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Research Article

Effectiveness of air cleaner on mitigating the transmission of respiratory disease in a dental clinic environment

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Abstract

In dental clinics with an open floor plan, the risk of patient-to-patient transmission of respiratory disease is a concern. During dental procedures large amounts of bioaerosol are produced and patients cannot wear personal protective equipment. This paper examines how to effectively deploy air cleaner to reduce the infection risk in dental clinics with an open floor plan. Various locations of air cleaners at various clean air delivery rates (CADRs) were investigated. The dispersion of bioaerosol was studied through numerical simulations, and risk assessment was performed by a dose-response method. The findings indicated that dental patients downstream of the background ventilation have a higher infection risk than those to the left and right of an infected patient (i.e., the source). The lowest infection risks for the adjacent patients were found when the air cleaner was place opposite to the dentists, i.e., on the floor at low CADR levels of 2.2 m^3/min or on the bench at CADR levels of 4.4 m^3/min or greater. The results of this study indicated that air cleaner can mitigate the risk of patient-to-patient transmission of SARS-CoV-2 in dental clinics with an open floor plan. Background CADR levels determine the optimal placement of air cleaners.

Keywords
infection risk
air cleaner location
dental clinic
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1 Introduction

Due to the high population densities in human society, highly infectious diseases can easily pose severe health threats to humans and cause incalculable economic losses to countries, as evidenced by COVID-19 which caused 18 million of deaths at the end of 2021 (Watson et al. 2022). Facing COVID-19 and potential future outbreaks, the importance of studying ways to block viral transmission is unquestionable. Prior to the emergence of SARS-CoV-2, studies have shown that the main transmission routes of H1N1 influenza and SARS CoV are airborne, close contact and fomites (Lei et al. 2018). In 2020, Zhang et al. (2020) confirmed that the primary transmission route of COVID-19 is through airborne route. Based on this finding, research on the relationship between the transmission of aerosols and ventilation systems in different indoor environments such as offices (Izadyar and Miller 2022), supermarkets (Vuorinen et al. 2020) and dental clinics (Clementini et al. 2022) has gradually become a focus. Considering that dental clinics are more likely to produce large number of aerosols (Kedjarune et al. 2000; Leggat and Kedjarune 2001; Harrel and Molinari 2004) and have higher safety risks than other places, research on preventing virus transmission in dental environment is more urgent and critical.

During dental procedures, large number of droplets will be generated from oral cavity, where airborne droplets with a diameter of smaller than 5 or 10 microns can be distributed around the entire clinic under background ventilation (Tang et al. 2006; Morawska and Cao 2020). The SARS-CoV-2 virus has been detected in the saliva of infected patients at concentrations of up to $10^{9\text{-}10}$ copies/mL (To et al. 2020; Wyllie et al. 2020), which can be easily

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spread in dental clinics via the generated bioaerosols. Grenier found that areas up to 11 m away from the active dental treatment area can experience increased air contamination by bacterial aerosols in a multi-chair dental clinic (Grenier 1995). The airborne droplets can be inhaled and deposited on the upper/lower respiratory tracts of nearby dentists, personnel, or other patients in the same room, which can lead to infections. These studies potentially point to a higher risk of disease transmission in dental clinics than in other settings. Personal protective equipment using close fitting facial protection, such as a N95 respirator, can be deployed to protect against aerosols (Bartoszko et al. 2020). However, in situations such as dental clinics, patients cannot wear facial masks while receiving dental care and are exposed to the risk of airborne transmission.

In order to prevent the spread of diseases inside dental clinics, some effective methods have been proposed. For example, a preoperative antiseptic mouth rinse can be used to reduce the saliva load of oral microorganisms, and a rubber dam can be used to reduce the generation of aerosols or spatter of saliva and blood contamination (Peng et al. 2020; Carrouel et al. 2021). However, antiseptic mouth rinse cannot be used in some patients, and a rubber dam is not feasible in many dental procedures that require access to oral soft tissues, e.g., in the treatment of periodontal diseases. As an alternative, air cleaner (AC) can be used to remove aerosols and spatters from the air (Buising et al. 2022). Several studies have demonstrated the effectiveness of ACs in mitigating the spread of disease (Chen et al. 2010; Qian et al. 2010; Cox et al. 2018; Ren et al. 2021). For instance, Cox et al. (2018) found that ACs can significantly reduce the traffic-related and other aerosols in different residential environments. Moreover, Chen et al. (2010) showed that ACs can control the spread of aerosols and droplets by effectively eliminating the virus aerosols exhaled by infected people. Another experiment carried out by Ren et al. (2021) on the use of ACs during dental procedures showed that it can accelerate the removal of aerosols, and the accumulated aerosols in the room are completely eliminated within 4–12 minutes. In addition to the use of static air cleaning systems, there are also studies on dynamic systems that use disinfection robots to remove aerosols (Yang et al. 2021; Yang et al. 2022; Liu et al. 2024). Although dynamic cleaning systems are flexible and can select the best strategy through their own programming, considering the cost of practical application, our study will focus on the strategies of static air cleaning systems in dental environments.

While the effectiveness of ACs has been demonstrated, research on the proper placement and suitable clean air delivery rate (CADR) of ACs in dental clinics is lacking. Usually, people think that putting the AC in the room is useful, no matter where it is located. However, studies have confirmed that its position in indoor environment has a significant impact on the effect of reducing the risk of infection (Dai and Zhao 2022) or particle removal efficiency (Lee et al. 2021). Studying the position of the AC has great potential to help find more effective ways to prevent the spread of respiratory diseases in dental clinic environments.

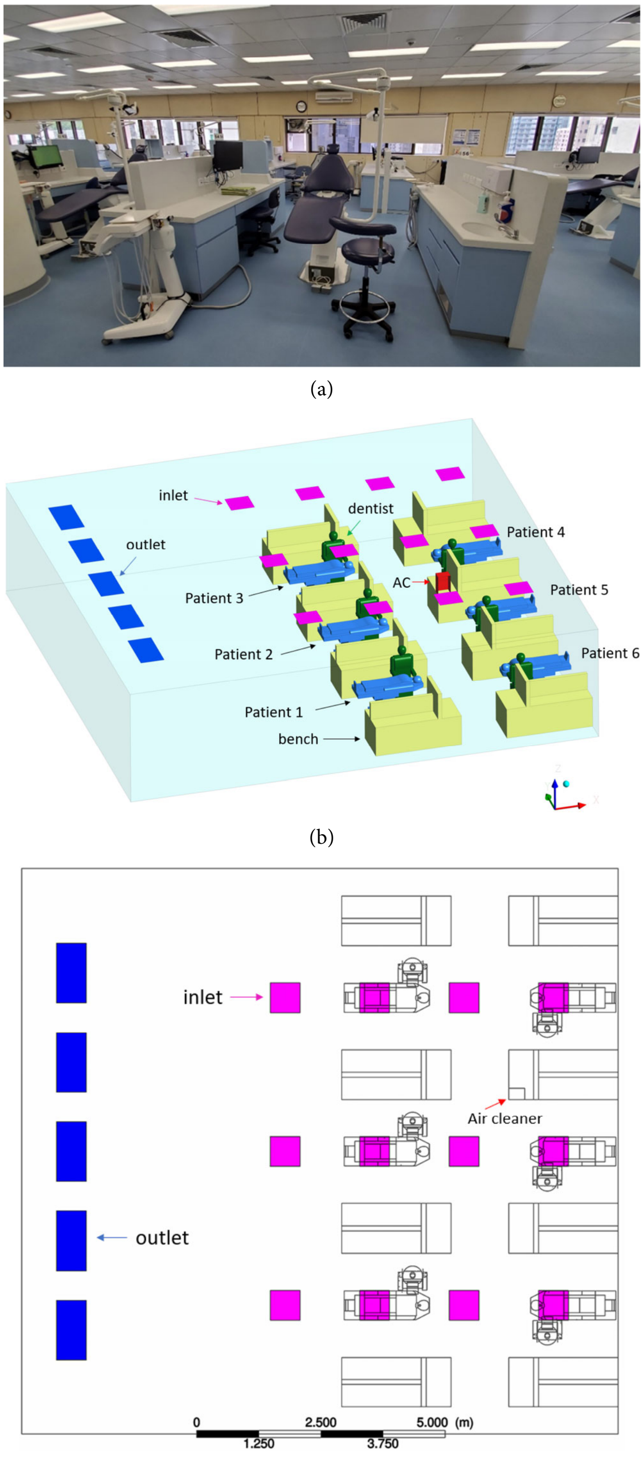
The objective of this study is to investigate the effects of AC location and parameter such as CADR on reducing the risk of infection in open floorplan dental clinics. To achieve this goal, real dental hospital will be selected as models, and simulations will be conducted assuming the presence of infected patients among dental patients. Numerical simulations were used to study the dispersion of bioaerosol, and dose-response method was employed to calculate the infection risk (Yang et al. 2022).

