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Aerosol generation and control in the dental operatory

Ph.D. Thesis

Dorottya Gheorghita, D.M.D.

Supervisor:

Dr. habil. Márk Ádám Antal, D.M.D., Ph.D.,

Department of Operative and Esthetic Dentistry

Faculty of Dentistry

University of Szeged

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1. LIST OF PUBLICATIONS

1.1. Publications covered in and related to the subject of the thesis

I. Kun-Szabó F, **Gheorghita D,** Ajtai T, Hodovány S, Bozóki Z, Braunitzer G, Antal MÁ. Aerosol generation and control in the dental operatory: An in vitro spectrometric study of typical clinical setups. PLoS One. 2021 Feb 4;16(2):e0246543. Doi: 10.1371/journal.pone.0246543. PMID: 33539439; PMCID: PMC7861533.

IF: 3.752 **SJR ranking: Q1**

II. **Gheorghita D**, Kun Szabó F, Ajtai T, Hodovány S, Bozóki Z, Braunitzer G, Antal MÁ. Aerosol Reduction of 2 Dental Extraoral Scavenger Devices In Vitro. Int Dent J. 2022 Oct;72(5):691-697. Doi: 10.1016/j.identj.2022.05.007. Epub 2022 Jun 2. PMID: 35810011; PMCID: PMC9159968.

IF:3.3 **SJR ranking: Q1**

Summed IF: 7.052

1.2. Publications not related to the subject of the thesis

I. **Gheorghita D**, Eördegh G, Nagy F, Antal M. A fogágybetegség mint az atheroscleroticus cardiovascularis betegség rizikófaktora [Periodontal disease, a risk factor for atherosclerotic cardiovascular disease]. Orv Hetil. 2019 Mar;160(11):419-425. Hungarian. Doi: 10.1556/650.2019.31301. PMID: 30852909.

IF: 0,497 **SJR ranking: Q3**

II. Battancs E, **Gheorghita D**, Nyiraty S, Lengyel C, Eördegh G, Baráth Z, Várkonyi T, Antal M. Periodontal Disease in Diabetes Mellitus: A Case-Control Study in Smokers and Non-Smokers. Diabetes Ther. 2020 Nov;11(11):2715-2728. Doi: 10.1007/s13300-020-00933-8. Epub 2020 Sep 25. PMID: 32975709; PMCID: PMC7547922.

IF: 2,945 **SJR ranking: Q2**

III. Nagy FT, **Gheorghita D**, Dharmarajan L, Braunitzer G, Achim A, Ruzsa Z, Antal MÁ. Oral Health of Patients Undergoing Percutaneous Coronary Intervention-A Possible Link between Periodontal Disease and In-Stent Restenosis. J Pers Med. 2023 Apr 28;13(5):760. Doi: 10.3390/jpm13050760. PMID: 37240930; PMCID: PMC10222515.

SJR ranking: Q2

IV. **Gheorghita D**, Antal MA, Nagy K, Kertesz A, Braunitzer G. Smoking and Psoriasis as Synergistic Risk Factors in Periodontal disease. Fogorv Sz. 2016 Dec;109(4):119-124. English, Hungarian. PMID: 29949256.

SJR ranking: Q4

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2. Abbreviations

CDC: Centers for Disease Control and Prevention

CI: confidence interval

CFU: colony forming unit

CMD: count median diameter

dN: total number concentration

Dp: particle diameter

DS-AE: direct spray with aerosol exhaustor

DS-HVE: direct spray with high volume evacuator

EEPS-3090: engine exhaust particle sizer spectrometer

EOS: extraoral scavenger device

FFPs: filtering facepieces (FFP1, FFP2, FFP3)

HVE: high volume evacuator

HST: high-speed turbine

IPS: instrument protecting shield (plastic shield to protect the spectrometer from the produced water aerosol)

IS-AE: direct spray with aerosol exhaustor

IS-HVE: indirect-spray with high volume evacuator

PPE: personal protective equipment

SARS: Severe Acute Respiratory Syndrome

SARS-CoV-2: Severe acute respiratory syndrome coronavirus 6

SE: saliva ejector

SST: sampling tube of the spectrometer

TNC: the total number of particles/cm^3

TNC 60.4-392.4: the number of particles in the 60.4-392.4 nm range/cm^3

US-AE: ultrasonic scaler with aerosol exhaustor

US-HVE: ultrasonic scaler with high volume evacuator

wa: water aerosol

WEL: workplace exposure limit

3. Introduction

Aerosol itself is a commonly known medium responsible for transmitting various diseases. During the COVID-19 epidemic the importance of prevention has risen steeply. So that, deeper interest towards the aerosol and its examination in different fields of medicine has appeared. Transmission routes for SARS-CoV-2 include airborne transmission through the inhalation of droplets and aerosols, with an apparent predominance of aerosol transmission [1-5]. It has been documented that approximately 1 in 5 to 1 in 10 asymptomatic individuals harbor SARS-CoV-2 in either their saliva or respiratory secretions [6]. Thus, it has been recommended that dental personnel use protective equipment during treatment, such as FFP 2 or 3 masks [7]. It has been concluded, though, that even FFP masks cannot offer complete protection [8]

In terms of aerosol production, dentistry is a high-risk profession [7, 9, 10]. The importance of aerosol and spatter contamination for dental professionals and their team has been investigated for about 30 years [1, 11, 12]. This topic has been investigated from different approaches. In 2015, Holloman et al. focused on the splatter reducing methods during ultrasonic scaling [13], while others tried to reduce the bacterial contamination of the aerosol with the help of preoperative rinsing and high-volume evacuators (HVE) [14]. Rupf et al. found HVE is a necessary and significant instrument in terms of reducing the exposure of the dental staff and the patient when ultrafine particles are applied during optical scanning methods [15]. On the contrary, according to Desarda and colleagues, the sole usage of HVE cannot reduce the aerosol counts [16]. Based on Devker's study, HVE alone is still effective in reducing environmental contamination, however it is suggested to be combined with chlorhexidine- containing pre-operative mouth rinsing for better results [17]. This method can decrease the amount of the mean colony forming bacterial units during ultrasonic scaling. These early studies were focusing on the 2 main sources of aerosol production in dentistry: dental turbine and ultrasonic scalers [15-18]. Nevertheless, before the pandemic, other methods – e.g., extraoral suction units, special protective layers, or protocols – were not in the centre of interest.

