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Bioaerosol distribution characteristics and potential SARS-CoV-2 infection risk in a multi-compartment dental clinic

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ABSTRACT

Dental clinics have a potential risk of infection, particularly during the COVID-19 pandemic. Multi-compartment dental clinics are widely used in general hospitals and independent clinics. This study utilised computational fluid dynamics to investigate the bioaerosol distribution characteristics in a multi-compartment dental clinic through spatiotemporal distribution, working area time-varying concentrations, and key surface deposition. The infection probability of SARS-CoV-2 for the dental staff and patients was calculated using the Wells–Riley model. In addition, the accuracy of the numerical model was verified by field measurements of aerosol concentrations performed during a clinical ultrasonic scaling procedure. The results showed that bioaerosols were mainly distributed in the compartments where the patients were treated. The average infection probability was 3.8% for dental staff. The average deposition number per unit area of the treatment chair and table are 28729 pcs/m² and 7945 pcs/m², respectively, which creates a possible contact transmission risk. Moreover, there was a certain cross-infection risk in adjacent compartments, and the average infection probability for patients was 0.84%. The bioaerosol concentrations of the working area in each compartment 30 min post-treatment were reduced to 0.07% of those during treatment, and the infection probability was <0.05%. The results will contribute to an in-depth understanding of the infection risk in multi-compartment dental clinics, forming feasible suggestions for management to efficiently support epidemic prevention and control in dental clinics.

1. Introduction

COVID-19 remains a global pandemic [1]. Dental treatment can cause significant health risks to dental staff and patients during pandemics [2]. During dental treatment, in addition to the droplets generated by communication, coughing, and sneezing among people [3–5], large amounts of aerosols contaminated by saliva and blood are emitted as a result of high-speed handpieces and ultrasound devices [6]. SARS-CoV-2 has been detected in the saliva of infected patients [7,8], and dental treatment can promote SARS-CoV-2 transmission [9]. Controlling the airborne transmission of pathogenic bioaerosols, including SARS-CoV-2, has become a key factor in reducing the risk of cross-infection [10].

Recently, studies have been conducted on the diffusion characteristics of dental aerosols. Researchers have used fluorescein or other colour-changing dyes as tracers to investigate aerosol contamination by simulating dental treatments in human models. Veena et al. [11] found that the dentist’s right arm and assistant’s left arm were the most contaminated by simulated ultrasonic scaling operations. According to Han et al. [12], contaminants at distances ranging from 0.2 to 1.2 m for four different types of dental treatments were found by placing filter paper at ten different locations around the manikin. In addition, Allison et al. [13] combined digital image analysis with fluorescein labelling, and contamination was found at 4 m. However, the natural sedimentation method used in the above study was not sensitive to indoor suspended submicron aerosols [14]. Therefore, researchers have used the laser light scattering method [15], particle counter [16], and aerodynamic particle sizer [17] to study suspended aerosols in simulated dental treatment experiments. Takanabe et al. [18] utilised dental micromotors to cut simulated mouths in a large super-clean laboratory and found that aerosols below 5 μm were predominant. Furthermore, Razavi et al. [17] believed that 0.5 μm aerosols in the dental clinic required 95 min to deposit. The general treatment of patients in an actual dental clinic takes approximately 30–40 min [19]. However,
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2. Methods

2.1. Physical model

As illustrated in Fig. 1(a), based on an actual multi-compartment dental clinic in Beijing, a physical model of \(x \times y \times z = 9.15 \times m \times 4.0 \times 3.5 \times m\) was numerically constructed. The clinic was divided into three equal-sized compartments by two 1.8 m high partitions for the simultaneous treatment of three patients. The clinic adopted an upper supply and upper return mode and symmetrically arranged the inlets and outlets. The inlets were square diffusers of 0.6 m × 0.6 m, and the outlets were louver tuyere of the same size.

For a more precise analysis and description of the multi-compartment dental clinic (Fig. 1(a)), the name of each wall was simplified, with X+ and Y representing the two sidewalls near the door and X and Y+ representing the two sidewalls away from the door. There was a long table at the Y wall side of the clinic, and a (short) table was placed in each compartment, which long-term places various equipment for daily use. Moreover, the height of each dental staff member (dentist and assistant) was 1.67 m in this physical model, and the body surface area was 1.49 m². Patients of the same size were placed in the treatment chair. The dental staff maintained a working posture that bent over approximately 20°−30° and placed their arms near the patient’s mouth; the location of the patient’s treatment was close to the direction of the X wall.

As shown in Fig. 1(b), they are called compartments A, B, and C, respectively, and start from the side of the X wall. Furthermore, the two compartments separated by a common partition are called adjacent compartments. Otherwise, they were called second adjacent compartments. For Cases 1, 2, and 3, the bioaerosols were generated in compartments A, B, and C, respectively. Thus, compartments A, B, and C are called the source compartments of Cases 1, 2, and 3, respectively. Except for the different locations of the source, the boundary conditions for the simulation settings of the three cases were consistent.

