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Research Article

Strategic Placement of Portable Air Cleaners for Enhanced Aerosol Control in Dental Treatment Rooms: A Computational Fluid Dynamics (CFD) Analysis

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Background. Adequate ventilation is imperative for controlling respiratory transmission, particularly in the context of the COVID-19 pandemic. The commercial portable air cleaners have emerged as practical solutions to reduce contaminated aerosols in dental treatment rooms. This study employs computational fluid dynamics (CFD) to assess their impact on airflow dynamics. *Methods*. Dental treatment room models were constructed using SolidWorks software, encompassing two distinct air conditioner grille orientations (straightening and 45-degree downward directions) and five different positions for the portable air cleaner (two located at the rear left/right of the dental unit and three at the foot end of the dental unit—center, left, and right corners). The study examined alterations in airflow direction and residual aerosol concentrations using ANSYS Fluent software. *Results*. The incorporation of portable air cleaners in dental treatment rooms significantly reduced aerosol levels across all model configurations. Notably, the placement of the portable air cleaner emerged as a critical factor influencing airflow patterns. In models with straightening and 45-degree downward air conditioner grille orientations, optimal positioning was near the operating field and at the foot end of the dental chair, respectively. *Conclusion*. This investigation highlights the pivotal role of strategic portable air cleaner placement in dental treatment rooms for effective aerosol removal. Placing the air cleaner near the operating field or at the foot end of the dental chair not only improved airflow patterns but also enhanced aerosol removal efficiency, ultimately promoting superior air quality within dental treatment environments.

1. Introduction

Dental professionals face a heightened risk of contracting contact-transmitted diseases during dental treatment procedures [1]. Their proximity to patients' oral cavities exposes them to saliva, blood, and other bodily fluids. The use of high-speed dental equipment, such as rotary handpieces and ultrasonic scalers, is a significant source of aerosol generation during dental treatments. The fine mist of water, saliva, and biological fluids generated during these procedures can become aerosolized and disperse throughout the dental workspace. Inhalation of these contaminated aerosols increases the risk of respiratory infections among dental staff, patients, and those in proximity, including the common cold, flu, and COVID-19.

The COVID-19 pandemic has heightened awareness of the potential for disease transmission through aerosolized saliva and aerosol-generating activities, particularly during dental treatments [2]. Studies indicate that dental procedures, especially those involving high-speed rotary handpieces or ultrasonic scalers, can generate aerosols of varying sizes, potentially carrying infectious agents [3–5]. For instance, one study reported the formation of aerosols with diameters ranging from 5 μm to 300 μm during dental scaling, with particles in the 10-50 μm range capable of penetrating the lungs, thereby increasing the risk of respiratory infections [3].

In response to the COVID-19 outbreak, guidelines developed by organizations like the Centers for Disease Control and Prevention (CDC) have become standard worldwide, emphasizing the importance of reducing or eliminating sources of contamination in dental settings [6]. Proper air ventilation in dental clinics has been identified as crucial for maintaining air quality [7, 8]. The recommended air change per hour (ACH) ranges from 12 to 24 ACH for effectively removing contaminated aerosols. Additionally, airflow direction plays a significant role in air quality control within dental clinics, necessitating ventilation systems that channel air from clean to less-clean areas to prevent airborne disease transmission.

In situations where ventilation is inadequate or aerosol-generating sources cannot be reduced, portable air cleaners have been proposed as an effective complementary strategy to improve air quality [9–14]. These devices employ filtration systems, including HEPA filters, activated carbon filters, UV-C germicidal lamps, and other technologies, to remove pollutants and contaminants. The effectiveness of various portable air cleaners varies, with reported removal rates ranging from 12% to 99% [15]. While portable air cleaners have been successful in reducing particulate matter (PM) levels in indoor environments, their application in healthcare facilities has demonstrated significant reductions in aerosol concentrations, benefiting both patients and healthcare workers [16, 17].

Nevertheless, the efficacy of portable air cleaners depends on several factors, including their positioning in relation to furniture and occupants, as well as the direction of air supply and exhaust fans [12, 18]. Recent research has suggested that optimal positioning of portable air cleaners near the patient's head can enhance their effectiveness in controlling droplets and aerosol particles during dental procedures [9]. However, its impact on airflow and air circulation, which significantly affect air quality control efficiency, has been notably absent in previous literature.

According to this reason, the present study utilizes computational fluid dynamics (CFD) simulations to investigate the enhancement of air quality in dental treatment rooms by strategically positioning portable air cleaners. Through a comprehensive examination of airflow patterns and the ideal positioning of these portable air cleaners, we aim to provide a practical solution to enhance ventilation and mitigate the dispersion of aerosol particles in dental treatment settings, thus reducing the risk of aerosol transmission.

2. Material and Methods

2.1. The Physical Model Preparation. The present study determined the details of room dimensions, dental unit size, and ventilation system to model the dental treatment room. The room was set to $3.5 \times 5 \times 3\,\text{m}^3$. The dental unit was located 1.2 m from the wall on the left side of the room. The ventilation system comprised one inlet vent, a wall-type air conditioner on the dental unit's right side, and one outlet vent, an 8-inch wall-type exhaust fan on the dental unit's foot side.

Table 1: Model boundary conditions.

Boundary	Volume flow rate (m^3/s)	Mass flow rate (kg/s)
Inlet air conditioner	0.27377	0.32415
Inlet air cleaner	0.08885	0.10520
Outlet exhaust fan	0.05405	0.06400

The air velocity from the exhaust fan, air conditioner, and air cleaner were measured by an anemometer (Testo 905i, Testo, Germany). The mass flow rate was calculated by multiplying the volume flow rate by the fluid's mass density, and the volume flow rate was determined by multiplying the flow velocity by the cross-sectional area perpendicular to the flow direction, as shown in

$$\dot{\text{m}} = \iint_A \rho v \cdot dA, \tag{1}$$

where ρ represented the mass density of the fluid, v represented the flow velocity of the mass, and A represented the cross-sectional vector area. The mass flow rate and the volume flow rate of the air conditioner, air cleaner, and exhaust fan are shown in Table 1.