It was foreseeable that the pandemic would boost the need –or aerosol control in dentistry, but in lack of empirical data on what concentrations of aerosol are generated during a treatment and how effectively aerosol concentration is reduced by aerosol control systems, it is difficult to give evidence-based recommendations. The available recommendations (mostly from before the outbreak) fail to offer more than emphasizing the importance of aerosol control. For instance, CDC has recommended the use of HVE for long, but it is not supported by actual measurements and no comparison is offered with other systems [19-21]. Of course, before COVID-19, aerosol generation did not seem to be a crucial issue, even if its importance was recognized. However, the new situation demands a different approach, especially that new aerosol control systems are appearing on the market.

It is already known that SARS-CoV-2 can remain viable and infectious in aerosols for up to 3 hours so to work with open windows and keep 10 to 15-minute periods of airing between patients are often seen recommendations [22]. Regarding air conditioning units, recommendations range from not to use [23] them at all to use but sanitize frequently [24].

3.1. Importance of the aerosol particle size

After the first pandemic, there was more understanding of the virus and the infection itself, so that dentists were able to prepare with effective preventive and protective methods. The virus may attach to aerosol particles of various sizes, resulting in combined particle sizes from 60 to 300 nm [25]. In 2004, it was declared that SARS or tuberculosis can be a dangerous airborne infection in dental the dental office, since these pathogens are able to travel on the aerosol particles produced during dental treatment. Aerosol particles under 10 μm (10 000 nm) can penetrate even the smallest airways in the lungs , the usage of facemasks and preoperative mouth rinsing are crucial elements of the infection control protocols [26]. While the expected performance of filtering facepieces (FFPs) is regulated in standards, relatively little is known about their real-life performance. The standards only determine the filtering efficacy in percentage, respectively 80% for FFP1, 94% for FFP2 and 99% for FFP3 masks [27]. These masks may be used with contaminant concentrations up to 4 -10 -20 times the workplace exposure limit (WEL). They are effective against airborne biological agents of the risk group 2+3 and enzymes -according to the EN 149:2001+A1:2009 European Union standardization [28]. Filtration efficacy of different respirator systems and protective layers was examined in 2013 by Jung et al. [27] They measured the inward and outward airflow direction with the help of a 2% NaOCl aerosol with a count median diameter (CMD) of 75 ± 20 nm. They found that the penetration efficiency of medical masks ranged from 10% to 90%, except for one product (certified as a N95 class), which showed 1.82% penetration. FFP2 masks had superior results compared to the conventional surgical or dental masks. Ever since then, only Lee and colleagues

[8], have paid attention to this question defining the size of particles can penetrate the FFP masks. They found that FFP 1-3 masks protected invariably well against particles in the 93-1610 nm range but found a range of (not significantly) weaker protection between 263 and 384 nm. Thus, while they perform well, even FFP masks cannot offer complete protection.

3.2. Extraoral scavenger devices (EOSs)

A recent study has described the contamination of the operatory during dental treatment of patients infected with SARS-CoV-2 and concluded that high-volume suction should be used during dental treatments in COVID-19 patients.[29] Such decontamination is especially important because SARS-CoV-2 can remain viable and infectious in aerosols for up to 3 hours, which puts not only the dental personnel at risk but also the patients who enter the same operatory where patients with COVID-19 have previously been treated. [30]

During certain dental treatment types, the risk of infection due to the aerosol production is extremely high. When ultrasound scalers are used for the removal of the temporary filling, or for professional oral hygiene treatment, the maxillary region is the most dangerous regarding the amount and spreading direction of the aerosol. The other scenario is the upper front class III or IV cavity preparation with palatal access, where the water spray is directed outwards. In such cases the use of rubber dam can prevent the mingling of the oral flora and the water spray of the high-speed turbine [31]. Based on clinical experience and the study of Al-Amad et al., by using the rubber dam, the aerosol is even more directed outwards, so that the amount of colony forming unit (CFU) detected on the facial area of the dentist is also higher. [32] Their results indicates that the use of rubber dam is associated with significantly higher bacterial aerosol levels. Based on these findings, proper evacuation is strictly necessary to reduce the chance of airborne infection.

As the rubber dam cannot be placed in all situations due to the wide range of dental treatments accompanied by aerosol formation, or in certain cases it can increase the infectious aerosol directly [32]. In these cases, the use of saliva ejector together with HVE is not sufficient for satisfactory aerosol control [33].

The availability of extraoral scavenger devices has increased after the outbreak of the pandemic. At the same time, there was scarce information on the effectivity and usage of these instruments in dentistry. Earlier studies were not specific enough due to the lack of purpose-manufactured equipment available on the market [34-36]. Teanpaisan et al. demonstrated that a modified household vacuum cleaner can be effectively used for reducing aerosol dissemination into the airspace of the dental operatory [34]. King et al. concluded that aerosol concentration was substantially reduced six inches away from a patient when using an aerosol reduction device [37]. However, until the outbreak of the COVID-19 pandemic, the topic had not generated much interest. Questions such as the above-mentioned particle size range in which such devices are effective or the comparative efficiency of the available models in specific dental interventions remained unanswered.

4. Aims of the study

Our research is composed of two different layers to understand the spreading properties of the aerosol formed during dental treatments and to measure the efficacy of the extraoral scavenger devices.

