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Numerical investigation of the impacts of environmental conditions and breathing rate on droplet transmission during dental service

Special Collection: Flow and the Virus

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ABSTRACT

Dental services are yet to return to a semblance of normality owing to the fear and uncertainty associated with the possible airborne transmission of diseases. The present study aims to investigate the impacts of environmental conditions [changes in ventilation location, ventilation rate, and relative humidity (RH)] and variations in dental patient's breathing rate on droplet transmission during dental service. Computational fluid dynamics simulation was performed based on our previous experimental study during ultrasonic scaling. The impacts of different factors were numerically analyzed by the final fate and proportion of emitted droplets in the dental surgery environment. The results revealed that about 85% of droplets deposited near the dental treatment region, where the patient's torso, face, and floor (dental chair) accounted for around 63%, 11%, and 8.5%, respectively. The change in the ventilation location had a small impact on the deposition of larger droplets ($> 60\,\mu$m), and a spatial region with high droplet mass concentration would be presented near the dental professional. The change in the ventilation rate from 5 to 8 ACH led to a 1.5% increment in the fraction of escaped droplets. 50% RH in dental environments was recommended to prevent droplets' fast evaporation and potential mold. Variations in the patient's breathing rate had little effect on the final fate and proportion of emitted droplets. Overall, environmental factors are suggested to maintain 50% RH and larger ACH in dental surgery environments. The findings can give policymakers insights into the role of environmental factors on infection control.

I. INTRODUCTION

Even though the considerable progress in vaccination has dramatically reduced the mortality rates and infection numbers, the emergence of new variants still promotes the recurrence of pandemics in various countries.[1] Unfortunately, in November 2022, the COVID-19 pandemic claimed more than 6.5×10^6 lives and 624×10^6 people infected worldwide.[2] Dental clinics are regarded as one of the most vulnerable institutions for medical services, with special characteristics that render them susceptible to virus transmission.[3] Dental agencies have implemented plenty of precautionary measures, including Rapid Antigen Tests (RATs) before the treatment, pre-examination, triage, and dental mouthwashes.[4–6] Owing to the limited performance of RATs in the early stages of the infection,[7] further reducing the fear and uncertainty associated with the possible airborne transmission of diseases would help the restoration of global dental services.

The virus can be transmitted by direct contact on the contaminated surface and by the airborne transmission route.[8,9] The oral mucosa and saliva are the most common receptors for SARS-CoV-2, and the viral copies/ml of the infected and asymptomatic individual can even reach 1.2×10^8.[10] The high-velocity coolant water stream is quite necessary for dental atomization procedures, such as vibrated ultrasonic scaling, high-speed drilling, and 3-in-1 spraying.[11] The dental procedures could aerosolize the combination of saliva, blood, and coolant water. Although the muco-salivary could be diluted by the coolant water reducing the viral load, prolonged dental procedures can still lead to high cross-infection risks between dental professionals and patients. Based on the case report forms and epidemiological investigations in Israel,[12] the cumulative infection rate between dental professionals and patients was about 0.7%. Although the infection rate in dental clinics is much lower than that in the crowded, targeted mitigation measures should be developed based on the transmission pattern of emitted droplets.

Experimental and numerical approaches have been employed to investigate the transmission of emitted droplets during dental atomization procedures. For instance, Li *et al.*[13,14] employed the laser light scattering method to investigate the airborne lifetime and spatial–temporal distribution of the emitted droplets during ultrasonic scaling. The luminescent tracer and experimental microbiological methods were also employed to investigate the high-contaminated regions in the dental surgery environment.[15,16] However, the dental procedures were conducted to forgo some of the geometric fidelity of the patients by replacing the patients with only the dental phantom head. As well, Komperda *et al.*[17] numerically investigated trajectories of virus-laden droplets in a dental center, but they mainly focused on the effect of main ventilation without considering the human micro-environment. However, ambient ventilation flow and the human micro-environment can influence the spatial–temporal distribution of emitted droplets. The human's thermal plume can help prevent droplets' penetration.[18,19] The respiratory pattern, rate, and tidal volume are the critical influencing factors for the direction and momentum of the breathing flow.[20] Generally, the aforementioned three breathing characteristics are determined by activity level and mood.[21] A positive correlation between breathing rate and dental anxiety has been found in dental surgery environments.[22–25] The interplay among the ambient ventilation flow, respiratory flow, and thermal plume would directly impact the flow field and droplet transmission. As far as we know, no study has been conducted with a specific focus on the impact of the breathing rate on droplet transmission during dental services. It is of critical importance to cover the gap in flow interaction on droplets in dental surgery environments. Therefore, the human thermal plume and ambient ventilation in the dental surgery environment are maintained in the numerical simulation, along with investigating the impact of the variations in the patient's breathing rate on the final fate and proportion of emitted droplets.

Droplets emitted during dental atomization procedures are composed of water and some nonvolatile materials such as protein and phosphate.[26] After leaving the dental treatment region, the droplets gradually dehydrate, generating the droplet nuclei. Therefore, some larger droplets would become suspended in the dental surgery environment,[27] increasing the mass percent of inhalable particles and the probability of infection.[28] In addition, the droplet diameter and environmental conditions, such as relative humidity (RH), ventilation rate, turbulence, and temperature, could also significantly affect the aforementioned evaporation process. Several recent studies have been performed to investigate the transmission of virus-laden droplets in different scenarios. Lieber *et al.*[29] coupled the experimental and numerical methods to investigate the evaporation characteristics of saliva droplets. They found that the evaporated droplet size correlated well with about 20% of the initial diameter. Biswas *et al.*[30] simulated the transmission of human respiratory droplets in the elevator with varying humidity levels. Fan *et al.*[31] conducted a similar study in an outdoor environment with different ambient wind speeds. They concluded that the social distance of two meters might not be sufficient for specific circumstances. Another study focused on the impacts of cough velocity profiles on the dispersion of cough droplets, and they found that the variable mouth opening could provide accurate droplet distribution and flow field.[32] Liu *et al.*[33] experimentally and numerically investigated the spatial distribution of bioaerosols during oral cleaning without considering evaporation. Since plenty of droplets would be emitted during atomization procedures, limited studies have been conducted to investigate the environmental conditions on droplet evaporation and transmission in dental surgery environments. That might impact the development of targeted mitigation measures. In addition, the moisture content and temperature of the droplets could significantly affect the viability of viruses within them,[34] the modeling of the dental-related droplets is quite critical to assess the infection probability of dental professionals and patients.

The study aims to explore the impacts of environmental conditions (changes in ventilation location, ventilation rate, and RH) and variations in patient's breathing rates on droplet transmission during dental service. Based on the measured diameter distribution (5–250 μm) and velocity of emitted droplets during ultrasonic scaling, computational fluid dynamics (CFD) simulations were conducted to evaluate the final fate and proportion of emitted droplets. The findings of the present study are valuable for policymakers to understand the role of environmental factors in reducing cross-infection risk in dental environments. The present paper is structured into six sections. Section II presents the settings of numerical modeling. Then, Sec. III illustrates boundary conditions and model validation, and Sec. IV presents the flow field characteristics and the impacts of various influencing factors. Finally, Sec. V presents the discussion with the findings summarized in Sec. VI.

II. METHOD

A. Computational domain

A dental surgery environment is generated with dimensions of $3.6 \times 2.7 \times 2.3\,\mathrm{m}^3$, which is the same as the room size of our prior experimental study.[13] As shown in Fig. 1, the dental patient (shown in red) is placed in the middle of the room, lying on the dental chair. A dental professional (in blue) sits near the patient's head. The manikin models are obtained from the virtual manikin library.[35] The dental professional's mouth and the dental treatment region are on the same plane ($y = 2.035\,\mathrm{m}$). During ultrasonic scaling, the oral cavity of the dental patient is the treatment region, which is employed as the sole source of droplet injection, with an area of $8\,\mathrm{cm}^2$. The dental patient maintains the nose inhalation/exhalation during dental service. The dental professional is in mouth inhalation/exhalation, indicating the most dangerous scenario. The physiological response to dental anxiety determines the breathing rate of the dental patient. The air supply and outlet are located on the ceiling, with the recommended ventilation rate.