2.2. The Numerical Model Preparation. The SolidWorks (version 2022, Massachusetts, United States) utilized the dental treatment room model based on the physical data previously described. ANSYS Fluent Meshing (version 2021 R2, Pennsylvania, United States) was used to generate an unstructured mesh for the computational domain. A grid independence study was conducted to validate the mesh simulation for the accuracy of the simulated model. The number of elements was set at 4×10^6 based on the grid independence evaluation.

The simulation utilized the ANSYS Fluent software to solve the governing equations for fluid flow. The models were determined as the steady state in which all flow conditions and properties of the system were constant. The simulation employed the k-omega models with species transport to simulate the turbulent flow of an incompressible fluid with zero velocity relative to the boundary. The solution was solved by discretizing six partial differential equations and utilizing the second-order upwind method.

The boundary conditions in Table 1 were applied to solve the equations. This investigation classified the air conditioner and the air cleaner as recirculation devices. The boundary conditions of the air conditioner and air cleaner outlets were 0.9 and 0.1, respectively. To maintain the equilibrium of mass conservation in this model, air leakage through the door edges occurred due to the blowing out by the exhaust fan. Therefore, the inlet pressure of the environment served as the limitation for air leakage (zero gate pressure).

This study employed species transport modeling to simulate the aerosol as a passive scalar. The injection point of the aerosol was assigned at 0.8 m higher from the floor to represent the position of the mouth when the patient laid down on the dental chair during the dental treatment. The passive scalar velocities of aerosols were determined at 1.5 m/s as the previous studies [19, 20].

2.3. The Study Design. The previous research has shown that the airflow direction within the room can be affected differently depending on the direction of the air conditioner grille [21]. In the present study, models with two different air conditioner grilled orientations, the straightening to the center (SC) and the 45-degree downward to the center (DC), with different five positions of portable air cleaner were generated as presented in Figure 1. The models were assigned to 12 groups according to the air conditioner grille orientation and the portable air cleaner position. The condition of each group is described in Table 2.

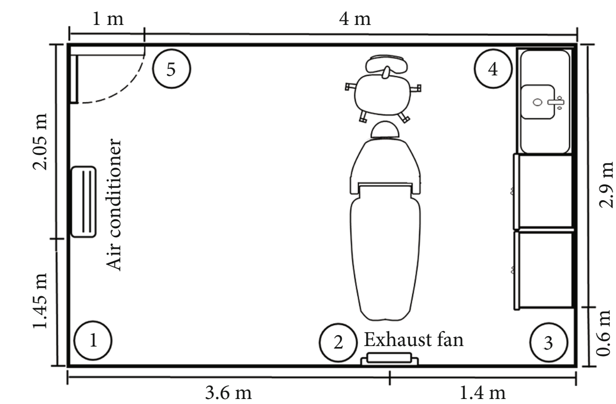

Figure 1: The model of the dental treatment room consists of the dental chair, dental stool, counters, wall-type air conditioner, exhaust fan, and portable air cleaner at the five different locations.

3. Results

This study delved into an investigation of air velocity and the dispersion of aerosols represented in the passive scalar form, with the aim of assessing air quality within dental treatment rooms. Air velocity was employed to examine airflow direction, particularly in zones where dental procedures were conducted and in the surrounding area of the dentist's head. Concurrently, passive scalars were employed to assess the performance of portable air cleaners positioned in various locations within the dental treatment room.

3.1. Analysis of the Air Velocity. Each model underwent analysis from a lateral perspective to investigate air velocity along the Z-axis (Z-velocity). When portable air cleaners were not employed (Figures 2(a) and 2(g)), noticeable distinctions in airflow direction were observed between the SC and DC groups. In the SC0 group, the Z-velocity exhibited negative values, signifying airflow away from the dentist. Conversely, the DC0 group displayed positive Z-velocity values, indicating airflow toward the dental professional. Introducing the portable air cleaners in the SC group did not significantly alter the airflow patterns, while the DC group exhibited substantial differences, as presented in Figure 2. In DC1 and DC4, airflow velocities in the operating field maintained positive Z-velocity, same as the scenarios without air cleaners.

The analysis focused on a center plane positioned between the dentist and the patient, monitoring Z-velocity within the breathing zone of the dentist, situated 0.8-1.6 meters above the ground. In Figure 3, positive Z-velocity values ranging from 0 to 0.14 m/s were observed in SC_4, while other groups exhibited negative Z-velocity values from 0 to 0.053 m/s.

Figure 4 reveals that DC0 had the highest positive Z -velocity in the range of 0.08-0.155 m/s, followed by DC4 with values of 0.04-0.09 m/s. Negative Z-velocity was only observed in DC2, ranging from 0 to 0.02 m/s at heights of 0.9-1.3 meters. DC_2 appeared to be the most favorable condition concerning air conditioner grille direction and portable air cleaner positioning.

Airflow direction and magnitude, represented as vectors over a virtual plane spanning from the dentist-patient coordinates to the center of an air cleaner along the x-axis, were also analyzed (Figures 5 and 6). For straightening direction models in the center position of the air conditioner grille, airflow patterns and velocities were similar. Notably, portable air cleaner positions in the SC group had a consistent impact on airflow direction. In contrast, for the downward direction in the center position of the air conditioner grille, airflow patterns differed. DC0 and DC4 exhibited significantly higher velocity magnitudes, with air initially directed toward the room center before returning to the dentist at reduced speeds. The placement of the portable air cleaner at position no. 2 enhanced air circulation toward the dentist, while other DC cases exhibited airflow in the same direction but with reduced velocity. Based on the results, portable air cleaner placement at position no. 4 was deemed unsuitable for improving room circulation.

3.2. Analysis of the Passive Scalar in the Dental Treatment Room. This study employed a species transportation model to track the formation of a passive scalar representing the dispersion of aerosols within the dental treatment room. Evaluation of passive scalars was performed using a lateral perspective, as depicted in Figure 7. Groups without air cleaners displayed more widespread dispersion of passive scalars throughout the room, whereas other groups exhibited less distinct differences.