The first in vitro study was to model typical treatment setups to find out about aerosol production and aerosol control in a clinically relevant manner. The setups were defined by the instrument (high-speed turbine with air spray or ultrasonic scaler with air spray) and the applied aerosol control system (the conventional high-volume evacuator or a lately introduced aerosol exhaustor). The turbine and the ultrasonic scaler are used differently: when used correctly, the water spray from the ultrasonic scaler always hits the teeth first (i.e., aerosol never gets directly in the air). In contrast, the turbine is moved around in all directions during a treatment, so aerosol spreads both directly and indirectly. Thus, for the turbine measurements, we differentiated between direct and indirect spray directions.

We hypothesized that both the instrument/spray direction and the aerosol control system would be significant determinants of aerosol concentration.

Other factor to be investigated was the effect of post-treatment airing:

We hypothesized that a regular method of airing manageable in any dental operatory would be sufficient to reduce aerosol concentration in a clinically reasonable timeframe between two treatments.

Based on the first investigation, the aim of the second study was to examine the aerosol reduction efficiency of 2 different extraoral scavenger devices (EOSs) in an experimental setting, modelling dental treatment with a high-speed turbine. Our aim was to model only the most difficult-to-control scenario, where aerosol gets in the air directly from the high-speed turbine. The effect of saliva ejector together with a high-volume evacuator (HVE) is not sufficient for satisfactory aerosol control.

We hypothesised that both EOSs would significantly reduce the aerosol load.

5. Materials and Methods

5.1. Measuring aerosol production and control

The setups to measure the aerosol production were defined by the instrument (high-speed turbine with air spray or ultrasonic scaler with air spray) and the applied aerosol control system (the conventional high-volume evacuator or a lately introduced aerosol exhaustor). The effect of post-treatment airing on aerosol concentrations was also studied for each setup.

An experimental setup was prepared in a regular dental operatory (4.15 m x 2.6 m) with one door and one window (**Figure 1.**).

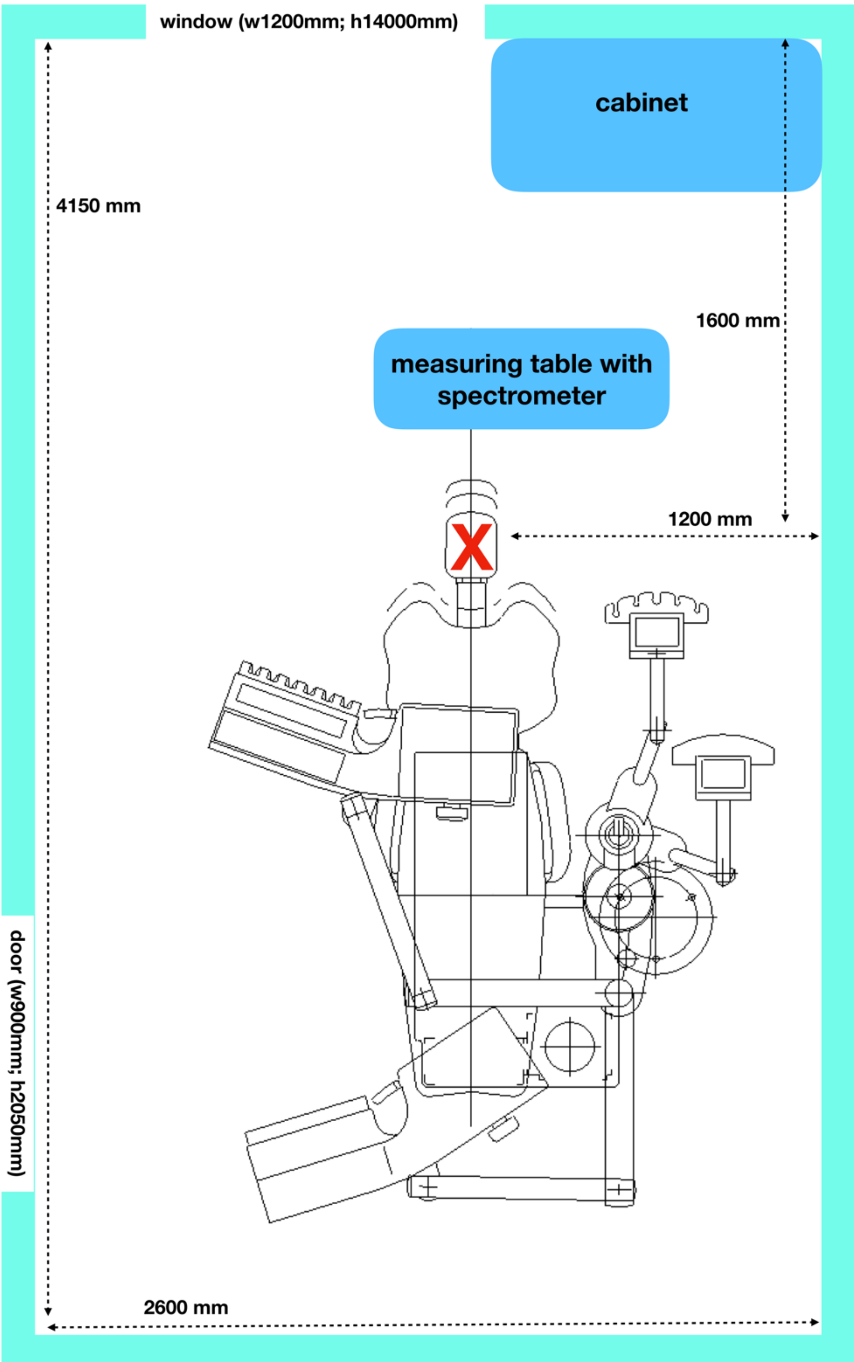

Figure 1. *Setup of the site. X marks the position of the mannequin head. The spectrometer was placed on a 935 mm high table, so its sampling tube was 970 mm above the floor of the room. At this height, the sampling tube was 20 cm over the mannequin head. The dimensions of the door and window are given as width x height.*