B. Grid independence test

In the present study, the unstructured mesh with tetrahedral elements is generated by the ICEM. The finest cell is located near the manikin's breathing zone, with a size of 0.0008 m (shown in Fig. 2). The cell size of the manikin body is kept within ten times that near the breathing zone. Detailed mesh information could be found in our previous study.[36] The prismatic cells are generated with five layers, keeping $y+ < 5$. The general requirement of enhanced wall treatment is to keep $y+$ less than 1.0.[37] However, several numerical studies[38–40] using

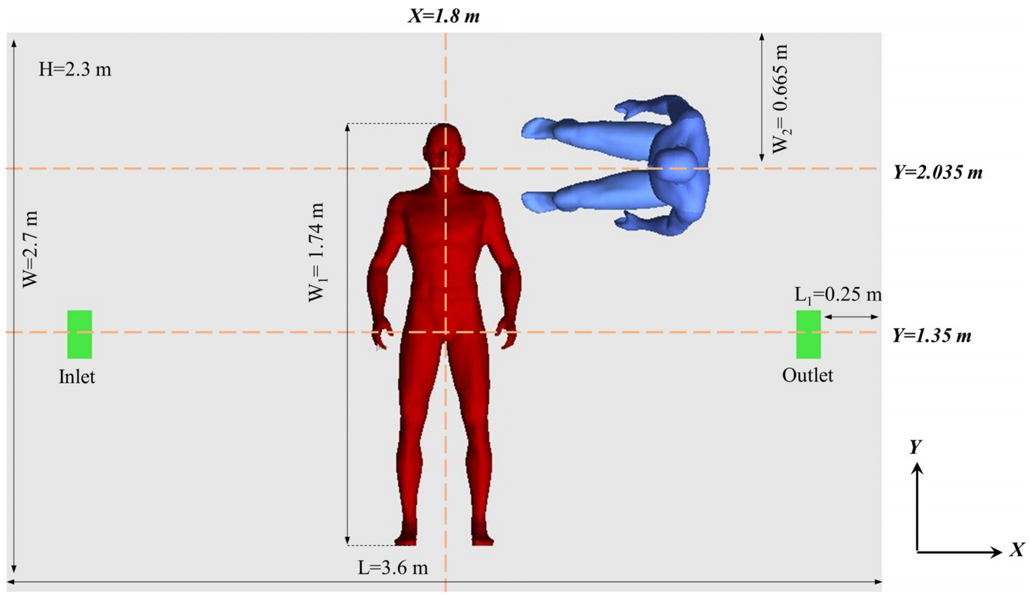

FIG. 1. Computational domain representing the dental surgery environment: the manikin in red is the dental patient, and the manikin in blue is the dental professional.

the enhanced wall treatment kept the y+ less than 5, presenting good performance and saving computation time. Grid independence study is performed without droplet motion. Three different grid sets with fine, medium, and coarse are generated with 14.2×10^6, 8.8×10^6, and 4.6×10^6, respectively. Grid independence test is assessed by comparing the velocity magnitude above the head of a seated dental professional (data line M-N as shown in Fig. 3). The similar variation is noticed in the results. Since the difference between the fine and medium grids is tiny, the medium grid of 8.8×10^6 is employed in the study to balance the computational cost and accuracy of the results.

C. Numerical modeling continuous phase

The Euler–Lagrangian method has been employed in the present study. The flow field in the dental surgery environment is solved by the incompressible Navier–Stokes equation. Figure 4 presents the flow chart for each step of the methodology. After resolving the steady flow field in the dental clinic, the model would then switch to the transient simulation. The validated droplet evaporation model can be employed to investigate the spatial–temporal distribution of emitted droplets. The impacts of investigated factors (ventilation location, ventilation

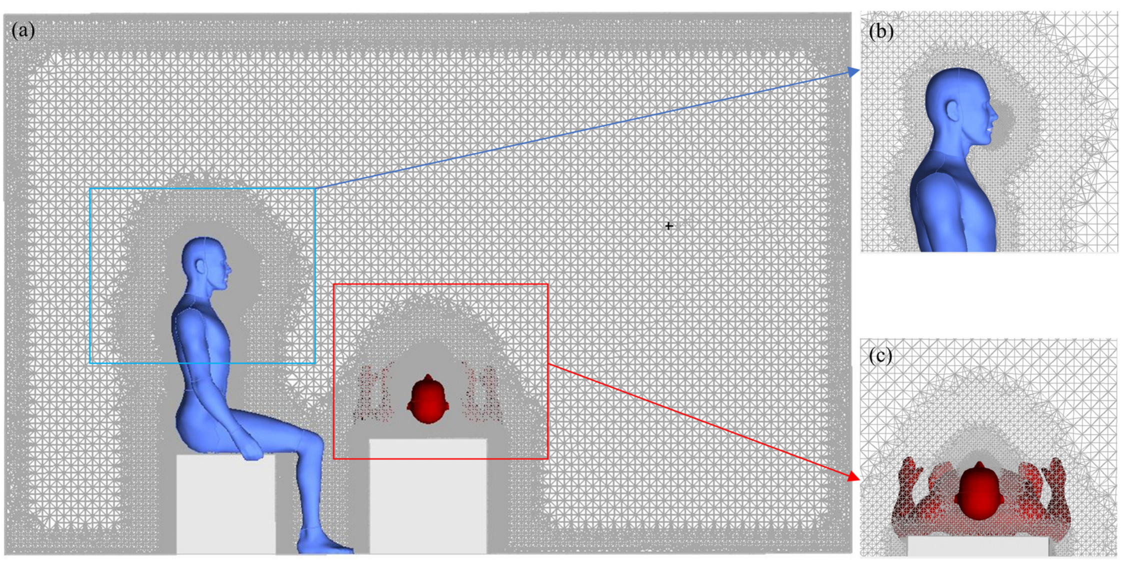

FIG. 2. Mesh domain of dental clinic: (a) in the plane y = 2.035 m, and zoomed view near the face of dental professional (b) and patient (c).

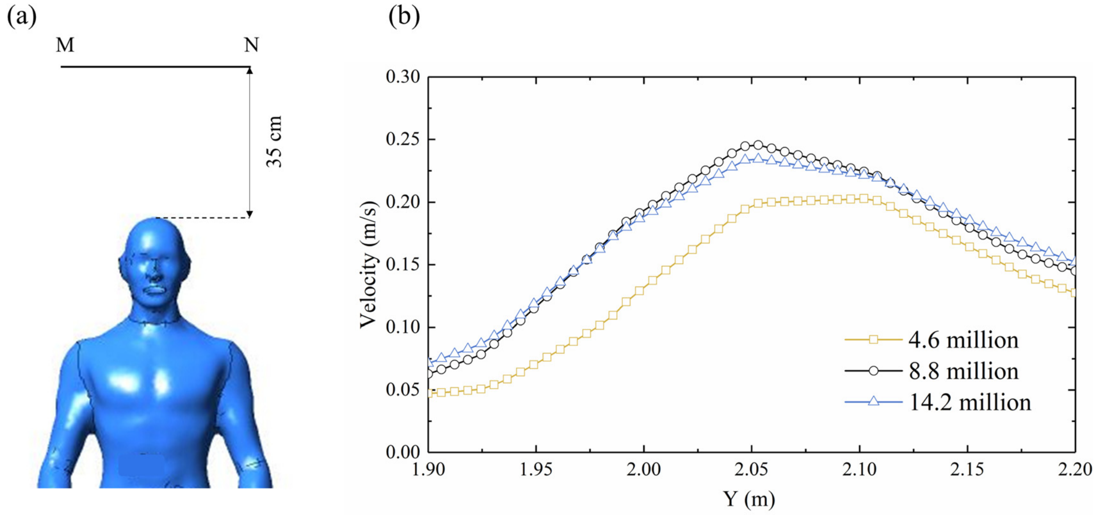

FIG. 3. Grid independence test: (a) data line M-N and (b) difference in the velocity magnitude.

rate, RH, and patient's breathing rate) are evaluated from the final fate and proportion of the emitted droplets.