To assess passive scalar behavior, the mass fraction average of H_2O was calculated and analyzed (Figure 8). Models without air cleaners (SC0 and DC0) showed the highest mass fraction averages of H_2O at 0.0242 and 0.0237, respectively. Introduction of portable air cleaners resulted in reduced mass fraction averages of H_2O, with SC3 at the highest (0.0129) and SC4 at the lowest (0.0122). In the DC group, DC5 had the highest (0.0129), while DC4 had the lowest (0.0119). These results aligned with the findings from the contour plots.

Focusing on aerosols inhaled by the dental professional, the mass fraction of H_2O within 0.3 meters around the head was evaluated (Figure 9). At this proximity, the mass

Table 2: The studied models.

Groups	Air conditioner grille directions	Locations of portable air cleaner
SC0	Straightening to the center direction	No portable air cleaner
SC1	Straightening to the center direction	At the lower left corner of the dental room (location 1 in Figure 1)
SC2	Straightening to the center direction	At the foot end of the dental chair (location 2 in Figure 1)
SC3	Straightening to the center direction	At the lower right corner of the dental room (location 3 in Figure 1)
SC4	Straightening to the center direction	Behind the dental chair on the right side (location 4 in Figure 1)
SC5	Straightening to the center direction	Behind the dental chair on the left side (location 5 in Figure 1)
DC0	45-degree downward to the center direction	No portable air cleaner
DC1	45-degree downward to the center direction	At the lower left corner of the dental room (location 1 in Figure 1)
DC2	45-degree downward to the center direction	At the foot end of the dental chair (location 2 in Figure 1)
DC3	45-degree downward to the center direction	At the lower right corner of the dental room (location 3 in Figure 1)
DC4	45-degree downward to the center direction	Behind the dental chair on the right side (location 4 in Figure 1)
DC5	45-degree downward to the center direction	Behind the dental chair on the left side (location 5 in Figure 1)

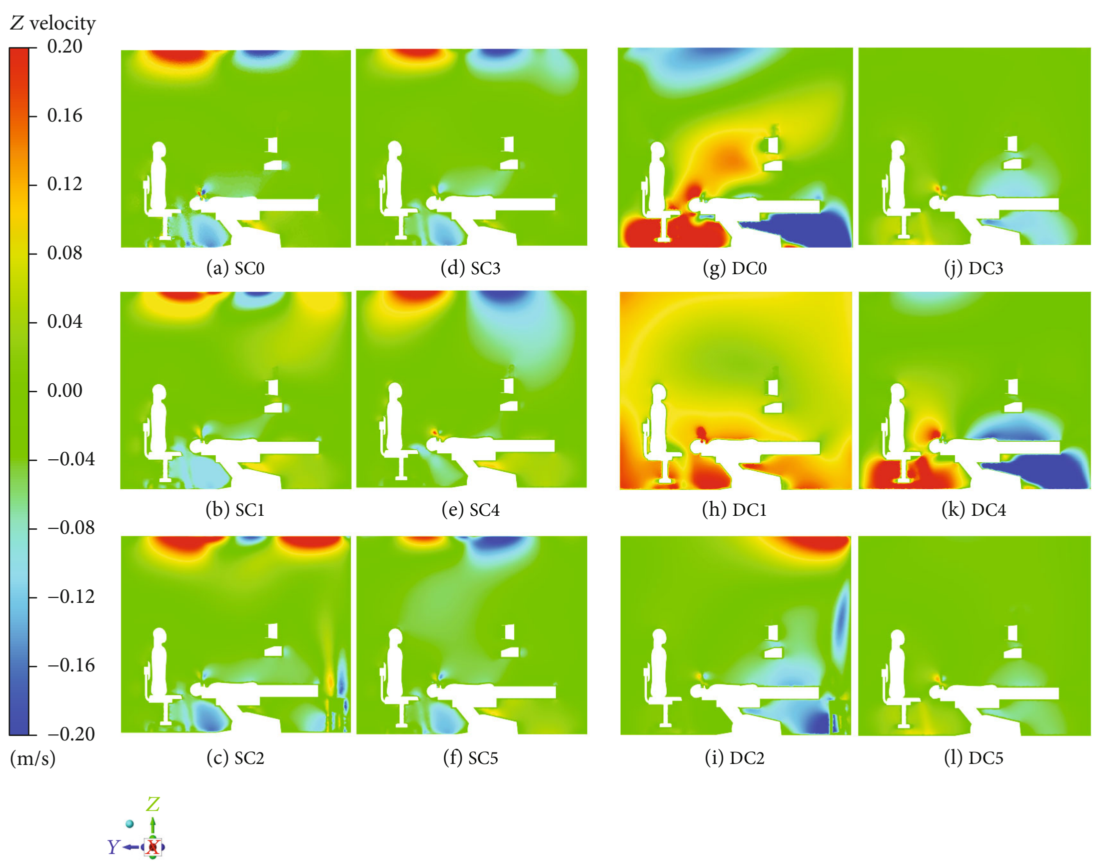

Figure 2: The air velocity contour in the center plane of each group.

fraction average of H_2O exhibited higher values compared to the entire room's mass fraction average of H_2O. SC3 showed the highest (0.0138), while SC4 had the lowest (0.0124). However, this trend was not observed in the DC group.

To assess the influence of the air cleaner, the flow rate of passive scalars passing through the air cleaner was evaluated (Figure 10). The DC group generally exhibited lower mass fraction average of H_2O values compared to the SC group, except for DC3. Nevertheless, air cleaner position no. 3 provided the maximum flow rate in both SC and DC groups (0.00132 and 0.00133 kg/s).