2.2. Numerical model

2.2.1. Airflow phase model

The airflow field in the multi-compartment dental clinic was solved using the Navier–Stokes (RANS) equations. The renormalisation group (RNG) k–\(\varepsilon\) turbulence model in the RANS method is widely used in indoor airflow simulations because of its simplicity, robustness, accuracy, and excellent performance [35,36]. The governing equations for the mass, momentum, energy, and turbulence are as follows [35,37]:

The mass equation is:

\[
\frac{\partial (\rho u_i)}{\partial x_i} = 0
\]  

(1)

The momentum equation is:

\[
\frac{\partial (\rho u_i u_j)}{\partial x_i} = \frac{\partial}{\partial x_i} \left[ \mu \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) - \frac{2}{3} \mu \frac{\partial u_i}{\partial x_i} \right] - \frac{\partial p}{\partial x_i} + \rho g_i + S_i
\]  

(2)

\((i,j,k = 1,2,3 \text{ and } i \neq j)\).

The energy equation is:

\[
\frac{\partial (u_i (\rho e + p))}{\partial x_i} = \frac{\partial}{\partial x_i} \left( \lambda \frac{\partial T}{\partial x_i} + u_i \left( \tau_{ij} \right)_{ij} \right) + S_i
\]  

(3)

The transport equations of turbulence kinetic energy \(k\) and its dissipation rate \(\varepsilon\) are:

\[
\frac{\partial (\rho k)}{\partial t} + \frac{\partial (\rho u_i k)}{\partial x_i} = \frac{\partial}{\partial x_i} \left[ \left( \mu + \frac{\mu}{\varepsilon} \right) \frac{\partial k}{\partial x_i} \right] + G - \varepsilon
\]  

(4)

In summary, most studies have focused on experimental studies of simulated dental treatment and several measuring points around patients in a single-person clinic. The transmission of bioaerosols and risk of cross-infection require further investigation in multi-compartment dental clinics. This study utilised CFD to investigate bioaerosol distribution characteristics in a multi-compartment dental clinic. The infection probability of SARS-CoV-2 for the dental staff and patients was calculated using the Wells–Riley model. The accuracy of the numerical model was verified by field measurements of aerosol concentrations performed during a clinical ultrasonic scaling procedure. In addition, three cases, that is, the patient’s treatment in three different compartments, explored the factors affecting bioaerosol transmission in a multi-compartment dental clinic. The results will contribute to an in-depth understanding of the infection risk in multi-compartment dental clinics, forming feasible suggestions for management to efficiently support epidemic prevention and control in dental clinics.
\[
\frac{\partial \rho_e}{\partial t} + \nabla \cdot (\rho_e \mathbf{u}) = \frac{1}{\rho} \frac{\partial \mu_t}{\partial x_i} \left( \frac{1}{k} \frac{\partial \rho_e}{\partial x_i} \right) + C_{\varepsilon} \frac{\varepsilon_1}{k} G - C_{\varepsilon} \frac{\varepsilon_2}{k} - C_\mu \eta \left( \frac{1 - \eta}{1 + \beta \eta} \right) \varepsilon^2
\]

where
\[
\mu_t = C_\mu \frac{k^2}{\varepsilon}
\]

\[
\eta = \left( 2E_{ij}E_{ij} \right)^{1/2} E_i = \frac{1}{2} \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right)
\]

In the \( k-\varepsilon \) equations, the parameters \( C_{\varepsilon 1} = 1.42, C_{\varepsilon 2} = 1.68, C_{\mu} = 0.0845, \sigma_k = 0.7194, \sigma_\varepsilon = 0.7194, \eta_0 = 4.38, \) and \( \beta_0 = 0.012 \) are from Ref. [35]. The definitions of the parameters in the formula above are listed in Table 1.

In this study, ANSYS Fluent 2020 R2 was used to solve the differential equations. An enhanced wall treatment was utilised to address the turbulent characteristics near the wall. Meanwhile, the second-order upwind discretisation scheme was used for the momentum, energy, turbulent kinetic energy \( (k) \), and dissipation rate of the turbulent kinetic energy \( (\varepsilon) \). The “PRESTO!” scheme was applied to the pressure equation. The coupling of the pressure and velocity fields was realised using the SIMPLEC algorithm. The time discretisation of the transient term was performed using the second-order implicit scheme. Furthermore, when the velocity residuals and continuity residuals were below \( 10^{-4} \) and the energy residuals were below \( 10^{-6} \), the solution was considered to have converged.

The boundary conditions for the airflow are listed in Table 2. The velocity inlet was set for the air supply diffusers [37, 38], which was due to the fact that the air supply direction was basically perpendicular to the air supply diffusers in the measurement of the actual air inlet. The turbulence intensity was set at 5%. The supplied air temperature was taken as 28 °C. In this study, the heating load of the room was mainly supplied by a certain temperature (28 °C) air supply. In addition, the convection heat flux was set to 58.5 W/m² for both the dental staff and patients.