The ideal-gas mixture of air and water vapor is employed to reproduce the RH in the dental surgery environment. The impact of RH on the dehydration of respiratory droplets and the viability of the virus in droplets has already been demonstrated.[41] The droplets generated during ultrasonic scaling are treated as the discrete phase. The Realizable $k-\varepsilon$ turbulence model is used along with the enhanced wall treatment. The SIMPLEC algorithm is used to solve the pressure-velocity coupling. The pressure equation is discretized by the pressure staggering option (PRESTO) scheme. Other equations are discretized by the second-order upwind method. Hybrid initialization is utilized in the present study. It can solve Laplace's equation to obtain the initial fields. Since the equations have been well-documented, detailed information can be found in the Fluent theory guide.[42] The convergence can be treated to be achieved when all residuals are lower than 10^{-6}.

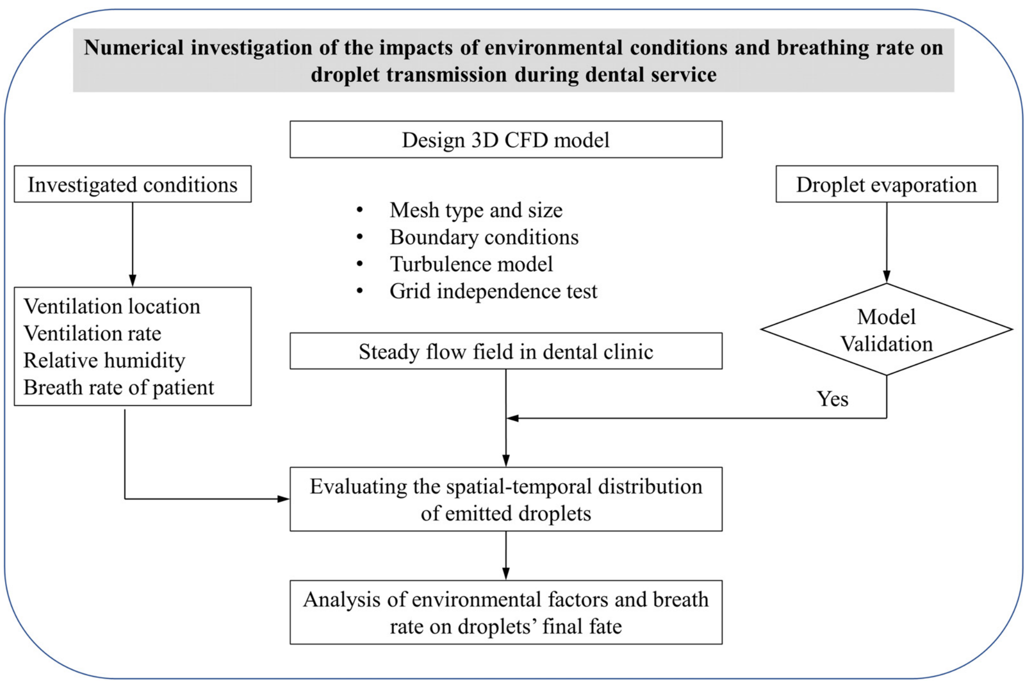

FIG. 4. Flowchart for each step of the methodology.

The present study aims to investigate the impacts of environmental conditions (changes in ventilation location, ventilation rate, and RH) and variations in patient's breathing rate on droplet transmission during ultrasonic scaling. The humidity range from 50% to 75% recorded in Hong Kong indoor environment is considered in the present study.[43] Figure S1 presents the breathing settings of the dental professional and patient, which can be determined by the user-defined function. A breathing cycle including inhalation (2.5 s), exhalation (2.5 s), and break (1.0 s) represents the human resting state. The detailed breathing settings can be found in our previous numerical studies.[9,36] Owing to the positive correlation between breathing rate and dental anxiety,[22] the nasal breathing rate of the dental patient is in variation. The detailed simulated scenarios and conditions are presented in Table I. Cases 2–4 are designed to examine the impact of variations in the patient's breathing rate. The remaining cases are employed to test the effects of environmental factors, like the changes in ventilation location, ventilation rate, and RH.

D. Droplet transmission

The discrete phase model (DPM) is used to track the dispersion of emitted droplets during ultrasonic scaling, one type of dental atomization procedure. After resolving the flow field, the emitted droplets would be tracked by the Lagrangian method. The one-way coupling method is employed to simulate droplet transmission in the air, with the negligible effect of droplets on the flow. Many studies focusing on the transmission of human respiratory droplets would adopt the DPM model.[17,30–32] The external forces acting on droplets should be equated with the inertia force (Newton's second law) to accurately predict the trajectories of emitted droplets. Gravitation force, drag force, thermophoretic force, and Saffman's lift force are included in the present study. As for the drag force, it can be obtained from the Morsi and Alexander model.[44] The thermophoretic force should be taken into consideration owing to the diameter distribution of emitted droplets in dental service. Notably, the thermophoretic force can only impact the suspension of aerosol and droplet nuclei after evaporation. The present study also considers Saffman's lift force induced by the shear. Several additional forces are not included in the study, like the Brownian force and Magnus lift force. For example, the Brownian force is mainly intended for particles smaller than 1 μm in laminar simulation. In addition, the droplet–droplet interactions are also neglected in the present study. The discrete random walk model is employed to examine the turbulent transmission of emitted particles, allowing for the instantaneous fluctuating components on the droplet trajectories. This model has been widely employed to track respiratory droplets in coughing and sneezing.[45–47] The equations of the aforementioned model have already been well documented in the Fluent theory guide.[48] Once the mass of escaped droplets from ventilation and evaporated droplets reaches the constant, the DPM solution could be treated as converged.

III. NUMERICAL SIMULATION IN THE DENTAL SURGERY ENVIRONMENT

A. Boundary conditions

The ventilation inlet on the ceiling corner provides fresh air to the dental surgery environment. The velocity, temperature, and RH of the supply air are obtained by our previous experimental study.[13] The turbulence intensity of 5% and the turbulent viscosity ratio of 10% are defined for the supply air inlet. The outlet is set as outflow. The height of a sitting manikin (dental professional) is 1.35 m, with a body surface area of 1.68 m^2. The body surface area of the lying manikin (dental patient) is 1.75 m^2. The convective heat power of manikin is set as 24 W. Even in the same environmental temperature, the surface temperature of different human body segments also presents a difference.[49] Therefore, the manikins are divided into four segments: face, arm, torso, and leg. The detailed manikin settings can be found in our previous numerical studies.[9,36] The surface boundary condition of each manikin is set as non-slip. Droplets would be expelled from the mouth of the dental patient during the ultrasonic scaling. The cone-type injection is maintained at a flow rate of 0.001 kg/s and a 30° cone angle. A fixed mean velocity of 2.6 m/s was also measured during ultrasonic scaling with 60 ml/min water flow.[50] A 30° cone angle could cover most of the emitted droplets[13] [shown in Fig. 5(a)]. The detailed boundary conditions can be found in Table II.

The diameter distribution of emitted droplets during ultrasonic scaling is obtained from the experimental measurement on the central incisor,[13,50] with a standard size distribution ranging from 5 to 250 μm. The Rosin–Rammler distribution used in the DPM model is employed to fit the experimental size distribution of droplets. The fit obey $Y_d = e^{-\left(d/\bar{d}\right)^n}$, where the Y_d refers to the mass percent of droplets of diameter larger than d. The $\bar{d}$ indicates the mean diameter, and n is the spread factor. As for the curve fitting, the DPM particle conditions are presented in Fig. 5(b).

Determining the number of tracked particles is quite necessary to obtain stable results in the Lagrangian simulation. Chen *et al.*[51] investigated particle transmission in dental clinics and found little fluctuation (lower than 0.58%) among the three particle parcel groups (40 000,

TABLE I. A list of simulated scenarios; the three numbers in the parameter "breathing cycle period (s)" correspond to the times for inhalation, exhalation, and pauses.