In models with air cleaners, SC4 displayed the lowest mass fraction average of H_2O within both the entire room and around the dentist's head. The air cleaner's performance was consistent with the mass average in the dental treatment rooms. In conclusion, the optimal position for the portable air cleaner in the SC group was position no. 4. In contrast, no direct correlation was observed between the mass fraction

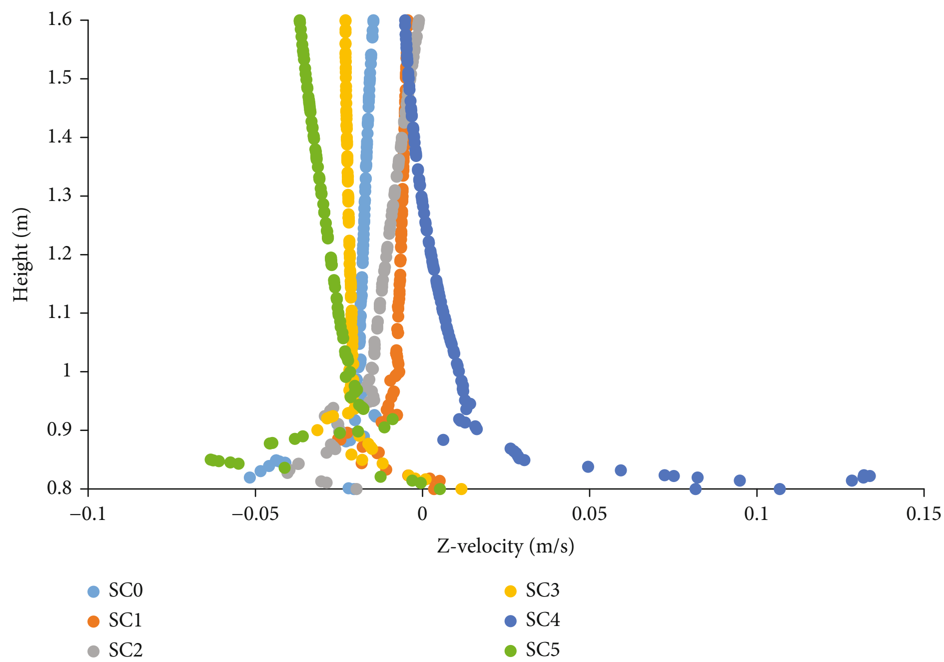

Figure 3: Graph depicting Z-velocity in the center plane between the dentist and the patient for the straightening direction in the center position of the air conditioner grille.

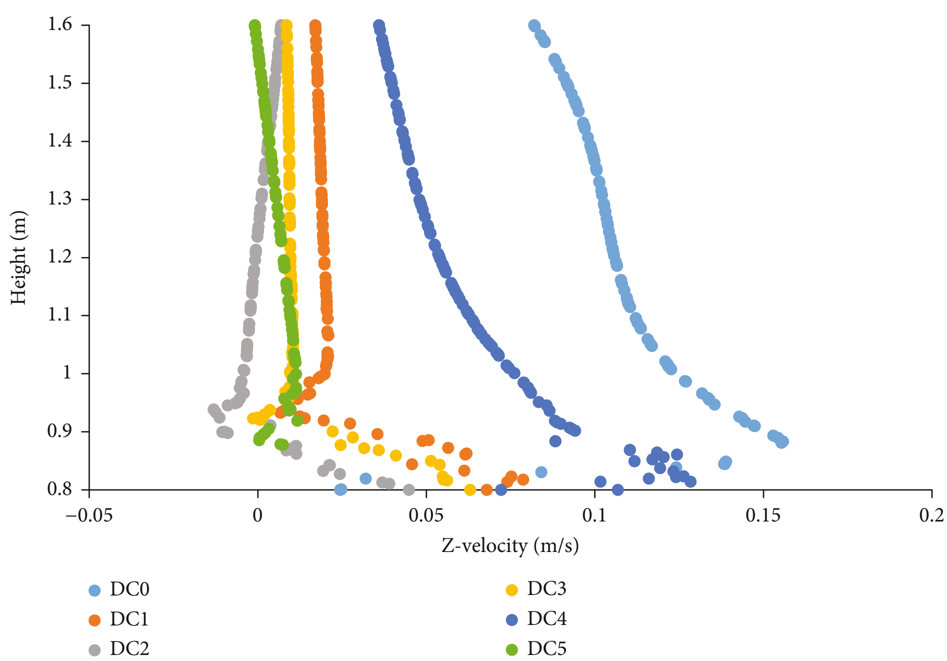

Figure 4: Graph depicting the Z-velocity in the center plane between the dentist and the patient for the downward direction in the center position of the air conditioner grille.

average of H_2O and the mass flow rate of H_2O entering the air cleaner in the DC group. Therefore, considerations involving velocity were vital in determining the suitable position of the portable air cleaner. The DC2 case exhibited the lowest mass fraction around the head and a favorable airflow direction, moving away from the dental professional. Hence, position no. 2 was the recommended location for the portable air cleaner in dental treatment rooms with a downward direction of the air conditioner grille (DC group).

4. Discussion

The findings of our study highlight the significant influence of air conditioner grille direction on airflow patterns within

