Preparing for the next pandemic: Minimizing airborne transmission in general inpatient wards through management practices

Abstract

Existing infection control studies in hospitals focused on rooms with special ventilation requirements. Study on proper management practices and ventilation strategies in general inpatient wards are critical but currently lacking. To identify the simple operational practices that can limit airborne transmission within a general inpatient ward with the patient cubicle, nursing station and corridor, this study investigates the effects of infected patient locations, air change rates (ACH) and door opening angles on bioaerosol dispersion using a novel tracer gas sensor network. Experimental results show that the supply inlet and infected patient locations significantly affects the distribution and dispersion of the tracer gas within the ward. Using a higher ventilation rate to achieve a lower average airborne pathogen concentration can cause more mixing of air and a wider dispersion of airborne pathogens. Localization of bioaerosols near the source through ventilation controls, a low ACH and proper patient location near the exhaust can minimize the air turbulence and the spread and reduce the infection risks of the susceptibles. Using physical partitions or objects as shields against airborne contaminants can unpredictably influence the airflow patterns, airflow evaluations should hence be done on a case-by-case basis. The methodology established in this study puts forward an economical and fast way for evaluating airborne infection risk, and the experimental results can be useful references for building engineers and hospital facility managers to formulate proper strategies for risk assessment and infection control.

Keywords: Airborne transmission, Tracer gas experiment, Infection risk, Healthcare-associated infections, Wireless sensor network

1. Introduction

Coronavirus Disease 2019 (COVID-19) pandemic has caused devastating effects worldwide. However, airborne nosocomial infections in general inpatient wards during the COVID-19 outbreak has been overlooked. A general inpatient ward can be a hub for airborne transmission as it consists of shared cubicles (some of them without closed doors) connected by a central nursing station [1]. Ventilation requirements in general inpatient wards are less stringent than those in special ventilation rooms [2]. In fact, a general inpatient ward usually has no exhaust grills built in the cubicles and air is exhausted to the corridor and eventually to the washroom [3].

Empirical evidence of airborne transmission of COVID-19 in hospitals can be found in the literature. In Singapore, field measurements in an airborne infection isolation room (AIIR) detected air and surface contamination with Severe Acute Respiratory Syndrome Coronavirus 2 (SARS-CoV-2), a strain of coronavirus that causes COVID-19 [3,4]. In China, significant amounts of SARS-CoV-2 were also obtained from the air samples and air outlet swab samples collected in different hospital wards (isolation and general) [5]. Furthermore, Cheng et al. [3] provided the first-ever environmental surveillance evidence that indicated the mechanism of possible airborne transmission of SARS-CoV-2 leading to a nosocomial point source superspreading event. Based on epidemiological findings, air outlet swab samples and whole genome sequencing, the authors postulated that airborne transmission promoted by the architectural design of ventilation systems was responsible for the outbreak.

A systematic review by Li et al. [7] concluded with significant evidence that ventilation and air movements in a built environment played an important role in the airborne transmission of infectious diseases. Airborne infection is especially dangerous in hospital settings due to high patient load. According to Abbas et al. [8], thousands of patients, visitors and healthcare workers (HCWs) got infected in general inpatient wards amidst the COVID-19 pandemic.

A number of studies have evaluated airborne transmission influenced by building ventilation in hospital settings. Tsang et al. [9] reviewed the research approaches of the relevant Computational Fluid Dynamics (CFD) studies. Despite the strength of computational simulation in creating various ventilation arrangements and scenarios, model validation with experimental or measurement results (though essential) was often omitted in those studies. On the other hand, experimental studies provide empirical evidence, knowledge and understanding through actual observations for engineering interpretation [10], yet they are often limited in scale in terms of sampling point density and experimental scenarios due to high implementation costs [11]. Although tracer gas whose molecules follow the path of small-size pathogen-laden particles is one of the most popular experimental techniques for interior airflow analysis [12], current commercial tracer gas measurement systems involve the use of long sampling cycles and limited sampling points or distances [13] and thus make the spatial and temporal evaluations of tracer gas levels difficult.

While some researchers used a tracer gas to assess the efficiency of various ventilation systems in removing contaminants from the breathing zone of a susceptible patient [14,15], some other employed it to assess the dispersion of exhaled pollutants and evaluate airborne infection risk. Sung et al. [16] identified the spatial distribution of a tracer gas at six sampling points in a hospital to examine the possibility of the spread of Middle East Respiratory Syndrome Coronavirus (MERS-CoV) through indoor airflow. Bolashikov et al. [17] measured the carbon dioxide levels in a patient room at three different locations away from a simulated coughing patient to evaluate the exposure of HCWs and occupants to coughed airborne pathogens. Under different exhaling modes and ventilation schemes, Yin et al. [18] and Nielsen et al. [19] considered the vertical tracer gas distribution in small-size inpatient rooms.

Although some studies have adopted tracer gas techniques in evaluating the dispersion of bioaerosols in hospitals under different ventilation configurations and emission scenarios,

they were mainly conducted in isolation rooms and operation theatres with high ventilation requirement for vulnerable groups of patients. Airborne transmission in general inpatient wards, on the other hand, was rarely discussed in the research field, despite that these rooms are often over-occupied, highly dynamic and engaged with healthcare workers, visitors and patients with various kind of known and novel diseases. General inpatient ward, for example the typical nightingale ward or the bay ward, is designed as one large room without or with bays that contain up to six beds, catering to a total of around 30 patients [20]. Ventilation facilities and infection control protocols in general inpatient wards may be inadequate for tackling the nosocomial airborne outbreaks. The inability of containing the outbreak at the hospitals in the beginning of COVID-19 has taught us the importance of early pandemic preparation through building ventilation and management practices in general occupied and public spaces in the hospitals [9]. Significant knowledge gap for ventilation studies in general inpatient wards is required to be filled [21].

In this study, spatial and temporal evaluations of the dispersion of airborne pathogens are presented to identify the appropriate management practices for minimizing airborne transmission in general inpatient wards. A 15-point wireless sensor network using a novel tracer gas system was constructed in a mock-up of a six-bed hospital inpatient ward cubicle with a connected nursing station to study the movement of bioaerosols under mixing ventilation. Using 1,1,1,2-tetrafluoroethane (R134a) as the tracer, the influences of infected patient locations, air change rates and door opening angles on the dispersion of the tracer gas were evaluated. The methodology established in this study puts forward an economical and fast way for evaluating airborne infection risk, and the experimental results can be useful references for building engineers and hospital facility managers to formulate proper strategies for risk assessment and infection control.

2. Materials and methods

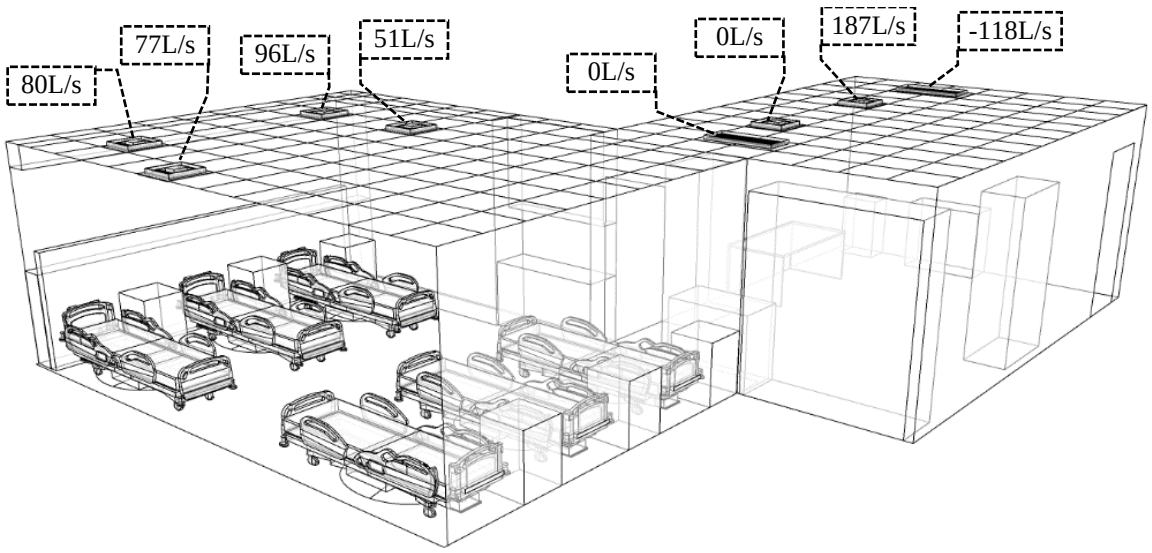
2.1 Tracer gas as a surrogate of small aerosols

