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Research Article

Determination of Particulate Matter in Dental Clinics: The Effectiveness of Different Air Purifiers and the Central Ventilation System

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The purpose of this study was to measure the number and concentration of airborne particulates occurring in a dental clinic while performing dental procedures, with and without the simultaneous use of air purifier systems and a central ventilation system. The initial background concentrations of airborne particulates recorded during dental procedures, i.e., grinding of natural teeth and metals, without the use of air purifier systems, and with closed windows, reduced by 68% for PM_{10}, 77% for $PM_{2.5}$, and 81% for PM_1 when the same procedures were carried out with the simultaneous use of air purifying systems. In addition, measurements taken during patient treatment showed that an operating central ventilation system contributes to the reduction of airborne particles by a significant 94% for PM_{10}, 94% for $PM_{2.5}$, and 88% for PM_1 compared to dental procedures performed without the simultaneous use of air purifiers. Air purifying systems were also observed to contribute to the further reduction of airborne particulates when dental procedures were performed in combination with an operating central ventilation system. The majority of particles captured had diameters of 0.25-0.30 μm, 0.5 μm, and 1.0-4.0 μm, while particles with diameters of >5.0 μm were the least commonly observed in all experiments. Finally, a statistically significant difference between concentrations of particulate matter was recorded during dental procedures carried out with and without the simultaneous operation of air purifiers and central ventilation system increasing the risk of SARS-CoV-2 virus contamination in dental clinics due to the aerosols emitted by the use of common dental instruments during standard treatments.

1. Introduction

Atmospheric pollution, especially airborne particulate matter in indoor environments, is a timely area of research for scientists and the whole world due to the damage it can cause to human health [1]. In emergency situations such as the current pandemic, there is an urgent need to take measures to improve both the short-term and long-term air qualities of indoor areas to protect the health of the general population and especially sensitive groups of citizens such as the elderly, health professionals, and individuals with preexisting medical conditions.

Following its detection in humans in the Chinese city of Wuhan in the late 2019, the SARS-CoV-2 virus has spread rapidly throughout the world [2]. Its emergence and transmission appears to be related to urbanization, animal husbandry, and population movements [2]. The virus can be transmitted either via direct or indirect contact, or by exposure to small droplets and particulates that contain viral load and can remain airborne for time periods ranging from several minutes to several hours [3, 4]. Dinoi et al. [5] put in evidence that airborne transmission could be an issue mainly related to poorly ventilated indoors or when relevant sources (i.e., number of infected individuals) are gathered together. As airborne droplets can contribute to the spread of SARS-CoV-2 [4, 6], recent studies have been carried out on the correlation between concentrations of airborne PM_{10} and $PM_{2.5}$ particulates and COVID-19 deaths [7]. Concerning the correlation between air pollutants and COVID-19 virus transmission, a study by Zoran et al. [8] carried out in the region of Lombardy near Milan in Italy showed that high levels of air pollution significantly contribute to COVID-19 transmission. Goumenou et al. [9] concluded that environmental factors negatively influence the human immune system and contribute to the more frequent occurrence of viral infections. Likewise, Setti et al. [10] applied PCR techniques to detect SARS-CoV-2 RNA in 34 samples of airborne PM_{10} particulate matter taken from Bergamo city in Italy. Two genes (genes E and RdRP) were detected in the PM_{10} samples, both of which are related to the SARS-CoV-2 virus. On the other hand, Chirizzi et al. [11] and Pivato et al. [12] found the opposite concluding that it is extremely unlikely to detect SARS-CoV-2 RNA in airborne samples in the outdoor environment, excluding crowded places.

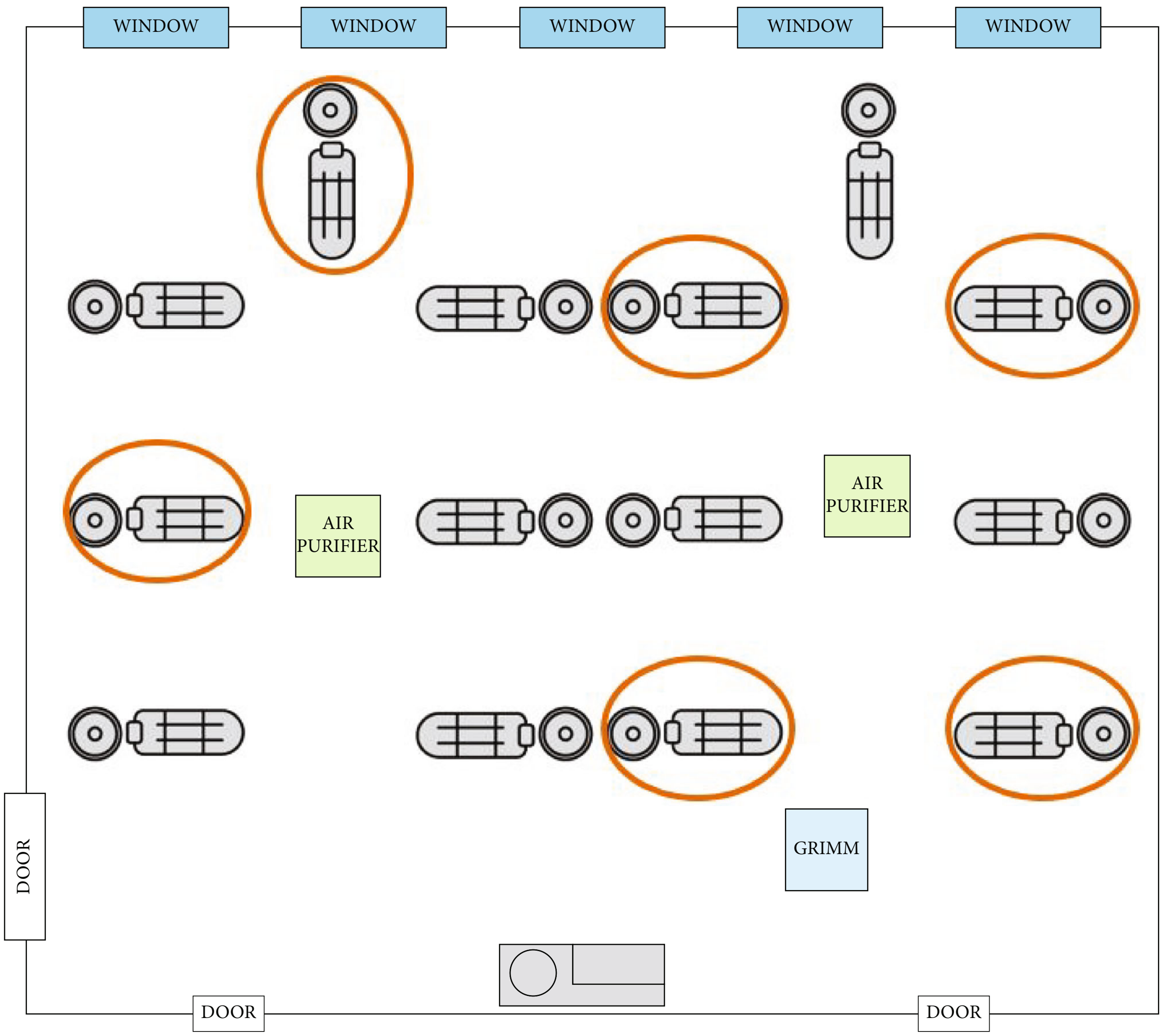
Data from the World Health Organization (WHO) show that 9 out of 10 people in the world are exposed to high levels of airborne particulates and 7-8 million premature deaths occur worldwide each year as a result of exposure to atmospheric pollution, including pollution of indoor spaces [13]. The current pandemic has increased the need to identify and fill gaps in the knowledge relating to the behavior of air-transmissible particles of biological origin that contain viral loads and also their impact on the air quality of indoor spaces such as health care premises, hospitals.

In light of the SARS-CoV-2 virus pandemic, the Occupational Safety and Health Administration of the US Department of Labor has classified dentistry as a very high risk profession for the virus transmission due to the aerosols produced during various dental procedures [14]. Most of the instruments used in standard dental procedures (low- and high-speed handheld instruments, drills, ultrasound equipment, water-air syringes, and air polishing tools) can produce aerosols [15, 16]. Exposure to aerosols and droplets that contain bacteria, viruses, and blood during dental treatments rarely leads to the transmission of infections between patient and dental staff when all necessary protective measures are adhered to. However, during the current pandemic, dentists run a high risk of infection as the possibility of contact with an infected patient is high, especially if that patient does not exhibit visible symptoms of the virus. It has been found that the use of dental ultrasound equipment can generate aerosols that spread out to distances of up to 2 metres from the patient and that can remain in the air for time periods ranging from 35 minutes to several hours [17]. The production of aerosols and saliva droplets can cause infection via air transmissible microbes. In this way, the use of dental equipment increases the dispersion of aerosols within the dental clinic itself [17]. Additionally, aerosol composition differs according to the type of dental treatment being performed and the microbial flora of the patient's mouth [18]. Research has shown that there is a high chance of microbial infection when aerosol particle diameters range from 0.5 to 20 μm [19]. Fine-sized (inhalable) particles that carry air-transmissible microorganisms can potentially enter lung alveoli and negatively affect human health [19–21].

Aerosols are characterized as solid or liquid particles (droplets) with an aerodynamic diameter (d) of 0.001 to 100 μm that are dispersed within the atmosphere [22]. Airborne particulates are classified according to their size: course particulate matter with diameters < 10 μm (PM_{10}), fine particulates with diameters < 2.5 μm ($PM_{2.5}$), and ultrafine particulates of <0.1 μm in diameter ($PM_{0.1}$). Human respiration can generate particles of <5 μm in diameter. These particles are generated by coughing or sneezing and either fall to the ground after a few seconds due to gravity or are transformed into much smaller-sized particles of <1 μm that remain in the atmosphere for many hours. These smaller particles can move around freely in the air and transfer their viral loads hundreds of metres away from their original emission source. This can increase the risk of infection as particulates < 2.5 μm can enter lung alveoli and ultrafine particles such as the SARS-CoV-2 virus with a diameter of 80-120 nm [23] can potentially enter the blood stream directly or be carried into it on larger-sized particulates [24].