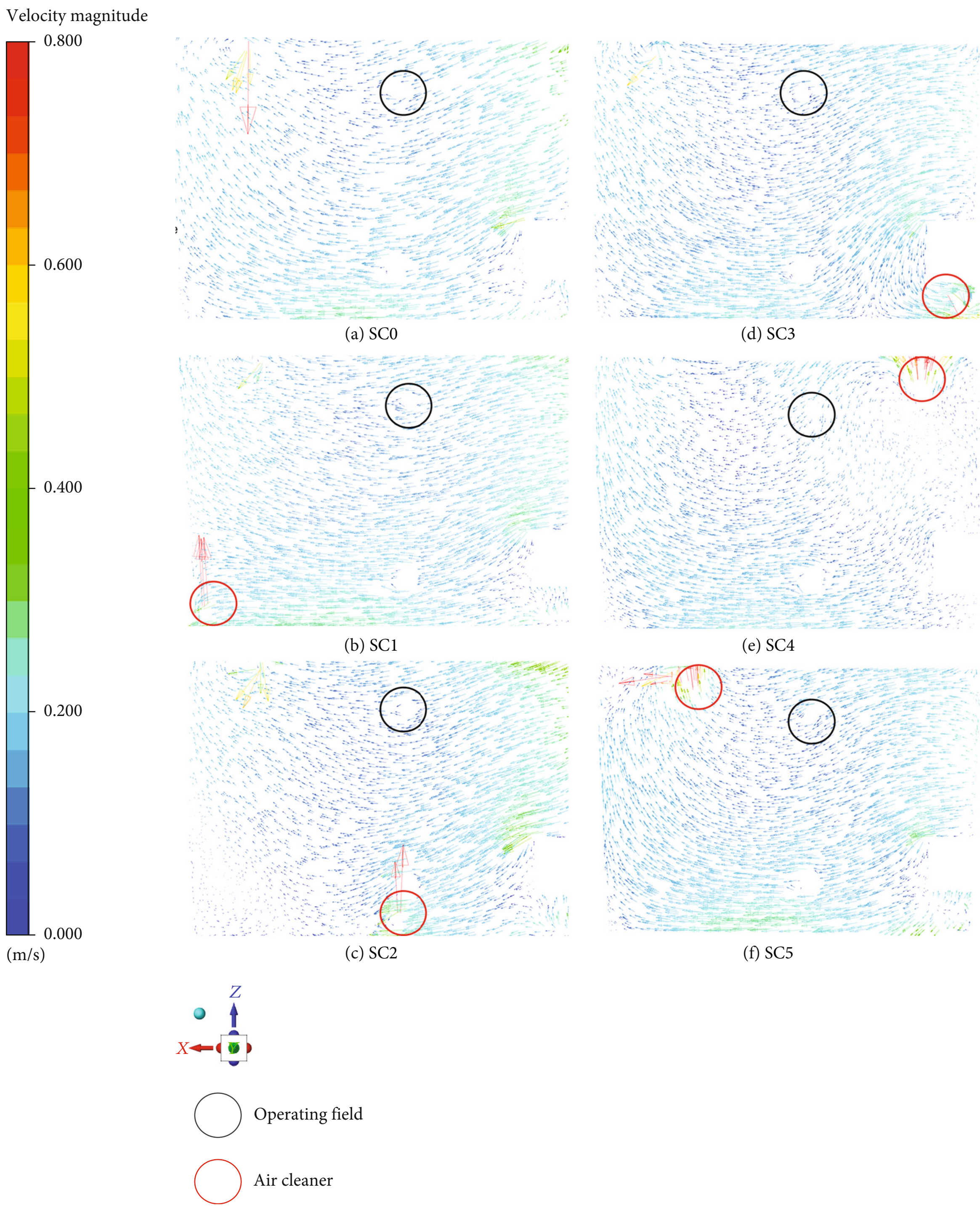

Figure 5: Velocity magnitude vector over the plane between the dentist-patient (coordinated) and the air cleaner for the straightening direction in the center position of the air conditioner grille.

dental treatment rooms. Specifically, we observed that the orientation of the air conditioner grille had a substantial impact on the movement of aerosols within the room. In the case of the straightening direction, airflow was most conducive to moving aerosols away from dental professionals, which is a favorable outcome. However, when the air conditioner grille was oriented downward, it resulted in the movement of contaminated aerosols toward dental operators, indicating an unfavorable airflow direction within the room.

To optimize airflow and minimized aerosol dispersion, we investigated the effect of strategically placing portable air cleaners within the dental treatment room. Prior research has addressed that the behavior of aerosols is largely influenced by their size, with larger particles settling on surfaces