To simulate a patient, a mannequin head was used in the supine position. The turbine (Gentle Silence, KaVo Dental, Germany) or ultrasonic scaler (Woodpecker UDS K-LED, Woodpecker, China) was attached to a holder, which allowed to fasten the instrument in a fixed and reproducible position. The high-volume evacuator (N1, Dürr Dental, Germany) or aerosol exhaustor (DentArt Technik, Hungary) were attached to the same dental unit (KaVo 1066 T, KaVo Dental, Germany) and positioned according to the manufacturer's instructions. According to the literature, the working distance in dentistry falls between 25 – 40 cm. [38-40] As protective equipment (such as a face shield) can compromise vision, this is reduced when working in such equipment, thus maximum aerosol load was measured at 20 cm from the mannequin head. Measurements were carried out with a Scanning Mobility Particle Sizer (SMPS-3938) spectrometer (TSI, Minnesota, USA). The endpiece of the spectrometer was positioned above the head of the mannequin at this distance. (**Figure 2**.)

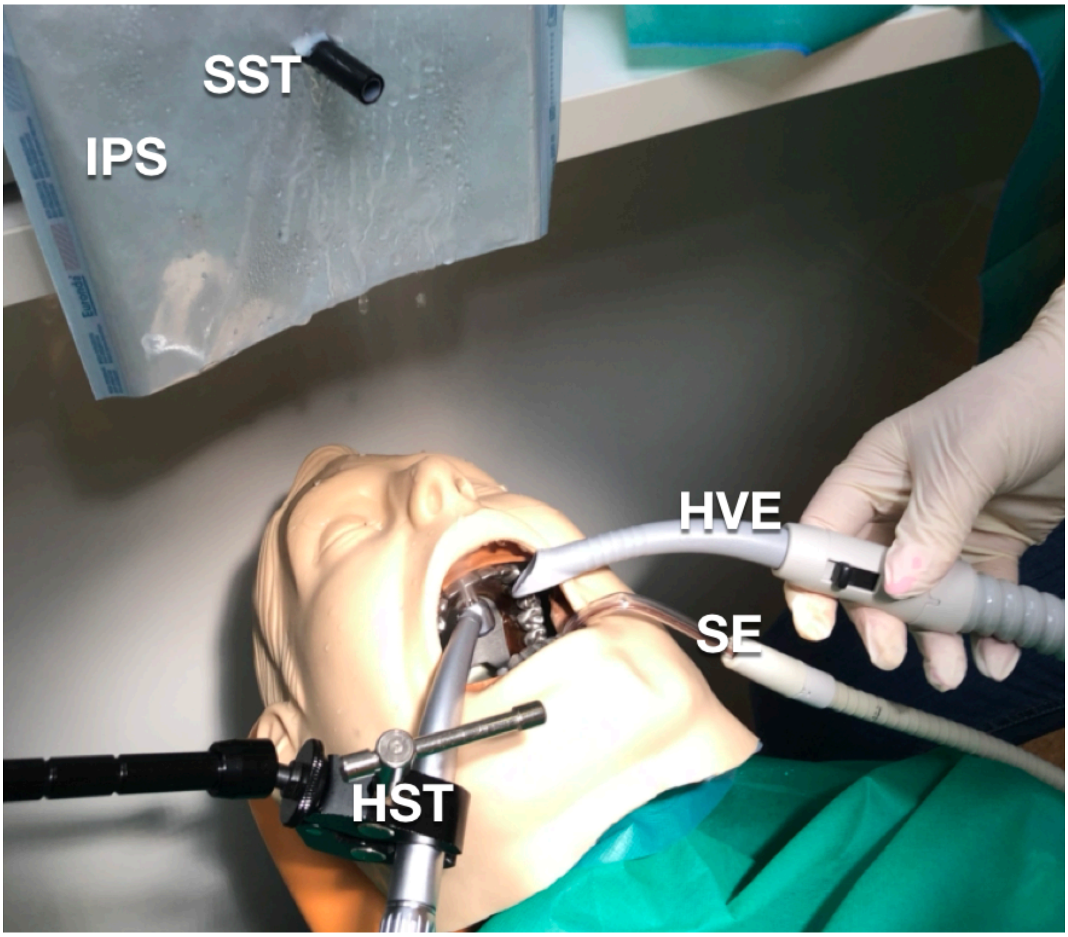

Figure 2. Close-up of the experimental setup. *The figure shows the direct spray-high volume evacuator setup (for the rest of the setups, see* ***Figure 3****). HST: high-speed turbine; SE: saliva ejector; HVE: high volume evacuator; SST: sampling tube of the spectrometer; IPS: instrument protecting shield (plastic shield to protect the spectrometer from the produced water aerosol)*

5.1.1. Test Measurements

All measurements were carried out in one day. Before the test measurements, the operatory had been intensively aired and air purified (AC3256/20, Philips, Eindhoven, Netherlands) for 12 hours. This was followed by baseline aerosol determination and then the measurements for the different setups. Aerosol reduction was repeated after each test measurement by airing (see below).