**Table 1**
The definition of parameters.

| Parameters | Meanings |
|------------|----------|
| \( u_i \) | The velocity in the \( x_i \) direction |
| \( g_i \) | The gravitation acceleration in the \( x_i \) direction |
| \( p \) | Pressure |
| \( \rho \) | Air density |
| \( T \) | Temperature |
| \( \mu_{\text{eff}} \) | Effective dynamic viscosity |
| \( \tau_{\text{eff}} \) | Effective stress tensor |
| \( \lambda_{\text{eff}} \) | Effective thermal conductivity |
| \( e \) | Specific energy |
| \( \delta_t \) | Momentum sink |
| \( \delta_h \) | Heat source |
| \( \mu_t \) | The turbulence kinematic viscosity |
| \( \sigma_k \) | The turbulence effective Prandtl number for \( k \) |
| \( \sigma_\varepsilon \) | The turbulence effective Prandtl number for \( \varepsilon \) |
| \( C_{\varepsilon 1}, C_{\varepsilon 2} \) | Empirical constant in generation/destruction term of \( \varepsilon \) equation |
| \( C_{\mu} \) | Empirical constant for eddy viscosity |
| \( \beta \) | Volumetric expansion coefficient |
| \( G \) | The source term |

**Table 2**
Boundary conditions for airflow simulation.

| Name          | Boundary conditions |
|---------------|---------------------|
| Inlet         | Velocity inlet, velocity is 0.18 m/s, temperature equals to 28 °C, turbulent intensity is 5% |
| Outlet        | Outflow boundary    |
| Long table    | No-slip wall boundary |
| Table         | No-slip wall boundary |
| Equipment tray| No-slip wall boundary |
| Partition 1/2 | No-slip wall boundary |
| Treatment chair| No-slip wall boundary |
| Human body    | No-slip wall boundary, heat flux is 58.5 W/m² for dental staff and patients |
the patient, which was based on the Yang et al. [36] setting of 58.5 W/m² and 26 W/m² for the driver and passenger, respectively. The same convection heat flux was set for the dental staff and drivers because they had similar postures and behaviours. Moreover, patients often experience physiological changes such as increased tension and heart rate during treatment [39]; therefore, a convection heat flux of 58.5 W/m² was also selected.

### 2.2.2. The age air model

The local mean age of air ($\tau_p$) was modelled to reflect the freshness of the indoor air. The smaller the value of $\tau_p$, the stronger the ability to remove pollutants [40]. The transport equation for $\tau_p$ is written as [41]:

$$\frac{\partial (\rho \tau_p \xi)}{\partial t} = \frac{\partial}{\partial x_j} \left( \frac{\partial (\rho \tau_p \xi)}{\partial x_j} \right) + S$$

where $S_c$ denotes the turbulent Schmidt number. In this study, the value of $S_c$ was set to 0.7. $S_i$ is the source term of $\tau$, which is generally set to a fixed value, that is, $S_i = 1$. To calculate the distribution of the age of air, a user-defined scalar is incorporated into the CFD model [42].

### 2.2.3. Particle phase model

The DPM is a model to track the transmission trajectory of spherical particles using the unidirectional coupled Lagrange method, which has been widely applied to simulate the diffusion of particles in the air [37]. The mass point trajectory is determined by the mass point force Equation (9).

$$\frac{d\mathbf{x}}{dt} = F_d(u_a - u_p) + g_x \cdot \left( \frac{\rho_a - \rho_p}{\rho_p} \right) + F_s$$

where $u_a$ and $u_p$ represent the velocities of airflow and particles, respectively. $F_d(u_a, u_p)$ is the drag force per unit particle mass, and $\rho_a$ and $\rho_p$ represent the density of the airflow and particles, respectively. $g_x$ is the gravitational acceleration, and $F_s$ represents the additional forces acting on the particles.

According to the basic theory of aerosol dynamics, additional forces depend on the properties of airflow and particles [43]. The pressure gradient, Basset, and virtual mass forces were ignored because of the small ratio of air density to particle density [43]. Therefore, the thermophoretic, Saffman lift, and Brownian forces were considered in this study.

The transient process simulation setting was the same as the experimental time, with a total time of 90 min. The bioaerosol was released during the first 30 min, which was set according to the average treatment time of the patients in the experiment. This is consistent with the results of previous studies [38]. According to the actual measurement, particles 0.3–0.5 μm in size were the most abundant, as shown in Fig. 2 (b). The bioaerosols diffusion of 0.3 μm and 0.5 μm was calculated by Case 2, and the relative errors of deposition numbers on the tables of different compartments (A, B and C) were 2.2%, 3.4% and 3.8%, respectively. The relative errors were sufficiently small. In addition, in previous studies, aerosol with a diameter of 0.5 μm was often used as the research object [17,21], which is representative. Therefore, bioaerosols 0.5 μm in diameter were adopted for this study. Moreover, a bioaerosol release rate of 2500 pcs/s was selected for the subsequent transient simulations by measuring oral source concentration.

In this study, the bioaerosol was regarded as a sphere with a density of 1000 kg/m³ [44]. An initial velocity of 0.68 m/s was selected [45,46]. The direction of the bioaerosol release was perpendicular to the back of the treatment chair. For solid walls, the trap condition was applied because aerosols do not have sufficient rebound energy to overcome adhesion [36]. The escape condition was applied to the air inlets and outlets. In addition, according to Hinds [47], the concentration is halved owing to solidification, which occurs after only 200 days. Therefore, no collision or solidification between the particles was assumed in this study. According to Morawska [48], the evaporation time of 1 μm particles takes only a few milliseconds. In addition to the extremely short evaporation time, the small particles hardly rupture [49,50]. Thus, the effects of rupture and evaporation were not considered in the CFD simulations because of the small size of the selected bioaerosols.