Respiratory processes like breathing and coughing generate expiratory droplets of a range of sizes [22]. Large droplets would deposit on the inanimate surfaces due to gravity, causing indirect person-to-person transmission through fomites. Some droplets would evaporate to form droplet nuclei of smaller size of 0.8–3 μm [23], which can suspend and remain in the air for a long period of time and move along the airflow over a long distance [24,25]. Notably, some may concern about the physical dissimilarities of expiratory droplets and tracer gas molecules and question the appropriateness of using tracer gas to mimic the movement of infectious aerosols. Several studies have addressed this issue by examining their movements under the influence of building ventilation and found that tracer gas behaved the same as small aerosols. With the aim of evaluating the performance of mixing and displacement ventilation in contaminant removal, Yin et al. [26] discovered that tracer gas and 1 or 3 μm particles produced similar distributions in the ward, except near the source and the ventilation exhaust where the flow was unsteady. Bivolarova et al. [27] investigated the distribution patterns of nitrous oxide (N_2O) and aerosol particles with a size of 0.7 μm in a hospital room at varying ventilation rates. The dispersion of the small-sized particles was found to be the same as that of the tracer gas under the influences of free convection flow and ventilation airflow. In the position paper by Ai et al. [28], based on a review of studies that demonstrated tracer gas could accurately simulate the movement of small particles with diameters of 3–5 μm, and the fact that the aerodynamics of fine droplet nuclei with infectious pathogens are more similar to those of a gas, the authors argued that tracer gas simulation is a suitable surrogate for studying airborne transmission in the built environment as it is less complex and requires less user expertise. Tracer gas therefore can be considered a good and practical indication of the movement of bioaerosols and is widely adopted in current experimental studies on long-range

airborne transmission such as Sung et al. [16] and Huang et al. [29]. It is noteworthy that the use of tracer gases may not adequately represent the deposition and resuspension of bioaerosols on surfaces, and the viability, and infectivity of bioaerosols can be influenced by elements such as temperature, humidity, and airflows, which may not be fully reflected by tracer gases [28]. Therefore, the use of tracer gases as surrogates should be carefully weighed against the individual research goals and experimental settings.

2.2 Experimental set-up

A tracer gas experiment was conducted in a mock-up six-bed teaching ward cubicle that was connected to a nursing station by a hinged door. The dimensions of the cubicle and the nursing station were 6.5m (*L*) × 4.8m (*W*) × 2.5m (*H*) and 6m (*L*) × 4m (*W*) × 2.5m (*H*) respectively. Figure 1 exhibits the layouts of the ward cubicle and nursing station. The effects of door opening angle on the transport of bioaerosols were studied by opening the door connecting the cubicle and the nursing station at angles of 30° (half-open) and 90° (wide-open). The door connecting the nursing station and the corridor was kept fully open throughout the experiment.



(a)

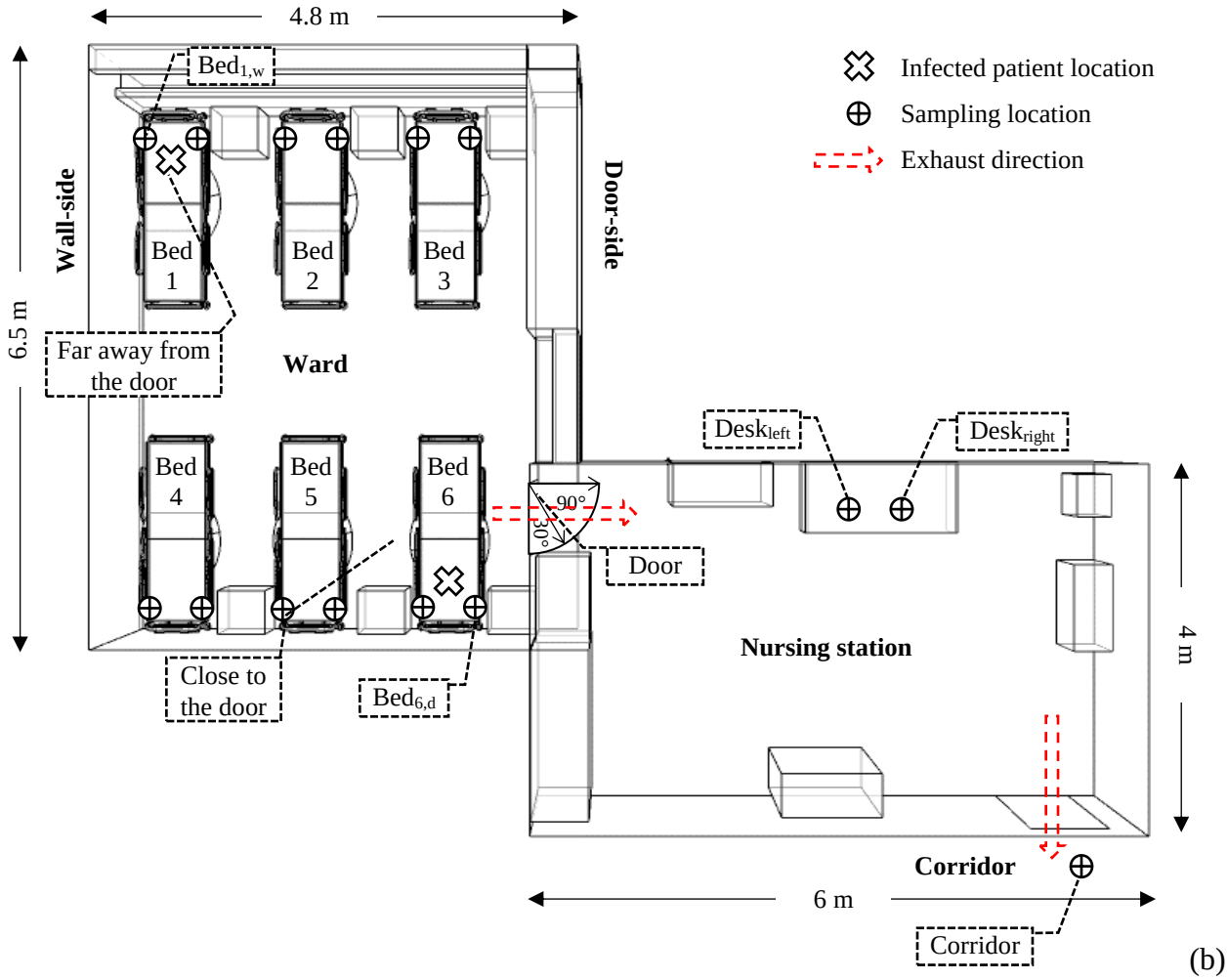


Figure 1. (a) Layout of the mock-up six-bed teaching ward cubicle with a nursing station connected by a hinged door in an isometric projection with measured volumetric flow rates of supply and exhaust air. (b) Top view of the cubicle with infected patient locations, sampling locations and exhaust directions.

Supply and exhaust airflow rates of supply inlets (0.5m × 0.5m) and exhaust outlets (1.0m × 0.5m) were measured using FlowHood Kits 8400 Series (Shortridge Instruments, Inc., USA). The air change rates (ACHs) were determined by the tracer gas decay method. The cubicle was equipped with four ceiling-mounted diffusers as the inlets for mixing ventilation. Although the nursing station was equipped with two supply-exhaust units, only one was operating. Overall, positive pressure in the cubicle relative to the corridor was maintained to ensure that air was exhausted from the cubicle to the nursing station and then to the corridor -

a typical hospital ventilation practice in Hong Kong for transferring air from “clean” to “dirty” zones [3]. Ventilation scenarios of the ward for assessment included full ventilation (all four supplies were on; approximately 6 ACH) and half ventilation with two different supply locations (either wall-side or door-side units were on; approximately 3 ACH).