2 Methods

2.1 Computational domain

In this paper, the geometry of a dental clinic with an open floor design at the Prince Philip Dental Hospital (PPDH) in Hong Kong SAR which can accommodate up to 80 patients, was used as reference for our study. As shown in Figure 1(a), dental units and benches at the dental clinic are evenly distributed, which allows for a section to be used for the simulation study. The selected area and its model are shown in Figure 1(b), with dimensions of 12 m × 11.5 m × 3 m ($L \times W \times H$). Figure 1(c) shows the top view of the room, which can be divided into two areas: the open area on the left is the pedestrian corridor, and there are five ceiling exhaust vents (1.2 m × 0.6 m) above; the operating area on the right contains two rows of chairs and benches, and there are 12 ceiling air inlets (0.6 m × 0.6 m) above. Each dental unit accommodates one dental patient and one dentist.

As the focus of this study is on how the position of the AC affects the infection risk of patients surrounding the infected individual, we simulated a group of six patients as experimental subjects. As shown in Figure 1(b), the source patient is Patient number 5. During a dental procedure, aerosols with virus are ejected from the patient's mouth and moved with the airflow. The dental patients' mouth is a circular area with a diameter of 4 cm in this model. Li et al. (2023) studied the impact of dental patient's breathing rate on the movement of aerosols in the dental clinic through simulations, and found that the final fate of emitted droplets was almost independent of the dental patient's breathing flow. Therefore, the breath of Patient 5 is omitted to save the computing resources. Except for Patient 5, the


(a)

(b)

(c)

Fig. 1 Schematic of the dental indoor environment: (a) PPDH; (b) simulation model; (c) top view of the simulation model

breathing of other dental patients should be considered because of the infection risk calculation (shown in Section 2.5). Their breathing process in the simulation is regarded as an inhalation process to simplify the calculation, and the volume flow rate is 13 L/min according to the previous research (Gupta et al. 2009). Since their mouth diameter being 4 cm, the velocity at their mouth is 0.172 m/s. The breathing rate of dentists was not considered because they should wear masks during dental procedures.

2.2 Air cleaner setting and parameter

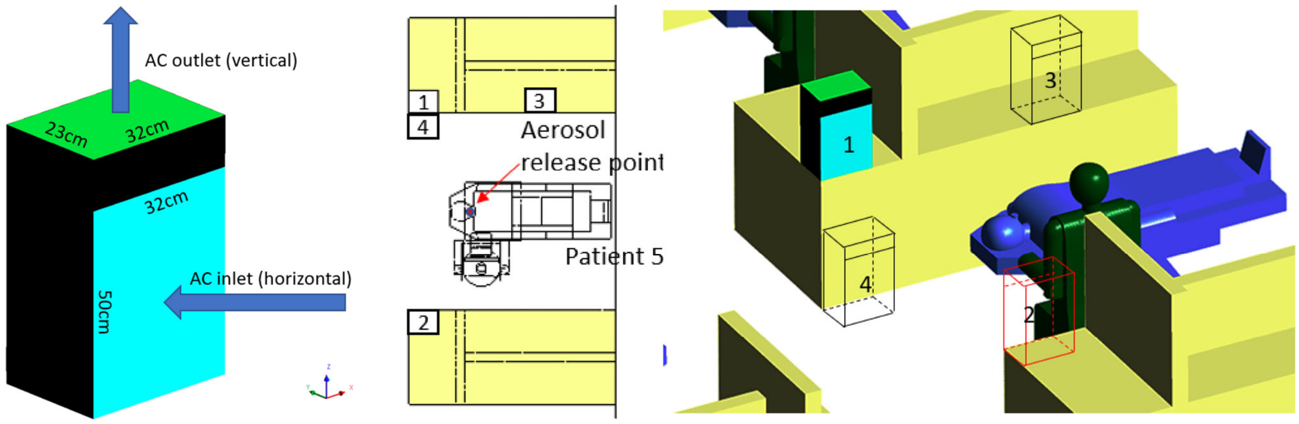
An AC (0.32 m × 0.23 m × 0.6 m) as shown in Figure 2(a) is employed to remove virus-laden aerosols, and its design is based on a popular product on the market. The purpose of using the AC is to eliminate the aerosols generated by the infected patient during surgery, so the AC should be placed as close to the source patient as possible. Considering the actual working conditions of dentists, a total of 4 positions were selected for the AC to ensure that it does not interfere with the dental surgery. The four locations of AC near Patient 5 are shown in Figures 2(b) and 2(c). Among them, AC is located on the bench at Locations 1, 2 and 3, while on the ground at Location 4. The AC outlet is in vertical direction, while the AC inlet is in horizontal direction. In order to remove the aerosols, the inlet of the AC at the four locations always face Patient 5. In general, each patient will have an AC, which theoretically will be turned on during dental surgery. However, to simplify the simulation, we assume that only patient 5 is undergoing surgery, while the other patients are in resting state before surgery begins. In other words, aside from the source patient, other patients breathe normally and may inhale the aerosols emitted from the source. This aligns with the purpose of this study, which is to investigate how the position of the AC near the infected patient affects the infection risk of the surrounding patients.

Besides the location, the CADR of the AC were also studied. According to the investigation on ACs in the market, it was found that most of them have a maximum CADR of no more than 6 m^3/min. Therefore, three values of them were selected as experimental parameters (as shown in Table 1). The inlet and outlet velocity were calculated by the CADR and their areas.

Table 2 shows all the cases that have been simulated. One of the cases, Case 1, which does not include an AC, is utilized as a basis for comparing the performance of ACs in the other cases.

2.3 Numerical modeling, droplet transmission and boundary conditions

To model the turbulent airflow indoors effectively, we employed the renormalization group (RNG) k-ε turbulence model with scalable wall function, which has been verified as appropriate for indoor airflow modeling (Yang et al. 2006; Nguyen and Reiter 2011; Liu et al. 2020). The CFD



(a) (b) (c)

Fig. 2 AC and its location: (a) AC structure; (b) top view of AC locations; (c) 3D view of AC locations

Table 1 The selected CADR and corresponding inlet & outlet velocity of AC

CADR (m^3/min)	AC inlet (m/s)	AC outlet (m/s)
2.208	0.230	0.500
4.416	0.460	1.000
6.000	0.625	1.360

Table 2 Simulated case

Case number	AC location	CADR (m^3/min)
1	No AC	No CADR
2	1	2.208
3	2	2.208
4	3	2.208
5	4	2.208
6	1	4.416
7	2	4.416
8	3	4.416
9	4	4.416
10	1	6
11	2	6
12	3	6
13	4	6

modeling was conducted using ANSYS Fluent 2020a. To factor in the thermal impact on dental clinics, the energy equation was also computed in the simulation. The flow field in the dental environment is solved by the incompressible Navier–Stokes equations. The SIMPLEC algorithm is used to solve the equation. After the steady flow field was obtained, we utilized the discrete phase model (DPM), a commonly employed method in simulating droplet transmission (Komperda et al. 2021; Fan et al. 2022; Ge et al. 2022), to track the movement of particles. Therefore, an Eulerian–Lagrangian multiphase numerical model was adopted in this study. The governing equations of the air phase were considered in the Eulerian frame (Navier-Stokes equations) and a steady state condition was assumed. The motion of each particle (or the discrete phase) was tracked by solving the force balance equation in a Lagrangian frame of reference in an unsteady state manner.