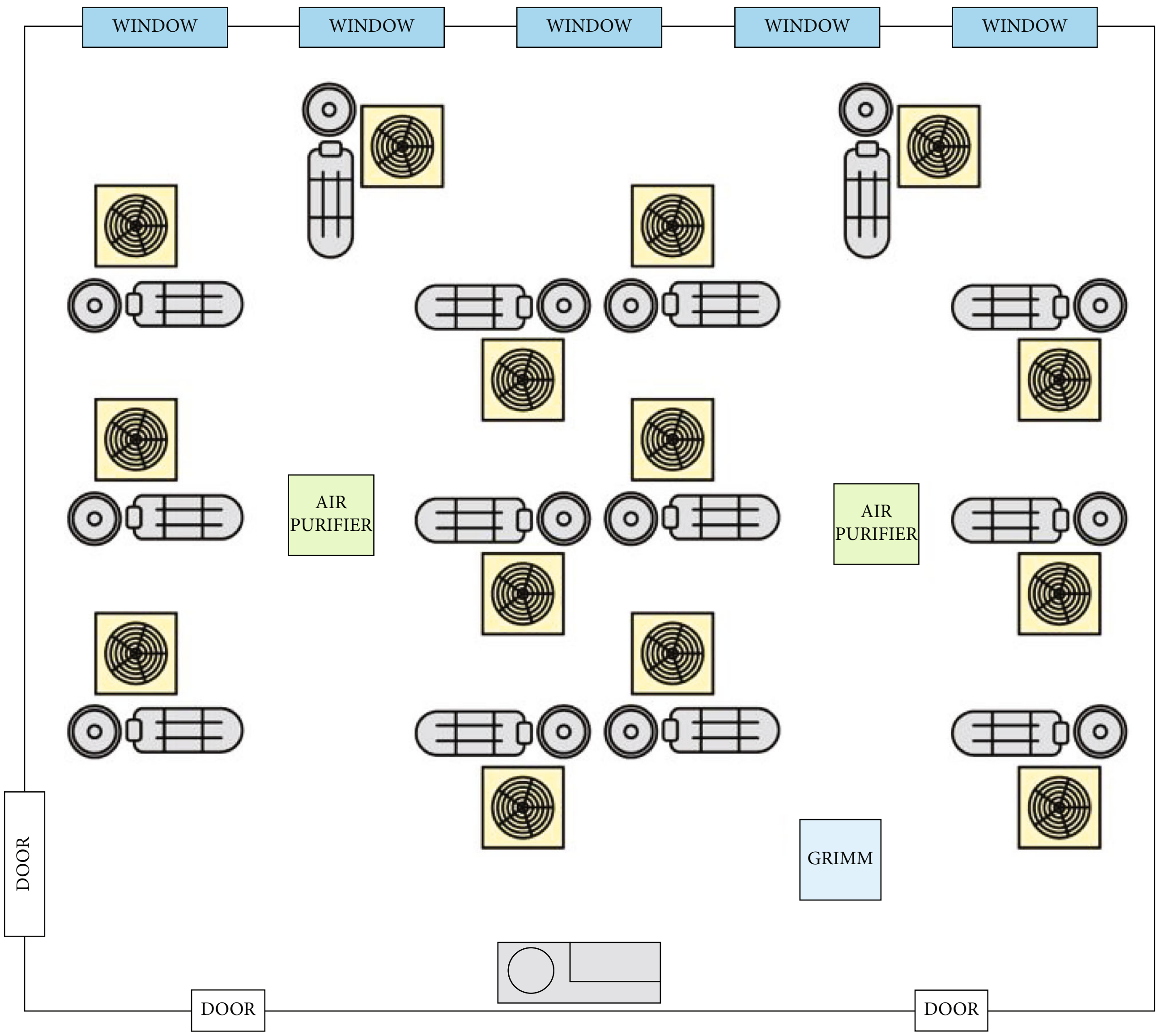
Recent studies have shown that the SARS-CoV-2 virus can be transferred by particulates [25] and a positive correlation has been found between airborne particulates $PM_{2.5}$ and the transmission of other viruses, including the influenza virus [26]. Another study found that SARS-CoV-2 occurs more frequently on airborne particulates with diameters of 0.25-1.00 μm and >2.5 μm [27]. Zhao et al. [28] reported that the use of air purification systems with HEPA and F6 class filters during dental treatments can reduce aerosol concentrations by 54-83%, and Conte et al. [29] put in evidence the importance of indoor ventilation to reduce virus-laden particles in different indoor environments. Another study carried out in a dental clinic found that air purifiers can reduce aerosol concentrations by 80-90%, therefore reducing pathogen exposure for both employees and patients.

The use of air purifying mechanisms in indoor areas has been found to reduce the number of particulates recorded. One study carried out in a dental clinic found that air purifiers can reduce aerosol concentrations by 80-90%, therefore reducing pathogen exposure for both employees and patients [30]. Another study found that SARS-CoV-2 occurs more frequently on airborne particulates with diameters of 0.25-1.00 μm and >2.5 μm [27]. The fact that the virus has been found on particles of >2.5 μm indicates that these are redistributed from surfaces or the protective clothing of



(a)

FIGURE 1: Continued.



(b)

FIGURE 1: Sketch of the dental clinic indicating the position of the air purifiers and the measurement instrumentation. The orange circles indicate the position of the patients. (a) 1st cycle of measurements (without central ventilation system) and (b) 2nd cycle of measurements (with central ventilation system).

medical staff. Zhao et al. [28] reported that the use of air purification systems with HEPA and F6 class filters during dental procedures can reduce aerosol concentrations by 54-83%. However, further research is required to investigate the effectiveness of air purifiers in indoor workplaces other than those used for health care facilities. Additionally, studies on central ventilation systems in health care premises have not been published.

The purpose of this study was to measure the number and concentration of different airborne particulates occurring in a dental clinic while performing standard dental procedures, with and without the simultaneous use of air purifier systems and a central ventilation system. To the best of our knowledge, no other studies comparing air purification units and ventilation systems have been conducted in dental clinics.

2. Materials and Methods

A Mini Laser Aerosol Spectrometer - IAQ-11R (by GRIMM Aerosol) automatic data recorder was used to determine particulate matter in real time. The Mini Laser captures airborne particulates with diameters of 0.25-32.0 μm and classifies them into 31 size channels. Samples were taken measurements once per minute. Two cycles of measurements were performed as described below. In the first cycle, the dental clinic was not open to the public, and experiments were carried out on the effectiveness of different air purifier

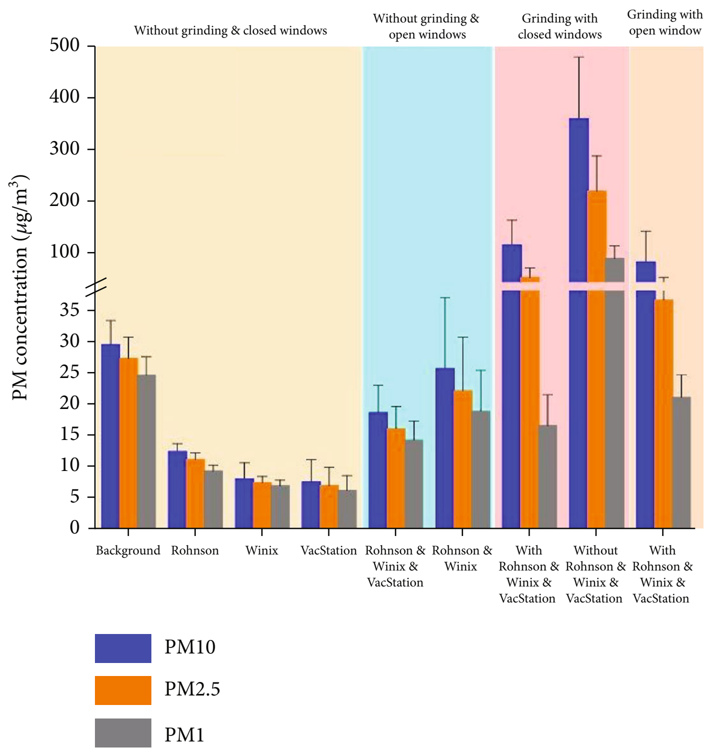


Figure 2: Mean concentrations of particulate matters PM_1, $PM_{2.5}$, and PM_{10} under different conditions. RWV = Rohnson and Winix and VacStation.

systems (Figure 1(a)). In the second cycle, the central ventilation system was switched on, and then, measurements were taken during real-time dental procedures on patients (Figure 1(b)).

2.1. 1st Cycle (without Central Ventilation System). The air purification systems investigated were the Winix Zero Pro, Rohnson Pure Air, and the extraoral dental vacuum system VacStation by Eighteeth. The Winix Zero Pro device has five air purifying stages with a prefilter and large True HEPA as well as activated carbon filters. It also has PlasmaWave technology which neutralizes viruses and microbes in indoor spaces. According to the manufacturer, the volume flow is at least 486 m^3/h when operated in turbo mode. The Rohnson Pure Air system has seven air purifying stages with formaldehyde, antibacterial and HEPA filters, and ultraviolet light (365 nm) that destroys bacterial DNA and hence achieves complete air purification. The maximum volume flow is 320 m^3/h. The department of Operative Dentistry of Aristotle University of Thessaloniki where the study was conducted is located on the first floor of the main building and expands to a space of 150 m^2 (360 m^3). The dental units and the other equipment occupy 18 m^3, so the actual size of the room is at about 342 m^3. The air exchange time for Winix is 42 minutes while the air will pass through the Winix air purifier and be cleaned about 1.4 times per hour. The air exchange time for Rohnson air purifier is 63 minutes while the air will pass through the Rohnson and be cleaned about 0.9 times per hour. During the first cycle of measurements (without central ventilation system), 5 out of 14 dental units were used for the experiments. VacStation is an extraoral dental vacuum system that is positioned over the patient's face and reduces the risk of air transmissible microorganisms being dispersed from the patient's mouth. It possesses a multilayered filter (HEPA, high-fiber cotton filter, fiberglass filter, activated carbon, $KMnO_4$, and ceramsite filter) and UV light, and the clean air delivery rate is 3.7 m^3/min.