Cases	Breathing rate-dental patient (l/min)	Breathing cycle period (s)	Air changes per hour (ACH)	Relative humidity (RH) (%)
1	0	0	5 h^{-1} and change in the ventilation location	72
2	0	0	5 h^{-1}	72
3	10	6.0 (2.5-2.5-1.0)	5 h^{-1}	72
4	12.5	4.8 (2.0-2.0-0.8)	5 h^{-1}	72
5	10	6.0 (2.5-2.5-1.0)	8 h^{-1}	72
6	10	6.0 (2.5-2.5-1.0)	5 h^{-1}	50

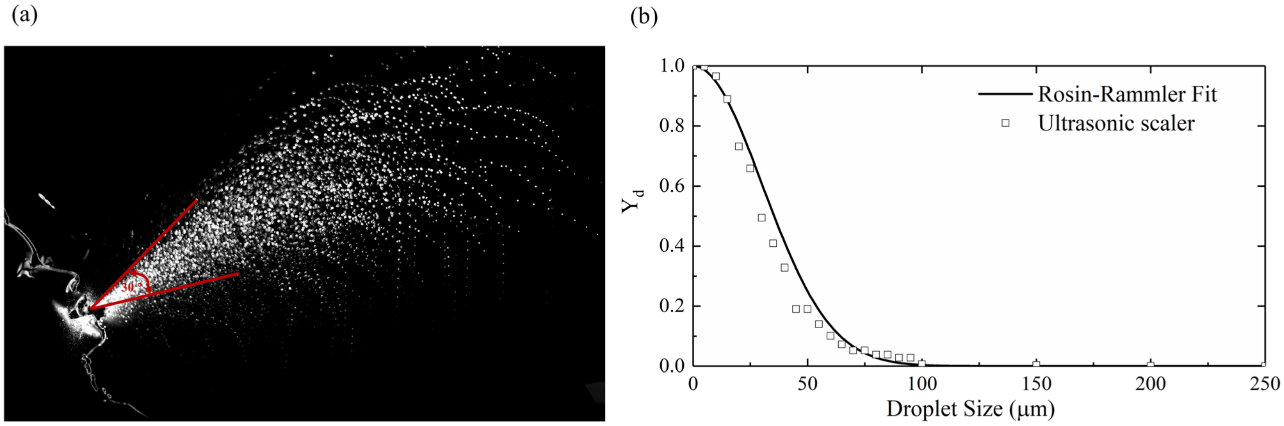

FIG. 5. Settings of the emitted droplets during ultrasonic scaling: (a) 30° cone angle covers most of the emitted droplets[13] and (b) experimental size distribution of droplets during ultrasonic scaling and the fit model.

80 000, and 120 000). As for the present study, the droplets would be emitted from the dental patient's oral cavity with a flow rate of 100 particle parcels per time step (t = 0.1 s). After 2 min dental procedures on the central incisor, a total of 120 000 particle parcels would be generated. In the DPM, each parcel consists of a number of real particles with similar characteristics like diameter, velocity, and so on.[52] Since the diameter distribution of droplet particles follows the Rosin–Rammler characteristics, the total number of emitted droplet particles can be over 2985×10^6 in the present study. Overall, the particle number employed in the present study can be enough to obtain stable results in the Lagrangian simulation.

TABLE II. Summary of boundary conditions.

Eulerian phase	Inlet	Velocity inlet; ACH = 5 h^{-1}, 8 h^{-1}; RH = 50%, 72%; Temperature = 23.5 °C; Turbulence intensity = 5%; Turbulent viscosity ratio = 10%; Escape
	Outlet	Outflow; Escape
	Human body	24W. Trap.
	Room wall	No-slip; Trap.
Lagrangian phase	Expiratory flow	Velocity = 2.63 m/s; Injection type: cone; Injection angle = 30°; mass flow rate = 0.001 kg/s
	Composition	98.2% water+ 1.8% Salt; Density = 1000 kg/m^3
	Droplet size	Minimum = 5 μm; Maximum = 250 μm; Mean = 42.5 μm; Spread parameter = 2.0095
	Temperature	37 °C
	Simulation	$\text{Time step} = \begin{cases} 0.1\,s & 0 \le t < 10\,\text{min} \\ 1\,s & t > 10\,\text{min} \end{cases}$

The emitted droplets during ultrasonic scaling would dehydrate while the droplet temperature is larger than the vaporization one. Since the droplets are composed of volatile and nonvolatile components, the evaporation would be in process until leaving the nonvolatile ones. The evaporation rate is presented in the following:

$$\frac{dm_{dro}}{dt} = A_{dro} k (C_s - C_g), \tag{1}$$

where m_{dro}, A_{dro} refer to the mass and surface area of emitted droplets. k is the mass transfer factor provided by the Sherwood relationship.[53] C_s and C_g represent the vapor concentration at the droplet surface and the bulk gas, respectively. The thermal balance between droplets and air is related to the convective and latent heat transfer,[48] as follows:

$$m_{dro} c_{dro} \frac{dT_{dro}}{dt} = h A_{dro} (T_a - T_{dro}) + L_h \left(\frac{dm_{dro}}{dt} \right), \tag{2}$$

where c_{dro}, T_{dro} refer to the specific heat and temperature of emitted droplets. T_a, L_h represent the ambient temperature and droplet's latent heat. h is the convective heat transfer factor, provided through a modified Nusselt number.[54]

Several experimental studies have been conducted to determine the evaporation rate and the eventual size of droplet nuclei.[29,55–57] The size of the dry nuclei mentioned by Basu *et al.*[55] was around 26% of the initial particle size for the studied RH range. To achieve this, the volatile mass percent should be assigned as 98.2%. Since there is no detailed estimation of dry nuclei diameter during dental procedures, the aforementioned volatile mass percent (1.8% salt) is in line with that during coughing. The density of emitted droplet density is set as 1000 kg/m^3. Considering the droplet size distribution ranges from 5 to 250 μm, the variable time step (from 0.1 to 1 s) is employed to capture the evaporation process accurately.

B. Validation

The evaporation of emitted droplets is simulated by the comparison with Li *et al.*[58] and Redrow *et al.*[59] The aforementioned

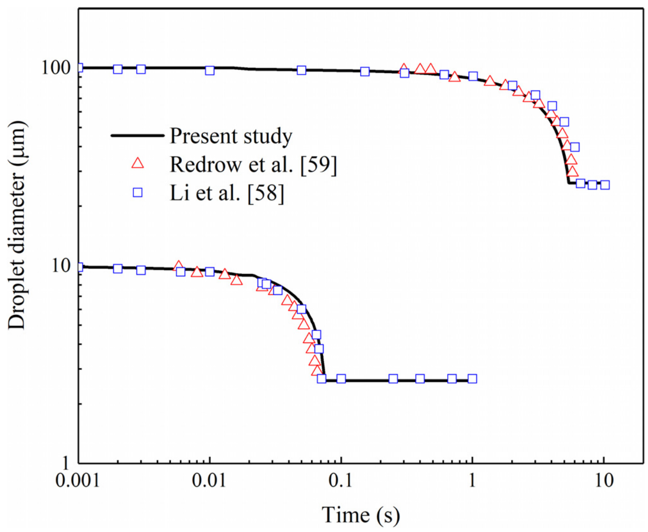

FIG. 6. Model validation of the droplet evaporation compared with data from Refs. 58 and 59.

evaporation results have been checked by several studies[60,61] with good acknowledgment and agreement. The predicted time-dependent droplet diameter (solid line) is employed to compare the verification results (blue squares) by Li *et al.*[58] and (red triangles) by Redrow *et al.*[59] Droplets with initial diameters of 10 and 100 μm fall freely in quiescent air and dry condition. The enclosed chamber maintains a constant temperature of 298.15 K. Single droplets are discharged one after the other with a temporal frequency of 0.01 s at 310.15 K. Droplet with a density of 1000 kg/m^3 is made up of 98.2% water and 1.8% nonvolatile materials. As presented in Fig. 6, a reasonable match between the numerical simulation and the date reported in the literature can be obtained. The little discrepancies might be accounted for by the difference in droplet composition materials.

IV. RESULTS

The flow field characteristics and transmission of the emitted droplets in the dental surgery environment are presented in Secs. IV A and IV B, respectively. The analysis of the flow field is first presented as the droplet dispersion is particularly concerned with the flow field characteristics.