### 2.3. Experimental method

#### 2.3.1. Measurement instruments

Before the aerosol concentration measurement experiment, an air velocity meter was used to measure the air supply velocity (0.18 m/s) and temperature (28 °C) perpendicular to the inlet direction, which meant the ventilation rate at six air changes per hour. Moreover, the air velocity every 0.5 m in the vertical direction from the floor to the air vents (three inlets and three outlets) was also measured. The air velocity in the multi-compartment dental clinic provided data for subsequent airflow phase simulations and numerical model validation.

The handheld PGM-300 particle counter was used to measure the aerosol concentration at each measuring point, as a typical method of measuring indoor aerosol concentration, which has been frequently used in previous studies [51,52].

An optical particle sizer spectrometer was used to measure the aerosol concentration of the oral source during dental treatment. This provided the source concentration for the subsequent particle-phase simulation.

Details of all the instruments are presented in Table 3.

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**Fig. 2.** Size distribution of the aerosols.
2.3.2. Field measurement

Nine measurements of aerosol concentration were conducted from 25 November 2021 to 3 December 2021. There were three compartments in the multi-compartment dental clinic; nine patients were invited to undergo the ultrasonic scaling procedure, and three measurements were conducted in each compartment. Several studies have shown that ultrasonic scaling can produce large amounts of aerosols contaminated by saliva and blood owing to the use of ultrasonic scrapers [11, 15]. Owing to the differences in each patient’s dental health, the treatment time varied from 20 to 40 min, similar to that in previous studies [19].

Six aerosol measuring sites were arranged in the entire clinic: A S1, B S1, and C S1 were placed 0.8 m from the floor to measure the change in aerosol concentration (aerosol number concentration) in the patient’s breathing area. Similarly, A S2, B S2, and C S2 measured the change in aerosol concentration in the dentist’s breathing area 1.1 m from the floor. Notably, the S1 measuring point in the source compartments of each case was placed on the long table (0.9 m from the floor) in the public area to prevent an impact on the regular operation of the dentist. The aerosol concentration per second at each measurement point was obtained using a handheld PGM-300 particle counter. To reduce the influence of background concentration on the measurement results, the clinic was empty for at least 2 h before each measurement until the concentration at each measuring point was stable. The patient underwent an ultrasonic scaling procedure performed by a dentist and assistant during one measurement. In addition, the source concentration was measured using an external nozzle with an optical particle sizer spectrometer [20] (Fig. 2(a)). After the treatment ended, three people (one patient and two dental staff) left the clinic immediately. The indoor aerosol concentration was measured until it returned to the level before treatment.

3. Results and discussion

3.1. Numerical model validation

The grid structure and density significantly influence the simulation results of the airflow field [53, 54]. Therefore, the grid independence of the CFD simulation for the multi-compartment dental clinic was tested. The ICEM software was used to discretise the geometry of the model. Three groups of tetrahedral unstructured grids with numbers of 553243, 6327615, and 7802322 were generated. Grid independence verification was applied to capture the main flow and heat transfer characteristics in the areas with the highest transport gradients, that is, the inlets, outlets, and particularly below the ceiling diffuser [53]. Therefore, this study selected the vertical line below the inlets and outlets for grid-independent verification. The results are shown in Fig. 3. The relative errors in airflow velocity between two consecutive grids were 5.64% and 1.89%. Consequently, 6327615 grids were selected for subsequent simulations to save computing resources and time.

An accurate continuous phase calculation model is particularly important for studying the transmission and distribution of bioaerosols, in which airflow plays an important role. Measurements were taken every 0.5 m (0.5, 1.0, 1.5, 2.0, 2.5, and 3.0 m) from the floor to the inlets and outlets. As shown in Fig. 4, the experimental airflow velocity is consistent with the numerical simulation results. The mean absolute percentage error of velocity was <10% [53], indicating that the boundary conditions of the flow field are reasonable. The errors caused

| Instrument name | Manufacturer | Model | Range Flow Rate | Accuracy |
|-----------------|--------------|-------|-----------------|----------|
| Air velocity meter | TSI Inc., USA | 9565 | 0.30 m/s | ≤ ± 3% |
| Optical particle sizer spectrometer | TSI Inc., USA | 3330 | 0.3–10 μm 1.00 L/min | ≤ ± 3% |
| Handheld particle counter | Korno Ltd., CHN | PGM-300 | 0.3–10 μm 2.83 L/min | ≤ ± 3% |

![Fig. 3. The velocity comparisons among three grid numbers on the vertical line of the inlet and outlet.](image-url)
Fig. 4. Comparison of experimental and simulated values of airflow velocity.

Fig. 5. Simulated and experimental concentration verification.
by the operation of the experimenters, simplification of the numerical model, and calculation errors of the software might lead to inevitable errors between the simulation and experimental test results. Overall, the agreement between the experimental and simulated results was acceptable.