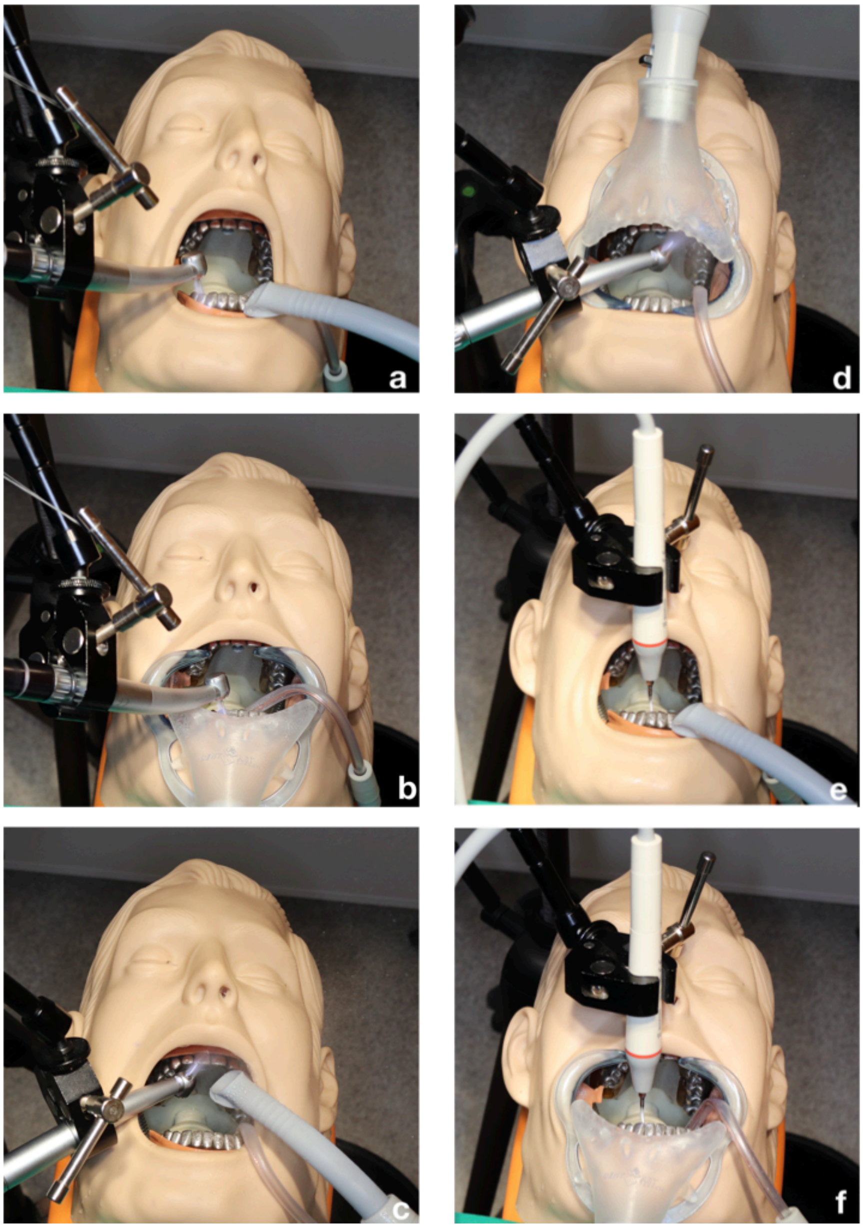

Figure 3. Setups for the modeling of the different clinical scenarios. a) *indirect spray with high volume evacuator (IS-HVE),* ***b)*** *indirect spray with aerosol exhaustor (IS-AE),* ***c)*** *direct spray with high volume evacuator (DS-HVE),* ***d)*** *direct spray with aerosol exhaustor (DS-AE),* ***e)*** *ultrasonic scaler with high volume evacuator (US-HVE),* ***f)*** *ultrasonic scaler with aerosol exhaustor (US-AE).*

The following setups were tested (shown on **Figure 3**.)

a) turbine, direct spray, high-volume evacuator (DS-HVE);

b) turbine, indirect spray, high-volume evacuator (IS-HVE);

c) turbine, direct spray, aerosol exhaustor (DS-AE);

d) turbine, indirect spray, aerosol exhaustor (IS-AE);

e) ultrasonic scaler, high-volume evacuator (US-HVE);

f) ultrasonic scaler, aerosol exhaustor (US-AE).

In the direct condition, the turbine faced the palatal surface of the maxillary front teeth allowing the spray to spread directly toward the spectrometer. In the indirect condition, the turbine faced the buccal surface of the mandibular front teeth, so the spray hit the teeth first and then spread indirectly toward the spectrometer. The measurements for each setup were carried out in triplicate, lasted 1 measurement cycle (326 s), and were separated by airing for 3 measurement cycles, during which concentration decay was measured. Values from all three measurements were used for the analyses.

Airing was done by opening both the door and the window of the operatory, while operating a standard fan directed toward the window.

5.1.2. Statistical Analysis

Two parameters were recorded and analyzed: total number concentration for the entire measurement range of the instrument, that is 1.02-982.2 nm (*TNC*: the total number of particles/cm^3) and total number concentration within the range 60 nm – 384 nm (*TNC 60-384*: the number of particles in the 60-384 nm range/cm^3). This latter range was defined as the combination of the results of Leung et al. regarding COVID-relevant aerosol particle sizes (60-300 nm) [25], and the particle size range of weaker FFP protection (263-384 nm) described by Lee and colleagues [8]. The resulting range, according to our present knowledge, is relevant both in terms of COVID and the known relative deficits of FFP mask protection. Aerosol control was defined as the degree to which a given aerosol control system managed to keep water aerosol concentrations close to the baseline in any given setup. Aerosol control for any given setup was expressed as the magnitude of the difference between mean baseline concentration and the mean concentration generated during the measurement cycles for the given setup.

Statistical analyses were performed in SPSS 23.0 (IBM, USA). Continuous variables were described as means, medians, standard deviations, minima, and maxima. Multiple linear regression analysis was used with instrument/spray direction (IS/DS/US) and aerosol control system (HVE/AE) as the independent variables for both *TNC* and *TNC 60-384*, to determine their relative contributions to the variance of the values of the parameters as dependent variables. Pairwise comparisons both in comparisons to the baseline and across-setups comparisons were performed with the t-test (two-tailed). Because of the multiple comparisons, the limit of significance was lowered to p=0.008.