Background concentrations of airborne particulates were initially recorded in the dental clinic before air purifier operation separately. Measurements were then taken when each air purifier (Winix, Rohnson, and VacStation) was in operation and under working combinations of these. The quantity of airborne particulates was also measured during dental procedures carried out with and without the simultaneous operation of the air purifiers. Five volunteers performed dental work using high- and low-speed rotating instruments to grind natural teeth and dental materials including polymers, composite resins, acrylics, and metals. Dental work was continuous and data was recorded at one-minute time intervals. The volunteers worked simultaneously on patients in different dental stations positioned at least three metres apart. The experimental conditions under which the airborne particles were measured are follows:

(a) Grinding of natural teeth and dental materials with the simultaneous operation of air purifiers (Winix, Rohnson, and VacStation) and intraoral suction, without natural aeration of the work space (i.e., with closed windows)

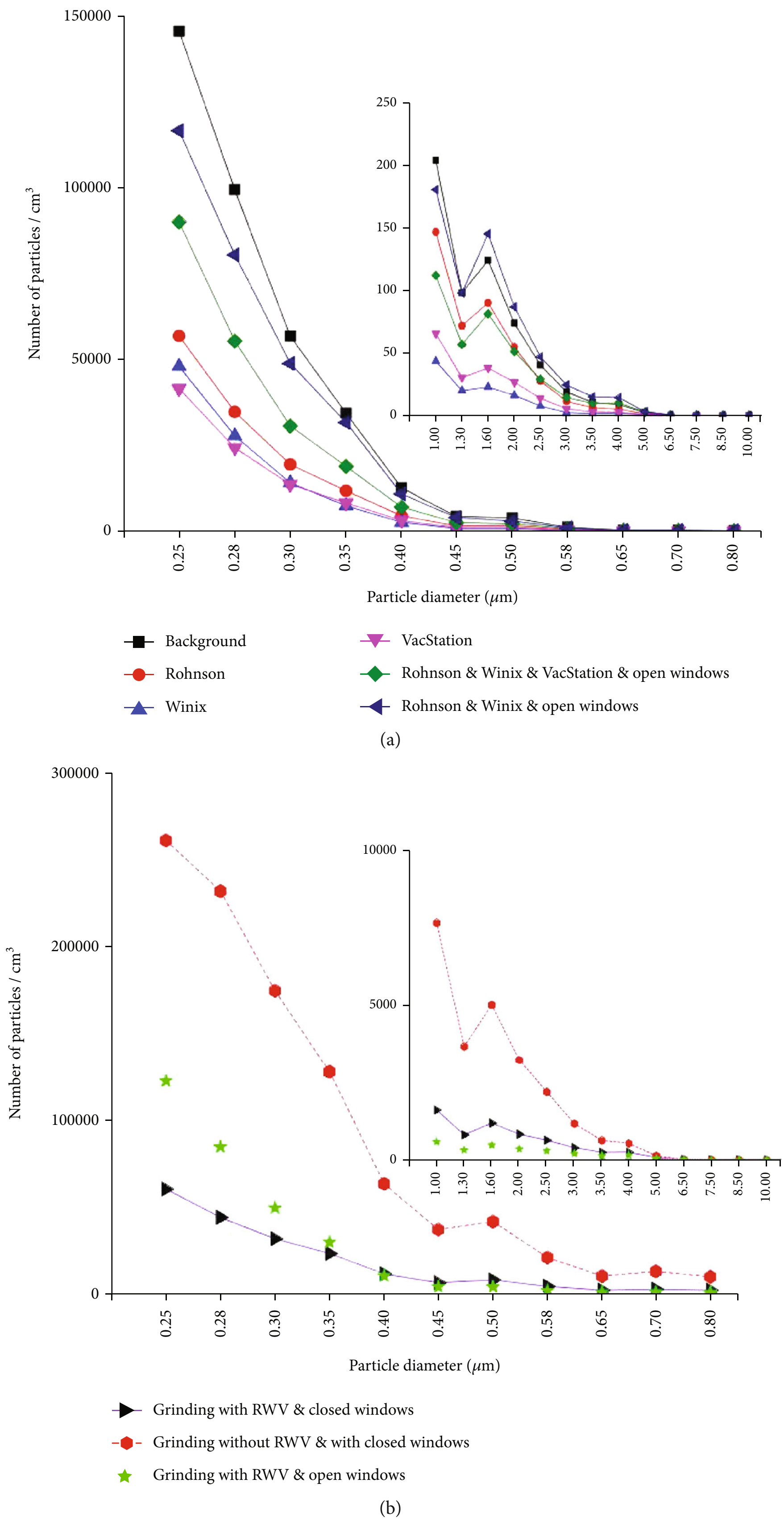
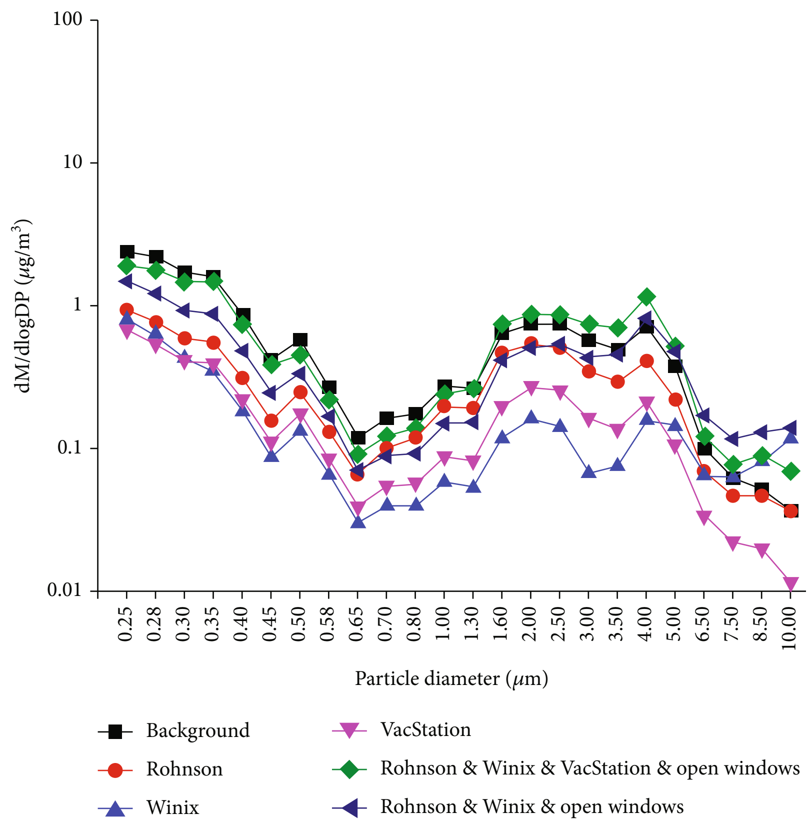
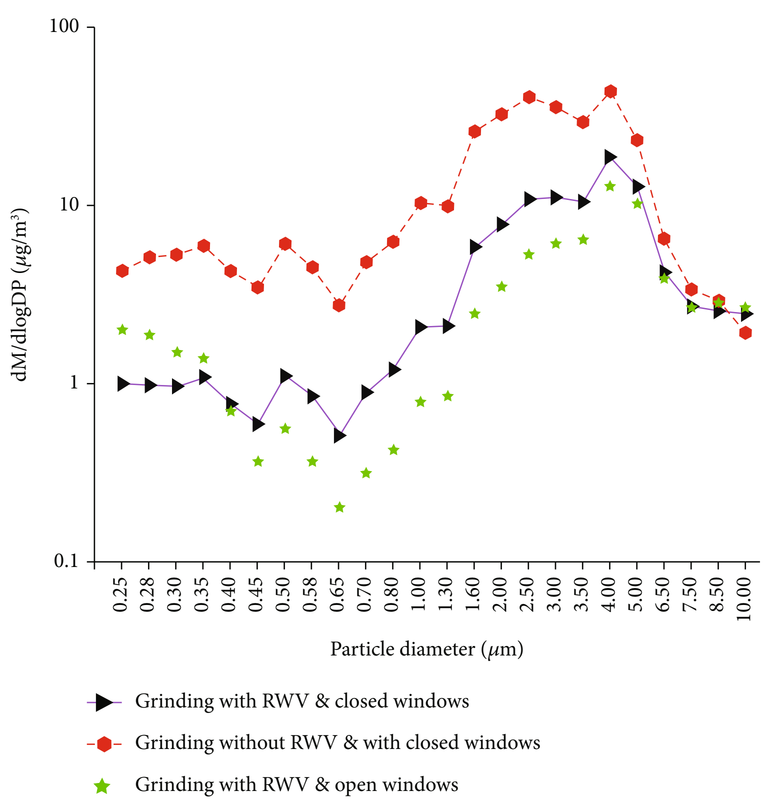


FIGURE 3: Number of different-sized particles recorded in the different experimental conditions: (a) when dental procedures were not taking place and (b) during dental procedures.



(a)



(b)

Figure 4: Mass of different-sized particles recorded in the different experimental conditions: (a) when dental procedures were not taking place and (b) during dental procedures.