A. Flow field in the dental surgery environment

Flow field characteristics in the dental surgery environment are first analyzed. Figure 7(a) refers to the temperature contour and velocity streamline map on the $x - z$ plane at $y = 2.035$ m. Here is the vertical section of the dental treatment region and dental professional's mouth. Figure 7(b) shows the velocity vector and streamline map on the $y - z$ plane at $x = 1.8$ m. The plane represents the room's central surface as well as a vertical section of the dental patient's mouth. The analysis of the flow field serves as the foundation for the subsequent research on the transmission of emitted droplets. The fresh air enters the dental environment through the ceiling inlet, then interacts with the human microenvironment and moves to the next side. Finally, the mixed air is expelled through the ceiling outlet. The large vortexes near the dental chair and dental professional are noticed, interacting with the upward thermal plume. Because the human body temperature is higher than the ambient environment, appreciable velocity and temperature fluctuations are presented in these regions. The human thermal plume should not be neglected for indoor environment analysis. The velocity in the plane ($x = 1.8$ m) is relatively small (less than 0.3 m/s). The interaction between the thermal plume and ventilation flow would significantly impact the transmission pattern of the emitted droplets.

B. Impacts of environmental conditions on droplet transmission

1. Change in ventilation location

Figure 8 indicts the spatial–temporal distribution of emitted droplets overtime under the change in ventilation location (case 1 and

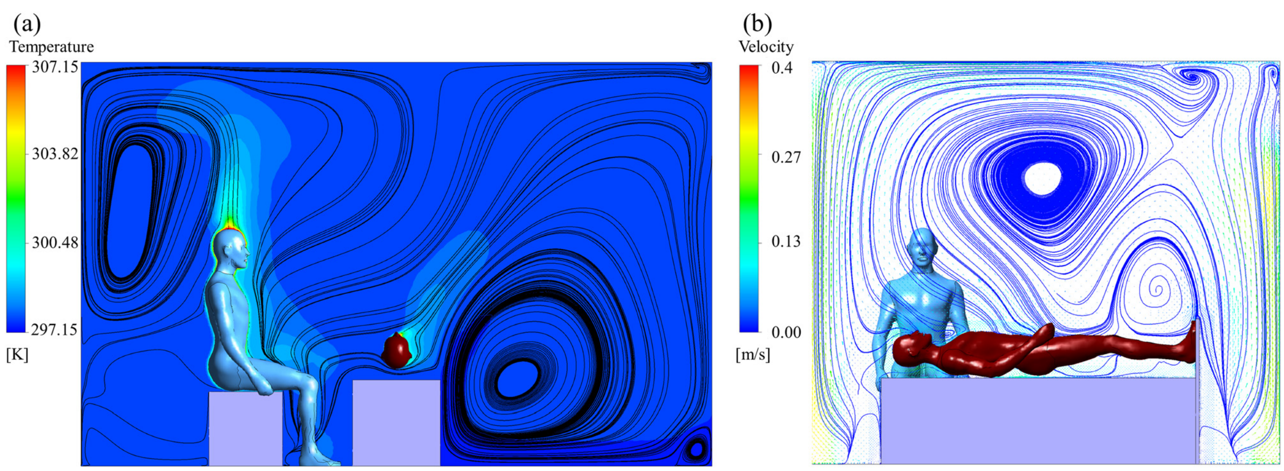

FIG. 7. Flow field characteristics in the dental surgery environment: (a) Body thermal plume in the plane $y = 2.035$ m and (b) velocity vector and velocity streamlines map on the mouth plane of dental patient $x = 1.8$ m.

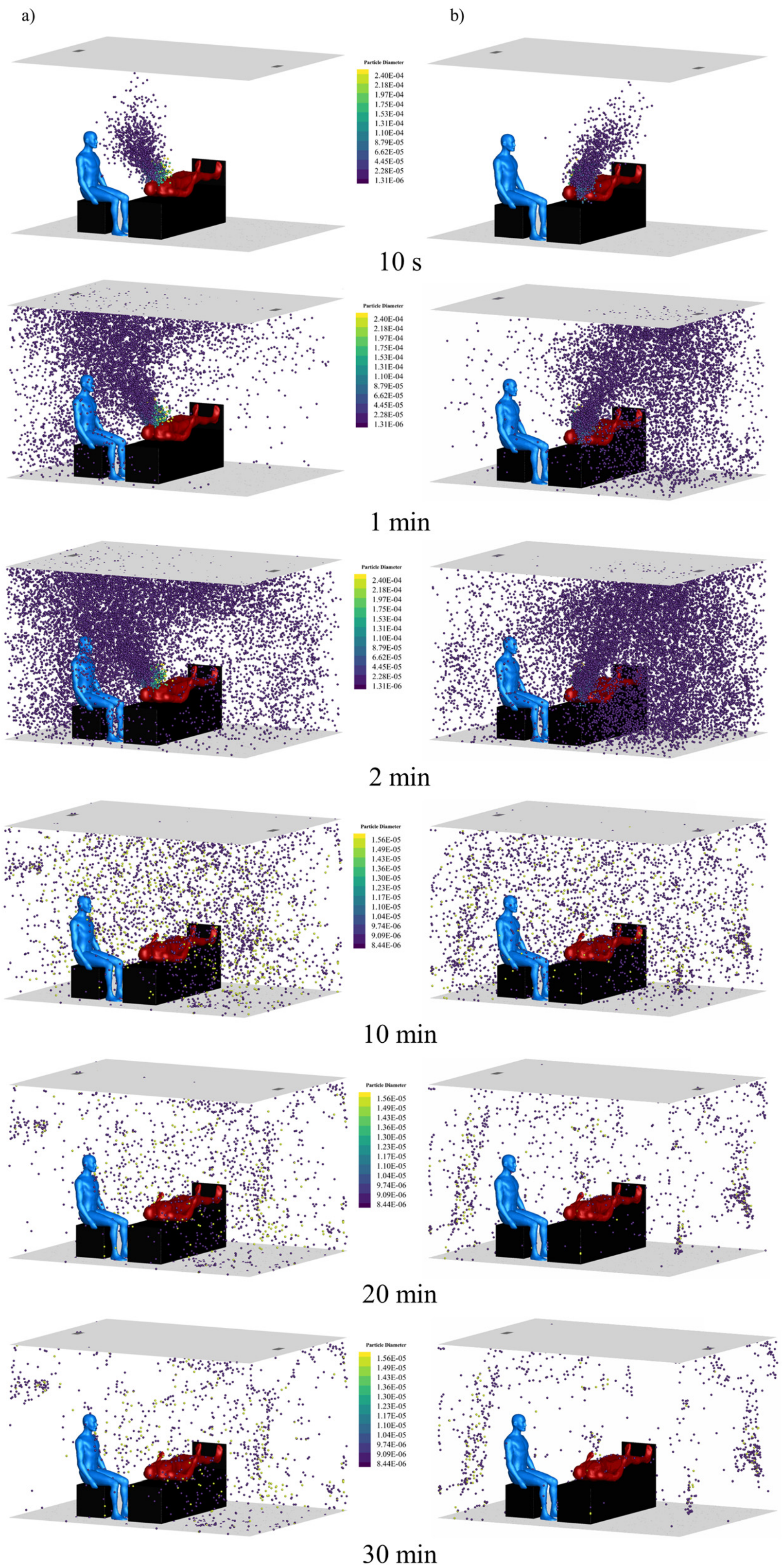

FIG. 8. Spatial–temporal distribution of emitted droplets under the change in ventilation location: (a) case 1 and (b) case 2.

case 2 in Table I). The substantially different behaviors are presented for the droplets larger and smaller than around the 60 μm thresholds, which is calculated based on the maximum diameter of suspended particles after 10 min (15.6 μm) and the volatile mass percent. Under the effect of gravity, larger droplets remain airborne for short periods. A majority of larger droplets over 60 μm would be deposited on the patient's torso, head, floor, and dental chair, contaminating surfaces in the dental surgery environment. The results highlight the significance of disinfecting surfaces around dental patients to avoid potential disease transmission. In addition, the widespread distribution of smaller droplets and aerosols in the dental environment should also be noted. The smaller droplets move with the flow, and the entire dental environment is almost brimming with small droplets after 2 min. Although the injected droplet size distribution is located in the scope of 5–250 μm, the droplet dehydration would decrease the diameter to 1.31 μm. After 30 min, the mass of evaporated and escaped droplets maintains nearly constant with the converged DPM solution. Figure S2 presents the non-uniform distribution of turbulent kinetic energy (TKE) in the dental surgery environment (case 1). Generally, a high TKE region near the dental professional (on the east side of the dental environment) indicates the presence of significant root mean square velocity fluctuation. The emitted droplets are of particular concern with the flow field characteristics. After emitting from the patient's oral cavity, some small droplets would concentrate in the aforementioned high-strain region,[62,63] leading to direct exposure to the dental professional [shown in Fig. 8(a)]. The spatial region has also been observed in our previous experimental study.[13] Different ventilation locations in case 2 [Fig. 8(b)] can avoid direct exposure to the dental professional. It has been found that the cooperation of high-volume evacuation can help eliminate the high-mass concentration region,[64] further reducing the contaminated regions and airborne lifetime of emitted droplets in the dental surgery environment.

