in patient rooms to address the non-uniform nature of airborne transmission under realistic conditions. For example, Zhang et al. (2022) found that wall-based attachment ventilation resulted in lower contaminant concentrations under the same airflow conditions compared with ceiling and sidewall air supply. Su et al. (2024) developed a bed ventilation system in a ward and achieved a concentration reduction of more than 50% compared with conventional conditions. Hagström et al. (2022) proposed a dynamic protective airflow system in a simulated patient room, where jet-integrated cooling and heating panel diffusers generated parallel airflow streams toward the patient bed, reducing healthcare workers' exposure risk by 65%–85% without compromising patient thermal comfort. These findings demonstrate the potential of local air distribution solutions with high ventilation efficiency to reduce healthcare-associated infection risks.

Attachment ventilation, which combines characteristics of mixing ventilation and displacement ventilation, delivers air downward along vertical surfaces such as walls or columns (Zhang et al., 2022). After reaching a horizontal surface, the airflow spreads into the occupied zone, a process commonly associated with the Coanda effect (Henri, 1936). In addition, the use of an adjustable deflector can further improve the performance of attachment ventilation by guiding clean air more precisely toward the occupied area through modifications in its angle or height (Hou et al., 2025). Compared with conventional mixing ventilation, attachment ventilation therefore shows strong potential for providing targeted ventilation in hospital environments.

This study aims to evaluate the ventilation performance, in terms of infection risk, of general mixing ventilation and wall attachment ventilation in a double-bed patient room when a staff member acts as the infector. Given that increasing airflow rates have been demonstrated to be an effective approach for removing contaminants from the occupied zone (Satheesan et al., 2020), two airflow rates (40 L/s and 80 L/s) were compared under a simulated mid-season heat gain of 17 W/m². By examining these factors, this study highlights the combined importance of airflow patterns, infection source location, and adequate ventilation rates in mitigating airborne infection risk.

2 METHODS

Chamber setups

The experiments were carried out in a full-scale climate chamber located in a laboratory hall at Aalto University, constructed as a mock-up of a patient room at one Finnish university hospital. During the experiments, the room was occupied by three simulated occupants, including one infected healthcare staff member (M5) represented by a thermal manikin and two susceptible patients (M1 and M2) represented by heated dummies. The chamber had internal dimensions of 5.50 m × 3.80 m × 2.70 m (length × width × height), measured from floor to ceiling, as illustrated in **Figure 1**.

Three air distribution approaches were applied and compared in this study: mixing ventilation (MV), exposed-side attachment ventilation (E-ATT), and infected-side attachment ventilation (I-ATT). For MV, a multi-nozzle diffuser was installed at the center of the ceiling to supply clean air in a four-way pattern. For both E-ATT and I-ATT, a perforated duct equipped with a deflector was installed on the left side of the chamber near the ceiling. The deflector was positioned at a height of 2.20 m to guide the downward airflow from the perforated duct toward the patients' breathing zone. The distinction between E-ATT and I-ATT lies in the manikin location (M5, **Figure 1**), which was placed either on the same curtain side as the attachment diffuser or on the opposite side.

The simulated infector was represented by a thermal breathing manikin (PT Teknik, Denmark) composed of 27 individually heated body segments and configured in a standing posture of staff member. The manikin was coupled with an artificial lung system to reproduce realistic human respiration, including air distribution, humidification, and control of the exhaled air temperature. Inhalation was performed through the nostrils, while exhalation occurred through the mouth, with a pulmonary ventilation rate maintained at 6.0 L/min. Each breathing cycle consisted of a 2.5-s inhalation phase, followed by a 1.0-s pause, a 2.5-s exhalation phase, and another 1.0-s pause. Two susceptible patients were simulated using heated dummies, which generated thermal plumes and could influence airborne transmission through buoyancy-driven airflow.