According to the experimental results in dental clinics, the size of the generated aerosol is mostly distributed from 0.01 μm to 10 μm during dental procedures (Polednik 2021). Aerosols within this size range will evaporate rapidly, taking only about 0.1 s (Li et al. 2018; Li et al. 2023). According to the simulation results of dispersion characteristics of human exhaled droplets (Chen and Zhao 2010), the droplet evaporation process at the mouth can be neglected in the simulation when the initial diameter is less than 100 μm and the virus-carrying droplets can be directly regarded as droplet nuclei for simulation. Therefore, in this simulation, the particles were assumed to be monodisperse, inert, spherical, and have density of 1500 kg/m^3 (Chen et al. 2021). Considering that the size of coronaviruses is in the range of 0.08 to 0.12 μm (Masters 2006), the size of 0.1 μm, 1 μm and 10 μm is chosen as droplet nuclei diameter. In each case of Table 2, simulations were performed three times for the three sizes. The number distribution of these three sizes is nearly 1000:10:1 (Polednik 2021). The aerosol release velocity was set as 0.6 m/s based on the experimental results (Plog et al. 2020) with vertical upward direction from Patient 5's mouth. A total number of 560,000 aerosols for each aerosol size were released during the simulation to ensure that the results are reliable.

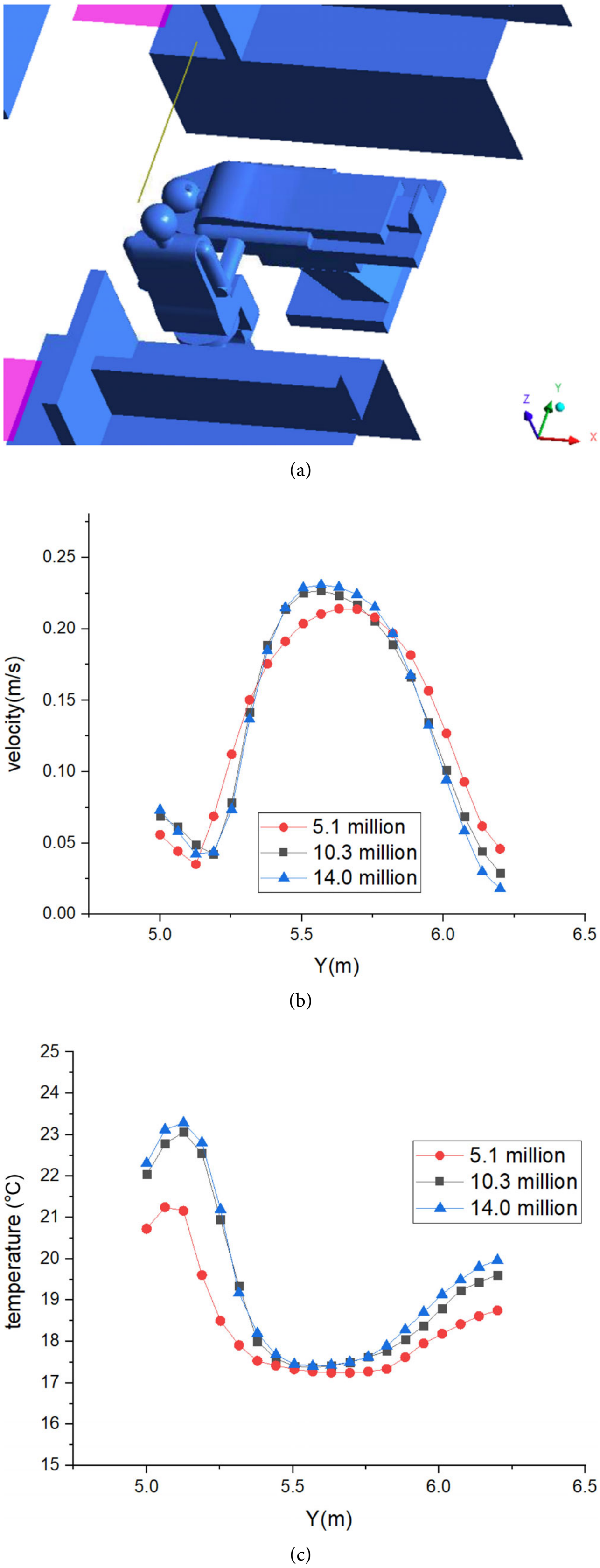
The discrete random walk model, widely used for simulating the turbulent dispersion of aerosols (Mirikar et al. 2021; Kumar and King 2022; Quiñones et al. 2022), was employed to track the respiratory droplets during the simulation. Given the small volume fraction of particles in the flow field, it was assumed that the airflow would remain unaffected by the aerosols. With regards to the aerosol dispersion, the drag force, gravitational force, thermophoretic force, and lift force were all taken into account. All the equations of the models mentioned above are presented in detail in the Ansys Fluent guide (Fluent 2011).

As the air changes per hour (ACH) of a dental clinic is required to be 9 per hour, the velocity of each inlet on ceiling was set as 0.25 m/s. The velocities of AC's inlet and outlet can be found in Table 1. The turbulence intensity and the turbulent viscosity ratio for the inlet were 5% and 10%, respectively. The outlets on the ceiling are set as the pressure outlet. The surface boundary condition is no-slip for the walls and manikin. The heat flux of the patients and dentists is set as 39 W/m^2 (Yan et al. 2009) and the indoor temperature is 23.5 °C. The DPM boundary condition for inlets, outlets (from ceiling and AC) and dental patients' mouth are set as escape which means that the trajectory calculations of particle will be terminated when it encounters these boundaries. Since the aerosol particles deposited on the surface of the environmental objects have the possibility of becoming suspended aerosols again when encountering the airflow, vibration or other mechanical forces (Lv et al. 2021), we set the DPM boundary condition of wall as reflect to assess the highest possibility of virus airborne transmission between the dental patients.

2.4 Grid independence check and model validation

A grid independence test was conducted with three different grid numbers: 5,068,072, 10,275,705 and 13,989,051. By comparing the velocity and temperature magnitude of a line above Patient 5's mouth and dentist's head (the yellow line shown in Figure 3(a)), the results calculated by different grid numbers are compared in Figure 3(b) and Figure 3(c). The grid convergence index (Dai and Zhao 2022) for last two grid cases is smaller than 5%. Therefore, in this study, simulated cases were based on the number of 10,275,705 grids to balance computational speed and accuracy.