5.2. Efficacy in aerosol reduction: comparison of two dental extraoral scavenger devices

5.2.1. Experimental design

An experimental setup was prepared in a regular dental operatory (4.15 m x 2.6 m) with one door and one window, the same as used in our initial research [41] (**Figure 1.**). A mannequin head was mounted on the dental unit to simulate the patient in the supine position. A high-speed turbine (Gentle Silence, KaVo Dental, Germany) was attached to a holder, which allowed to fasten the instrument in a fixed and reproducible position.

Measurements were carried out with an Engine Exhaust Particle Sizer (EEPS-3090) spectrometer (TSI, Minnesota, USA). According to the previous study design, the maximum aerosol load was measured at 25 cm from the mannequin head. The endpiece of the spectrometer was positioned above the head of the mannequin at this distance. Following the manufacturer's instructions, the EOS devices were positioned at 20 cm above the mannequin head, on the right side of the patient, below the level of the sampling tube of the spectrometer (**Figure 4**).

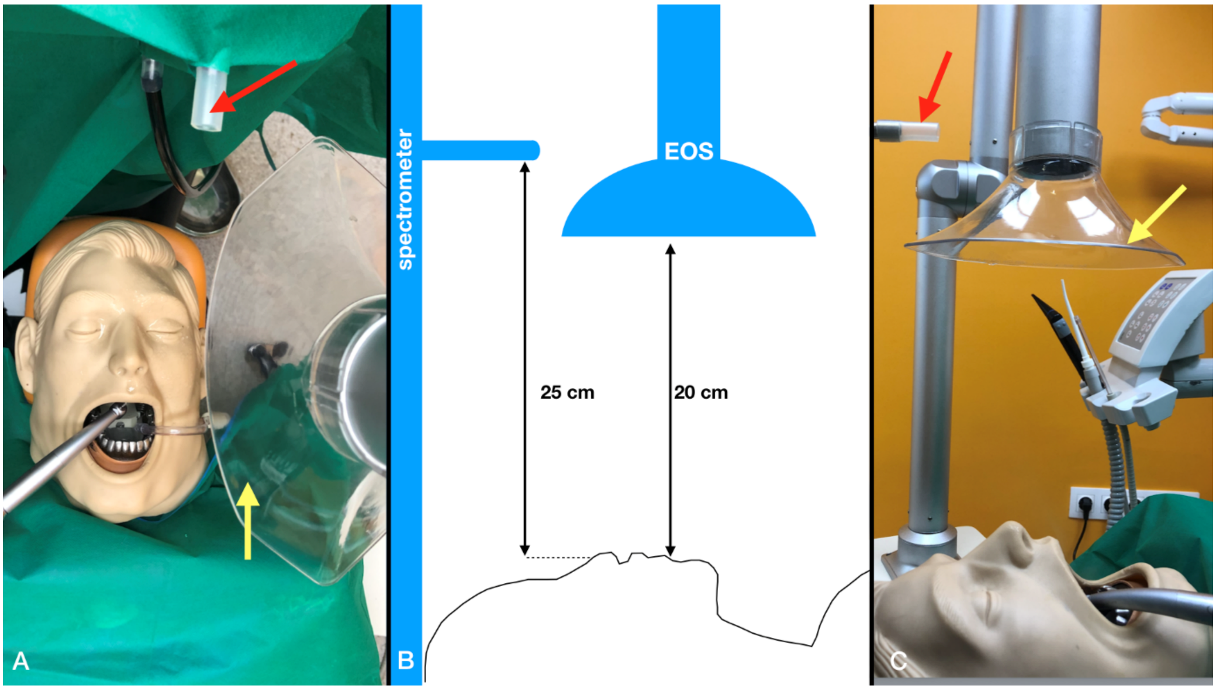

Figure 4. Arrangement of the instruments*. The red arrows point to the sampling tube of the spectrometer. The yellow arrows point to the extraoral scavenger device (EOS).* ***A)*** *top view.* ***C)*** *lateral view. Red arrow: spectrometer sampling tube. Yellow arrow: EOS.* ***B)*** *a schematic representation of the setup.*

5.2.2. Test measurements

All measurements were carried out during the same day. Before the test measurements, the operatory had been intensively aired and air purified (AC3256/20, Philips, Eindhoven, Netherlands) for 12 hours. The following setups were tested:

For the baseline measurements, all units were arranged as during the test measurements (setups 2 to 4, below) but only the measuring unit was on. Neither the dental turbine nor any aerosol control unit was operated. This was the control setup.

For all the study setups, the dental turbine was set in a way to face the palatal surface of the maxillary front teeth, allowing the spray to spread directly toward the spectrometer (modeling the preparation of the palatal surface of the right central incisor). A high-volume evacuator (N1, Dürr Dental, Germany) and a saliva ejector were attached to the same dental unit (KaVo 1066 T, KaVo Dental, Germany) and positioned according to the manufacturer's instructions. In study setup 1 (NO EOS), no EOS was used in combination with the above. In study setup 2

(EOS A), we used Dental Aerosol System (Foshan COXO Medical Instrument Co., Ltd., Guangdong, China), and in study setup 2 (EOS B), we used Eighteeth VacStation (Changzhou Sifary Medical Technology Co., Ltd, Changzhou, China). (**Figure 5.**)

For all 4 setups, 3 measurement cycles were carried out. Each cycle lasted 5 minutes and included 10 consecutive scans (sampling frequency: 30 s). Aerosol reduction by airing was repeated after each measurement by airing. Airing was done by opening both the door and the window of the operatory while operating a standard fan directed toward the window and air purifier turned on. An airing cycle lasted 5 minutes.