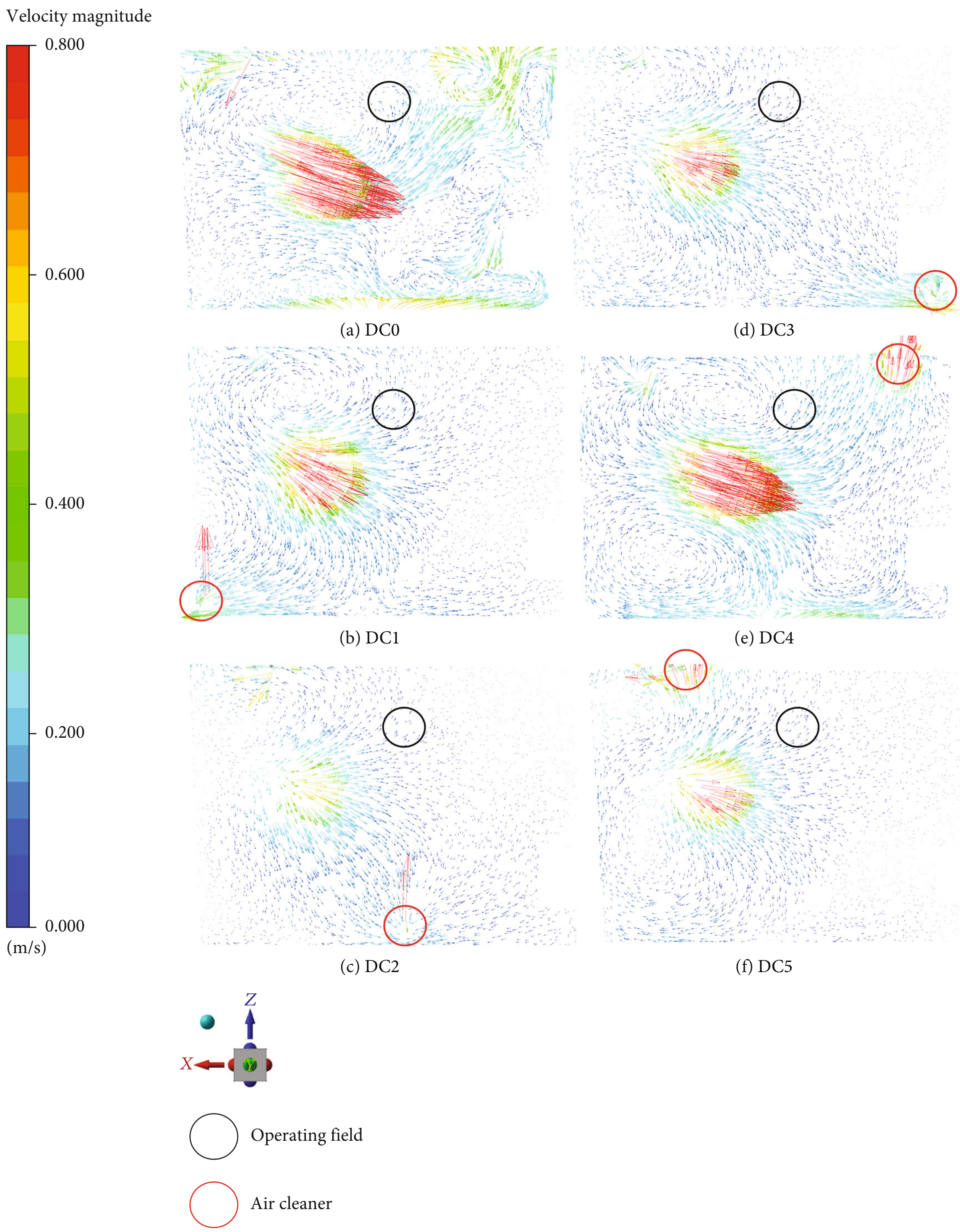

Figure 6: Velocity magnitude vector over the plane between the dentist-patient (coordinated) and the air cleaner for the downward direction in the center position of the air conditioner grille.

due to gravity and smaller particles remaining suspended in the air [3]. In our study, we employed a species transport model, commonly used for modeling pollution transport, to assess aerosol behavior generated during dental procedures [22]. Our results confirmed the positive impact of portable air cleaners on reducing aerosol concentrations in the dental treatment room, aligning with previous research [9, 10, 12]. Consequently, the strategic placement of these air cleaners lowered the risk of respiratory aerosol exposure during dental procedures.

Additionally, the installation of portable air cleaners led to a substantial increase in ventilation rates, effectively doubling the air change rate from 6 ACH to 12 ACH. This finding is consistent with recommendations in previous articles, which

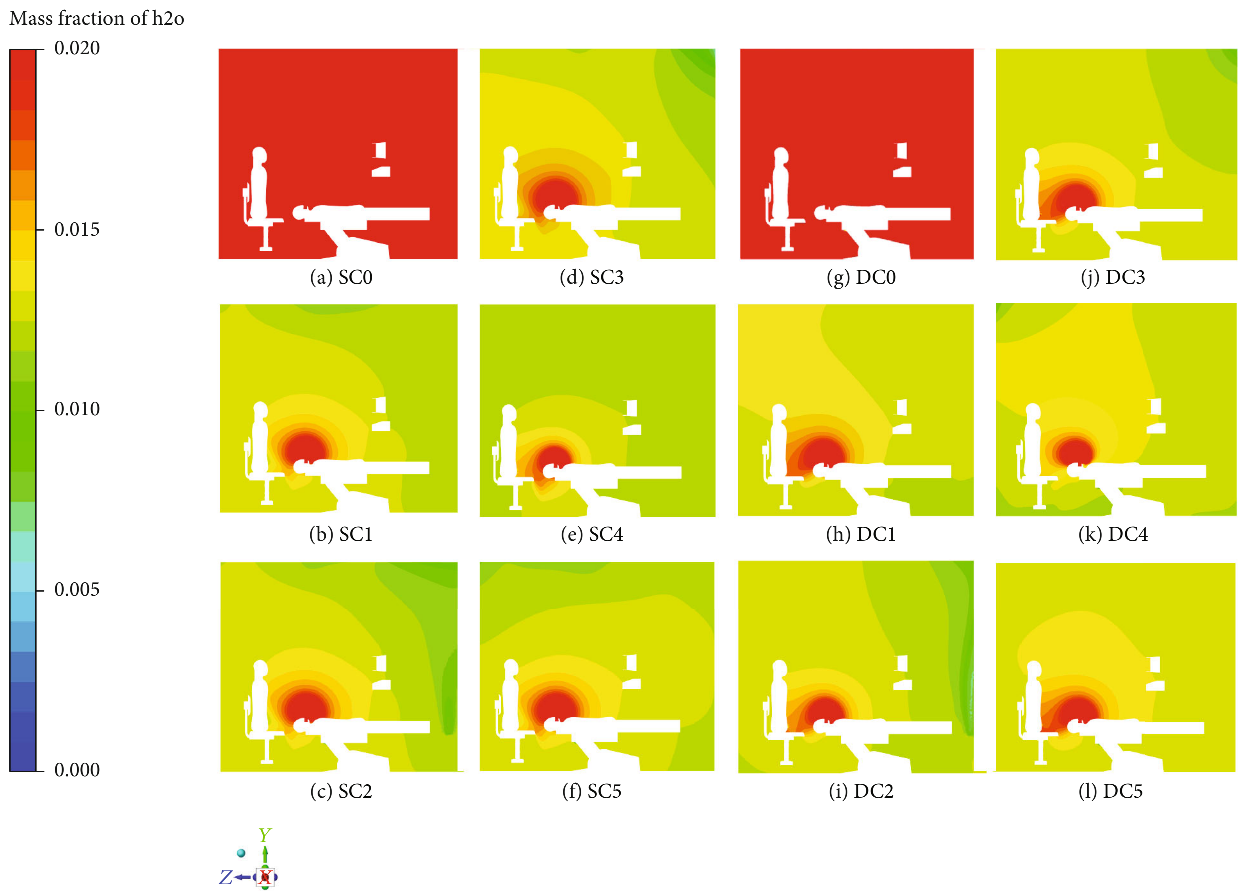

Figure 7: Mass fraction average of H_2O contour in the center plane of each group.