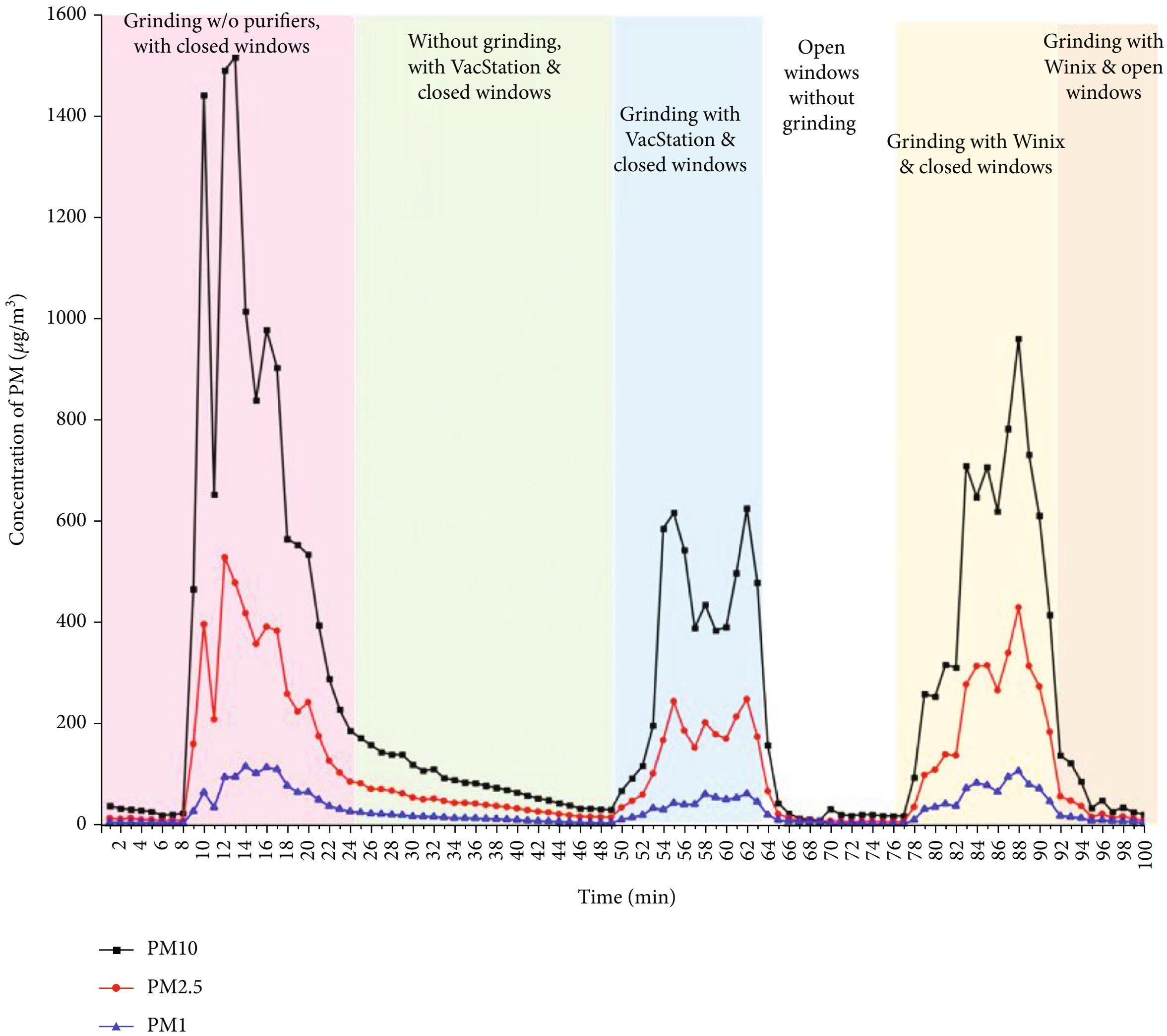


FIGURE 5: Concentrations of PM_1, $PM_{2.5}$, and PM_{10} particulate matters recorded during grinding procedures on natural teeth using high-speed rotating instruments with and without the simultaneous use of air purifiers.

(b) Grinding of natural teeth and dental materials with the simultaneous operation of air purifiers and intraoral suction, with natural aeration of the work space (i.e., with open windows)

(c) Grinding of natural teeth and dental materials without the simultaneous operation of air purifiers and intraoral suction and without natural aeration of the work space (i.e., with closed windows)

When used, the clinical VacStation was positioned at a distance of 40 cm from the grinding area. This distance is the same as that used in real treatment procedures, i.e., on the patient's chest and in front of his/her mouth. All the air purifiers were operated at maximum capacity. Concentrations of airborne particles originating from natural tooth grinding using high- and low-speed rotating instruments were also compared with and without the simultaneous use of the VacStation.

2.2. 2nd Cycle (with Central Ventilation System). In this cycle, measurements were taken when the central ventilation system (CVS) was switched on. The CVS comprises two air-air exchangers of 3500 m^3/h capacity each. The average number of persons (patients and medical personnel) in the treatment area during the experiments was 18, and the number of dental units used was 6 of the available 28. The CVS remained switched on continuously, and only the air purifiers were interchanged. The treatments performed on the patients included operative, endodontic, and periodontic treatments.

The air purifying systems applied were Winix, Rohnson, and Airocide, the former two of which are described above. Airocide (APS-200 model) is a nonfilter photocatalyst air purification system that was developed by NASA to safely remove organic matter from air. It is suitable for the removal of harmful pathogens and major allergens, such as dust, from the atmosphere. According to manufacturer, the clean air delivery rate is 114 m^3/h.

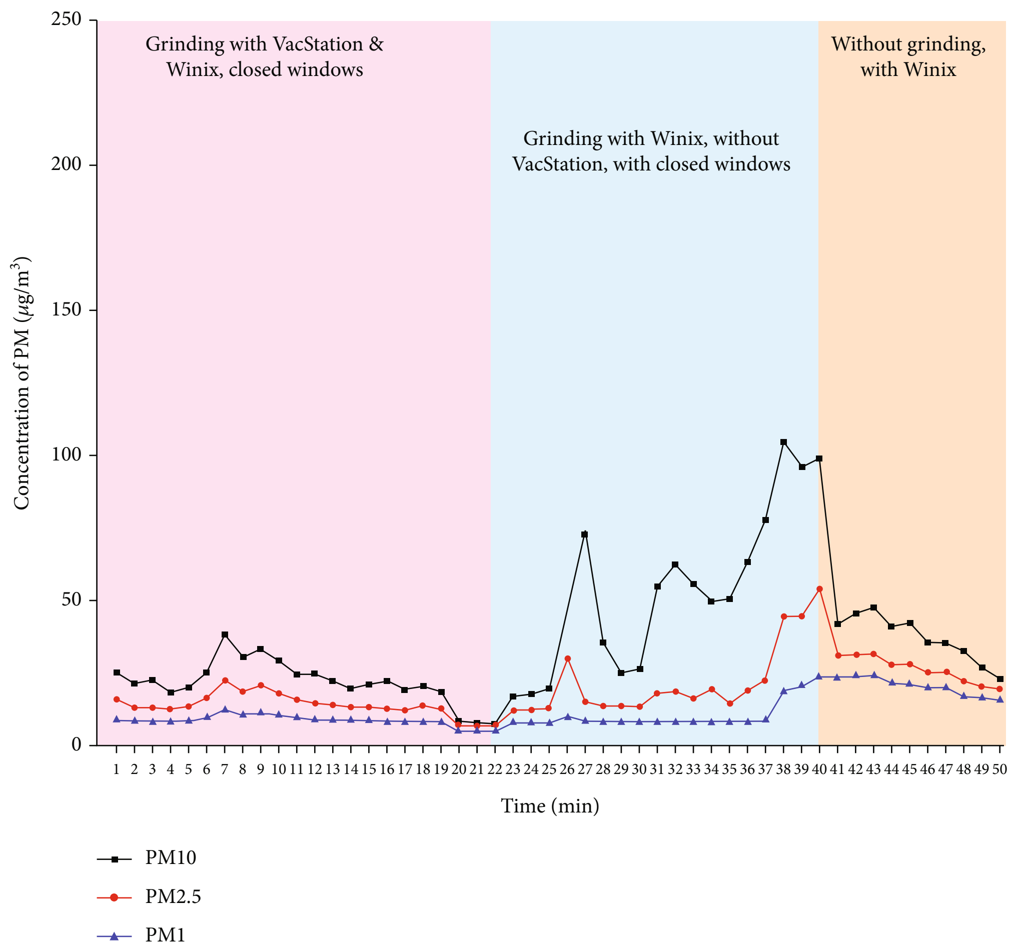


FIGURE 6: Concentrations of PM_1, $PM_{2.5}$, and PM_{10} particulate matters recorded during grinding procedures on natural teeth using low-speed rotating instruments with and without the simultaneous use of air purifiers.

Appropriate protection measures against the SARS-CoV-2 coronavirus were taken throughout all the dental work carried out in the framework of this research.

3. Statistical Analysis

Statistical analysis of the results was performed using IBM SPSS Statistics Version 25. Results were compared by applying one-way ANOVA (analysis of variance), and the Tukey test was used to determine statistically significant differences between particulate concentrations ($p < 0.05$ was considered statistically significant).

4. Results

4.1. First Measurement Cycle (without Central Ventilation System). Figure 2 shows the mean concentrations of particulate matters PM_1, $PM_{2.5}$, and PM_{10} recorded in the different experimental conditions. Figure 2 shows that when the Rohnson air purifier was operated, the mean concentrations of PM_{10}, $PM_{2.5}$, and PM_1 fell by 58%, 59%, and 62%, respectively, compared to the background concentrations. The mean PM concentrations recorded with the working Winix purifier reduced by 72% for both PM_{10} and $PM_{2.5}$ and by 71% for PM_1 as compared to the background values. VacStation use appears to have reduced background concentrations of PM_{10} by 74%, $PM_{2.5}$ by 72%, and PM_1 by 74%. It can also be seen from Figure 2 that on days when the clinic's windows were open to aerate the treatment area and all three air purifiers (Winix, Rohnson, and VacStation) were operated, concentrations of particulate matter reduced by 37% for PM_{10}, 41% for $PM_{2.5}$, and 42% for PM_1 compared to background levels, despite the introduction of outside (urban) air into the treatment area. Lastly, it can be seen that the continuous operation of air purifiers contributes decisively to maintain low levels of particulates within treatment areas.