The renormalization group (RNG) k-ε turbulence model has been validated to be useful in predict the velocity and temperature distribution in indoor thermal environment by Ahmed and Gao (2017). As for particle distribution, this model has also been validated for predicting indoor pollutant distribution in ventilation rooms (Yuan et al. 1999; He et al. 2005). In this research, our group also conducted the aerosol concentration measurements in the dental clinic (PPDH). The measurement setting is shown in Figure 4(a). A humidifier which contains artificial saliva solution (g/L: sodium chloride 12 g; glycerol 76 g (Wang et al. 2021; Yang et al. 2023)) was used as an aerosol generator and placed on the head part of the bed to simulate the particle

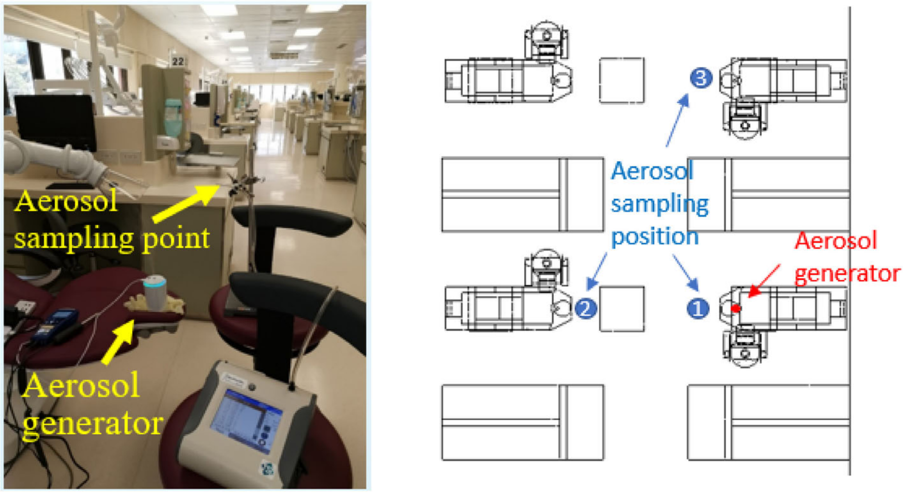


(a)

(b)

(c)

Fig. 3 Grid independence test: (a) data line; (b) difference in velocity; (c) difference in temperature



(a) (b)

Fig. 4 Measurement and validation: (a) experimental setup; (b) aerosol sampling positions.

released from a patient. The aerosol number concentration was measured at three positions (as shown in Figure 4(b)) by an optical particle counter (OPS, Model 3330, TSI, USA). Its aerosol test range is 0.3–10 microns, and the accuracy is plus or minus 5%.

The aerosol ratio, which is the ratio of particle numbers measured at Positions 2 or 3 to that at Position 1 (i.e. particle ejection point), was used to compare the results between simulation and experiment. The results are shown in Table 3. From the comparison, it is fair to say that the selected model can efficiently determine the particle distributions.

2.5 Risk assessment by dose-response method

The dose-response method is an effective method in estimating the risk of infection and has been widely used in the literature (Sze To and Chao 2010; Watanabe et al. 2010; Lei et al. 2018; Martins et al. 2022; Yang et al. 2023). This method can be applied to all respiratory diseases that can be transmitted through aerosols. This paper chose COVID-19, the most impactful disease in recent years, as an example for the study. The viral dose in the upper and lower respiratory tracts via inhalation, denoted as D_u and D_l, can be calculated by Equations (1) and (2), respectively.

$$D_u = \beta_u \cdot N_v \cdot P_i \tag{1}$$

$$D_l = \beta_l \cdot N_v \cdot P_i \tag{2}$$

where β_u and β_l are the deposition fractions for the upper respiratory tract and lower respiratory tract, respectively, and their values at different aerosol sizes can be obtained through the ICRP model (Yeh et al. 1996). Three aerosol sizes and their corresponding deposition fractions are studied and shown in Table 4. It should be noted that since the infection risk can be obtained by each aerosol nuclei size, the final infection risk displayed in the results is the weighted average of these different infection risks based on the aerosol size distribution mentioned in Section 2.3.

N_v in Equations (1) and (2) is the quantity of total viruses contained in the aerosol sprayed by the Patient 5 during dental process, which can be calculated by Equation (3):

$$N_v = (M_a / \rho) \cdot c \tag{3}$$

where ρ is the density of droplet and is assumed to be 1 g/cm^3, c is the average viral load of SARS-CoV-2 in saliva and its value has been found to be 7×10^6 copies/mL through experiments (Wölfel et al. 2020), and M_a is the total aerosol mass generated during dental procedure. In the experiment done by Polednik (2021), the mass concentration of aerosols with size less than 10 μm is nearly 60 μg/m^3. Moreover, based on the experiment result (Li et al. 2021), the high-level contaminated area will be within 1 m from

Table 3 Results of simulation and experiments

Case	Aerosol concentration at Position 1	Aerosol concentration at Position 2	Aerosol concentration at Position 3	Ratio at Position 2 and Position 3
Experiment	1,047,028 (#/cm^3)	93,706 (#/cm^3)	2,432 (#/cm^3)	8.95%, 0.2%
Simulation	225	20	0	8.89%, 0%

Table 4 Aerosol nuclei size and corresponding deposition fractions

Aerosol nuclei size (μm)	β_u	β_l
0.1	0.05	0.2
1	0.2	0.2
10	0.8	0.05

the oral cavity. Therefore, to simplify the complexity of calculation, we assume that the aerosol is ejected uniformly from the patient's mouth and evenly distributed within 1 cubic meter, getting that M_a is 60 μg.

P_i in Equations (1) and (2) is the proportion of particles inhaled by each dental Patient (except the source Patient 5) to the total ejected particles, and it can be calculated by Equation (4):

$$P_i = N_i / N_e \tag{4}$$

where N_i is the number of inhaled particles by each patient (except the source Patient 5) and can be obtained after simulation, N_e is the number of particles emitted by Patient 5 and was set as 560,000 in simulation.

The infection risk (IR) can then be determined by dose-response model according to the following equation:

$$\mathrm{IR} = 1 - \exp\left[-\left(r_u \cdot D_u + r_l \cdot D_l\right)\right] \tag{5}$$

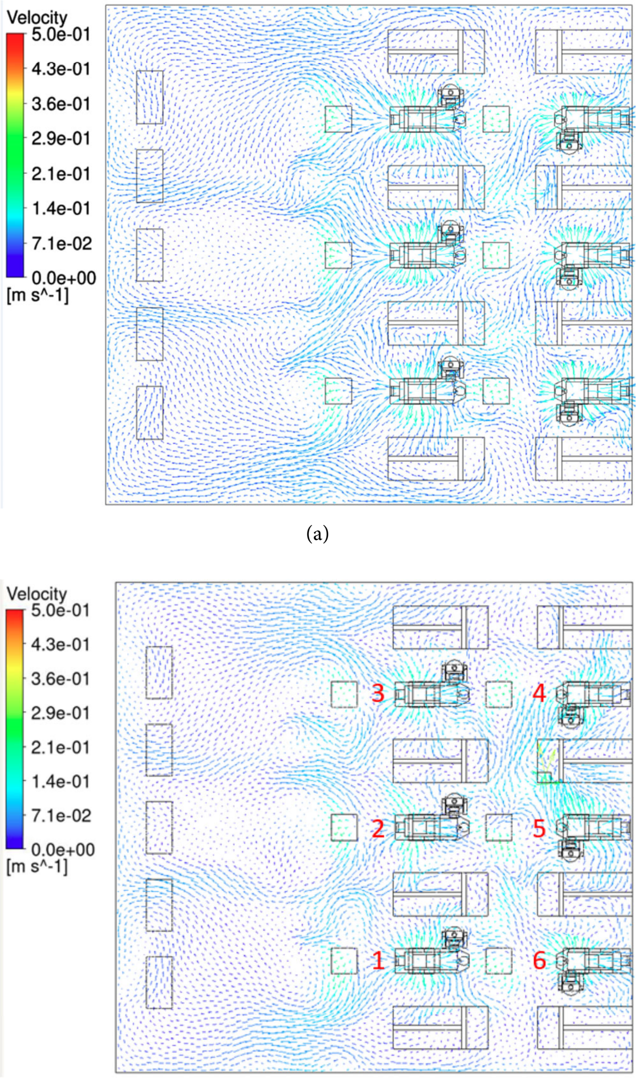
where r_u and r_l are the fitting parameters evaluating infectivity of the pathogen in upper and lower respiratory tracts, respectively. Martins et al. (2022) used ferrets to study the effect of age on SARS-CoV-2 infection and found that the median infection dose (ID50) in upper respiratory tract are 32 PFU for aged animals and 100 PFU for young animals. To obtain results in common situation, we choose 70 PFU as the ID50 for upper respiratory infection. Due to the lack of experimental data for the infectivity of the SARS-CoV-2 in the lower respiratory tract, we assumed the ID50 in the lower respiratory tract was 1/1000 of the ID50 in the upper respiratory tract. This estimation proportion "1/1000" is based on the data of influenza A H1N1 virus and has been found useful in predicting the ID50 of SARS coronavirus (Lei et al. 2018). Therefore, the r_u and r_l are calculated as 0.01 and 9.9 based on the ID50 of 70 PFU and 0.07PFU in upper and lower respiratory tracts for SARS-CoV-2.