The proportion ($C\%$) of the respective concentration sum of each of the two measuring points in each compartment, it is more distinct to compare the experimental data with numerical results, which can be expressed as

$$C\% = \frac{\sum_{i=0}^{5400} iSf(t)}{\sum_{i=0}^{5400} (iS1(t) + iS2(t))}$$

(10)

where $t$ represents different moments (s), $i$ is different compartments (A, B, and C), $f$ represents two different measuring points in each compartment (1, 2), and $iSf(t)$ represents the instantaneous concentration of each measuring point in each compartment. The three $C\%$ values at each measuring point were then averaged and the error value was obtained by calculating the standard deviation, as shown in Fig. 5.

Although the experimental results are not entirely consistent with the simulation results, these errors are understandable considering the complexity of the experiment, sensitivity of the instrument, fluctuation of the background concentration, simplification of the numerical model, and calculation errors of the software. In addition to the error in Case 1 which was caused by these common reasons, the errors in Cases 2 and 3 also had their own reasons. In Case 2, because the patient’s treatment position was close to the partition, the aerosol was hindered in the process of diffusion to compartment A, and the airflow was unstable, which caused a large error between the simulated and experimental values of the measuring points ($AS1$, $AS2$) in compartment A. For Case 3, the aerosols in the source compartment (compartment C) were far from the adjacent second compartment (compartment A), in addition to being greatly affected by the partition. The aerosols from compartment C could hardly be detected by the handheld particle counter at the two measuring points of compartment A; therefore, the experimental values of $C\%$ for $AS1$ and $AS2$ were basically identical, which caused a large error with the simulated value. In conclusion, the simulated concentrations were in good agreement with the experimental results, which ensured the validity of the subsequent simulation.

3.2. Airflow field

First, the airflow distribution in the simulation results was analysed using velocity vector and streamline diagrams, as shown in Fig. 6. The breathing zones height of the dental staff and patients are $Z = 0.8$ m and $Z = 1.1$ m, respectively, and these two planes are representative.

The airflow in each compartment first diffuses around the walls and partitions, and then most of it returns to the centre of the compartments, forming multiple vortex zones around the dental staff. The part of airflow in compartment C is blocked by the side of the long table, causing more vortexes in compartment C. The vortex would weaken the particle-carrying capacity of the airflow. Thus, bioaerosols in the compartment C may spread less to other compartments than in the
compartment A. According to the velocity vector analysis, there is air exchange between compartment B and the compartments on both sides, therefore, the ventilation in compartment B is relatively better. In short, the horizontal airflow velocity is low, particularly around the dental staff and patients, and the maximum velocity is not more than 0.1 m/s.

Second, the degree of air freshness in each compartment was analysed based on the air age. Air age is an essential indicator for the comprehensive measurement of the indoor ventilation effect and indoor air quality evaluation, which refers to the time of airflow into the room to a certain point. An isosurface diagram for different air ages (300–800 s) is shown in Fig. 7. As shown in Fig. 7(a) and (b), the air ages on the inner side of each compartment (Y+ wall side) are younger. The air inlets were close to the Y+ wall side, which facilitated the diffusion of the airflow below. Meanwhile, areas with older air ages appeared in compartments A and C, mainly around the working area of the dental staff, as shown in Fig. 7(c) and (d).

The results show that air freshness in different areas is mainly related to the airflow distribution. Based on the above analysis, the bioaerosols in different compartments require further investigation.

### 3.3. Distribution characteristics of bioaerosols in the multi-compartment dental clinic

#### 3.3.1. Spatiotemporal distribution

Fig. 8 illustrates the spatiotemporal distribution of bioaerosols generated in the three different source compartments. Bioaerosols are coloured according to particle birth time. Most bioaerosols remained in the source compartments, and the rest diffused with airflow to other compartments. The initial state of bioaerosol movement with airflow was observed at T = 1 min. Under the influence of airflow, bioaerosols generated by compartments A and C first moved towards the direction of the partition. The patient in compartment C was closer to the side of the partition than that in compartment A. The bioaerosols in Case 3 were quickly blocked and captured by partition 2 and affected by the updraft until they diffused to the whole compartment C. However, the initial bioaerosols in Case 1 appeared to be less limited by partition 1, and the bioaerosols were more easily diffused throughout compartment A. In addition, bioaerosols in Case 1 were relatively more diffused with airflow into other compartments, which can be seen from T = 15, 30, and 40 min. The bioaerosols in Case 2 diffused to both sides owing to the airflow. The position of the patients in compartment B was similar to that in compartment C, both close to the side of the partition. The

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Fig. 7. Isosurface diagram of different air ages.
bioaerosol diffused in the direction of compartment A was first captured or blocked by the partition, and the bioaerosol diffused to compartment C was relatively less bound by the obstacles. Therefore, for Case 2, more bioaerosols diffused to compartment C than to compartment A. Only 0.05% of the bioaerosols were suspended in the multi-compartment dental clinic 30 min after treatment ended, $T = 60$ min. Currently, anyone in the clinic has a low risk of inhaling bioaerosols from the mouth and nose.