The mean concentrations of particulate matter recorded during grinding procedures when clinic windows were closed and purifiers were not operating were $354 \pm 119\,\mu g/m^3$ for PM_{10}, $216 \pm 68\,\mu g/m^3$ for $PM_{2.5}$, and $86 \pm 25\,\mu g/m^3$ for PM_1. However, on the days when dental procedures were performed with open windows and the simultaneous operation of Winix, Rohnson, and VacStation, concentrations of particulate matter fell by 78% for PM_{10}, 83% for $PM_{2.5}$, and 76% for PM_1. Concentrations of particulate matter recorded

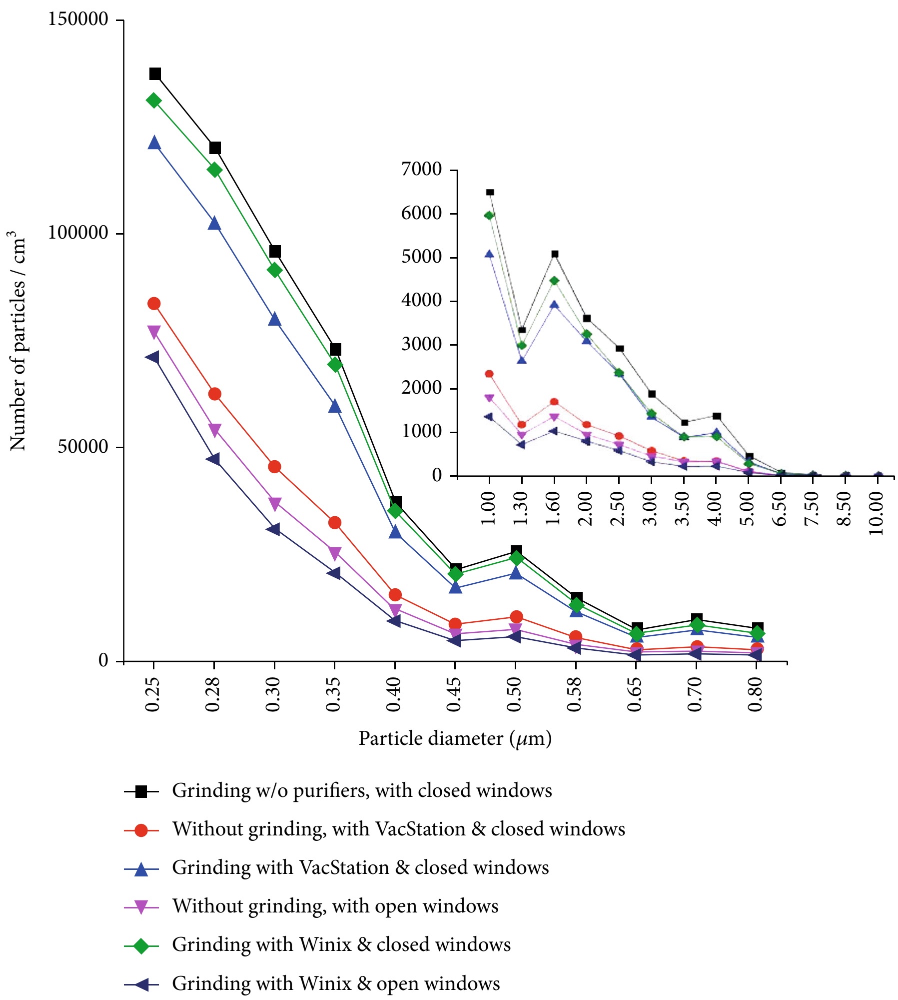


Figure 7: Number of particulate matters recorded during grinding of natural teeth using high-speed instruments.

with closed windows and the simultaneous operation of Winix, Rohnson, and VacStation reduced by 68% for PM_{10}, 77% for $PM_{2.5}$, and 81% for PM_1, as also indicated from the preliminary research [31]. It can also be seen from Figure 2 that mean concentrations of PM_1 during grinding procedures with simultaneous operation of Winix, Rohnson, and VacStation were still lower than the background values even when the clinic windows were closed. In addition, it seems that mean concentrations of particulate matter increased compared to background levels when dental procedures were not performed, clinic's windows were open, and all three air purifiers were operated (Winix, Rohnson, and VacStation). The fact that the School of Dentistry is located on a busy road with heavy traffic results in increased outdoor concentrations of particles entering indoors through open windows [32]. To investigate whether the differences in mean concentrations of PM_1, $PM_{2.5}$, and PM_{10} fractions in the various experimental conditions were significant, the Tukey test was performed. Significance level was set at $p < 0.05$ for all analyses. The latter test indicated significant differences for the concentrations of PM_1, $PM_{2.5}$, and PM_{10} during grinding with and without the simultaneous operation of Winix, Rohnson, and VacStation and with closed windows to all other experiment (Supplementary material Tables S1, S2, S3) whereas no significant differences were found for the concentrations of PM_1, $PM_{2.5}$, and PM_{10} of background measurements and measurements during the simultaneous operation of Rohnson and Winix with open windows and without grinding.

Figure 3 shows the number of particulates recorded per size group in the different experimental conditions. The percentage reduction of particulates recorded when the Rohnson purifier was operated compared to when it was not operated was 61% for $PM_{0.25}$, 65% for $PM_{0.28}$, 66% for $PM_{0.30}$, and 65% for $PM_{0.35}$. When Winix was switched on, the number of particulates reduced by 67% for $PM_{0.25}$, 72% for $PM_{0.28}$, 75% for $PM_{0.30}$, and 78% for $PM_{0.35}$ (compared to the background values). Quantities of particles recorded when clinic windows were open and with the simultaneous use of both the Winix and Rohnson purifiers reduced by 20% for $PM_{0.25}$, 19% for $PM_{0.28}$, 14% for $PM_{0.30}$, and 8% for $PM_{0.35}$, and when all three purifiers were operated simultaneously, particulate matter in the air reduced by 38% for $PM_{0.25}$, 44% for $PM_{0.28}$, 46% for $PM_{0.30}$, and 45% for $PM_{0.35}$. Keeping windows open is the only way to increase air exchange within an indoor

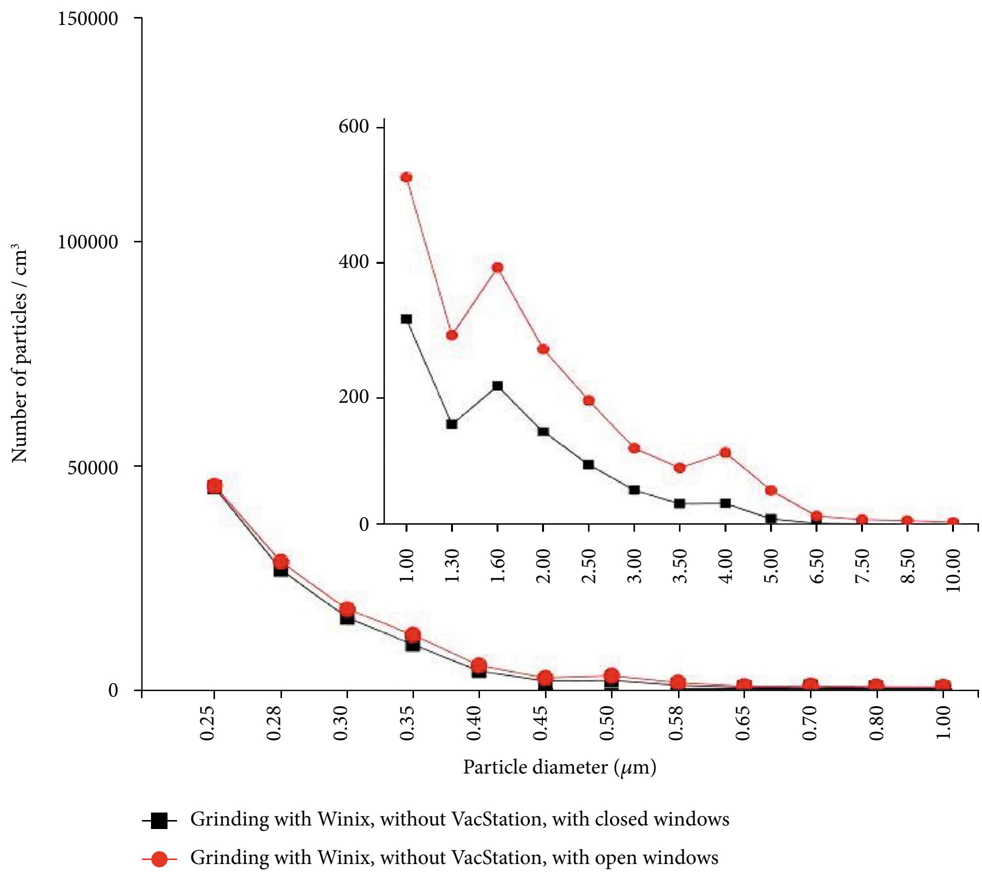


FIGURE 8: Number of particulate matters measured in different conditions while grinding using low-speed instruments.

workspace and results in reduced numbers of potentially infectious entities occurring within that space. Therefore, the time needed for an individual to be exposed to an infection-inducing dose of viral load increases. Frequent air renewal also helps to improve the air quality of indoor spaces as it lowers concentrations of airborne particulates. However, the introduction of outdoor particulate matter into indoor areas can sometimes reduce indoor air quality (e.g., in urban housing close to main roads), and for this reason, a lower percentage reduction of airborne particles was observed when air purifiers were used in combination with open clinic windows. The number of particles recorded during grinding with the simultaneous operation of the three air purifiers reduced by 77% for $PM_{0.25}$, 81% for $PM_{0.28}$, 82% for $PM_{0.30}$, and 82% for $PM_{0.35}$, while under the same conditions but with open clinic windows, the particles reduced by 53% for $PM_{0.25}$, 64% for $PM_{0.28}$, 72% for $PM_{0.30}$, and 77% for $PM_{0.35}$.