3 Results and discussion

3.1 Simulation results of the flow field

To start with, a steady-state simulation was used to get the background ventilation flow. Figure 5 illustrates the velocity magnitude on a horizontal plane at a distance of 1 meter above the ground, which is at the same height as the patient's mouth. Here, we use Case 1 and Case 6 for examples to show the influence of AC on airflow. The legends of the two pictures are set to the same, in order to better compare the colors and velocities.

Figure 5(a) shows that the areas with higher air velocity (nearly 0.14 m/s) are mainly distributed under the location of inlets. The airflow diffuses approximately evenly in all directions after coming into contact with the patient's surface. When the AC starts operating, the airflow around Patients 4 and 5, who are closer to its location, undergoes a noticeable change and begins to move in the direction of the AC. In this Case 6, the AC's CADR is set to medium level, with an inlet air velocity of 0.46 m/s. As shown in Table 1, for all CADR cases, the velocities of AC's inlet and



(a)

(b)

Fig. 5 Velocity magnitude of 1-meter height horizontal plane: (a) Case 1; (b) Case 6 outlet are almost higher than that of the ventilation inlet (0.25 m/s), which probably change the airflow pattern to all the patients nearby. The overall direction of the flow inside the room is from right side (upstream) to left side (downstream).

3.2 Primary routes of aerosols absorption by the downstream patients

In the second stage, the results of final fate and transmission routes of the aerosols were found by using DPM model. The results showed that no matter where the AC is placed, downstream Patients 1–3 always have higher infection risk than Patients 4 and 6 (will be shown in Section 3.4). Therefore, three of the aerosol trajectories that Patients 1–3 absorbed were selected to analyse the routes on aerosol transmission. Using the results of Case 4 as an example, the routes of aerosols are shown in Figure 6.

In Figure 6, the AC is placed at Location 3 with CADR of 2.208 m^3/min. From the top view of the three trajectories

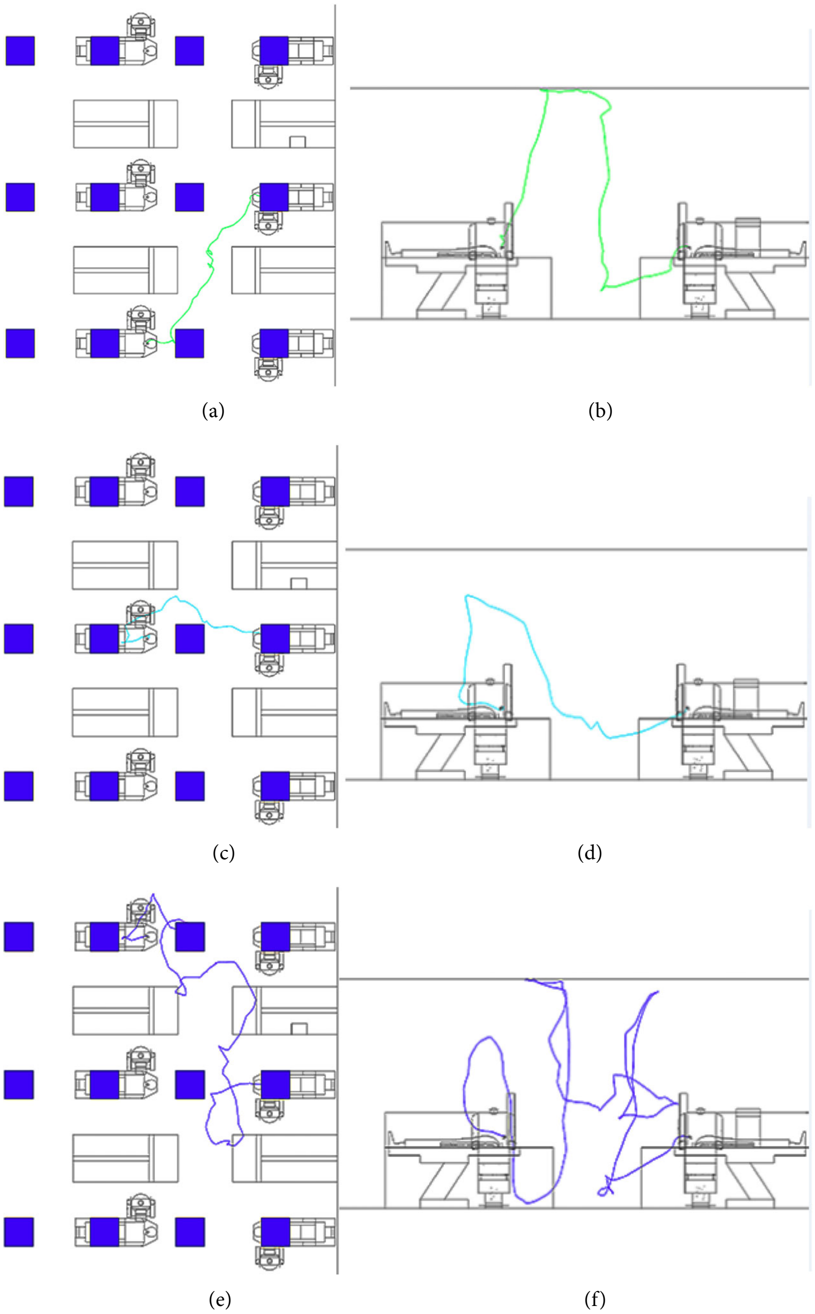

(a) (b)
(c) (d)
(e) (f)

Fig. 6 Three trajectories of aerosols absorbed by Patients 1–3: (a) top view of trajectory 1; (b) front view of trajectory 1; (c) top view of trajectory 2; (d) front view of trajectory 2; (e) top view of trajectory 3; (f) front view of trajectory 3 as shown in Figures 6(a)(c)(e), the aerosols released from the source travel to downstream patients' position, carried by the flow field. The trajectory 1 in Figure 6(a) appears in the x-y plane as a straight-line between Patient 1 and the source Patient. However, it traverses a large distance between the ceiling and the floor along the z-axis, as shown in Figure 6(b). The trajectory 2 in Figure 6(c), on the other hand, is slightly different from the first trajectory as it passes the dentist next to Patient 2 before reaching the patient's mouth, and the motion in the z-direction occurs near the dentist, as shown in Figure 6(d). The trajectory 3 in Figure 6(e) is longer and more winding compared to other paths, such as the continuous circling in the corridor between two rows of patients. From Section 3.1, it has been found that the presence of AC can significantly affect the direction of airflow around patients and cause it to move towards the AC. Although this can help to eliminating aerosols, it also leads to a disordered indoor flow field, causing some aerosols to escape the AC through unpredictable paths. From the front view (Figure 6(f)), it can be observed that the aerosols continuously move up and down between the ceiling and the floor before being absorbed by the Patient 3. Moreover, when the aerosol moves directly below the air inlet in Figures 6(a)(c)(e), the aerosols will quickly fall from a high altitude and then absorbed by the Patients 1–3. This pattern of falling and being absorbed trajectory due to the influence of the air inlet of the background ventilation was found in all 13 simulated cases. The aerosol removal efficiency of AC may play a dominant role in preventing the aerosol transmission and reducing the infection risks. The results of the aerosol removal efficiency of AC are shown in the next section.