### 3.3.2. Bioaerosols concentration in the working area

In addition, a $1.4 \text{ m} \times 1.1 \text{ m} \times 0.6 \text{ m} (x \times y \times z)$ cube was constructed in the whole area of dental staff and patients from the waist to the top of the head, representing the working area. The height coordinate range of these three working areas in the physical model was $Z = 0.6–1.2 \text{ m}$. The width coordinate range was $Y = 1.38–2.48 \text{ m}$. The length coordinate range of the working area in each compartment is different. $X_A = 0.2–1.6 \text{ m}$, $X_B = 3.33–4.73 \text{ m}$, and $X_C = 6.35–7.75 \text{ m}$. The average concentration in the cube was determined to obtain the variation in the

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**Fig. 8.** Spatiotemporal distribution of bioaerosols in three cases.
concentration in the working area with time [55]. Fig. 9(a) shows the variation in the working area concentrations in the different source compartments. During the treatment, the working area concentration increased rapidly and remained high. Owing to the higher air freshness in compartment B, the average working area concentrations of the source compartments in Case 2 increased rapidly and then decreased, which may have been due to a large number of vortices. Vortices can weaken the ability of airflow to carry particles, causing bioaerosols to be shed to reduce the working area concentrations. The working area concentrations decreased rapidly within 30 min of the end of the treatment, however, the average concentration remained as high as 5512 pcs/m$^3$. Therefore, to prevent cross-infection risk, it is not recommended to immediately receive subsequent patients until the working area concentration returns to a safe level.

The effect of the different source compartments on the working area concentration of the other compartments is shown in Fig. 9(b). The working area concentrations in the adjacent compartments were influenced by the source compartments. In addition, there is a relationship with the source location. The source in Case 1 had the most significant impact on the working area concentrations in compartment B. This again proves that the bioaerosols in compartment A diffuse more easily into other compartments. Although the working area concentrations of compartment C were unstable in Case 2, they were always higher than those in compartment A. In addition, during long-distance propagation of bioaerosols, a large number of bioaerosols are deposited and discharged. Thus, Cases 1 and 3 had little effect on the bioaerosol concentration in the working area of the second adjacent compartment. Except for the abovementioned reasons, the bioaerosol in the dental treatment of Case 3 was quickly captured by one side of the partition, and part of the airflow was blocked by the side of the long table. Consequently, fewer bioaerosols diffused into other compartments in Case 3. This phenomenon can be observed more intuitively in Fig. 8.

In conclusion, the concentration in the working area of the source compartments was the highest. Adjacent compartments have a certain cross-infection risk; the average highest concentration of the working area in adjacent compartments is 1131 pcs/m$^3$ during treatment. Moreover, the source compartments had little effect on the second adjacent compartments. Approximately 30 min post-treatment, most bioaerosols have been discharged, inhaled, or deposited, and the bioaerosol concentration of the working area in each compartment was reduced to 0.07% of that during treatment.

### 3.3.3. Bioaerosols deposition

The deposition of bioaerosols on key surfaces was explored to further elucidate the distribution of bioaerosols in a multi-compartment dental clinic. In addition to the close relationship between the spatial bioaerosol concentration and the respiratory risk of dental staff and patients, surface contamination caused by pathogenic microorganisms may pose a risk of contact transmission [56]. Therefore, the deposition distribution of bioaerosols in a multi-compartment dental clinic is described by the deposition rate and unit area deposition number. The deposition rate is defined as the percentage of the deposition amount on different surfaces to the total amount of original release, which reflects the proportion of bioaerosol deposition on different surfaces. The unit area deposition number is defined as the ratio of the deposition number of different surfaces to the surface area, which quantitatively describes the degree of bioaerosol pollution on different surfaces. Their calculation formula is defined by Equations (11) and (12):

$$D_i = \frac{N_i}{A} \times 100\%$$  \hspace{1cm} (11)

$$\theta_i = \frac{N_i}{S_i}$$  \hspace{1cm} (12)

where $D_i$ is the deposition rate of different surfaces, $N_i$ is the deposition number of bioaerosols on the $i$th surface, $A$ is the total number of bioaerosols released, $\theta_i$ is the unit area deposition number of different surfaces, and $S_i$ is the area of the $i$th surface.

Fig. 10(a) shows the bioaerosol deposition situation of the key surfaces in different source compartments. Because vortices can weaken the ability of airflow to carry particles, Cases 2 (6.32%) and 3 (4.83%) showed a higher deposition rate on dental staff surfaces than that of Case 1 (2.66%). Overall, higher deposition rates were found on the surfaces of dental staff and patients. Previous studies have reported similar results [11,43]. Therefore, dental staff need timely post-work disinfection of clothes to avoid cross-infection with subsequent patients. In addition, the average deposition number per unit area of the treatment chair and the table are 28729 pcs/m$^2$ and 7945 pcs/m$^2$, respectively, which poses a possible contact transmission risk. Fig. 10(b) shows the influence of different source compartments on bioaerosol deposition in public areas. A large proportion of bioaerosols were deposited on the inner surface of buildings, with deposition rates of 12.61%, 8.31%, and 12.60%.

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**Fig. 9.** Concentration of bioaerosols of the working area in three cases: (a) source compartments and (b) other compartments during 90 min.
Fig. 10. Bioaerosol deposition on different surfaces in three cases: (a) source compartments and (b) public areas.