Six regular hospital beds of size 2.16m (*L*) × 1.0m (*W*) × 0.6m (*H*) were placed in the mock-up ward, the spacing between the beds was approximately 0.8m. A 0.5m (*L*) × 0.5m (*W*) × 0.7m (*H*) bedside cabinet was set next to each bed. To simulate the effect of a thermal plume from an infected patient on the distribution of bioaerosols, a thermal manikin (PT Teknik, Denmark) with the metabolic rate of a sleeping person, i.e. about 0.7 met (40 W/m^2), was put on one bed [30]. Five adiabatic manikins were put on the remaining beds. Infected patient locations (bioaerosol emission locations) considered were at the far end of the ward (Far; Bed 1) and near the door next to the nursing station (Close; Bed 6). Isothermal conditions were maintained in every experiment with the thermal manikin and the ceiling lights as heat sources. To investigate the dispersion of airborne pathogens from an infected patient to the surrounding area, tracer gas R134a (density: 4.25kg/m^3, molar mass: 102.03 g/mol) was adopted in this study as it is low in toxicity and does not usually exist in a regular indoor environment. Several studies also used R134a to investigate the distribution of bioaerosols and evaluate the performance of different ventilation strategies in reducing infection risks in hospital settings [31–34]. For multi-point tracer gas measurements, an IoT-based novel tracer gas system developed previously for affordable and fast-response tracer gas evaluation was employed in this study [35]. The system utilizes Wi-Fi for sending commands and transferring measurement data to the server for storage and real-time visualization. It is a stand-alone, and highly mobile system with a short sampling cycle of 10s and without any sampling point limitations. If multiple units are deployed, the system is ideal for comprehensive evaluations of the spatial and temporal variations of a tracer gas within an indoor environment [11]. Table 1 shows the

specifications of the tracer gas system. In addition to R134a, the system can also measure air temperature, relative humidity, air velocity, carbon dioxide (CO_2), particulate matter ($PM_{2.5}$ and PM_{10}) and volatile organic compounds (VOCs). However, since the ventilation system and the environmental conditions were kept constant throughout each experiment, the data collected were relatively stable and was disregarded in the discussion.

Table 1. Specifications of the IoT-based novel tracer gas system for R134a detection

Parameter	Specification
R134a detection range	5–100 ppm
Sensitivity (change ratio of Rs)	$\leqslant$0.85
Sampling time	10 second
Measurement error	8%
System communication	2.4 or 5 GHz Wi-Fi

A total of 15 tracer gas receivers were placed in the mock-up ward and the nursing station for continuous sampling. Two receivers were placed on each side of a patient's head as shown in Figure 2. Each receiver was referred to according to its location, for example, $Bed_{1,w}$ was the receiver located near the wall side of Bed 1 and $Bed_{6,d}$ was the one close to the door side of Bed 6 as labelled in the figure. The two receivers on the work desk of the nursing station were denoted as $Desk_{left}$ and $Desk_{right}$, and the one placed in the corridor outside the nursing station (in the breathing zone of a standing person, i.e. height = 1.65m) was labelled as Corridor. The door connecting the nursing station and the corridor was kept open.

Tracer gas R134a was released from the mouth of the thermal manikin at a constant rate of 6L/min, and that was the average minute ventilation of a typical adult male (average tidal volume of 0.5L at a rate of 12 breaths per minute) [36]. Although breathing involves both

inspiration and expiration, for simplicity, R134a was released continuously for 10 minutes to simulate the exhalation of pathogen-laden droplets through the breathing process. The infected patient locations, the sampling locations, and the exhaust directions are illustrated in Figure 1. Figure 2 shows the photos of the experimental set-up. Figure 2

(a) (b)

Figure 2. Experimental set-up of a) the infected patient (emission location); and b) the susceptible patient.

Table 1 lists the case scenarios considered in this study. There were a total of eight cases with two infected patient locations namely far away from and close to the doorway to the nursing station. The ‘Control’ cases were the configurations of a general inpatient ward cubicle under normal operation, providing a baseline for the movement of airborne contaminants. While the ‘Door-side only’ and ‘Wall-side only’ cases were for evaluating the effects of reduced air change rates and supply outlet locations on the dispersion of airborne pathogens, the ‘Half-open door’ cases were for studying the influences of an obstructed airflow on the transport of airborne pathogens from the cubicle to the nursing station and the corridor. The operational changes considered in these cases, unlike strategies such as modifying the ventilation system and installing an air purification system, can be easily implemented without any additional cost and manpower. Understanding the effects of the changes can help to determine proper management practices for handling patients with unknown diseases when they are admitted to a general inpatient ward, thus minimizing airborne nosocomial infections and preventing outbreaks among hospital patients, HCWs and visitors.

By altering the experimental conditions including the emission locations, ventilation schemes and door opening angles while keeping other environmental conditions the same, the spatial and temporal changes in the tracer gas concentration at various locations were evaluated and discussed. Extraction of tracer gas was considered completed when the gas levels at all sampling points returned to the original levels (sensor noise) for more than 10 minutes. Each experiment was repeated at least two times to ensure the consistency of the results.

Table 1. Case scenarios

Case	Ventilation rate	Door opening
Control	100%; ACH = 6 h^{-1}	Wide-open
Door-side only	50% (door-side only); ACH = 3 h^{-1}	Wide-open
Wall-side only	50% (wall-side only); ACH = 3 h^{-1}	Wide-open
Half-open door	100%; ACH = 6 h^{-1}	Half-open by 30°

3. Results

3.1 Control cases

Case 1: Infected patient far away from the doorway

The control cases involved 100% ventilation with an ACH of 6h^{-1} and a wide-open door. Figure 3 exhibits the tracer gas profiles of these cases in logarithmic scale. When tracer gas was release from Bed 1, the bed farthest from the nursing station, high levels were first detected on the beds at the same end (i.e. Beds 1–3) with the following descending order: $Bed_{1,d}$, $Bed_{2,w}$, $Bed_{2,d}$, $Bed_{3,w}$, $Bed_{3,d}$ and $Bed_{1,w}$. The level of tracer gas detected at $Bed_{1,d}$ (peaked at about 250ppm) was much higher than that at $Bed_{1,w}$ (about 45ppm), suggesting an airflow away from the wall to the opposite side of the ward in the full ventilation scenario. Similar levels of tracer gas were recorded by the receivers on Beds 2 and 3, indicating a similar airborne infection risk. The tracer gas level fluctuations (i.e. irregularities on the curve) implied there were some turbulences brought about by the supply air.

At the other end of the ward, the tracer gas, whose level fluctuations were fewer, was detected a few minutes after the release. Similar levels (peaked at 38–42ppm) were recorded at all locations except for $Bed_{4,w}$. The accumulation of tracer gas near the wall side of Bed 4 indicated a stagnant area with little air movement. The tracer gas level in that area later

surpassed the highest level measured at $Bed_{2,w}$, the next closest receiver to the emission point, suggesting a relatively higher airborne infection risk for a patient on Bed 4 than on Bed 2.

In the nursing station, the tracer gas level was 2.7 times higher at $Desk_{right}$ than at $Desk_{left}$. The cabinet next to the work desk might have been obstructing the airflow and therefore shielding the receiver on the left from the tracer gas. Besides being extracted through the exhaust in the nursing station, part of the tracer gas left the room through the door to the corridor.

Case 2: Infected patient close to the doorway

When the tracer gas was released from Bed 6, which was closest to the nursing station, gas levels increased immediately at $Bed_{6,d}$ and $Bed_{6,w}$ that remained high up to 900ppm and 400ppm respectively. It is noteworthy that throughout the 10-min tracer gas release, in Control Case 1, increase in tracer gas levels were already observed at all sampling locations within a few minutes, whereas in this case the increase at other locations in the cubicle were observed only after the release. Moreover, the levels of tracer gas at other locations in the cubicle and the nursing station remained low (<30ppm) throughout the experiment. This phenomenon suggested that little dispersion occurred in the ward in contrast to Control Case 1, and it is possible that the high levels of tracer gas concentrated near the emission location was attributed to the diffuser locations. As the diffusers were directly above Beds 1 and 3, more mixing of air at that end could lead to less dispersion of tracer gas near Bed 6. Besides being exhausted through the return air grills and to the corridor, some tracer gas was believed to have escaped the ward through the false ceilings and the gaps between the wall and the partition separating the mock-up ward from the rest of the room.