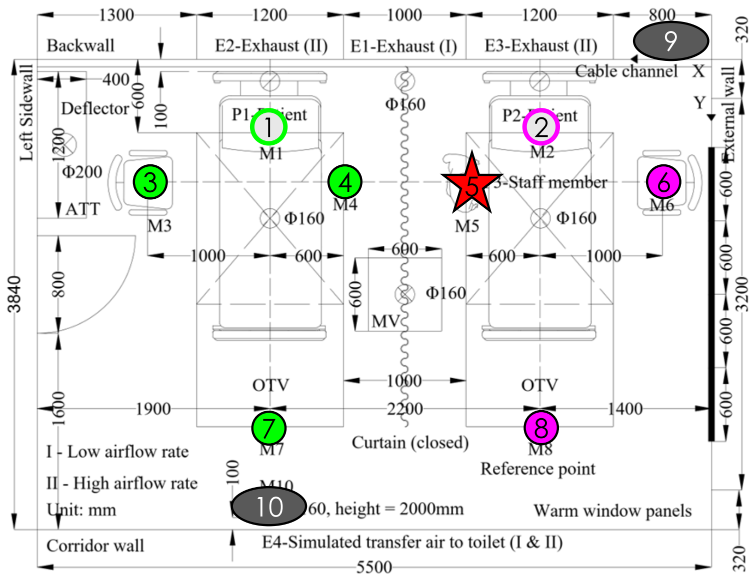

Figure 1. Air distribution methods and locations of SF_6 measurement points in the chamber.

Experimental conditions and test cases

The operative temperature in the thermal chamber was controlled at 24 ± 1 °C at a height of 1.1 m based on heat balance conditions. The relative humidity varied slightly during the measurements, ranging from 30% to 40%. Internal heat gains in the chamber were generated by occupants, lighting, and equipment, and were balanced by air cooling. The supply air temperature was maintained at 20 °C, representing mid-season climate conditions corresponding to a heat gain of 17 W/m². According to the R^3 Nordic guideline (2024), the low airflow rate was set at 40 L/s to meet the minimum ventilation requirement for a general patient room. For the high airflow condition, intended to enhance airborne contaminant removal efficiency (Satheesan et al., 2024), the airflow rate was doubled to 80 L/s during the experiments.

Nine measurement points were monitored simultaneously using tracer gas (SF_6) during the experiments. The tracer gas was employed to simulate virus-containing particles in the exhaled air of an infected occupant. As shown in **Figure 1**, the target locations included the exhaled concentration of one infected staff member (M5) and the inhaled concentrations of two susceptible patients (M1 and M2). Additional points without occupants included two assumed sitting visitor locations (M3 and M6), one assumed standing staff location (M4), and two reference points near the end of the beds (M7 and M8). In addition, M10 represented a simulated toilet exhaust with a fixed airflow rate of 30 L/s, while M9 corresponded to the total exhaust. Before each measurement, the tracer gas concentration was allowed to reach a steady state, after which ten steady-state samples were recorded, requiring approximately two hours. **Table 1** summarizes the six test cases considered in this study, including key parameters such as air distribution, heat gain, airflow rate, and infector location.

Table1. Test cases with different air distribution methods.

Case	Air distribution	Heat flux (W/m²)	Airflow rate (L/s)	Infector
1	MV	17	40	Staff (M5)
2	MV	17	80	Staff (M5)
3	E-ATT	17	40	Staff (M5)
4	E-ATT	17	80	Staff (M5)
5	I-ATT	17	40	Staff (M5)
6	I-ATT	17	80	Staff (M5)

Evaluation indices

The dilution ratio was calculated as the concentration at the infectious position divided by that at the susceptible position, as shown in Eq. (1). In this study, the source concentration of the infected occupant was approximately 20000 ppm. To evaluate airborne infection risk in non-uniform indoor environments, the dilution-based Wells–Riley model proposed by Zhang et al. (2021) was adopted. By calculating the number of quanta inhaled by an individual at targeted locations over a given exposure period, the infection risk can be determined based on indoor air dilution, as expressed below.