The impact of the change in ventilation location on the fraction of escaped and deposited droplets is presented in Figs. 9(a) and 9(b). As illustrated, changing the ventilation location can slightly modify the final fate and proportion of emitted droplets. Case 1, with a higher fraction of escaped droplets, indicates fewer droplets left inside the dental surgery environment. After 20 min, the escaped rates among the two cases are almost constant, in the range of 3.5%–4.4%. The results are in line with a prior simulation study in a large dental center, with an escaped rate of 3.953%.[17] The virus-laden droplets entering the air conditioning system may lead to the possible transmission route in dental clinics. The cleaning or disinfection of the air conditioning system should be noticed. In Fig. 9(b), the fraction of deposited droplets in case 2 is quite similar to that in case 1. After the cessation of ultrasonic scaling (2 min), the fraction of deposited droplets can reach about 75%. Over time, the final deposited rate would plateau at around 85%. Overall, the change in ventilation location has a small impact on the deposition of emitted larger droplets (>60 μm), but the spatial region with high droplet mass concentration would not be presented near the dental professional in case 2.

2. *Change in ventilation rate*

The impact of ventilation rate on the droplets' final fate and proportion during ultrasonic scaling is investigated. Based on the thermal comfort requirement, only the ventilation rate has been changed (case 3 and case 5 in Table I), maintaining the RH = 72% and temperature = 300.15 K of the air conditioning system.

The impact of ventilation rate on the fraction of escaped and suspended droplets is presented in Figs. 10(a) and 10(b), respectively. Due to the change in ventilation rate, the spatial and temporal distribution of emitted droplets presents a significant difference. Increasing the ventilation rate to 8 ACH can help to increase the fraction of escaped droplets from 3.5% to 5.0%, leaving relatively fewer droplets in the dental environment. Since the increase in ventilation rate would raise the flow momentum, the imbalance in the physical forces acting on droplets would force the droplets toward the ventilation exhaust. In Fig. 10(b), at the cessation of ultrasonic scaling (2 min), the fraction of suspended droplets is quite similar in different ventilation rates. That might be accounted for by the less effect of increased flow momentum on the deposition of larger droplets (over 60 μm). However, the fraction of suspended droplets in case 5 drops more quickly than in case 3, remaining at around 10% after 20 min. Further droplets and aerosol removal in the dental environment necessitate the cooperation of air purifiers. Overall, the ventilation rate of 5 ACH is less effective in removing the emitted droplets in comparison with the rate of 8 ACH. Increasing the ventilation rate is of benefit to the smaller droplet dilution and excretion, significantly reducing the corresponding airborne

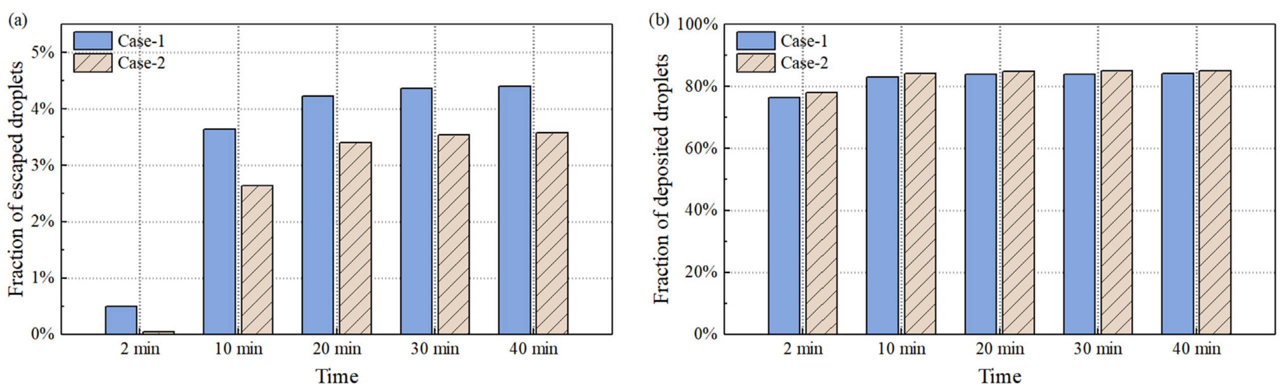

FIG. 9. Analyze the impact of the change in ventilation location on the fraction of (a) escaped and (b) deposited droplets. Notes: case 1 refers to the condition of ACH-5 RH-72% and the change in ventilation location; case 2 refers to the condition of ACH-5 RH-72%.

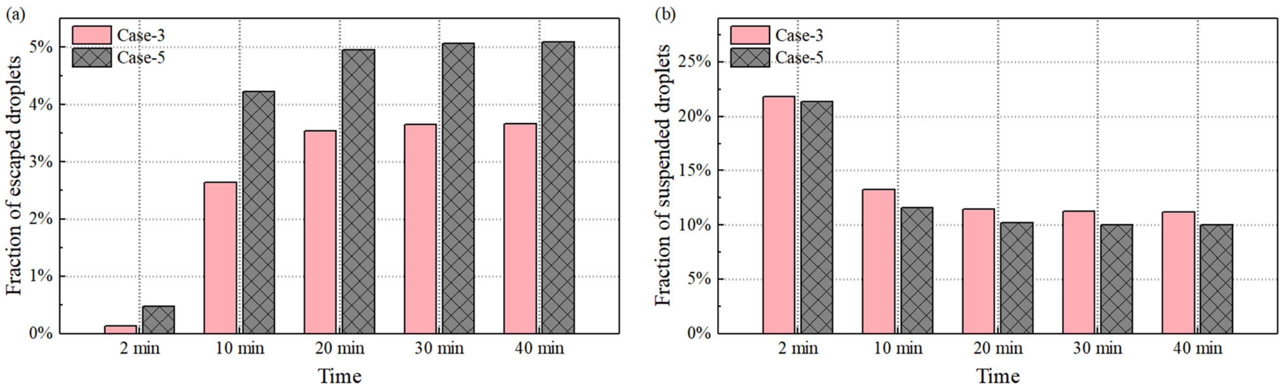

FIG. 10. Impact of ventilation rate on the fraction of (a) escaped and (b) suspended droplets. Notes: case 3 refers to the condition of ACH-5 RH-72%; case 5 refers to the condition of ACH-8 RH-72%.

lifetime. In the dental environment, the "fallow time (FT)" is defined as the time taken for the number of suspended droplets to drop to a defined safe level after dental atomization procedures for dental patients have been completed.[14] Increasing the ventilation rate is effective in reducing the required FT.