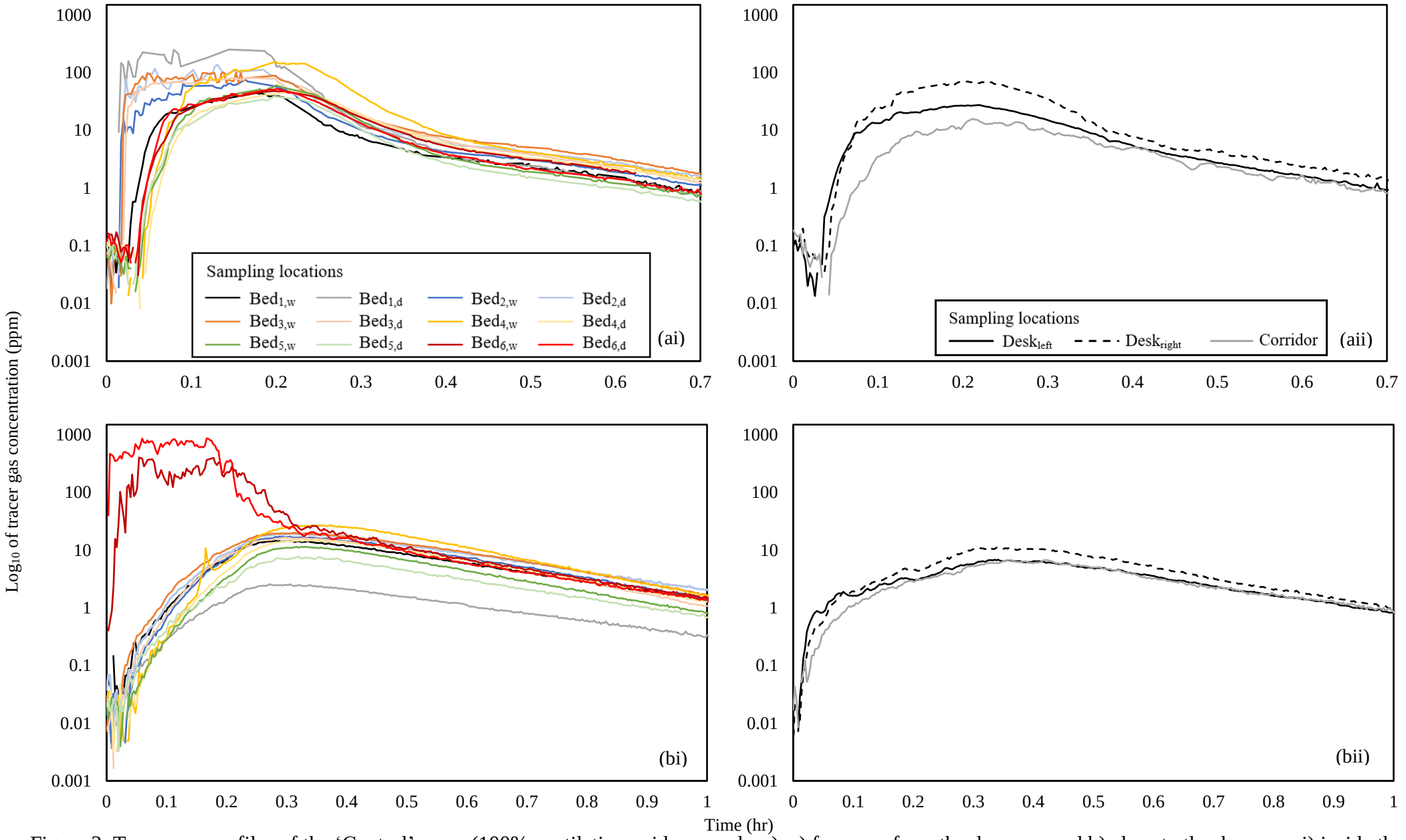


Figure 3. Tracer gas profiles of the 'Control' cases (100% ventilation, wide-open door). a) far away from the doorway and b) close to the doorway; i) inside the ward and ii) in the nursing station and corridor. y-axis: $\log_{10}$ of tracer gas concentration in ppm; x-axis: time in hours; legend: sampling locations.

3.2 Ventilation cases

In the following part, ventilation cases were described by indicating the side of ventilation supply operated during the experiment (i.e. door-side or wall-side ventilation only). Together with two different infected patient locations (i.e. far away and close to the doorway), a total of four scenarios were evaluated. Figure 4 graphs the tracer gas profiles of the 'Door-side only' Case 1 and Case 3. Figure 5 shows the tracer gas profiles of the 'Wall-side only' Case 2 and Case 4.

Case 1: Infected patient far away from the doorway, door-side ventilation only

When only the door-side ventilation was on, a significant increase in tracer gas concentration (peaked at around 500ppm, the highest measured level among all receivers) was observed near the wall side of Bed 1 ($Bed_{1,w}$). Potentially due to fewer turbulences from the supply air as two of the diffusers were off, the levels of tracer gas at all other locations were relatively steady (peaked at 25–40ppm) and similar except for $Bed_{4,w}$. Under the influence of ventilation, the tracer gas spread to the wall side of Bed 4 and peaked at around 100ppm. Compared to Control Case 1, less tracer gas went to the nursing station and even lesser escaped to the corridor, and the time needed to extract all the tracer gas in this case was almost double.

Case 2: Infected patient far away from the doorway, wall-side ventilation only

When the wall-side ventilation was on, significant differences in tracer gas patterns were identified at various locations. Tracer gas levels on the door side of Bed 1 and both sides of Bed 2 increased almost instantly after the tracer gas was released, and the gas spread to other locations quickly afterwards. The level of tracer gas on the wall side of Bed 1 remained low in the beginning and rose later when the overall tracer gas level within the ward increased. Under this ventilation scheme, $Bed_{4,w}$ detected the highest level (peaked at around 400ppm) among

all receivers. Interestingly, the receivers located at the same end where the gas was released measured lower tracer gas levels than those at the opposite end. The tracer gas level at $Bed_{6,d}$ was 3.6 times higher than that at $Bed_{6,w}$, although both receivers were on the same bed. As compared with Ventilation Case 1, more tracer gas went to the nursing station. However, the tracer gas level detected in the corridor in this case was the highest among all case scenarios.

Case 3: Infected patient close to the doorway, door-side ventilation only

Compared to Control Case 2, similar tracer gas patterns were observed, except for a much lower peak (550ppm) at $Bed_{6,d}$. Besides, similar tracer gas levels were observed at $Bed_{6,d}$ and $Bed_{6,w}$ in this case. Again, due to the position of the diffusers, there was less dispersion of gas to other locations at which the levels detected were around half of those measured in Control Case 2. Similarly, an accumulation of tracer gas was found near the wall side of Bed 4 but with a lower peak, and less tracer gas (<10ppm) spread to the nursing station and the corridor.

Case 4: Infected patient close to the doorway, wall-side ventilation only

When only the wall-side ventilation was on, the tracer gas levels and patterns at most locations were similar to those observed in Ventilation Case 3. However, both $Bed_{6,w}$ and $Bed_{6,d}$ detected a lower peak and there was a quicker dispersion after the gas release. The tracer gas levels in the nursing station and the corridor were also slightly lower.