$$D = \frac{C_i}{C_s} \tag{1}$$

$$C_q = \frac{q}{D \times p_i} \tag{2}$$

$$N_q = \int_0^T p_s \times C_q(t) dt \tag{3}$$

$$P_D = 1 - e^{-N_q} \tag{4}$$

$$P_D = 1 - e^{-\int_0^T \frac{q \times p_s}{D(t) \times p_i} dt} \tag{5}$$

where D is the dilution ratio at the target position; C_i and C_s are the airborne contaminant concentrations at the infectious and susceptible position, respectively (ppm); C_q is the airborne quantum concentration at the susceptible position (quanta/m^3); q is the quanta produced by each source infector (h^{-1}); p_i and p_s are the breathing rates of the infected and susceptible person (m^3/s), respectively; N_q is the inhaled quanta by the susceptible person during the exposure period; T is the total exposure time (h); and P_D is the airborne infection risk for the susceptible person estimated by the dilution-based method.

3 RESULTS

Dilution ratio

Figure 2 presents the dilution ratios at local areas under different air distribution methods at low and high airflow rates, excluding the infected standing staff member (M5). At an airflow rate of 40 L/s (**Figure 2a**), the ventilation performance was relatively uniform across measurement points, with an average dilution ratio of 850. The susceptible patient in the exposed area (M1) exhibited an average dilution ratio 19.1% higher than that of the patient in the infected area (M2), indicating that areas surrounding the infector were associated with higher contaminant concentrations and therefore require particular attention.

When the airflow rate was increased to 80 L/s (**Figure 2b**), greater variability was observed among air distribution methods and local areas. In particular, infected-side attachment ventilation generally outperformed mixing ventilation and exposed-side attachment ventilation, achieving average dilution ratios of 1890 in the exposed area (M1, M3, M4, and M7) and 1450 in the infected area (M2, M6, and M8). Consequently, doubling the airflow rate resulted in increases of 105.4% and 87.2% in dilution ratio in the exposed and infected areas, respectively. In contrast, when the attachment diffuser was located on the exposed side, the air distribution performance was comparable to that of mixing ventilation, and not all exposed-area measurement points exhibited higher dilution ratios. These results indicate that attachment ventilation can effectively enhance local indoor air quality when appropriately designed near the infection source.

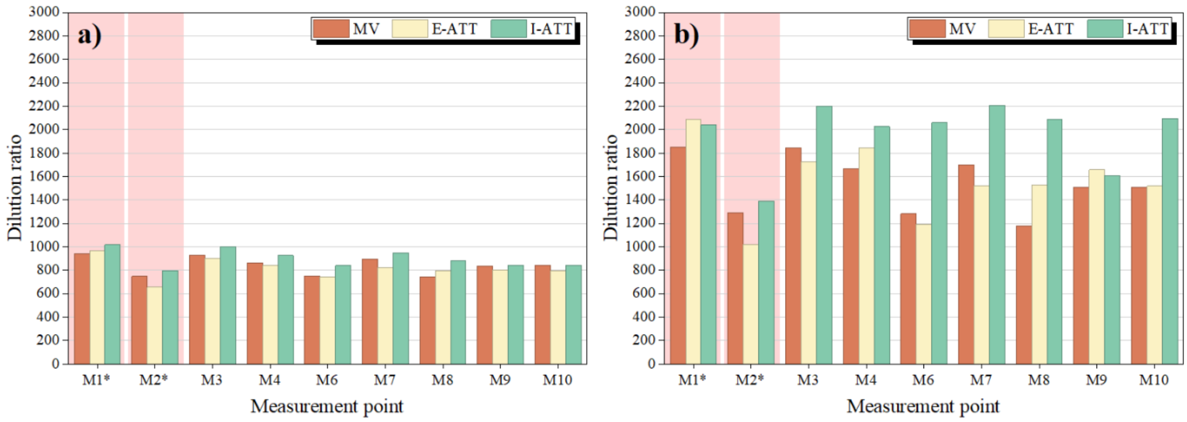

Figure 2. Dilution ratio with different air distribution methods a) 40 L/s, b) 80 L/s.