Fig. 11. Spatial distribution of breathing surface exposure risk in three cases, the treatment period (0–30 min).
Consequently, the clean inner surfaces of buildings require attention. Combined with previous analysis, the main diffusion path of bioaerosols occurred in the airflow path. Thus, the deposition rate of the long table in Case 1 was more significant than that in the other cases. In addition, the deposition rates of Case 2 in partition 1 (1.2%) and Case 3 in partition 2 (4.3%) were higher than those of Case 1 in partition 1. Therefore, partition plays a positive role in reducing the diffusion of bioaerosols into other compartments.

In short, bioaerosols are mainly distributed in the source compartments, however, a certain amount of bioaerosols can reach the adjacent compartments. Moreover, the comparison of the three cases showed that different source compartments caused different bioaerosol distributions in the multi-compartment dental clinic. Airflow distribution is the key factor that affect the distribution of bioaerosols. Partitioning also plays a positive role in reducing bioaerosol diffusion to other compartments.

### 3.4. Quantitative calculation of infection risk

To quantify the infection risk in the multi-compartment dental clinic, the infection probability of SARS-CoV-2 for the dental staff and patients was calculated. In this study, the clinic was divided into 18 parts (Figs. 11–13) and into three periods: the treatment period (0–30 min), after the treatment period (30–60 min), and 30 min post-treatment (60–90 min). The spatial distribution of the infection risk of dental staff and patients in three cases and three time periods are shown in Figs. 11–13.

#### 3.4.1. Calculation method of infection probability

The improved Wells–Riley model coupled with the CFD method was used to calculate the infection probability of SARS-CoV-2 for dental staff and patients, as follows:

\[
P = 1 - \exp[-(1 - \theta) p N t]
\]  

where \(P\) is the infection probability, \(\theta\) is the filtration efficiency of the N95 masks (95%) \([57,58]\), and patients have no mask protection during treatment. The respiration rate of a person with light activity \((0.72 m^3/h)\) \([59]\) is represented by \(p\), and \(N\) is the pollutant concentration \((\text{quanta/m}^3)\). \(t\) is the exposure time, and 30 min was used as the exposure time for each calculation of the infection probability.

Quanta \((q)\) refers to the number of airborne particles that can infect a person, which may consist of one or more airborne particles \([60]\). This is a hypothetical unit of infection dose, which is usually back-calculated based on epidemiological studies \([31]\). To date, quanta values of SARS-CoV-2 during dental treatment have not been obtained. To evaluate the quanta value during dental treatment more accurately and reasonably, this study calculated the quanta value based on Equation (14) \([61]\).

\[
q = c_v \times c_i \times R \times V
\]  

where \(q\) is the quanta, \(c_v\) is the SARS-CoV-2 viral load in sputum \((10^{10} \text{ RNA copies/mL})\) \([61,62]\), and \(c_i\) is the corrective coefficient of infectivity (0.08) \([61]\). \(R\) is the number of bioaerosols generated per hour during dental treatment \((\text{pcs/h})\), and a bioaerosol release rate of 2500 pcs/s was selected for this study. Therefore, the value of \(R\) is \(2500 \times 3600 \text{ (pcs/h)}\). \(V\) is the volume of spherical bioaerosol with a diameter of 0.5 μm \((\text{cm}^3)\).

This equation assumes that the droplets generated by an infected person have the same viral load as that of sputum \([61]\). Certain dental treatments produce aerosol concentrations of microorganisms that exceed those produced during coughing or sneezing \([63]\). Therefore, it is reasonable to apply this equation in this study. Wang et al. \([64]\) used 100 quanta/h for aircraft COVID-19 infection risk analysis. However, Zhang et al. \([65]\) reported that the quantum generation rate of SARS-CoV-2 during air travel was 375 per hour. In addition, Chen et al. \([66]\) showed that the SARS-CoV-2 quantum generation rate was 185.63 per hour by estimating the virus emission rate using the Diamond Princess Cruise Ship. The above study focused on an infection caused by talking and coughing. Dental treatment could be considered as a high emission behaviour of microorganisms \([63]\). In this study, 471 quanta/h was obtained using Equation (14), which was considered reasonable.

| Patient | 30-60min | Dental staff |
|---------|----------|--------------|
| Case 1  | 2.75     | 1.14         |
|         | 6.21     | 0.31         |
|         | 0.63     | 0.83         |
|         | 0.29     | 0.08         |
|         | 0.12     | 0.08         |
|         | 0.07     | 0.01         |
| Case 2  | 0.69     | 0.02         |
|         | 0.51     | 0.14         |
|         | 0.51     | 0.03         |
|         | 0.51     | 0.03         |
|         | 0.51     | 0.03         |
| Case 3  | 0.01     | 0.02         |
|         | 0.01     | 0.02         |
|         | 0.02     | 0.02         |
|         | 0.24     | 0.02         |
|         | 0.48     | 0.02         |
|         | 1.14     | 0.02         |
|         | 0.39     | 0.02         |

Fig. 12. Spatial distribution of breathing surface exposure risk in three cases, after the treatment period (30–60 min).
3.4.2. The treatment period (0–30 min)

The infection risk was highest in the source compartments (Fig. 11). Although dental staff had protective measures, the infection probability was 2.53% (Case 1), 4.49% (Case 2), and 4.38% (Case 3). The partitions of Cases 2 and 3 hinder the diffusion of bioaerosols to other compartments, however, more bioaerosols are concentrated on the breathing surface of the dental staff, therefore, the infection risk is higher for dental staff than in Case 1. In short, the protective measures of the dental staff require further strengthening.