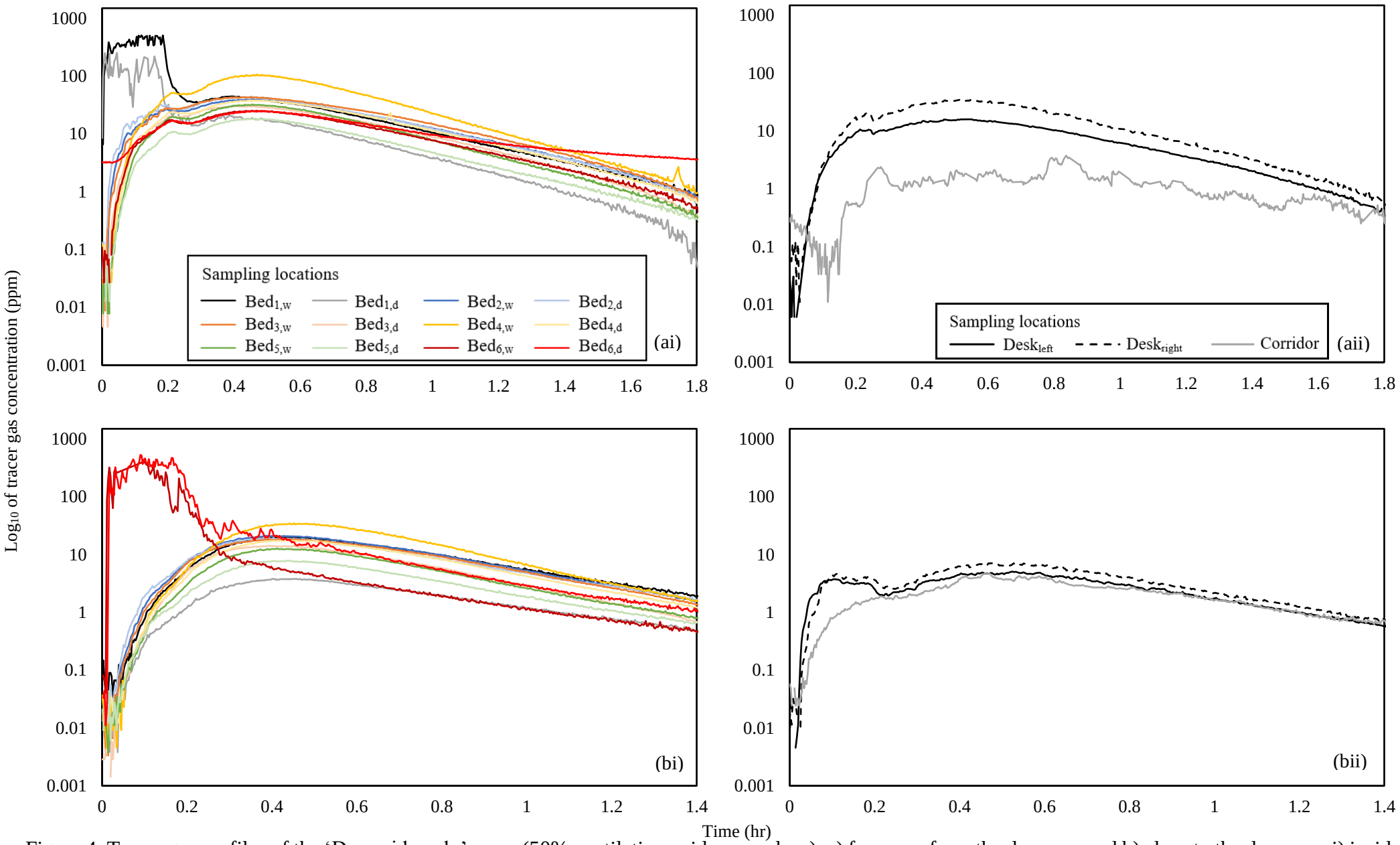


Figure 4. Tracer gas profiles of the 'Door-side only' cases (50% ventilation, wide-open door). a) far-away from the doorway and b) close to the doorway; i) inside the ward and ii) in the nursing station and corridor. y-axis: $\log_{10}$ of tracer gas concentration in ppm; x-axis: time in hours; legend: sampling locations.

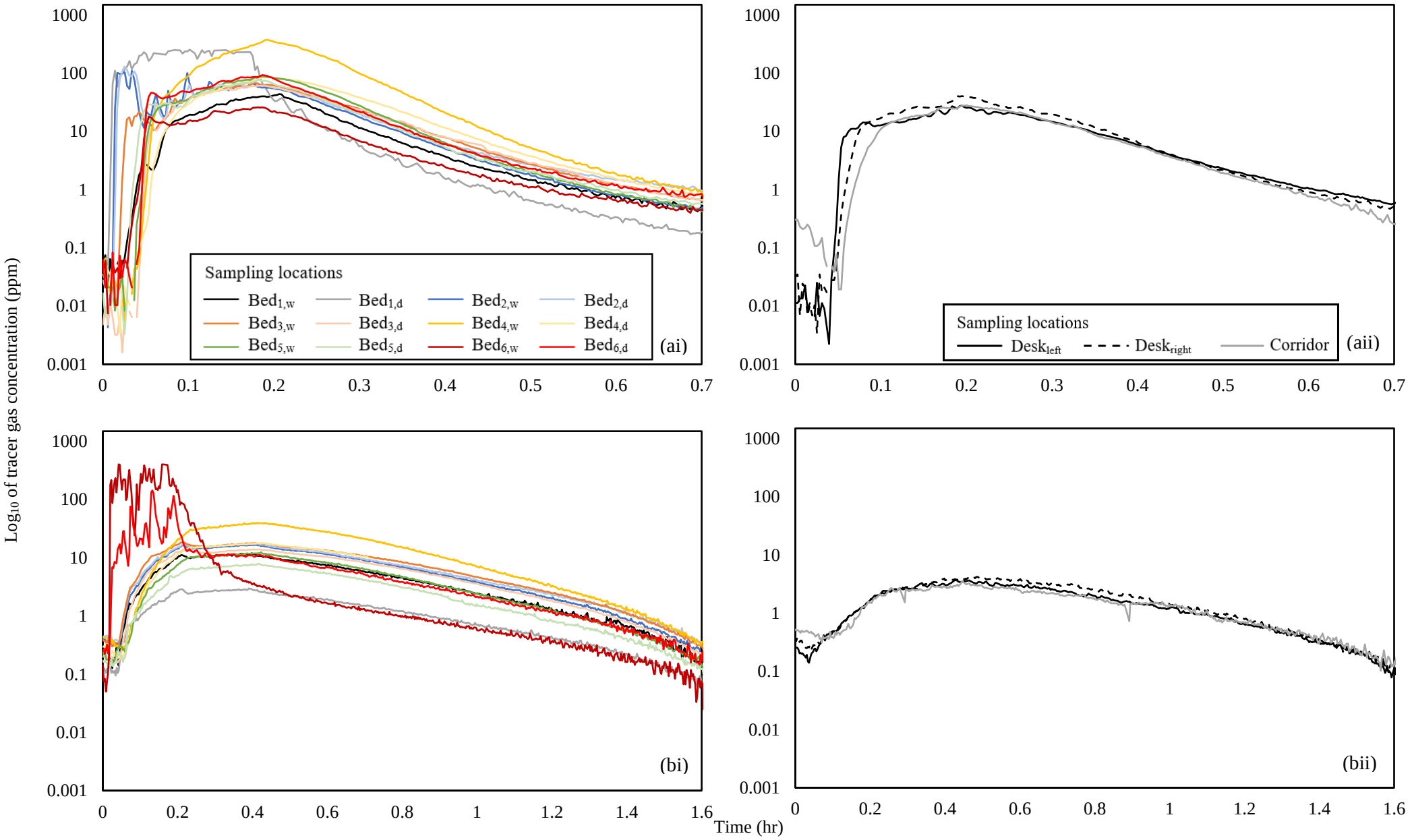


Figure 5. Tracer gas profiles of the 'Wall-side only' cases (50% ventilation, wide-open door). a) far-away from the doorway and b) close to the doorway; i) inside the ward and ii) in the nursing station and corridor. y-axis: $\log_{10}$ of tracer gas concentration in ppm; x-axis: time in hours; legend: sampling locations.