3. Change in relative humidity (RH)

Figure 11 presents the impact of RH on the fraction of escaped and suspended droplets, respectively. The supply air temperature and ventilation rate are maintained at 300.15 K and 5 ACH, respectively. The dental patient is in normal nasal breathing during ultrasonic scaling. Based on the previous experimental measurement in the Hong Kong dental surgery environment, the RH varies between 72% and 50% (case 3 and case 5 in Table I). In Fig. 11(a), the fraction of escaped droplets (4.2%) in case 6 with 50% RH is quite similar to that in case 3 with 72% RH (3.7%). Although decreasing the RH of the supply air could slightly accelerate the escape process of droplets from the dental environment, the change in RH is far less efficient than the change in the ventilation rate. In Fig. 11(b), change in RH leads to the difference among cases at the cessation of ultrasonic scaling (2 min), emphasizing that RH significantly impacts the fraction of suspended droplets. About 21% of dental emitted droplets in RH-72% (case 3) would be suspended in the dental surgery environment as soon as the atomization procedure is ceased. When decreasing the RH to 50% (case 6), the evaporation rate of droplets has also been slightly accelerated, and the fraction of suspended droplets in the dental surgery environment would increase by 1.5% after 2 min. Overall, the RH in the range of 50%–72% significantly affects the evaporation process of emitted droplets during ultrasonic scaling. Given the slight divergence in the fraction of suspended droplets in case 3 and case 5 after 30 min, controlling the RH in the dental surgery environment at 50% is reasonable to prevent droplets' fast evaporation and potential mold. The result is in line with a prior experimental study focusing on droplets in the dental clinic. Adjusting 50% RH can help keep the droplets large in dental environments.[65]

C. Variation in patient's breathing rate

Droplet transmission patterns in the dental surgery environment can be significantly impacted by indoor flow interaction, such as ambient ventilation flow, human thermal plume, and breathing flow. In comparison with ambient ventilation flow, the nasal breathing flow of dental patients can directly interact with droplet ejection. Generally,

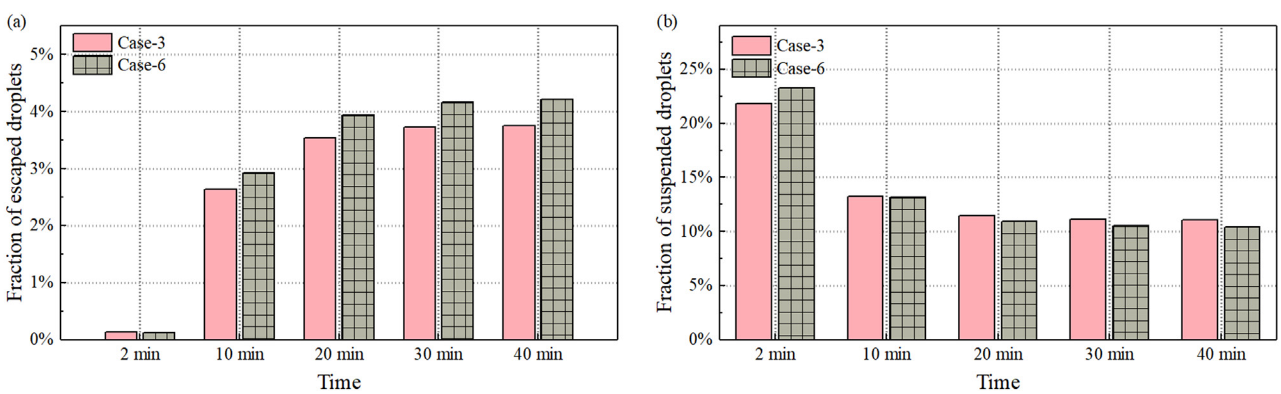

FIG. 11. Analyze the impact of RH on the fraction of (a) escaped and (b) suspended droplets. Note: case 3 refers to the condition of ACH-5 RH-72%; case 6 refers to the condition of ACH-5 RH-50%.

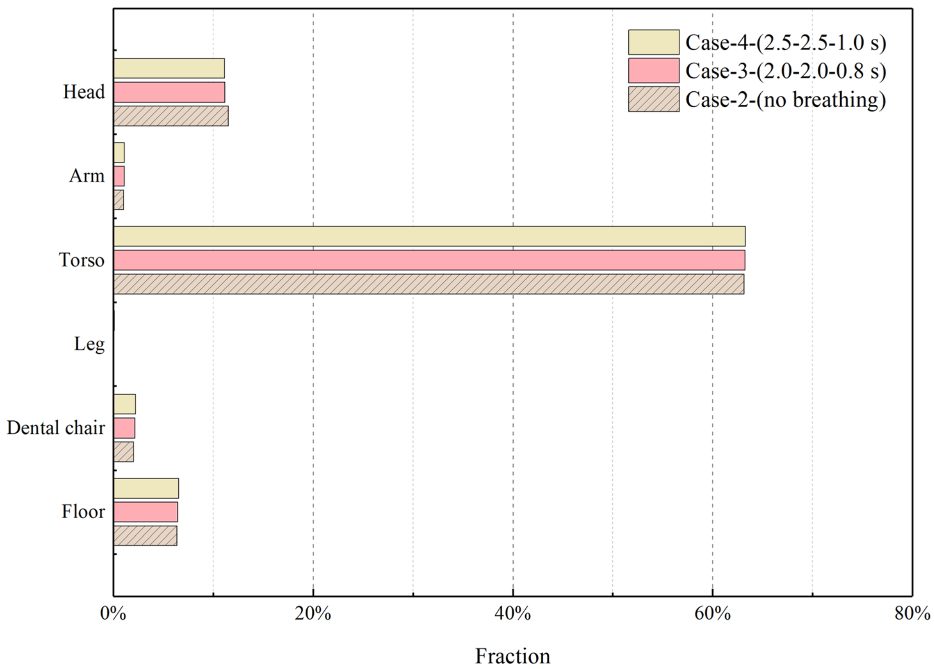

FIG. 12. Analyze the impact of the patient's breathing rate on the fraction of droplets deposited on the parts of the dental patient and surrounding at RH = 72% (The number of emitted droplet parcels is 120 000).

the breathing rate is determined by activity level and mood. A positive correlation between breathing rate and dental anxiety has been found in dental environments.[22] In this section, the supply air temperature (300.15 K), RH (72%), and ventilation rate (5 ACH) are maintained fixed for the air conditioning system. Only the breathing rate of the dental patient is in variation (case 2–4 in Table I). The fraction of droplets deposited on the parts of the dental patient and surroundings are presented in Fig. 12, with the region of the dental patient's head, arms, torso, leg, dental chair, and floor. Over 60% of emitted droplets would deposit on the dental patient's torso, then about 11% deposit on the head, 6% on the floor, and 2.5% on the dental chair. The result of the contaminant regions is in line with previous experimental studies using the luminescent tracer and microbiological methods.[15,16] It highlights that the decontamination and disinfection inside the dental surgery environment should consider all equipment surfaces. Variations in the patient's breathing rate have a small impact on the fraction of deposited droplets near the dental treatment region (as shown in case 3 and case 4). The final fate and proportion of emitted droplets are almost independent of the dental patient's nasal breathing flow. It might be accounted for by the low momentum and periodic nasal breathing flow. Future simulations about droplet transmission in dental environments may consider omitting the patient's breathing flow to save computer resources.

V. DISCUSSION

Dental clinics have been widely treated as one of the most vulnerable institutions for medical services during the COVID-19 pandemic. Plenty of droplets would be emitted during the dental atomization procedures. Dental professionals and patients have been significantly affected by the fear and uncertainties associated with the possible airborne transmission of SARs-CoV-2.[66] It is of critical importance to investigate the transmission of emitted droplets under different environmental conditions and flow interactions. The strength of this study lies in the analysis of the changes in ventilation location, ventilation rate, RH, and variations in the patient's breathing rate on the final fate and proportion of emitted droplets during ultrasonic scaling. The ambient ventilation flow in the dental surgery environment is controlled by the air conditioning system,[67] and the influencing factors like RH, ventilation rate, and ventilation locations have been systematically investigated. The change in the ventilation location has a small impact on the deposition of emitted larger droplets (>60 μm). Figure 8(a) presents a spatial region with high magnitude TKE and droplet mass concentration near the dental professional (case 1). The convenient way to avoid dental professionals' direct exposure is to change the ventilation location. As presented in Fig. 8(b), the dental professional's direct exposure to the high-mass concentration region has been avoided after changing the ventilation location. Of course, the best way to eliminate the region is to change the ambient flow field by adding an air cleaner or high-volume evacuation system.[64] The placement location of the equipment should consider the application scenarios.[68] As expected, the increase in the ventilation rate would raise the flow momentum. The imbalance in the physical forces acting on droplets would force the droplets to follow the flow streamlines created toward the ventilation exhaust. When the ventilation rate increases from 5 to 8 ACH, about a 1.5% increment is presented in the fraction of escaped droplets (shown in Fig. 10). The RH in the Hong Kong dental surgery environment was measured to vary between 50% and 75%.[64] RH can significantly affect the evaporation process of emitted droplets during dental service. Two RH levels (72% and 50%) are numerically evaluated in Fig. 11. Although the difference in the fraction of suspended droplets is apparent during the dental service, it becomes smaller after the cessation of procedures. Adjusting 50% RH is enough to keep the droplets large in dental environments. Overall, maintaining 50% RH is suggested in dental clinics to fulfill the infection control and thermal comfort requirement and prevent potential mold. The result aligns with a prior experimental study on droplet transmission in the dental clinic.[65]