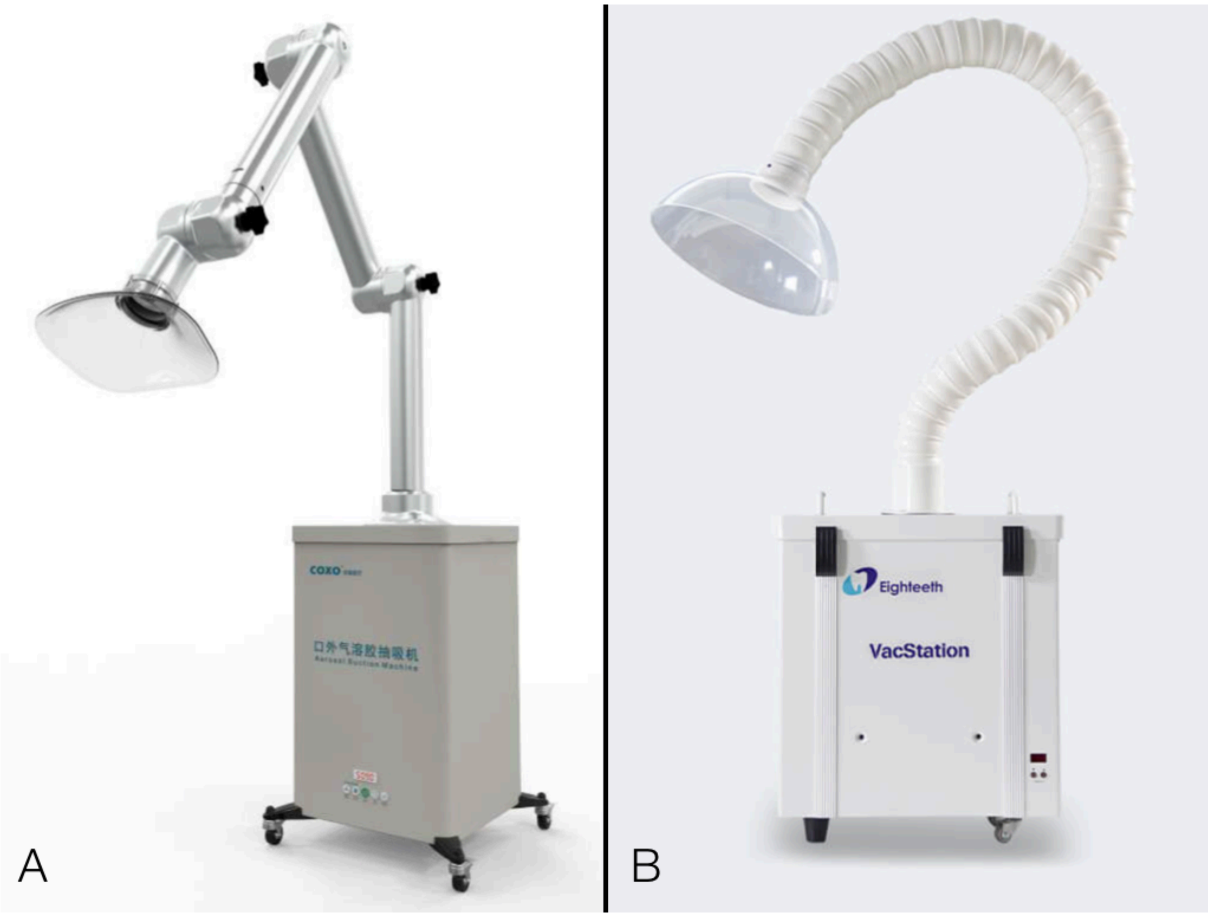

Figure 5. The tested units. *A) EOS A: Dental Aerosol Suction System, Foshan COXO Medical Instrument Co., Ltd., Guangdong, China; B) EOS B: Eighteeth VacStation, Changzhou Sifary Medical Technology Co., Ltd, Changzhou, China.*

5.2.3. Parameters and statistical analysis

Measurements were done in the entire measurement range of the spectrometer (5.6-560 nm) and a critical range (60.4-392.4 nm).

Two parameters were recorded and analyzed: total number concentration for the entire measurement range of the spectrometer, that is 5.6-560 nm (*TNC*: the total number of particles/cm^3) and total number concentration within the range 60.4-392.4 nm (*TNC 60.4-392.4*: the number of particles in the 60.4-392.4 nm range/cm^3).

We had to slightly modify the range tested in the 1st in vitro study, as the spectrometer we used performs a stepwise range analysis, and the closest available range to the earlier described critical range was 60.4-392.4 nm.

To characterize the size distribution of particles in the generated aerosol, number concentrations by particle diameter were also calculated and plotted for both size ranges.

Aerosol control was defined as the degree to which a given aerosol control system managed to keep water aerosol concentrations close to the baseline in any given setup. Aerosol control for any given setup was expressed as the magnitude of the difference between the mean baseline concentration and the mean concentration generated during the measurement cycles for the given setup.

Statistical analyses were performed in SPSS 26.0 (IBM, USA). Both parameters of all setups were characterized by the 30 data points from the 3 measurement cycles.

Shapiro-Wilk normality tests were performed for both variables in each setup. As the test indicated non-normal distribution in most cases ($p<0.05$), the Kruskal-Wallis test was used for the hypothesis tests. The level of significance was lowered to $p = 0.008$ (according to Bonferroni) because of the multiple comparisons. Post-hoc pairwise comparisons were also performed. For the descriptive characterization of the data, medians, minima, and maxima were used. Aerosol control was also characterized by a multiplier calculated as $median_{test\ setup}$ /$median_{baseline}$.

6. Results

6.1. Measuring aerosol production and control

6.1.1. Aerosol control: the baseline and deviations from it

After 12 hours of airing, the following values were measured: *TNC* – 696.6±94.3/cm^3; *TNC 60-384* – 243.3±28.1/cm^3. These were considered as the baseline or background values.