3.3 The results of aerosol removal percentage of AC at different locations and different CADRs

The aerosol removal percentage is defined as the ratio of aerosols absorbed by the AC to the aerosols ejected by Patient 5. Figure 7 displays the aerosol removal percentage of AC when aerosol diameter is 0.1 μm. The results of 1 μm and 10 μm aerosols are not shown here because they are almost the same as that of 0.1 μm aerosol and the differences are within 1%, which demonstrates that the aerosol size has insignificant impact on AC's performance. In contrast, the location of the AC can greatly affect the aerosol removal percentage across different CADR values. For instance, the greatest aerosol removal percentage can achieve around 86% while the smallest is nearly 5%, as shown in Figure 7 when CADR is 4.416 m^3/min. By comparing the aerosol removal percentage in each scenario, it is observed that Location 4 exhibits the highest aerosol removal percentage at low CADR, while Locations 1 and 2 are most effective at middle CADR, and Location 1 is optimal at high CADR.

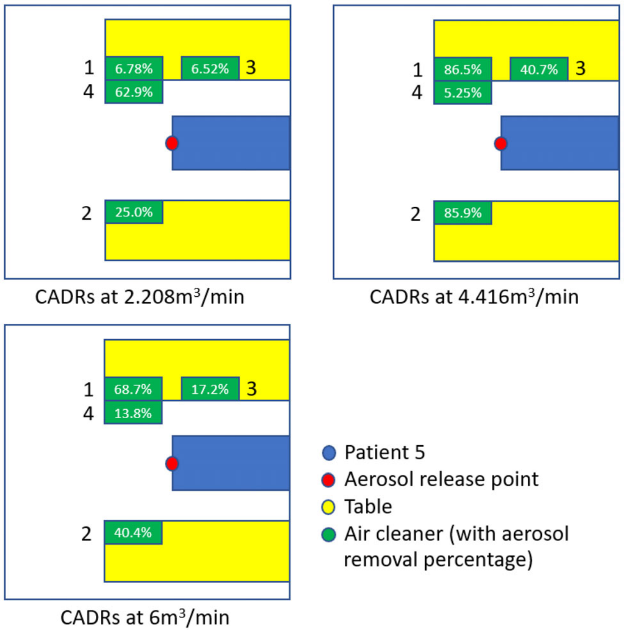


Fig. 7 Aerosol removal percentage of the AC

In addition, we find that increasing the CADR does not always lead to improved efficiency in removing aerosols from the same location. For instance, at Location 4, the aerosol removal percentage is 62.9% with a CADR of 2.208 m^3/min, but decreases significantly to 5.25% with a CADR of 4.416 m^3/min. This is primarily due to the significant changes in the inlet and outlet velocity of the AC, which greatly affects the flow field near the patient generating the aerosols. Figure 8 displays the trajectories of the aerosols for further visualization.

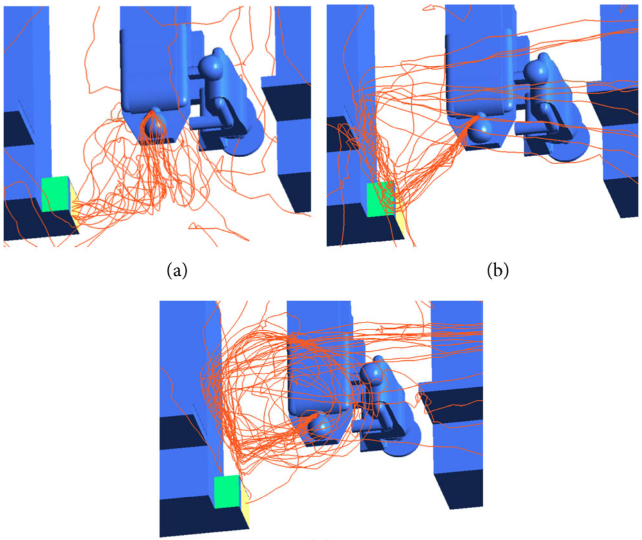


Fig. 8 Aerosol trajectories when AC at Location 4: (a) CADR at 2.208 m^3/min; (b) CADR at 4.416 m^3/min; (c) CADR at 6 m^3/min

As shown in Figures 8(b)(c), since Location 4 is on the ground, when CADR becomes higher, the increased velocity of the AC outlet pushes the aerosols up to ceiling before removed by the AC inlet, leading to a lower aerosol removal percentage. Generally, the positioning of the AC plays a crucial role in reducing aerosol transmission, and the ideal location varies depending on the chosen CADR. Then, to understand how the AC affects the infection risks for nearby patients, the dose-response method (in Section 2.5) is used and the results are displayed in subsequent sections.

3.4 The effects of air cleaner location on the infection risk of different patients at different CADR levels

3.4.1 Low CADR level

The infection risks of dental patients near the source, including Cases 1–5, are depicted in Figure 9. In these cases, the CADR of the AC is 2.208 m^3/min. For clarity, the diagram does not display the inlets, outlets, dentists, and most of the tables.

In Case 1, Patients 1 and 2 had the highest infection risks, followed by Patient 3. Because of the background ventilation in the room, the aerosol moves with the flow field from Patient 5's mouth to the left, thus Patients 1–3 are at a higher risk of infection, while Patients 4 and 6 are relatively safe. Although Patients 1 and 3 are symmetrically distributed, the dentist (as shown in Figures 1(a) and 1(b)) acts as a heat source affecting the flow field, resulting in an asymmetric result.

The results of Cases 2–5 showed that location have a great impact on the infection risks of nearby patients. Location 4 is the best location for the AC in low CADR, which is consistent with the aerosol removal percentage results shown in Figure 7. When the AC was placed at Location 1, it slightly reduced the infection risk to Patient 1 but greatly increased the infection risk to Patient 2, showing an undesirable result in preventing the spread of virus. The AC performed better in Location 2 because the overall infection risk was reduced, despite the risk for Patient 2 was slightly increased while Location 3 had the least effect on reducing infection risks. This is because it is positioned upstream of the aerosol release point, leading to the poorest outcomes in aerosol removal efficiency (as shown in Figure 7). Compared with it being placed at Locations 1 to 3, AC performs better when placed on the ground (Location 4). Although it slightly increases the risk of infection for Patient 3, it significantly reduces the risk of infection for Patients 1 and 2. In Cases 1–5, the probability of infection for Patients 4 and 6 remained extremely low. These results show that the AC's position is the main factor that determines the infection risk of downstream patients. The inappropriate placement (such as Location 3) of AC increases the downstream patients' risk of infection.