Infection probability

Figure 3 shows the infection probability at two susceptible patients (M1 and M2) under different air distribution methods at low and high airflow rates. Following Aganovic et al. (2024), the quanta generation rate from a standing person was set at 16 quanta per hour. The breathing rate of the infected manikin was fixed at 0.36 m^3/h. For the susceptible patients, the breathing rates depended on their metabolic levels and were set to 0.24 m^3/h (ASHRAE, 2023).

According to the dilution-based Wells–Riley model (Zhang et al., 2021), the infection probability under fully mixed conditions was calculated using the concentration measured at M9, which represents the total exhaust point where the contaminant removal effectiveness (CRE) equals 1. At a low airflow rate of 40 L/s (**Figure 3a**), the infection probability under fully mixed conditions was 2.8%. Compared with the fully mixed condition, the susceptible patient in the exposed area (M1) experienced a lower average infection probability of 25.0% than the patient in the infected area (M2). Under infected-side attachment ventilation, M2 exhibited the lowest infection risk, which was 6.5% lower than that with mixing ventilation and 17.1% lower than that with exposed-side attachment ventilation.

When the airflow rate was increased to 80 L/s (**Figure 3b**), the infection probability under fully mixed conditions decreased to 1.4%. Similarly, the susceptible patient in the exposed area (M1) exhibited a lower average infection probability (1.2%) than that under fully mixed conditions across all three air distribution methods, indicating that increasing the airflow rate reduced the infection risk at the exposed position by 50.0%. For the patient in the infected area (M2), infected-side attachment ventilation continued to outperform the other air distribution methods, consistent with the low-airflow results. These findings demonstrate the effectiveness of attachment ventilation in enhancing local contaminant removal when applied in infected zones.

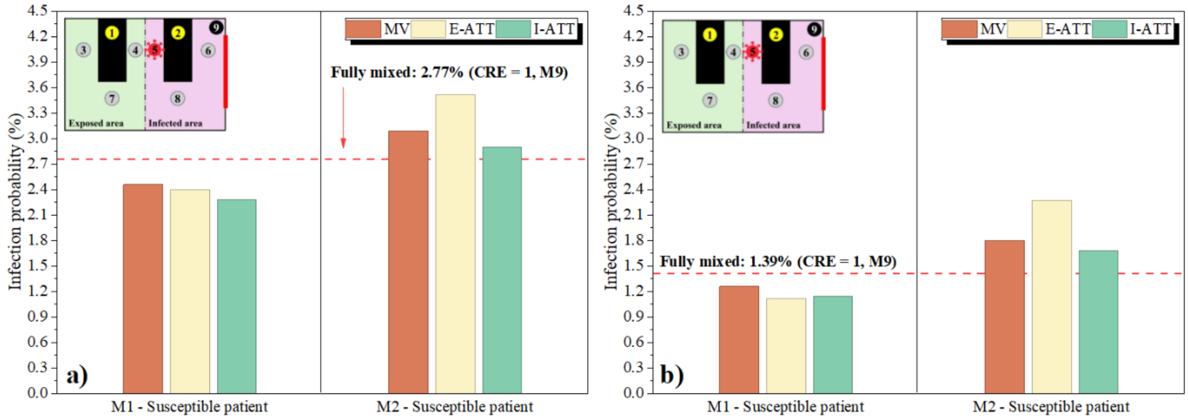

Figure 3. Infection probability with different air distribution methods a) 40 L/s, b) 80 L/s.