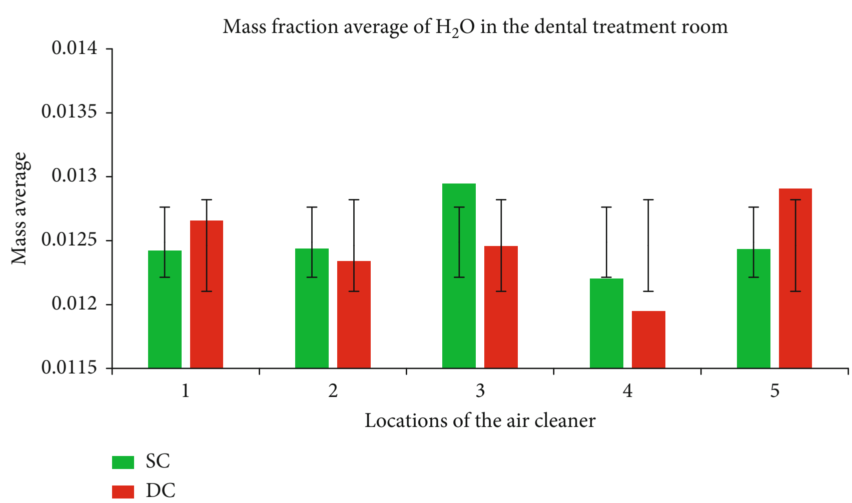

Figure 8: Mass fraction average of H_2O in the dental treatment room at the air cleaner location.

suggested using portable air cleaners as supplemental ventilation in dental offices with air change rates below 6 [23].

Moreover, the presence of portable air cleaners significantly influenced airflow direction, particularly in models where the initial airflow was improper due to the downward orientation of the air conditioner grille. Placing the portable air cleaner at the foot end of the dental chair notably improved overall air circulation. These results underscore the intricate relationship between airflow dynamics and the strategic placement of portable air cleaners in dental treatment rooms, supporting earlier research on air cleaner placement [15]. In models with proper initial airflow, the position of the portable air cleaner had less impact on airflow direction. Nevertheless, positioning the air cleaner at

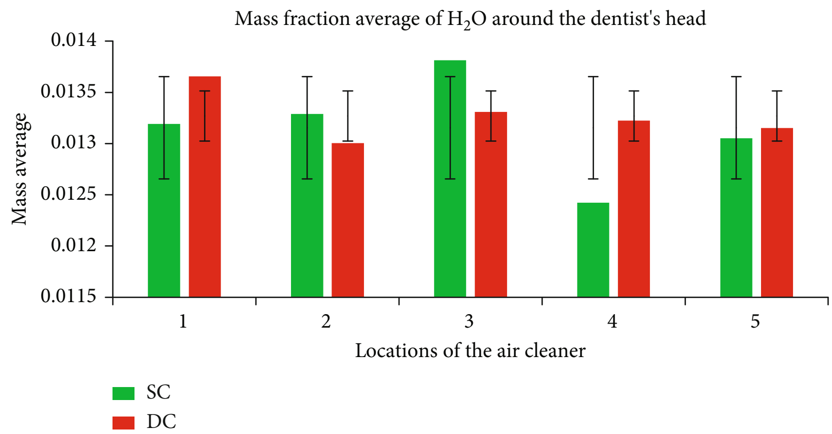

Figure 9: The average mass fraction of H2O around the dentist's head at the air cleaner location.

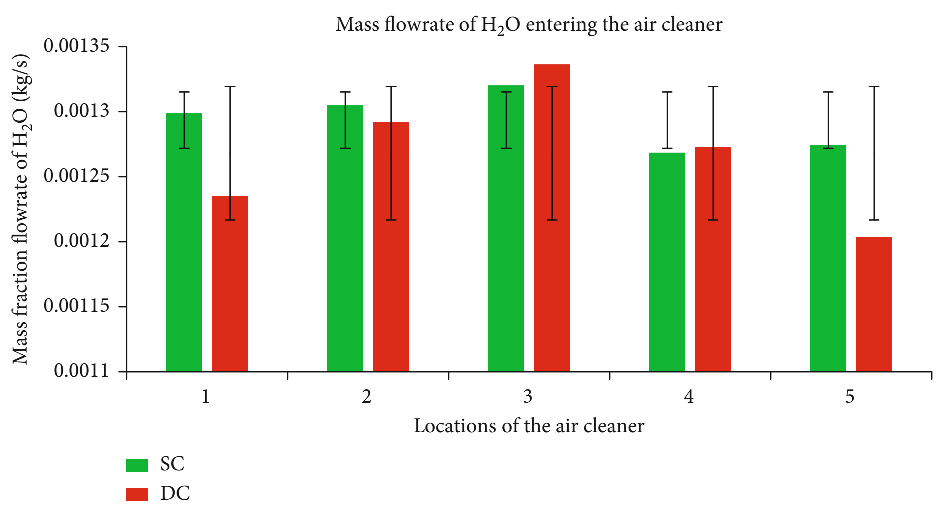

Figure 10: Mass fraction flow rate of H_2O entering to the air cleaner in each location.

the rear right of the dentist's workspace led to the maximum reduction of remaining aerosols, thereby reducing the risk of respiratory transmitted diseases. This finding aligns with previous research emphasizing the practical benefits of placing portable air cleaners near the operating field for the benefit of dentists, dental assistants, and patients [9]. However, it is important to note that our study had some differences from previous research, primarily related to the airflow system used. Previous studies employed vertical downward air supply systems, whereas our study focused on horizontal air supply systems, which are commonly used in single dental treatment rooms.

In dental treatment rooms, air conditioner grilles are often directed downward toward the dentist. This configuration leads to airflow moving from the operating field toward the dentist, indicating an improper airflow direction within the room. Placing the portable air cleaner at the foot end of the dental chair efficiently improved ventilation by reducing remaining contaminated aerosols, particularly in the operating area. This placement also reduced the dentist's risk of inhaling contaminated aerosols.