3.4.2 Middle CADR level

Figure 10 shows the results of the infection risks of the six patients when the CADR of AC increased to 4.416 m^3/min, including Case 1 and Cases 6–9. In this series of Cases, the AC performs effectively at Locations 1 and 2, which lowers the overall infection risks of downstream patients. As for the Location 3 case, AC performs unsatisfactorily. Although the risk of infection for Patients 1 and 2 are reduced, the risk for Patient 3 is increased. Different from the low CADR case, the AC performs poorly at Location 4, which greatly increases the infection probability of Patients 1–2. The main reason of this change is because the significant

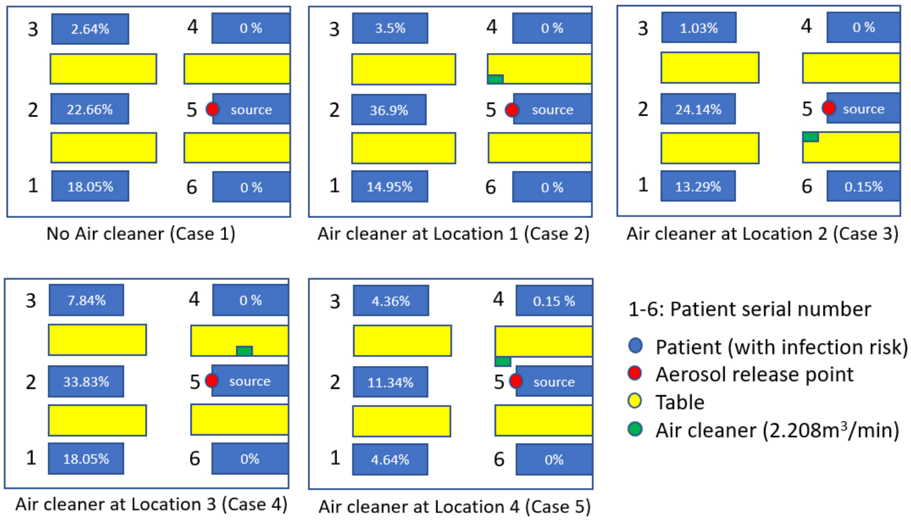
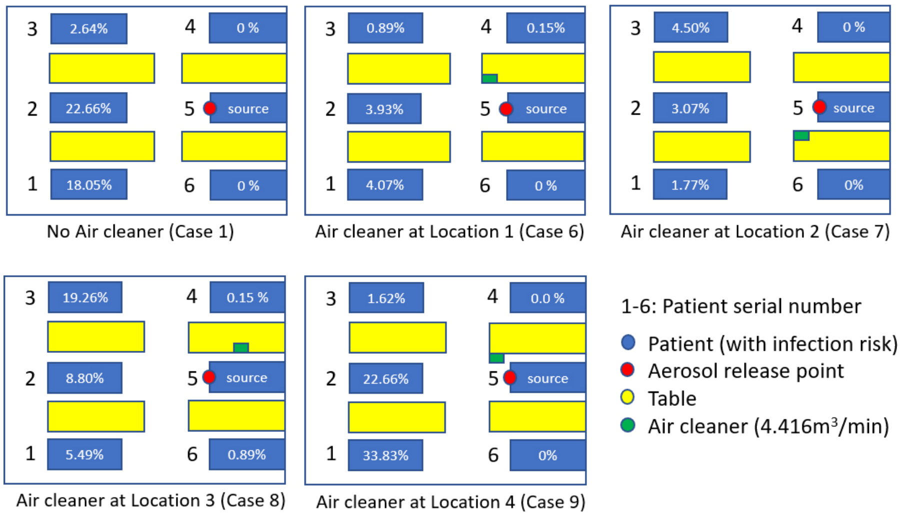


Fig. 9 The results of the infection risks of the six patients under CADR of 2.208 m^3/min



No Air cleaner (Case 1)   Air cleaner at Location 1 (Case 6)   Air cleaner at Location 2 (Case 7)

Air cleaner at Location 3 (Case 8)   Air cleaner at Location 4 (Case 9)

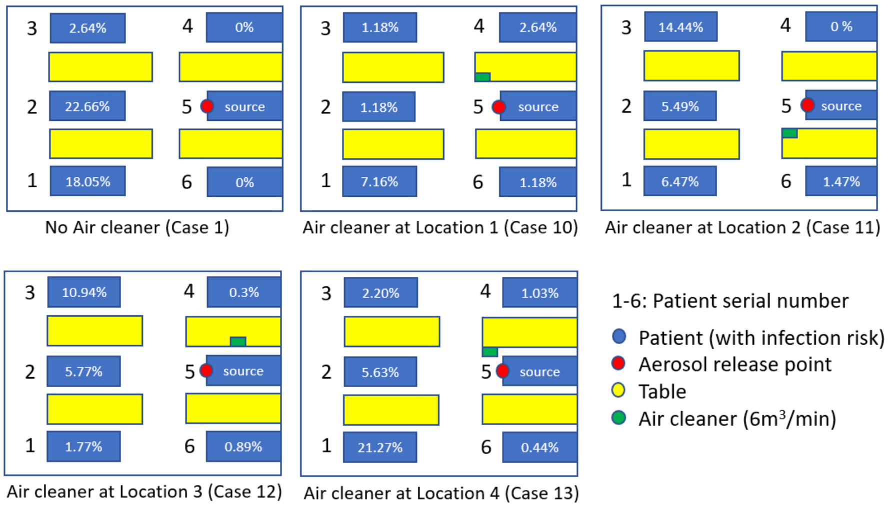
Fig. 10 The results of the infection risks of the six patients under CADR of 4.416 m^3/min

decrease in aerosol removal efficiency after increasing CADR when AC is on the floor (as shown in Figures 7 and 8). This result shows that the more aerosols are removed by the AC, the better is the effectiveness in reducing the risk of infection. Furthermore, compared with downstream Patients 1–3, Patients 4 and 6 in these cases only have a small risk (still lower than 1%) when AC has a higher CADR.

3.4.3 High CADR level

The results of infection risks of Case 1 and Cases 10–13 are shown in Figure 11. In the last series of simulations, AC has the highest CADR of 6 m^3/min to remove the source ejected aerosols. The results in Figure 7 show that Location 1 has the highest removal percentage in these cases. Combined with the results of Figure 11, AC indeed can give the smallest overall infection risks for all patients at Location 1 (13.34%). However, one drawback for Location 1 is that the infection risk of Patient 4 increased from 0% to 2.64%. Although the risk is not very high compared to Patients 1 and 2, it has reached the same risk level with Patient 3 in Case 1. The reason for this uncommon increase in risk is mainly due to the impact of airflow field affected by the large wind speed (AC outlet 1.36 m/s) from the AC (compared to the ventilation inlet velocity 0.25 m/s). The aerosols ejected from the source patient could be transported to Patient 4's location by the airflow pattern. Except for Patient 4, Patient 6's highest infection risk is 1.47% in Case 11, which may also cause concern on the safety. Compared with Location 1, Locations 2–4 can also lower the overall risks for nearby patients, but the effect is not ideal due to the increasing risks for Patient 1 (Case 13) or Patient 3 (Cases 11, 12).

In addition, higher aerosol removal efficiency does not



No Air cleaner (Case 1)   Air cleaner at Location 1 (Case 10)   Air cleaner at Location 2 (Case 11)

Air cleaner at Location 3 (Case 12)   Air cleaner at Location 4 (Case 13)

Fig. 11 The results of the infection risks of the six patients under CADR of 6 m^3/min necessarily reduce the probability of infection. For instance, the AC can remove 25% of aerosols at Location 2 when CADR is 2.208 m^3/min (Case 3), which is higher than the 17.2% when AC is placed at Location 3 with CADR of 6 m^3/min (Case 12). However, the overall infection risk for Case 3 is 38.61% which is higher than 19.66% of Case 12. Therefore, only considering the percentage of aerosols removed by AC is not enough to find valid strategies on reducing virus transmission.

3.4.4 The relationship between the total risk of dental patients and AC location

In this study, we aim to investigate and discuss the optimal placement of the AC that can effectively reduce the infection risk for surrounding patients. To more clearly illustrate how the AC's position affects the infection risk, Figure 12 is used to compare the total infection risks for patients under different locations and CADR settings.