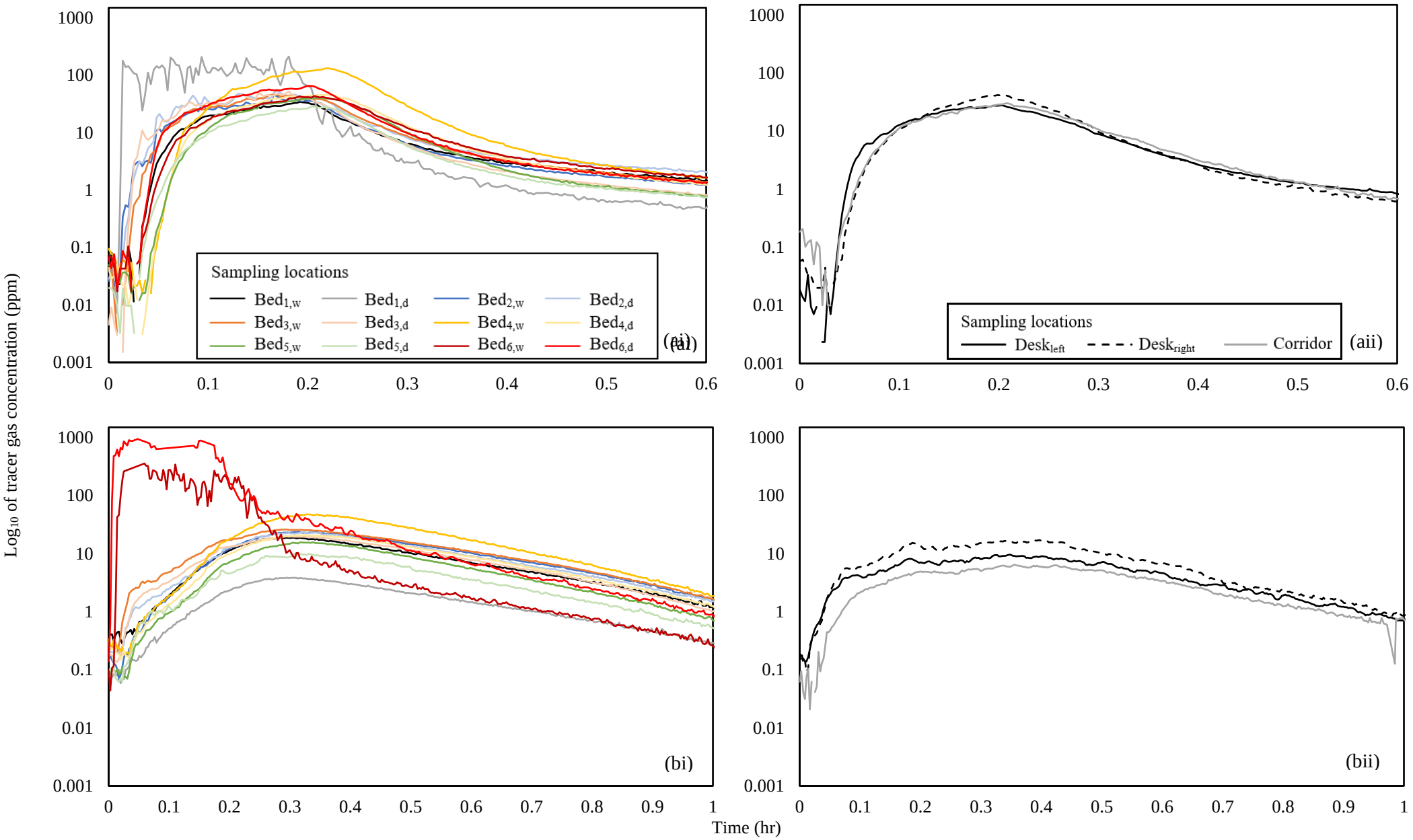


Figure 6. Tracer gas profiles of the 'Half-open door' cases (100% ventilation, half-open door). a) far-away from the doorway and b) close to the doorway; i) inside the ward and ii) in the nursing station and corridor. y-axis: $\log_{10}$ of tracer gas concentration in ppm; x-axis: time in hours; legend: sampling locations.

3.3 Door opening angles

Case 1: Infected patient far away from the doorway, half-open door

The main purpose of investigating the effects of door opening angle was to identify the change in exposure levels inside the nursing station, as the door could act as a partition to shield the HCWs sitting at the work desk against the tracer gas. From the tracer gas profiles shown in Figure 6, when the door was half-open, the tracer gas levels at the same end of gas emission were lower (with small turbulence) than the levels measured when the door was wide open (Control Case 1). The tracer gas levels at the opposite end were similar except for a higher level (the third highest peak among all measured levels) detected at $Bed_{6,d}$. The formation of a stagnant zone near the door side of Bed 6 can be explained by the half-open door that was obstructing the escape of the gas from the ward to the nursing station. In the nursing station, while the tracer gas level on the right side of the work desk was reduced by one third, it remained similar on the left side. On the contrary, a much higher level of tracer gas, almost doubled the one in Control Case 1, was detected in the corridor in this case. It is believed that the half-open door created a passage towards the door connecting the nursing station and the corridor, thus more tracer gas was able to escaped to the corridor than reaching the right side of the desk and being extracted by the ventilation exhaust as in Control Case 1.

Case 2: Infected patient close to the doorway, half-open door

A similar situation was observed in the case where Bed 6 was the emission location. The tracer gas patterns were very similar to Control Case 2, except for the level measured at $Bed_{4,w}$ which was slightly higher. In the nursing station, all tracer gas levels were one-third higher as compared to the control case. Despite that, the levels in the nursing station were still relatively low considering the cases with source patient far away from the doorway.

3.4 Limitations

A critical limitation of this study is the lack of control over the heat sources from the outdoor environment. Windows on the side with Beds 1–3 allowed natural sunlight during daytime. Another limitation is the only thermal manikin available was taken as the infected patient, meaning there was no heat dissipation from the remaining five regular manikins. It is known that the heat from people and medical equipment can disturb air movement, although the effect can be negligible compared to other variables such as emission sources, ventilation strategies and physical obstructions [37–39]. The effect of thermal plumes shall be considered in future studies.

4. Discussion

4.1 Inlet and outlet locations concerning the infected patient location

The importance of proper inlet and outlet positions relative to the infected patient location was discussed in the literature. A CFD study by Anghel et al. [40] suggested that local turbulences induced by the inlet and outlet air could cause an unpredictable particle dispersion within a hospital ward. Using the age of the air at the nostrils of the patients as an indication of inhaled air quality, Yang [41] simulated the airflow distribution under different ventilation opening positions and concluded that installing supply grills on the ceiling above the head of an infected patient could efficiently improve air quality. His CFD results agree with the experimental results found in Control Case 1, where more dispersion and mixing of air and faster reduction in the tracer gas levels around the patients were observed after the release of the gas. Moreover, compared to Control Case 2, more tracer gas spread to the nursing station in Yang's study. It is noteworthy that when discussing airborne transmission and infection risk, the dose-response relationship governs the infection probability, which is not necessarily a linear relationship [42]. Enhancing air dispersion for a more well-mixed environment to

achieve a lower average airborne pathogen concentration may lead to airborne transmission to a wider extent. Localization of tracer gas near the emission location as in Control Case 2, on the other hand, can minimize the spread of airborne pathogens and provide more protection to other patients in the ward as well as the HCWs in the nursing station.

4.2 Effects of air change rates on bioaerosol dispersion

Results of the Ventilation cases in Figures 4 and 5 suggested that although a higher ventilation rate could remove the tracer gas (or the contaminants) faster, it did not guarantee lower tracer gas concentrations in the breathing zones of the susceptible patients. With a higher ACH, more dispersion was observed. Similarly, a study by Mousavi and Grosskopf [43] for evaluating the influence of ACH on aerosol concentration found that the particle level in the breathing zone of a patient was 40% higher under a higher ACH. Villafruela et al. [44] also reported a higher infection risk when displacement ventilation with a higher ACH was adopted. All these studies concluded that enhanced ventilation produced by a higher ACH can result in more mixing of air and thus intensifying airborne transmission. A lower ACH, on the other hand, can minimize turbulence and better contain airborne pathogens [45].

4.3 Influence of obstacles on airborne transmission

There have been some studies discussing the effects of physical walls and partitions on airflow. Wang et al. [46] assessed the improvement of contamination control with physical partitions of different lengths using CFD techniques in an operating room. A full height partition between hospital beds was found to limit the transfer of infection between patients, although the effectiveness depended largely on the emission location and the ventilation strategies [47]. The presence of a partial wall was deemed essential to maintain the unidirectional downward flow of supply air for reducing the infection risk of the surgical team

in an operating room [48]. Even though some forms of physical barriers may protect the susceptible patients or HCWs against airborne infection, from the results of this study, the effectiveness depends on the location of emission, the position of the susceptible individual and the scheme of ventilation; therefore, case-by-case evaluation is necessary.