In all our models, the primary focus was on tracking the movement of contaminated aerosols within the dental room. We observed that aerosols generated during dental procedures tended to return to the air conditioner before being released back into the dental room. To enhance the air-denominating effect of portable air cleaners, it would be advisable to equip air conditioners with appropriate filters capable of capturing these contaminated aerosols. Implementing this protocol can minimize the risk of respiratory transmission diseases spreading from dental procedures to dental staff, including the dentist, dental assistants, and patients.

Considering the efficiency of portable air cleaners in models with different airflow patterns due to varying air conditioner grille orientations, we found that the mass flow rate measured on the air cleaner in the straightening direction group showed a higher value compared to the downward direction group. The airflow originating from the air conditioner played a critical role in determining the volume of air passing through the air cleaner, explaining the higher mass flow rate observed in the straightening direction group.

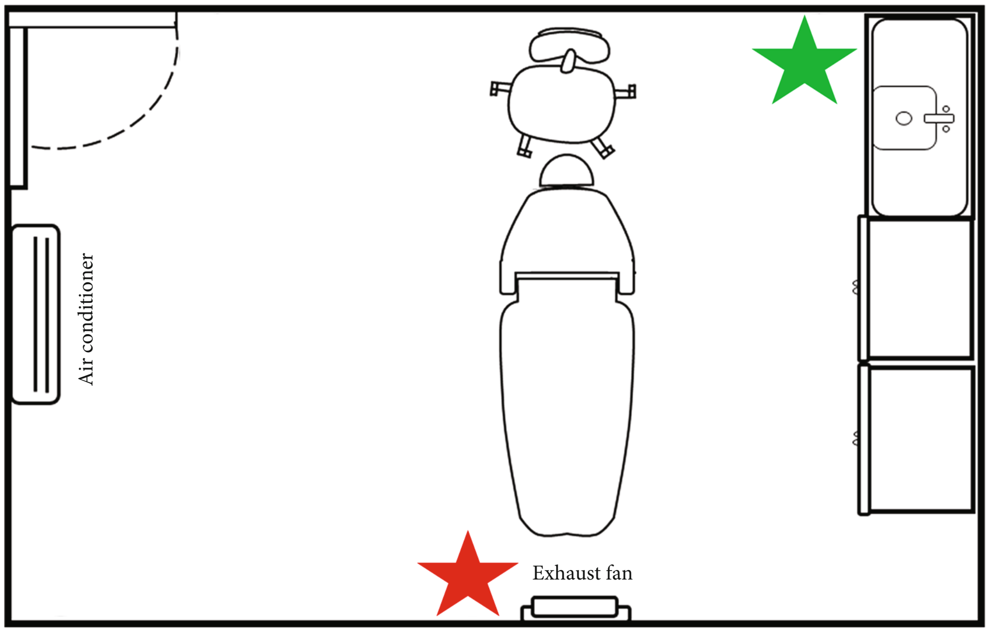

Figure 11: The green and red stars represent the optional positions of a portable air cleaner in the dental treatment room when the airflow is proper and improper, respectively.

Based on our findings, it becomes evident that the presence of effective air ventilation systems plays a pivotal role in mitigating the transmission of airborne diseases like Mycobacterium tuberculosis, hepatitis B virus (HBV), and COVID-19 infections within dental treatment rooms. In this context, our study is aimed at offering a practical and complementary approach to controlling air ventilation in dental treatment rooms through the utilization of readily available portable air cleaner devices. Our choice of portable air cleaner for this study was based on its ease of acquisition, affordability, and user-friendly operation. This deliberate selection ensures that our research outcomes can be readily applied in real-world dental settings, enabling dental practitioners to make informed decisions when procuring and installing commercially available devices.

When considering a portable air cleaner for dental treatment rooms, it is imperative to consider the clean air delivery rate (CADR) that corresponds to the room's size, as this is fundamental to achieving optimal performance [24]. Furthermore, our research strongly advocates for the adoption of portable air cleaners equipped with high-efficiency particulate air (HEPA) filter technology, specifically focusing on medical-grade HEPA 13 and HEPA 14 filters. Recent studies have demonstrated the remarkable efficacy of these filters, resulting in a substantial reduction in suspended particles generated during dental procedures, ranging from 69% to 80% [12]. Moreover, these filters have showcased their effectiveness in capturing a wide spectrum of airborne particles, including the coronavirus and other potential pathogens [25]. This emphasis on filter technology ensures that dental facilities are equipped with a reliable defense against the dispersion of contaminants, fostering a safer and more secure environment for dental practitioners and patients alike.

According to the results from the present study, the placement of portable air cleaners should be evaluated based on the airflow direction from the air conditioner. If the airflow passes through areas where procedures are performed before reaching the dentist, the optimal position for installation is at the foot end of the dental chair. However, in cases where this placement is impractical, positioning the portable air cleaner in close proximity to the dentist, without obstructing the dental treatment procedure, is recommended (Figure 11).

It is crucial to emphasize the necessity for further research encompassing diverse dental treatment room models, considering factors such as room design, room dimensions, airflow direction, the positioning of air conditioner units, exhaust fan locations, and areas where dental procedures are performed. Such comprehensive studies are essential for providing practical and tailored recommendations to control the dissemination of contaminated aerosols in dental treatment rooms. These insights will furnish invaluable real-world applications, ultimately enhancing safety and efficacy in dental practice.

5. Conclusion

In summary, our findings establish a significant correlation between the placement of portable air cleaners and their effectiveness in mitigating aerosol dispersion within dental treatment rooms. The optimal positioning of these devices, either near the operating field or at the foot end of the dental chair, hinges on the prevailing airflow direction within the dental room. Importantly, the strategic placement of portable air cleaners not only enhanced their efficacy in aerosol control but also facilitated improved airflow patterns, particularly within the critical operating field.

Therefore, achieving optimal air quality in dental treatment rooms requires a comprehensive strategy. This strategy involves optimizing airflow patterns and strategically placing portable air cleaners to enhance ventilation while simultaneously reducing the risk of infection transmission during dental procedures. By addressing these essential components, dental practitioners can substantially improve the safety and hygiene of their practice environments.

Data Availability

The document data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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