In Figure 12, L, M, and H represent low, medium, and high levels of CADR, respectively. Compared to the infection risk when no AC is used (43.35%), as shown on the far left of the figure, among the 12 cases using AC, Locations 1, 3, and 4 each had one instance where the total infection risk was higher (approximately 55% to 60%), with two instances at the low CADR level and one at the medium CADR level. Additionally, the lowest infection risk (approximately 9% to 13%) also occurred three times, specifically at Location 1 with medium and high CADR levels and at Location 2 with medium CADR level. In comparison, Locations 3 and 4 performed relatively poorly, with the best outcomes still having a high infection risk of about 20%. Finally, it is evident that regardless of where the AC is placed, the setting of the CADR significantly affects the infection risk to surrounding dental patients, as seen with Location 1 where the difference between low and medium CADR levels was nearly 45%. In summary, Locations 1 and 2 for the AC show better performance, but the ultimate effectiveness is closely related to the setting of the CADR. The CADR should be set to at least a medium level (approximately 4.416 m^3/min) to achieve a better effect in reducing infection risk.

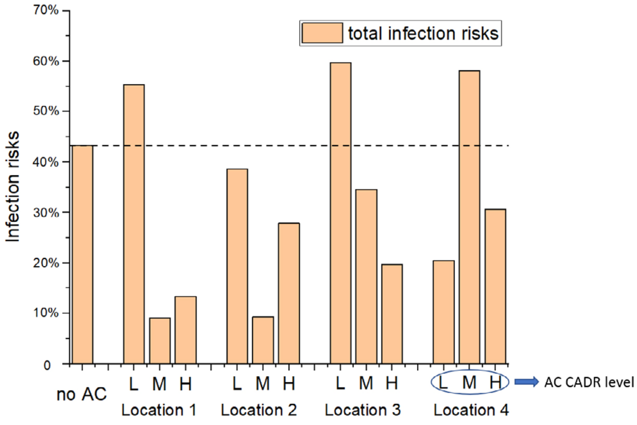


Fig. 12 The total infection risks under different AC locations and CADR levels

3.5 Comparison with previous research

As an efficient tool for removing aerosols, there is some research on the use of air cleaner in dental and hospital environments. It was found that Portable HEPA AC can effectively remove aerosols within hospital wards, and the removal efficiency varies for particles of different sizes at different locations (Qian et al. 2010). Meanwhile, using AC in single dental ward can reduce the likelihood of dentist being exposed to aerosols (Chen et al. 2010). The relative position of the AC to the source of aerosol and the dentist is an important factor in reducing the exposure of dental practitioners to aerosols. Although these articles do not specify the optimal location for air cleaner, they do highlight the importance of location on the efficiency of aerosol removal, which is consistent with our results.

In the context of the COVID-19 pandemic, an increase in the number research exploring the role of air cleaners in reducing the risk of aerosol transmission infections has been observed recently. An article comparing the effects of air cleaner and natural ventilation demonstrates that the placement of air cleaner can affect the age of the air in localized areas of a classroom (Lee et al. 2021). They found that increasing the airflow of air cleaners can effectively reduce the concentration of particles produced indoors, including viruses. Furthermore, another article also indicates that the placement and airflow rate of portable AC are crucial to the impact on infection risk in an office (Dai and Zhao 2022). The results in office showed that to achieve the optimal scenario where the probability of infection is less than 10%, it is necessary to place the portable AC in the center of the room, provided that the airflow rate is above a certain level. In our paper, the results also show the importance of CADR on infection risk (Figure12), but higher CADR is not necessarily the best. This is mainly due to the difference in simulated environments; the position of the classroom windows affects the direction of airflow, while the overall volume inside an office is relatively smaller, making the impact of the AC airflow rate on the indoor flow field relatively higher. In dental hospitals, the positions of the air inlets and outlets determine the main direction of airflow, and the high-speed airflow from AC results in a more uniform mixing of the room's internal airflow, thereby making it easier to spread to patients in other locations. Our main contribution is shown in Table 5.

Table 5 Main contribution

Method/parameter	Finding/contribution
Combined CFD with dose-response method	Providing a new way to calculate the patient's risk of aerosol-transmitted infection
AC location and CADR	Highly related to aerosol removal efficiency and risk of infection to surrounding patients. The best locations with the lowest risk of infection are Locations 1 and 2. Optimal CADR level depends on AC location
Aerosol removal efficiency and infection risk	Studying only the efficiency of aerosol removal has its limitations. In some cases, even when the AC is operational, the overall infection risk may be higher than not using an AC. Patients located downstream of indoor airflow have a higher risk of infection, but increasing the CADR of the AC can also raise the infection risk for patients who were originally in a safe position

In addition, the results of the final distribution of droplets within a room can provide valuable insights for optimizing the placement of HVAC systems and air cleaner. By studying the path of droplet spread and the quantity inhaled by patients, different positions within the room that carry infection risks can be identified. Then, the HVAC system and place air cleaners to achieve a reduction in the probability of spreading infection risks can be altered strategically. Secondly, understanding droplet distribution also helps in designing airflow patterns to minimize the spread of droplets from one area to another. For example, HVAC systems can be configured to create directional airflow that pushes droplets away from patients and towards air filtration units.

4 Limitations

Some assumptions were made in the simulations including simplified dental patient's breathing process to inhalation and averaged virus concentration in saliva to calculate the risk of infection, which may affect the accuracy of the results of risks. Since this work is aiming at the strategy of block virus transmission, we focused on observing the infection risks change under different AC parameters, thus those assumptions are acceptable when all the dental patients (except source patient) are in the same conditions. In addition, this study has not yet studied how parameters such as multiple sources of disease, multiple ACs will affect the final virus transmission prevention strategy. By using the similar methodology of this research, those problems will be investigated in the future.

5 Conclusions

To find the most effective way of using AC to reduce the infection risks of patients in dental clinics with an open floor plan, four locations near the source patient and three different CADRs were investigated. By using the CFD simulation and dose-response method, the flow field, particle trajectory, aerosol removing percentage of AC and dental patients' infection risks were obtained. Based on the findings of this study, it can be determined that:

1) The location of AC has a significant impact on the infection risk of nearby patients. Although AC can effectively remove the sprayed bioaerosols after being turned on in some situations, it cannot guarantee a reduced risk of infection for all patients. Instead, it is possible to increase the risk of infection for someone under some cases. Also, aerosol removal efficiency alone does not accurately determine its impact on reducing the infection risks.
2) Comparing the risk of infection for patients in different cases, the dental patients downstream from the source patient were at high risk of infection, while others were relatively safe. However, when the CADR of AC becomes higher at 6 m^3/min, dental patients on the left and right sides of the source require some attention due to the slightly increased risks. Regardless of the location, simply increasing the CADR of AC cannot guarantee an improvement in the efficiency of aerosol removal or a reduction in the risk of infection for patients.
3) In terms of reducing the overall infection risk, the optimal placement of the AC is on the table opposite or behind the dentist, but its effectiveness is highly influenced by the level of the CADR. To achieve better results, the CADR should be set to at least a medium level, which is around 4.416 m^3/min. In cases 6, 7, and 10, the overall infection risk was minimized, reducing the original 43% to approximately 10%.

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Declaration of competing interest

The authors have no competing interests to declare that are relevant to the content of this article. Christopher Y.H. Chao is an Editorial Board member of *Building Simulation*.

Author contribution statement

Gang Yang: conceptualization; methodology; formal analysis; investigation; writing—original draft. Thomas F. Flemmig, Ka Chung Chan: conceptualization; resources; writing—review & editing. S. Thomas Ng, Kwok Wai Mui: formal analysis; resources; writing—review & editing. Yifan Wang: investigation; software; validation. Christopher Y.H. Chao, Sau Chung Fu: conceptualization; supervision; project administration. All authors approved the final version of the manuscript.

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