Figures 4(a) and 4(b) show the masses of the particulate matter recorded in the experiments when dental procedures were not carried out (Figure 4(a)) and when dental procedures were carried out (Figure 4(b)). The majority of the particulates captured had diameters of 0.25-0.30 μm, 0.5 μm, and 1.0-4.0 μm, while particulates with diameters of 0.65 μm and >5.0 μm were the least commonly observed in all experiments.

Concentrations of PM_1, $PM_{2.5}$, and PM_{10} recorded during grinding procedures carried out using high-speed rotating instruments with and without the simultaneous use of air purifiers are shown in Figure 5. In experiments where dental procedures were performed without air purifiers and with closed windows, the mean concentrations recorded were $547 \pm 517\,\mu g/m^3$ for PM_{10}, $205 \pm 180\,\mu g/m^3$ for $PM_{2.5}$, and $51 \pm 43\,\mu g/m^3$ for PM_1. In these conditions, the highest recorded concentrations of PM_{10}, $PM_{2.5}$, and PM_1 were 1535, 485, and 97 $\mu g/m^3$, respectively. When grinding was performed in combination with operational VacStation and closed clinic windows, the mean concentrations recorded were $400 \pm 205\,\mu g/m^3$ for PM_{10}, $161 \pm 75\,\mu g/m^3$ for $PM_{2.5}$, and $41 \pm 18\,\mu g/m^3$ for PM_1, with the highest concentrations measured being 635 $\mu g/m^3$ for PM_{10}, 253 $\mu g/m^3$ for $PM_{2.5}$, and 64 $\mu g/m^3$ for PM_1. The percentage reduction of particles recorded before and after the use of VacStation during tooth grinding was 27% for PM_{10}, 21% for $PM_{2.5}$, and 19% for PM_1. Figure 5 also presents the particle concentrations measured during grinding with the simultaneous use of the Winix purifier, without the use of VacStation, and with closed clinic windows. In these conditions, the mean concentrations of PM_{10}, $PM_{2.5}$, and PM_1 were $402 \pm 325\,\mu g/m^3$, $175 \pm 145\,\mu g/m^3$, and $47 \pm 36\,\mu g/m^3$, respectively. It can be seen that concentrations of particles measured during grinding procedures with either operational Winix or VacStation

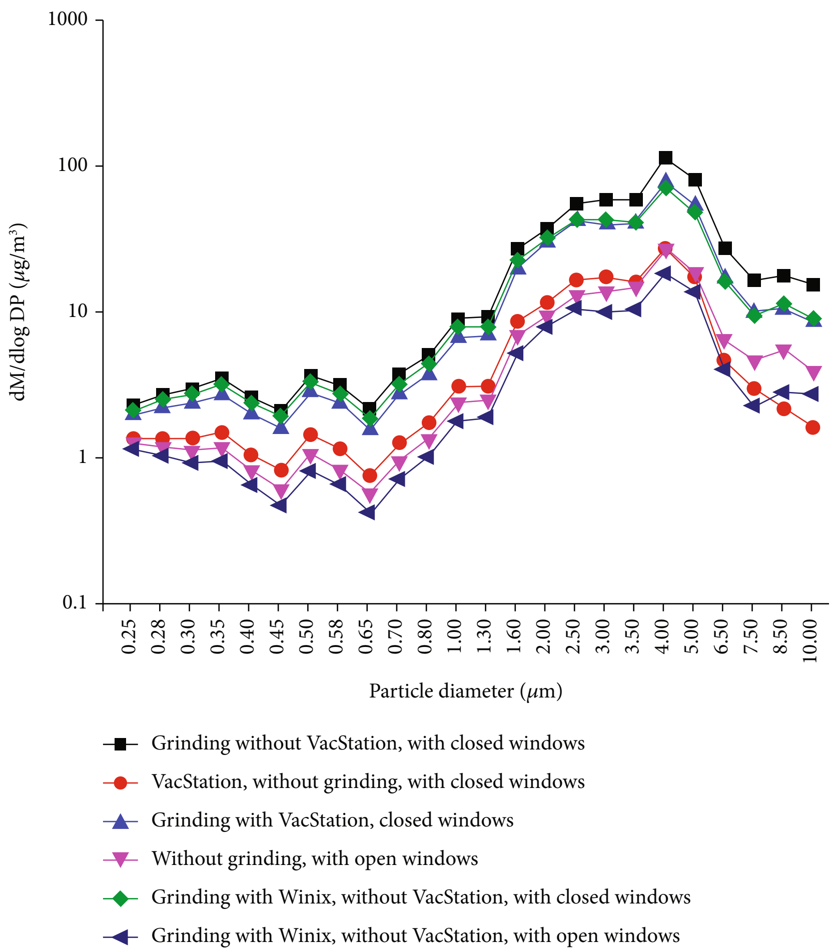


Figure 9: Mass of different-sized particles measured in different conditions while grinding using high-speed instruments.

and closed windows remained roughly the same. However, when grinding was carried out with the simultaneous use of Winix, without VacStation, and with open clinic windows, particle concentrations reduced by 73% for PM_{10}, 73% for $PM_{2.5}$, and 65% for PM_1. The differences recorded between concentrations of particulate matter in the various experimental conditions were found to be statistically significant (Tukey, $p < 0.05$).

Concentrations of PM_1, $PM_{2.5}$, and PM_{10} recorded during grinding procedures carried out using low-speed rotating instruments with and without the simultaneous use of air purifiers are shown in Figure 6. During grinding with the simultaneous use of Winix and VacStation and with closed clinic windows, the mean concentrations of PM_{10}, $PM_{2.5}$, and PM_1 were $22 \pm 7\,\mu g/m^3$, $14 \pm 4\,\mu g/m^3$, and $8 \pm 2\,\mu g/m^3$, respectively. When grinding was carried out using low-speed instruments with the simultaneous use of Winix, without VacStation, and with closed clinic windows, mean particle concentrations were $60 \pm 40\,\mu g/m^3$ for PM_{10}, $22 \pm 13\,\mu g/m^3$ for $PM_{2.5}$, and $10 \pm 5\,\mu g/m^3$ for PM_1. The reduction in particle concentrations observed when using both Winix and VacStation was 63% for PM_{10}, 37% for $PM_{2.5}$, and 18% for PM_1.

Figure 7 shows the number of particles recorded per size class during grinding procedures on natural teeth using high-speed rotating instruments with and without the simultaneous use of air purifiers. Most of the particles generated in these conditions were found to be 0.25-0.35 nm in size. During grinding with closed windows and operational VacStation, the number of particles reduced by 12% for $PM_{0.25}$, 20% for $PM_{0.50}$ and $PM_{2.5}$, 30% for PM_5, and 40% for PM_{10} compared to values recorded when VacStation was not applied. It is notable that particle numbers reduced by 44% for $PM_{0.25}$, 70% for $PM_{0.5}$, 75% for $PM_{2.5}$, 76% for PM_5, and 68% for PM_{10} when the clinic windows were opened and dental procedures were not taking place. It can be seen in Figure 7 that during grinding using high-speed instruments with only the Winix purifier operating, the number of particles is greater than that observed when using VacStation. However, particle numbers appear to reduce significantly when dental procedures are performed with a working Winix and open windows. In this case, reductions of 46%, 76%, 75%, 71%, and 70% were observed for $PM_{0.25}$, $PM_{0.5}$, $PM_{2.5}$, PM_5, and PM_{10}, respectively. The differences recorded between concentrations of particulate matter in the three experimental conditions were found to

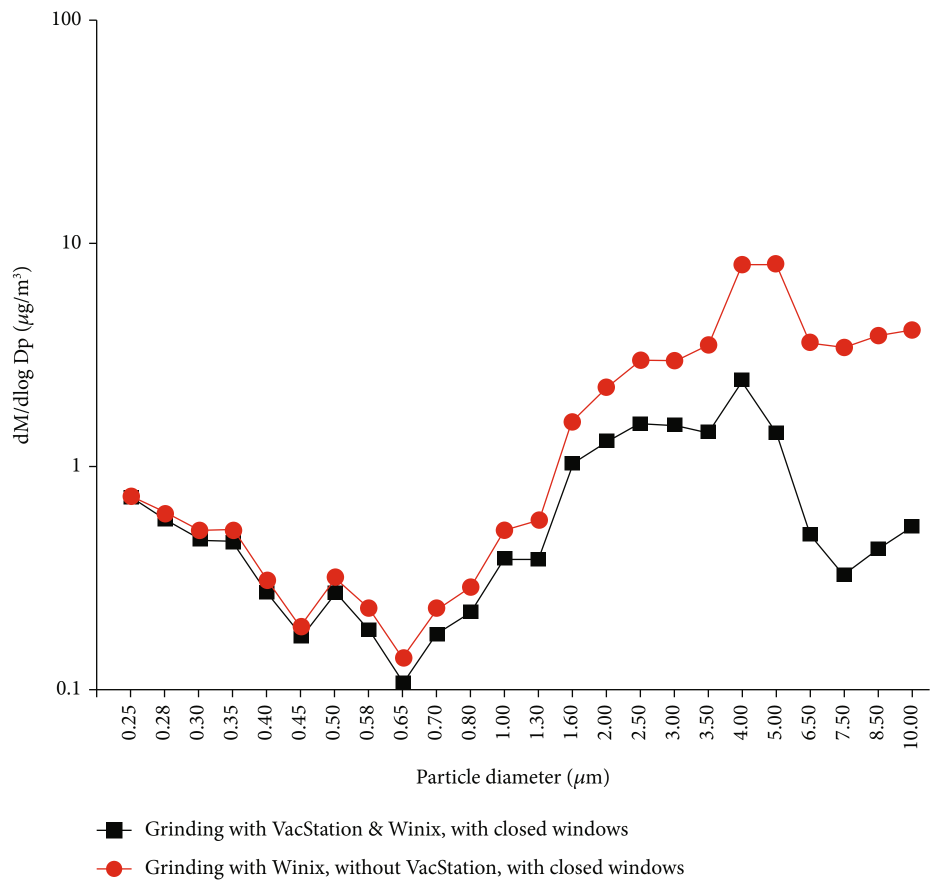


Figure 10: Mass of different-sized particles measured in different conditions while grinding using low-speed instruments.

be statistically significant (Tukey, $p < 0.05$). Grinding using high-speed equipment produced particles of sizes 0.25 μm, 0.30 μm, 0.35 μm, and 1.60 μm. This result is in agreement with the work of Liu et al. [27], who found that most particles produced in dental procedures have diameters of <5 μm. Comparison of the two figures shows that high-speed rotating instruments generate more aerosols than low-speed instruments.