In addition to the ambient ventilation flow, human breathing flow and thermal plumes should not be neglected in indoor environments, as they might influence the droplet transmission pattern near the human body. However, the prior study conducted by Komperda *et al.*[17] numerically investigated droplet dispersion in a large dental clinic without considering the human micro-environment. That may introduce an error in the proportion and final fate of emitted droplets. The human breathing characteristics, including the breathing pattern, breathing rate, and tidal volume, can be impacted by human activity levels and mood.[21] Plenty of experimental and numerical studies have been conducted to investigate the effect of human breathing characteristics on the transmission of respiratory diseases.[20,36,69,70] For example, Ai *et al.*[20] experimentally found that the breathing rate would significantly impact the exposure index with a physical distance of less than 1.0 m. When conducting atomization procedures in the dental surgery environment, the distance between the dental treatment region and the dental professional's face is generally less than 0.5 m.[71] In addition, a positive correlation between breathing rate and dental anxiety has been founded in dental environments.[22–25] In the present study, case 2–4 are employed to investigate the impact of physiological response, variations in the patient's breathing rate, on the final fate of emitted droplets. Our study verifies that the variations in the patient's nasal breathing flow have a small impact on the fraction of deposited droplets near the dental treatment region. Since the experimentally measured droplet velocity was about 2.6 m/s and the mean diameter was 42.5 μm, the droplet transmission would be less impacted by the low momentum and periodic nasal breathing flow. The final fate and proportion of emitted droplets are similar for the simulations with or without the presence of the dental patient's nasal breathing flow. Therefore, the omission of the patient's breathing flow is reasonable for future simulation about the droplet transmission in dental environments to save computer resources.

The diameter of emitted droplets during ultrasonic scaling is located mainly in the range of 5–250 μm. T he transmission pattern depends on the acting force, evaporation, and interaction with the surrounding flow field.[72] Therefore, the tracer gas as a surrogate for droplet nuclei is not adopted in the present study.[73] Our study verifies that smaller droplets with an initial diameter of less than 60 μm can follow the flow field and spread through the dental surgery environment. In comparison, the larger droplets with an initial diameter of 60–250 μm would deposit on the dental patient's torso, head, dental chair, and floor. The mixing ventilation pattern makes the virus-laden droplets propagate the entire dental environment, and the fraction of escaped droplets is in the range of 3.5%–5.0%. The results are in line with a prior simulation study in a large dental clinic, with an escaped rate of 3.953%.[17] Although relatively few droplets exit through the ventilation exhaust, the decontamination of the air conditioning system should receive attention. Since a vast majority of droplets become deposited or suspended within the dental environment, decontamination, and disinfection should be extended to cover all possible surfaces. In addition, the cross-infection between the appointed patients in the same dental surgery environment should be highly noticed. It is of critical importance to institute the FT between dental appointments.[74] The FT is defined as the time taken for the number of suspended particles to drop to a defined safe level after dental atomization procedures for dental patients have been completed.[14] Nevertheless, the balance between the exposure risk and the number of daily appointments has never been established. Determining the minimum required FT under different dental atomization procedures and environmental conditions is necessary.

The present study mainly focuses on the impacts of environmental conditions and patient's breathing rates on the final fate and proportion of emitted droplets in dental service. As for the large droplets ($>$60 μm), they can travel a long distance owing to their large initial momentum, even when subjected to the drag force induced by the air. After losing their initial momentum, gravity acting as the dominant force on droplets would lead to deposition near the dental treatment region. Among the investigated environmental conditions, the RH can significantly impact the transmission pattern of large droplets. When decreasing the RH to 50% (case 6), the fraction of suspended droplets in the dental surgery environment would increase by 1.5%. By contrast, different transmission behavior is noted for the small droplets. They first move along the ejection path, then rise following the thermal plume near the dental patient, and spread with the ambient ventilation flow. Some small droplets would concentrate in the high-strain region in the dental clinic, leading to the high-mass concentration region. Except for the changes in ventilation rate, the alteration of other conditions has little impact on the final fate of small droplets. Since the increase in ventilation rate would raise the flow momentum, the imbalance in the physical forces acting on small droplets would force the droplets toward the ventilation exhaust.

Several limitations of the present study should be acknowledged. Different dental atomization procedures, including ultrasonic scaling, high-speed drilling, 3-in-1 spraying, etc., can generate plenty of droplets in different sizes and velocity distribution.[75] Only the ultrasonic scaling on the central incisor was considered in the present study because our preliminary experimental studies have analyzed the spatial–temporal distribution and transmission of emitted droplets. In the future, more dental atomization procedures and more influencing factors (e.g., use of air purifiers, high-volume evacuation, ambient temperature, a more comprehensive range of RH, etc.). Meanwhile, the changes in the final fates of emitted droplets deserve much more investigation under the combined effect of the flow field and acting forces. The general requirement of enhanced wall treatment is to keep y+ less than 1.0.[37] However, several numerical studies[38–40] using the enhanced wall treatment kept the y+ less than 5, presenting good performance and saving computation time. In addition, the flow field characteristics and the final fate of emitted droplets in the present study are generally in line with the previous experimental study.[13] Since the viral load in the emitted droplets during dental atomization procedures is unknown,[17] the cross-infection risk was not analyzed between dental patients and professionals in this study. Calling for viral load measurement in dental procedures will promote the future quantitative evaluation of dental professionals' exposure. Overall, reducing the number of suspended droplets by modifying environmental conditions is beneficial to reduce infection risks. Additionally, owing to the fear and uncertainty associated with the possible airborne transmission of diseases in dental environments, dental patients have postponed their treatment schedule, significantly influencing human health and well-being. Therefore, it is worth further investigating the droplet transmission pattern using recommended mitigation measures in dental environments.

VI. CONCLUSION

The present study investigates the impacts of environmental conditions (changes in ventilation location, ventilation rate, and RH) and variations in patient's breathing rates on droplet transmission during ultrasonic scaling. The findings can give policymakers insights into the role of environmental factors in infection control.

Some meaningful conclusions can be stated as follows:

(1) The fraction of deposited droplets increased progressively with time and remained essentially constant at about 85% for around 20 min, where the patient's torso, face, and floor (dental chair) accounted for around 63%, 11%, and 8.5%, respectively. Decontamination and disinfection inside dental environments should be extended to cover all possible surfaces.
(2) During ultrasonic scaling, the change in the ventilation location had a small impact on the deposition of larger droplets ($> 60\,\mu$m). A spatial region with high droplet mass concentration would be presented near the dental professional.
(3) When the ventilation rate increased from 5 to 8 ACH, about a 1.5% increment was presented in the fraction of escaped droplets. 50% RH in dental environments was recommended to prevent droplets' fast evaporation and potential mold. Overall, environmental factors are suggested to maintain 50% RH and larger ACH in dental surgery environments.
(4) Physiological response representing the variations in the patient's breathing rate had a small impact on the deposition and final fate of emitted droplets.

SUPPLEMENTARY MATERIAL

See the supplementary material for the graphical abstract, highlights, schematic figure about the breathing pattern (Fig. S1), and distribution of turbulent kinetic energy (Fig. S2).

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AUTHOR DECLARATIONS

Conflict of Interest

The authors have no conflicts to disclose.

Author Contributions

Xiujie Li: Conceptualization (equal); Formal analysis (equal); Investigation (equal); Methodology (equal); Writing – original draft (equal); Writing – review & editing (equal). **Cheuk Ming Mak:** Conceptualization (equal); Methodology (equal); Project administration (equal); Resources (equal); Supervision (equal); Writing – review & editing (equal). **Zhengtao Ai:** Methodology (equal); Resources (equal); Writing – review & editing (equal). **Kuen Wai Ma:** Methodology (equal); Resources (equal); Writing – review & editing (equal). **Hai Ming Wong:** Methodology (equal); Resources (equal); Writing – review & editing (equal).

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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