4.4 Suggestions for management practices and infection control strategies

From the experimental results of this study, it can be concluded that by placing an infected patient near the door (i.e. Bed 6) where most air is extracted from the ward can limit the dispersion of airborne pathogens. Although a higher ventilation rate can speed up the removal of exhaled contaminants, a lower ventilation rate with appropriate supply inlet locations can contain the airborne pathogens locally and minimize their dispersion. Moreover, depending on the location of a susceptible person, using physical objects as shields can influence the normal airflow patterns and reduce the infection risk. In most of the experimental scenarios, the patient on Bed 4 was exposed to high levels of contaminants due to accumulation caused by little air movement. Hence, additional air treatment devices or personal ventilation may be required to reduce the risk of infection for that patient.

5. Conclusion

Proper management practices in general inpatient wards must be established to minimize the risk of nosocomial outbreaks of novel infectious diseases through airborne transmission. Existing studies on airborne transmission in hospitals relied mainly on CFD simulations, they also focused on rooms with special ventilation requirements such as isolation wards and operation theatres. Since experimental studies using a tracer gas as the representative of airborne pathogens involve high implementation costs due to the lack of economical sampling instrument, high-resolution spatial and temporal evaluations of tracer gas distribution

are lacking. This study conducted a set of tracer gas experiments to evaluate the air distribution under various operational scenarios inside the hospital general inpatient ward. The effects of infected patient locations, air change rates and door opening angles on tracer gas dispersion was investigated using a novel tracer gas sensor network with 15 sampling points. Experimental results showed that the infected patient location (relative to the supply inlet locations) markedly affected the distribution and dispersion of the tracer gas within the ward. When the infected patient was placed furthest from the doorway with the ventilation supplies on the same side of the ward, local turbulences induced by the incoming air caused a wider extend of dispersion within the ward. Higher ventilation rates could also cause more mixing of air and wider spread of airborne pathogens and lead to less effective containment. Alternatively, localization of tracer gas near the source minimized the spread of airborne pathogens and provide more protection to the others. A stagnant zone in the ward could lead to high exposure to airborne pathogens and hence should be identified and rectified. Using physical partitions or objects as shields against airborne contaminants could unpredictably influence the airflow patterns. In this study, half-opening door might be able to protect the healthcare workers in the nursing station, however one must note that the airflow evaluations should be done on a case-by-case basis due to unique layouts and space arrangements of the ward. This study identified simple operational practices that can limit airborne transmission within a general inpatient ward, which could be useful for hospital management as references for formulating hospital outbreak preparation and infection control strategies. Lastly, this study also presented a simple and economical airborne transmission assessment method for case-by-case evaluation not just in hospitals but also other indoor environments with risks of airborne infection.

Funding: This work was jointly supported by a grant from the Collaborative Research Fund (CRF) COVID-19 and Novel Infectious Disease (NID) Research Exercise, the Research Grants

Council of the Hong Kong Special Administrative Region, China (Project no. PolyU P0033675/C5108-20G); and the Research Institute for Smart Energy (RISE) Matching Fund (Project no. P0038532).The funding sources had no involvement in study design; in the collection, analysis and interpretation of data; in the writing of the report; and in the decision to submit the article for publication.

Author contribution: Tsz-Wun Tsang: Conceptualization, Methodology, Investigation, Validation, Formal analysis, Writing - Original Draft, Visualization. Ling-Tim Wong: Project administration, Supervision, Writing - Review & Editing. Kwok-Wai Mui: Funding acquisition, Project administration, Supervision, Writing - Review & Editing. Manoj Kumar Satheesan: Investigation, Validation.

References

[1] M. Johanes, P. Atmodiwirjo. Visibility analysis of hospital inpatient ward. International Journal of Technology 6(3) (2015) 400-409.

[2] NHS England and NHS Improvement. (2021). Health Technical Memorandum 03-01 Specialised ventilation for healthcare premises Part A: The concept, design, specification, installation and acceptance testing of healthcare ventilation systems. United Kingdom: London.

[3] V.C. Cheng, K.S. Fung, G.K. Siu, S.C. Wong, L.S. Cheng, M.S. Wong, L.K. Lee, W.M. Chan, K.Y. Chau, J.S. Leung, A.W. Chu, W.S. Chan, K.K. Lu, K.K. Tam, J.D. Ip, K.S. Leung, D.C. Lung, H. Tse, K.K. To, K.Y. Yuen. Nosocomial Outbreak of Coronavirus Disease 2019 by Possible Airborne Transmission Leading to a Superspreading Event. Clinical infectious diseases: an official publication of the Infectious Diseases Society of America 73(6) (2021) e1356-e1364.

[4] S.W.X. Ong, Y.K. Tan, P.Y. Chia, T.H. Lee, O.T. Ng, M.S.Y. Wong, K. Marimuthu. Air, surface environmental, and personal protective equipment contamination by severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) from a symptomatic patient. Jama 323(16) (2020) 1610-1612.

[5] P.Y. Chia, K.K. Coleman, Y.K. Tan, S.W.X. Ong, M. Gum, S.K. Lau, X.F. Lim, A.S. Lim, S. Sutjipto, P.H. Lee, T.T. Son. Detection of air and surface contamination by SARS-CoV-2 in hospital rooms of infected patients. Nature communications 11(1) (2020) 1-7.

[6] Z.D. Guo, Z.Y. Wang, S.F. Zhang, X. Li, L. Li, C. Li, Y. Cui, R.B. Fu, Y.Z. Dong, X.Y. Chi, M.Y. Zhang. Aerosol and surface distribution of severe acute respiratory syndrome coronavirus 2 in hospital wards, Wuhan, China, 2020. Emerging infectious diseases 26(7) (2020) 1586.

[7] Y. Li, G.M. Leung, J.W. Tang, X. Yang, C.Y. Chao, J.Z. Lin, J.W. Lu, P.V. Nielsen, J. Niu, H. Qian, A.C. Sleigh. Role of ventilation in airborne transmission of infectious agents in the built environment-a multidisciplinary systematic review. Indoor air 17(1) (2007) 2-18.

[8] M. Abbas, T. Robalo Nunes, R. Martischang, W. Zingg, A. Iten, D. Pittet, S. Harbarth. Nosocomial transmission and outbreaks of coronavirus disease 2019: the need to protect both patients and healthcare workers. Antimicrobial Resistance & Infection Control 10(1) (2021) 1-13.

[9] T.W. Tsang, K. W. Mui, L. T. Wong. Computational Fluid Dynamics (CFD) studies on airborne transmission in hospitals: A review on the research approaches and the challenges. Journal of Building Engineering 63(A) (2022) 105533.

[10] D.J. Daegling, W.L. Hylander. Experimental observation, theoretical models, and biomechanical inference in the study of mandibular form. American Journal of Physical Anthropology 112(4) (2000) 541–551.

[11] T.W. Tsang, K. W. Mui, L. T. Wong. Experimental studies on airborne transmission in hospitals: A systematic overview. Submitted. (2022)

[12] M. Bivolarova, J. Ondráček, A. Melikov, V. Ždímal. A comparison between tracer gas and aerosol particles distribution indoors: The impact of ventilation rate, interaction of airflows, and presence of objects. Indoor Air 27(6) (2017) 1201-1212.

[13] LumaSense Technologies. (2008). User manual for 1303 multipoint sampler and doser.

[14] A. Aganovic, G. Cao. Evaluation of airborne contaminant exposure in a single-bed isolation ward equipped with a protected occupied zone ventilation system. Indoor and Built Environment 28(8) (2019) 1092-1103.

[15] P. Kalliomäki, K. Hagström, H. Itkonen, I. Grönvall, H. Koskela. Effectiveness of directional airflow in reducing containment failures in hospital isolation rooms generated by door opening. Building and Environment 158 (2019) 83-93.

[16] M. Sung, S. Jo, S.E. Lee, M. Ki, B.Y. Choi, J. Hong. Airflow as a possible transmission route of Middle East respiratory syndrome at an initial outbreak hospital in Korea. International journal of environmental research and public health 15(12) (2018) 2757.