Figure 8 presents the number of particles per size recorded during grinding procedures on natural teeth using low-speed rotating instruments with and without the simultaneous use of air purifiers. The numbers of particles recorded when using low-speed instruments and air purifiers were three (3) times lower for $PM_{0.25}$, ten (10) times lower for $PM_{0.5}$, twenty-eight (28) times lower for $PM_{2.5}$, forty (40) times lower for PM_5, and fifteen (15) times lower for PM_{10} than when high-speed equipment was used in the same conditions. The figures show that grinding using high-speed equipment generated more particles.

Particle masses per size class recorded in different conditions during grinding using both high-speed (Figure 9) and low-speed (Figure 10) instruments are shown below. It can be seen that when using both high- and low-speed instruments, most of the particles generated were 2-5 μm in size.

4.2. Second Measurement Cycle (with Central Ventilation System). The measurements of airborne particles taken in a dental clinic with the simultaneous operation of a central ventilation system are described below. Figure 11 presents the mean concentrations of particulate matters PM_1, $PM_{2.5}$, and PM_{10} recorded in different conditions. The mean concentrations of particles recorded while dental procedures were being carried out and the central ventilation system was switched on were $20 \pm 4\,\mu g/m^3$ for PM_{10}, $12 \pm 1\,\mu g/m^3$ for $PM_{2.5}$, and $10 \pm 1\,\mu g/m^3$ for PM_1. It should be noted that on days when dental work was carried out on real patients, a window was left open to aerate the treatment room. The concentration of particles recorded with the simultaneous operation of both ventilation system and air purifiers fell by 30% for PM_{10} compared to concentrations recorded when only the central ventilation was switched on. However, the combination of ventilation and Airocide reduced concentrations of PM_{10} by 15%, $PM_{2.5}$ by 26%, and PM_1 by 27%. The simultaneous use of ventilation and Winix reduced PM_{10} concentrations by 15% while concentrations of $PM_{2.5}$ and PM_1 remained constant. Figure 11 also shows that the mean concentrations of PM_1 recorded during dental procedures carried out with ventilation and Airocide remained lower than those recorded when using ventilation alone. Significant differences in particle matter concentrations were not observed with the simultaneous operation of the central ventilation system and Winix and Rohnson air purifiers whereas significant differences were found during the operation of the central ventilation system and Airocide.

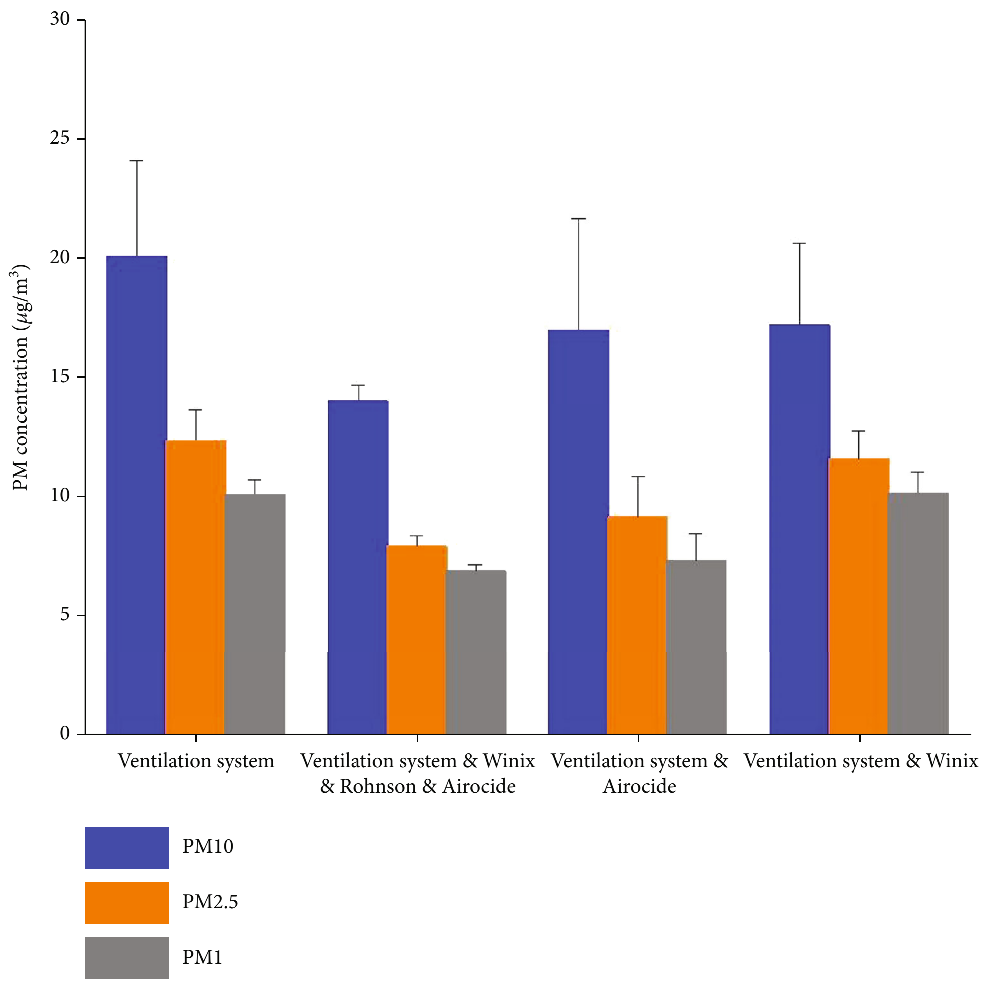


Figure 11: Mean concentrations of PM_1, $PM_{2.5}$ and PM_{10} recorded during dental procedures carried out with the simultaneous operation of the central ventilation system and various air purifiers.

The statistically significant differences recorded between results of different conditions are shown in Tables S5-S6-S7 in the Supplementary Material.

The number of particles per size class measured in the different experimental conditions is presented in Figure 12. It can be seen that a reduction of particulate matter occurs when the central ventilation system is used in combination with the Winix, Rohnson, and Airocide air purifiers. A 51% reduction in 0.25 μm particles was achieved when using ventilation with the Airocide purifier.

Figure 13 shows the mass of particles per size measured while dental procedures were being carried out in the clinic with the simultaneous operation of the central ventilation system and air purifiers. The majority of the particulates captured had diameters of 0.25-0.30 μm, 0.5 μm, and >0.8 μm, while particulates with diameters of 0.65 μm were the least commonly observed in all experiments.

5. Discussion

The purpose of this study was to measure the number and concentration of airborne particulates occurring within a dental clinic while performing different dental procedures that produce aerosols, with and without the simultaneous use of air purifier systems and a central ventilation system. The results showed a reduction in airborne particulates and hence a potential reduction in SARS-CoV-2 virus transmission risk. The aerosols generated by standard dental procedures can cause transmission of the virus to both staff and others present within the treatment area. As with all infections, although it is impossible to completely eliminate the risk of transmission, it is crucial that appropriate air purifying systems are applied to minimize risk of transmission as much as possible [33].

Results from the first measurement cycle conducted without the use of the clinic's central ventilation system showed that the use of air purifiers during dental work can reduce concentrations of particulate matter during dental procedures. The initial concentrations of airborne particulates recorded during dental procedures, i.e., grinding of natural teeth and metals, without the use of air purifier systems, and with closed windows, reduced by 68% for PM_{10}, 77% for $PM_{2.5}$, and 81% for PM_1 when the same procedures were carried out with the simultaneous use of air purifying systems (Winix, Rohnson, and VacStation). Reduced concentrations were also recorded when clinic windows were kept