From the distribution of the infection probability, Case 1 shows a more significant impact on other compartments than in other Cases. Compared with Case 2 (1.28%) and Case 3 (0.19%), the infection probability for patients in the working area of adjacent compartments in Case 1 (1.39%) was highest. Because patients do not have any protective measures during treatment, the overall infection risk is 15 times higher for patients in adjacent compartments than for the dental staff. Therefore, how patients receive effective protection requires further investigation.

3.4.3. After the treatment period (30–60 min)

The concentration of suspended bioaerosols in the source compartments remained high within 30 min of treatment. If the next patient was immediately arranged in the compartment, the infection probability for the patients reached 10%, and the maximum infection probability for dental staff approached 1% (Fig. 12). Thus, it may pose a significant threat to the lives and health of dental staff and patients. Case 2 had a lower infection probability in the source compartments (B) than in other cases. Because the freshness of air in compartment B is high, once the compartments stop generating bioaerosols, the self-purification ability will play a role.

Moreover, the highest infection probability of patients in adjacent compartments was 1.09%, and Case 3 showed the lowest infection risk (0.24%). Patients in the adjacent compartments are vulnerable to bioaerosols. The infection probability of dental staff in adjacent compartments is still low. Dental staff, compared with patients, although they had protective measures, needed to work for a longer time in the clinic. Infection risk is closely related to the exposure duration. Therefore, after the end of treatment, dental staff should leave the working area in time to reduce the exposure time.

3.4.4. Thirty min post-treatment (60–90 min)

Thirty min after treatment ended, small amounts of suspended bioaerosols were not sufficient to threaten dental staff and patients, with infection probability below 0.05% in each compartment (Fig. 13). Therefore, 30 min is recommended as the minimum safety interval between patients.

Overall, dental staff in the source compartment and patients in the adjacent compartments had a high probability of infection. Thirty min after treatment ended, the infection probability of each compartment was <0.05%. However, the second adjacent compartments were always at low risk. Moreover, the infection probability on the inner side of each compartment was the lowest, corresponding to air age. The corridors between compartments are high-infection areas, which may be an important path for bioaerosol transmission between compartments.

3.5. Limitations of this study

This study explored the distribution characteristics of bioaerosols in multi-compartment dental clinics and quantitatively evaluated the potential SARS-CoV-2 infection risk in dental staff and patients at different time periods. First, this study was conducted in a closed room. If the window is opened, natural convection might form inside and outside the clinic, which would affect the airflow distribution and the bioaerosol distribution characteristics in the clinic. In addition, the locations of the inlet and outlet and the overall layout of the clinic also had an important impact on the transmission of bioaerosols. The effects of these factors should be systematically considered in future studies on cross-infection in multi-compartment dental clinics.

4. Conclusion

This study investigated the bioaerosol distribution characteristics in a typical multi-compartment dental clinic through spatiotemporal distribution, time-varying concentrations of the working area, and key
surface deposition. Additionally, the infection risk of COVID-19 for the dental staff and patients was quantitatively calculated. The main conclusions are as follows:

1) Bioaerosols are mainly distributed in compartments where patients are treated (source compartment); however, adjacent compartments have a certain cross-infection risk. In source compartments, the average infection probability was 3.8% for dental staff. The average deposition number per unit area of the treatment chair and table are 28729 pcs/m² and 7945 pcs/m², respectively, which pose a possible contact transmission risk. In adjacent compartments, the average infection probability was 0.84% for patients. However, the second adjacent compartments (compartment C in Case 1, and compartment A in Case 3) were always at low risk.

2) The bioaerosol concentration in the working area of the source compartments remained high after the treatment ended. The average concentration reached 5512 pcs/m³. The infection probability reached 10% for the next patient treated immediately. Therefore, it is necessary to pay close attention to disinfection of follow-up source compartments.

3) Thirty min after treatment ends, the bioaerosol concentration of the working area in each compartment was reduced to 0.07% of that during treatment, and the infection probability was <0.05%, which provides a scientific basis for a safe time interval between patients’ treatments.

4) Airflow distribution is the key factor affecting the transmission of bioaerosols in the multi-compartment dental clinic. Bioaerosols mainly diffuse with the airflow direction, which results in a high infection probability in the corridor below the outlet. Therefore, personnel should reduce the time they stay near the air outlet. The higher the air freshness, the lower the concentration of suspended bioaerosols. Therefore, it is necessary to increase the ventilation of dental clinics. In addition, partitioning plays a positive role in reducing bioaerosol diffusion to other compartments.

CRediT authorship contribution statement

Zhijian Liu: Writing – review & editing, Validation, Supervision, Resources, Project administration, Investigation, Funding acquisition, Formal analysis, Conceptualization. Guangpeng Yao: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation. Yabin Li: Resources, Project administration, Funding acquisition, Conceptualization. Zhenze Huang: Writing – review & editing, Validation, Methodology, Investigation. Chuan Jiang: Writing – review & editing, Investigation. Junzhou He: Writing – review & editing, Software, Methodology. Minnan Wu: Writing – review & editing, Software. Jia Liu: Investigation. Haiyang Liu: Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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