4 DISCUSSION

Air distribution methods play a crucial role in reducing infection probability in healthcare indoor environments (Stockwell et al., 2019). This study highlights the importance of applying local air distribution solutions that are easy to implement and adapt to improve air quality within the occupied microenvironment. However, ventilation effectiveness was strongly influenced by airflow rate and infector location. The results indicate that, under adequate airflow conditions, infected-side attachment ventilation achieved higher dilution ratios and lower infection probabilities at susceptible positions than mixing ventilation. These findings are consistent with the observations of Hatif et al. (2023), who suggested that mixing ventilation is preferable under high supply airflow rates when the infector location is uncertain.

Moreover, exposed-side attachment ventilation resulted in higher infection risks at two susceptible positions (M1 and M2), demonstrating the sensitivity of attachment ventilation to the location of the infection source. This effect may be attributed to the fact that the airflow supplied by the attachment diffuser was not directed toward the breathing zone of the lying patient. When the patient acted as the infector, the supplied clean air could hinder effective pollutant removal from the source region. Conversely, when the patient was susceptible and required protection, the clean air was unable to reach the breathing zone efficiently, leading to an increased infection risk. These findings highlight that airflow patterns and source location are critical parameters that must be considered alongside airflow rate (Liu et al., 2017). Therefore, a comprehensive assessment of airflow distribution along the transport path from the contaminant source to the exhaust outlet is essential for optimizing local indoor air quality.

This study employed a tracer gas approach to simulate influenza transmission in a double-bed patient room under steady-state conditions. However, this method cannot capture dynamic concentration variations, as it does not account for occupant movement, walking, or room entry and exit, all of which may influence air quality in occupied zones (Liu et al., 2025). In real clinical settings, inpatients typically remain in the room for extended periods, whereas healthcare staff usually stay for less than 15 minutes per patient during ward rounds (Ratelle et al., 2021). Consequently, the two-hour exposure duration used to calculate infection probability may not fully represent the short and variable nature of staff activities. Further studies are therefore required to investigate multiple infection scenarios, including variations in the number and roles of infectors.

5 CONCLUSIONS

In this chamber study, the performance of different air distribution methods: mixing ventilation (MV), exposed-side attachment ventilation (E-ATT), and infected-side attachment ventilation

(I-ATT) was evaluated in a full-scale mock-up double-bed patient room. The simulated room accommodated three occupants, including one infected staff member represented by a thermal manikin and two susceptible patients represented by heated dummies. Two airflow rates, 40 L/s and 80 L/s, were investigated and compared under a low heat gain condition of 17 W/m². The main conclusions are summarized as follows:

- At a low airflow rate of 40 L/s, the dilution ratio was relatively uniform across measurement points for different air distribution methods. The susceptible position in the exposed area exhibited an average dilution ratio 19.1% higher than that in the infected area.
- At a high airflow rate of 80 L/s, the dilution ratio varied among locations. Infected-side attachment ventilation generally outperformed mixing ventilation and exposed-side attachment ventilation, whereas exposed-side attachment ventilation showed performance comparable to that of mixing ventilation.
- Doubling the airflow rate resulted in increases of 105.4% and 87.2% in dilution ratio in the exposed and infected areas, respectively. It indicates that adequate ventilation can effectively enhance local indoor air quality.
- Regarding infection probability, the susceptible position in the infected area exhibited the lowest infection risk with infected-side attachment ventilation, which was 6.5% lower than that with mixing ventilation and 17.1% lower than that with exposed-side attachment ventilation at an airflow rate of 40 L/s.
- When the airflow rate was increased to 80 L/s, the average infection risk at the exposed position was reduced by 50.0%. For the susceptible position in the infected area, infected-side attachment ventilation continued to outperform the other air distribution methods, consistent with the low-airflow results.

ACKNOWLEDGEMENT

HumanIC project has received funding from the European Union’s Horizon Europe research and innovation program under the Marie Sklodowska-Curie (HORIZON-MSCA-2022-DN-01, project no 101119726). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union. Neither the European Union nor the granting authority can be held responsible for them.

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Funded by the European Union