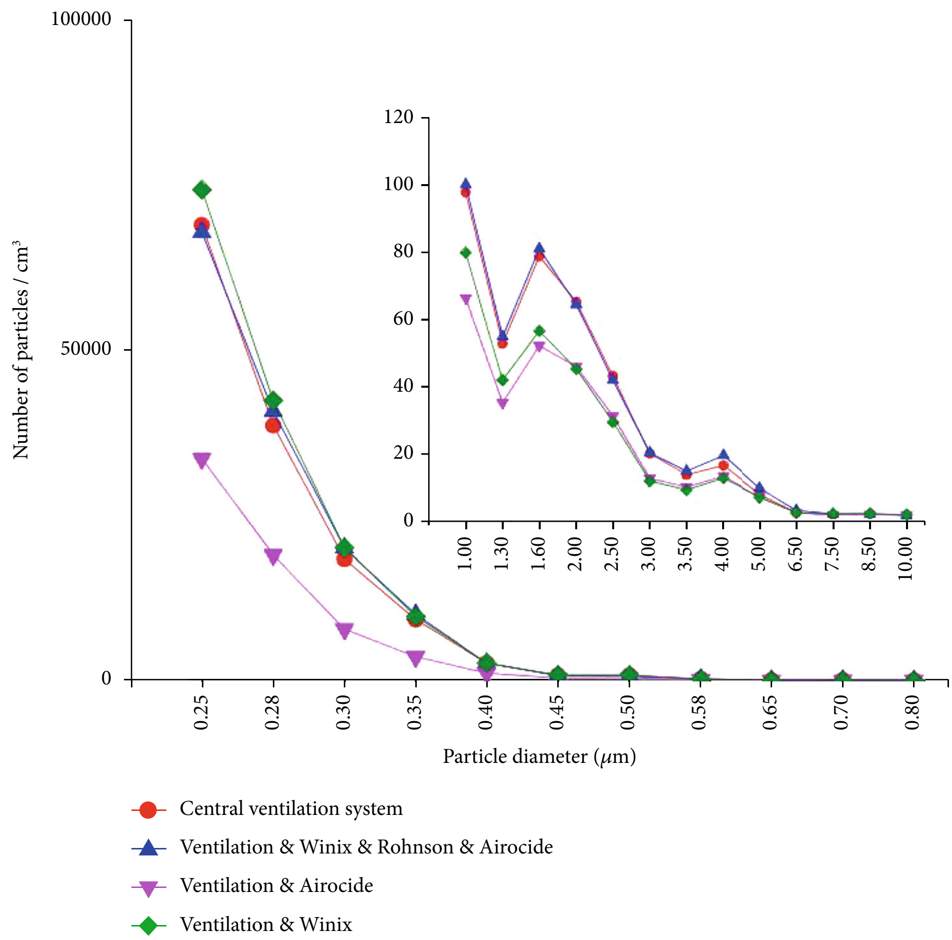


Figure 12: Sizes of particles recorded with the simultaneous operation of the central ventilation system and air purifiers.

open during tooth grinding work and air purifying systems were used (Winix, Rohnson, and VacStation). In this case, concentrations of airborne particles reduced by 78% for PM_{10}, 83% for $PM_{2.5}$, and 76% for PM_1. Mean concentrations of particulate matter recorded during grinding procedures reduced significantly when clinic windows were opened and air purifiers were used. Indeed, in this study, the use of air purifiers reduced concentrations of particles with diameters < 1 μm. The number of particles observed during grinding procedures with simultaneous use of air purifier systems reduced by 77% for particles with diameters of 0.25 μm ($PM_{0.25}$), 81% for $PM_{0.28}$, 82% for $PM_{0.30}$, and 82% for $PM_{0.35}$.

As airborne particles < 1 μm in diameter can enter human lung alveoli, they can also potentially harm the respiratory system [34]. The use of air purifiers can significantly reduce numbers of <1 μm sized particles and therefore improve air quality in indoor spaces.

Recent studies have shown that the SARS-CoV-2 virus can be transmitted by particulate matter [25] and a positive correlation has been found between airborne particulates $PM_{2.5}$ and the transmission of other viruses, including the influenza virus [26]. The correct positioning of air purifier and extraoral vacuum systems close to a patient's body can reduce aerosol spread by up to 90%. A clinical study carried out by Nulty et al. [33] found a statistically significant difference between the numbers of particles recorded during a variety of dental procedures when the VacStation system was in operation. The continuous operation of air purifiers in combination with aeration acts definitively in maintaining low levels of particles within treatment facilities.

When grinding was carried out with the simultaneous operation of the Winix purifier and the clinic's windows were open, concentrations of PM_{10} airborne particles reduced by 73%, while those of $PM_{2.5}$ and PM_1 reduced by 73% and 65%, respectively. In addition, the present study showed that concentrations of particles measured during grinding of natural teeth using low-speed equipment and an air purifier were lower than those recorded when using high-speed equipment.

Results of the second measurement cycle carried out during dental procedures showed that an operating central ventilation system contributes to the reduction of airborne particles by a significant 94% for PM_{10}, 94% for $PM_{2.5}$, and 88% for PM_1 compared to dental procedures performed without the simultaneous use of air purifiers. Air purifying systems were also observed to contribute to the further reduction of airborne particulates when dental procedures

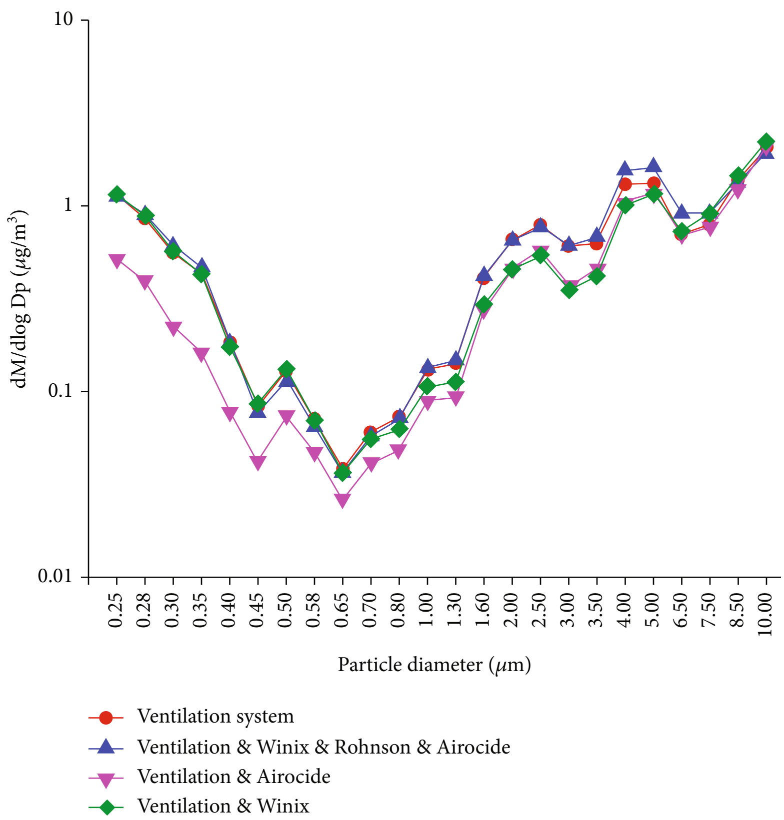


FIGURE 13: Mass per size of particles recorded with the simultaneous operation of the central ventilation system and air purifiers.

were performed in combination with an operating central ventilation system. The number of particles observed when carrying out dental treatments on patients with the central ventilation system switched on was seen to reduce by 74% for those with diameters of 0.25 μm ($PM_{0.25}$), 83% for $PM_{0.28}$, 90% for $PM_{0.30}$, and 93% for $PM_{0.35}$.

These results show that the use of a central ventilation system is advised for any dental clinic and indeed for any busy indoor spaces, especially health care facilities. Additionally, the results of this study indicate that air purifier systems operated in combination with a central ventilation system contribute to the further reduction of potentially hazardous aerosols.

As the cost of installing a central ventilation system in the premises of a small, private, dental clinic is often prohibitive, it is recommended to use air purifiers during treatment procedures. Results of this study showed that PM_{10} concentrations reduced by 60%, $PM_{2.5}$ by 37%, and PM_1 by 18% during grinding procedures when VacStation and Winix were applied without central ventilation. Chen et al. [30] used computational fluid dynamics (CFD) and observed that particles generated by dental procedures with diameters < 10 μm are more likely to be removed from the atmosphere by air purifiers.

This is the first study to investigate the effects of a central ventilation system and different air purification systems on the size of the aerosols generated by standard dental treatment procedures. The results showed a statistically significant difference between the concentrations of particulate matter generated by dental procedures under different conditions. There is a high risk of SARS-CoV-2 virus transmission in dental clinics due to the aerosols emitted by the use of common dental instruments during standard treatments. Considering the necessity of dental treatments even during the SARS-CoV-2 pandemic, the use of air purifiers is highly recommended as an effective and economic means of reducing virus transmission, especially in small clinics/treatment areas.

Data Availability

Data are available upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Supplementary Materials

The supplementary material presents the statistical analysis of the results compared by applying one-way analysis of variance (ANOVA), with a Tukey significance level of 0.05. Comparisons of means recorded during dental procedures carried out with and without the simultaneous operation of air purifiers and central ventilation system. Table S1 presents the statistical results of the Tukey comparison of

PM_{10} means for every dental procedure between the grinding occurred with and without the use of each air purifier (Winix, Rohnson, and VacStation) with opened or closed windows and the background measurements. Significance level was set at $p < 0.05$ for all analyses. Table S2 presents the statistical results of the Tukey comparison of $PM_{2.5}$ means for every dental procedure between the grinding occurred with and without the use of each air purifier (Winix, Rohnson, and VacStation) with opened or closed windows and the background measurements. Significance level was set at $p < 0.05$ for all analyses. Table S3 presents the statistical results of the Tukey comparison of PM_1 means for every dental procedure between the grinding occurred with and without the use of each air purifier (Winix, Rohnson, and VacStation) with opened or closed windows and the background measurements. Significance level was set at s for all analyses. Table S4 presents the statistical analysis of the results of the Tukey comparison of every dental procedure when grinding natural teeth using low-speed instruments with and without the use of each air purifier (Winix and VacStation) with opened or closed windows. Significance level was set at $p < 0.05$ for all analyses. Table S5 presents the statistical results of the Tukey comparison of PM_{10} means for every dental procedure when using the central ventilation system alone or using it in combination with each air purifier (Winix, Rohnson, and Airocide). Significance level was set at $p < 0.05$ for all analyses. Table S6 presents the statistical results of the Tukey comparison of $PM_{2.5}$ means for every dental procedure when using the central ventilation system alone or using it in combination with each air purifier (Winix, Rohnson, and Airocide). Significance level was set at $p < 0.05$ for all analyses. Table S7 presents the statistical results of the Tukey comparison of PM_1 means for every dental procedure when using the central ventilation system alone or using it in combination with each air purifier (Winix, Rohnson, and Airocide). Significance level was set at $p < 0.05$ for all analyses. *(Supplementary Materials)*

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