[17] Z.D. Bolashikov, A.K. Melikov, W. Kierat, Z. Popiołek, M. Brand. Exposure of health care workers and occupants to coughed airborne pathogens in a double-bed hospital patient room with overhead mixing ventilation. Hvac&R Research 18(4) (2012) 602-615.

[18] Y. Yin, J.K. Gupta, X. Zhang, J. Liu, Q. Chen. Distributions of respiratory contaminants from a patient with different postures and exhaling modes in a single-bed inpatient room. Building and Environment 46(1) (2011) 75-81.

[19] P.V. Nielsen, Y. Li, M. Buus, F.V. Winther. Risk of cross-infection in a hospital ward with downward ventilation. Building and Environment 45(9) (2010) 2008-2014.

[20] H.M. Pattison, C.E. Robertson. The effect of ward design on the well-being of post-operative patients. Journal of Advanced Nursing 23(4) (1996) 820-826.

[21] Y.H. Yau, D. Chandrasegaran, A. Badarudin. The ventilation of multiple-bed hospital wards in the tropics: A review. Building and Environment 46(5) (2011) 1125-1132.

[22] C.Y.H. Chao, M.P. Wan, L. Morawska, G.R. Johnson, Z.D. Ristovski, M. Hargreaves, K. Mengersen, S. Corbett, Y. Li, X. Xie, D. Katoshevski. Characterization of expiration air jets and droplet size distributions immediately at the mouth opening. Journal of Aerosol Science 40(2) (2009) 122-133.

[23] X. Xie, Y. Li, H. Sun, L. Liu. Exhaled droplets due to talking and coughing. Journal of the Royal Society Interface 6(suppl_6) (2009) S703-S714.

[24] L.J.G.R. Morawska, G.R. Johnson, Z.D. Ristovski, M. Hargreaves, K. Mengersen, S. Corbett, C.Y.H. Chao, Y. Li, D. Katoshevski. Size distribution and sites of origin of droplets expelled from the human respiratory tract during expiratory activities. Journal of Aerosol Science 40(3) (2009) 256-269.

[25] N. Van Doremalen, T. Bushmaker, D.H. Morris, M.G. Holbrook, A. Gamble, B.N. Williamson, A. Tamin, J.L. Harcourt, N.J. Thornburg, S.I. Gerber, J.O. Lloyd-Smith. Aerosol and surface stability of SARS-CoV-2 as compared with SARS-CoV-1. New England Journal of Medicine 382(16) (2020) 1564-1567.

[26] Y. Yin, W. Xu, J.K. Gupta, A. Guity, P. Marmion, A. Manning, B. Gulick, X. Zhang, Q. Chen. Experimental study on displacement and mixing ventilation systems for a patient ward. HVAC&R Research 15(6) (2009) 1175-1191.

[27] M. Bivolarova, J. Ondráček, A. Melikov, V. Ždímal. A comparison between tracer gas and aerosol particles distribution indoors: The impact of ventilation rate, interaction of airflows, and presence of objects. Indoor Air 27(6) (2017) 1201-1212.

[28] Z. Ai, C.M. Mak, N. Gao, J. Niu. Tracer gas is a suitable surrogate of exhaled droplet nuclei for studying airborne transmission in the built environment. Building Simulation 13(3) (2020) 489-496.

[29] Y.C. Huang, H.C. Tu, H.Y. Kuo, P.L. Shao, Y.N. Gong, H.Y. Weng, H.Y. Shu, C.H. Kuo, P.H. Kuo, C.H. Chien, C.C. Wu. Outbreak Investigation in a COVID-19 Designated Hospital: The Combination of Phylogenetic Analysis and Field Epidemiology Study Suggesting Airborne Transmission. Journal of Microbiology, Immunology and Infection. (2023).

[30] American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE). (2020). ASHRAE standard thermal environmental conditions for human occupancy (ANSI/ASHRAE Standard 55-2020). Atlanta, Ga.: The Society.

[31] Z.D. Bolashikov, M. Barova, A.K. Melikov. Wearable personal exhaust ventilation: Improved indoor air quality and reduced exposure to air exhaled from a sick doctor. Science and Technology for the Built Environment 21(8) (2015) 1117-1125.

[32] F.A. Berlanga, M.R. de Adana, I. Olmedo, J.M. Villafruela, J.F. San José, F. Castro. Experimental evaluation of thermal comfort, ventilation performance indices and exposure to airborne contaminant in an airborne infection isolation room equipped with a displacement air distribution system. Energy and Buildings 158 (2018) 209-221.

[33] F.A. Berlanga, M.R. de Adana, I. Olmedo, J.M. Villafruela, J.F. San José, F. Castro. Experimental assessment of different mixing air ventilation systems on ventilation performance and exposure to exhaled contaminants in hospital rooms. Energy and Buildings 177 (2018) 207-219.

[34] I. Olmedo, F.A. Berlanga, J.M. Villafruela, M.R. de Adana. Experimental variation of the personal exposure in a hospital room influenced by wall heat gains. Building and Environment 154 (2019) 252-262.

[35] T.W. Tsang, K.W. Mui, L.T. Wong, K.Y. Law, K.W. Shek. A Novel IoT-Enabled Wireless Sensor Grid for Spatial and Temporal Evaluation of Tracer Gas Dispersion. Sensors 2023, 23, 3920.

[36] J.D. Pleil, M.A.G. Wallace, M.D. Davis, C.M. Matty. The physics of human breathing: flow, timing, volume, and pressure parameters for normal, on-demand, and ventilator respiration. Journal of Breath Research 15(4) (2021) 042002.

[37] Q. Chen, Z. Jiang, A. Moser. Control of airborne particle concentration and draught risk in an operating room. Indoor air 2(3) (1992) 154-167.

[38] P. Luscuere, T. Lemaire, P.J. Ham. Improvement capabilities of operating theatres with the help of computer flow modeling. Indoor Air'93 (1993) 575-580.

[39] T.T. Chow, X.Y. Yang. Ventilation performance in the operating theatre against airborne infection: numerical study on an ultra-clean system. Journal of Hospital Infection 59(2) (2005) 138-147.

[40] L. Anghel, C.G. Popovici, C. Stătescu, R. Sascău, M. Verdeș, V. Ciocan, I.L. Șerban, M.A. Mărănducă, S.V. Hudișteanu, F.E. Țurcanu. Impact of HVAC-systems on the dispersion of infectious aerosols in a cardiac intensive care unit. International journal of environmental research and public health 17(18) (2020) 6582.

[41] J.H. Yang. CFD analysis of the inhaled-air quality for the inpatients in a four-bed sickroom. Journal of Asian Architecture and Building Engineering 12(1) (2013) 109-116.

[42] L. Wang, X. Dai, J. Wei, Z. Ai, Y. Fan, L. Tang, T. Jin, J. Ge. Numerical comparison of the efficiency of mixing ventilation and impinging jet ventilation for exhaled particle removal in a model intensive care unit. Building and Environment 200 (2021), 107955.

[43] E.S. Mousavi, K.R. Grosskopf. Ventilation rates and airflow pathways in patient rooms: A case study of bioaerosol containment and removal. Annals of Occupational Hygiene 59(9) (2015) 1190-1199.

[44] J.M. Villafruela, I. Olmedo, F.A. Berlanga, M. Ruiz de Adana. Assessment of displacement ventilation systems in airborne infection risk in hospital rooms. Plos one 14(1) (2019) e0211390.

[45] E.S. Mousavi. Toward an energy efficient healthcare environment: a case study of hospital corridor design. International Journal of Environmental Science and Technology 16(12) (2019) 7633-7642.

[46] F.J. Wang, Y.H. Yau, W.B. Ng, C.M. Lai. Improvement of the Indoor Environment and Airborne Contamination Control in an Operating Room. Advanced Materials Research 255 (2011) 1532-1536.

[47] C.J. Noakes, P.A. Sleigh, A.R. Escombe, C.B. Beggs. Use of CFD analysis in modifying a TB ward in Lima, Peru. Indoor and Built Environment 15(1) (2006) 41-47.

[48] T.T. Chow, X.Y. Yang. Ventilation performance in the operating theatre against airborne infection: numerical study on an ultra-clean system. Journal of Hospital Infection 59(2) (2005) 138-147.