The only setup where no significant difference from the baseline was found was US-HVE. **Table 1** shows that neither of the measured parameters rose above or sunk below the baseline to a statistically significant extent in this setup. It was in this setup that the values remained the closest to the baseline.

Table 1. The results of the measurements. *TNC: total number count, TNC 60-384: total number count within the range 60 nm – 384 nm. Conventions regarding the study setups are the same as in* ***Figures 1 and 2.*** *Baseline: values measured at the beginning of the day, after 12 hours' airing. Means and standard deviations in each group come from 3 consecutive measurements (N=3, see Test Measurements).*

SETUP	TNC (mean ±SD, 1/cm^3)	TNC 60-384 (mean ±SD, 1/cm^3)
Baseline	696.6±94.3	243.3±28.1
IS-HVE	626.4±87.1	351.5±24.2
IS-AE	1951.1±120.5	864.5±136.7
DS-HVE	8530.5±1639	4557.9±2575.5
DS-AE	4742.3±407.1	2189.5±174.6
US-HVE	621.3±249.4	240.4±76.0
US-AE	509.8±27.9	188.1±25.8

As for the rest of the setups: in IS-HVE, only TNC 60-384 ($t = -5.06$, $df=4$, $p= 0.007$) was significantly elevated as compared to the baseline.

In IS-AE, significant elevation was observed for both study parameters, as follows: TNC ($t = -14.19$, $df =4$ $p< 0.001$), TNC 60-384 ($t = -7.70$, $df =4$ $p= 0.002$)

In DS-HVE, TNC ($t = -8.26$, $df = 4$ $p = 0.001$) was significantly higher than the baseline, but TNC 60-384 ($t = -2.9$, $df = 4$ $p = 0.044$) was not. It must be seen, though, that the latter was still a considerable difference.

In DS-AE, similarly, to IS-AE, both study parameters were significantly elevated in comparison to the baseline: TNC ($t = -16.77$, $df = 4$ $p < 0.001$), TNC 60-384 ($t = -19.06$, $df = 4$ $p < 0.001$).

In US-HVE, both parameters showed a decreasing tendency, but it was not significant: TNC ($t = 0.49$, $df = 4$ $p = 0.651$), TNC 60-384 ($t = 0.06$, $df = 4$ $p = 0.953$).

Finally, in US-AE, similarly to US-HVE, both parameters showed a decreasing tendency, which was not statistically significant: TNC ($t = 3.286$, $df = 4$ $p = 0.03$), TNC 60-384 ($t = 2.509$, $df = 4$ $p = 0.07$).

As shown in **Table 1**, the outcome variables showed elevation compared to the baseline in all setups, which was almost always statistically significant, except for TNC 60-384 in DS-HVE. In US-HVE and US-AE, decreasing tendencies were observed, but these were not statistically significant for any of the variables. All in all, in terms of aerosol control, the most well-controlled setups were US-AE and US-HVE, followed by IS-HVE, IS-AE, DS-AE and DS-HVE, the latter being the least efficient.

From this, we inferred that the applied instrument/spray direction (DS/IS/US) was of primary importance in terms of aerosol control. So that, multiple linear regression analysis was conducted for both study parameters to determine the relative contributions of the applied instrument/spray direction (DS/IS/US) and the applied aerosol control system (HVE/AE) to the variance of TNC and TNC 60-384. The results indicated that the model was a significant predictor of TNC ($F(2,15) = 17.75$, $p<0.001$, $R2 = 0.70$. Instrument/spray direction contributed significantly to the model ($\beta = -0.83$, $p < 0.001$), but aerosol control did not ($\beta = 0.143$, $p = 0.326$). The model was also a significant predictor of TNC 60-384 ($F(2,15) = 9.18$, $p<0.01$, $R2 = 0.55$. Instrument/spray direction contributed significantly to the model ($\beta = -0.72$, $p < 0.01$), but aerosol control did not ($\beta = 0.178$, $p = 0.321$). Aerosol control alone did not contribute significantly to the variance of either parameter. Thus, all further analyses were done within the groups defined by instrument and spray direction.

6.1.2. Aerosol control: comparisons within the groups defined by instrument and spray direction

The comparisons brought the following results: IS-AE was characterized by significantly higher values in both study parameters than IS-HVE: *TNC* ($t = -15.42$, $df = 4$ $p < 0.001$) ; *TNC 60-384* ($t = -6.40$, $df = 4$ $p = 0.003$). DS-HVE was characterized by higher values in both parameters than DS-AE, but the difference was not significant. The same was seen when US-AE was compared to US-HVE. In other words, the aerosol control system had a significant effect only in the case of indirect spray with high-speed turbine, and in that case, HVE was the more efficient method.

6.1.3. Number concentrations and particle sizes

Figure 6 shows number concentrations and particle sizes. AE and HVE are compared within the groups defined by instrument and spray direction. IS-HVE resulted in moderate number concentration and larger particles, while IS-AE yielded a remarkably higher number concentration in mostly the same size range (for the exact significances see above). As for DS, DS-HVE generated higher number concentrations of smaller particles in comparison with DS-AE. In US, HVE and AE resulted in almost the same outcomes, both in terms of number concentration and particle size. This description fits both the entire range and the 60-384 nm subrange, except for DS, where an interesting difference can be observed between HVE and AE (Fig.4, bottom, middle panel). With HVE, the size distribution of particles is markedly shifted toward the small end of the spectrum: the number concentration of the smallest particles is the highest in the sample, and, progressing toward the high end of the size spectrum, the concentration is steadily on the decline, apart from an insignificant bump between 100 and 150 nm. In contrast, with AE, a near normal size distribution was achieved, with the highest number concentrations toward the middle of the size spectrum.

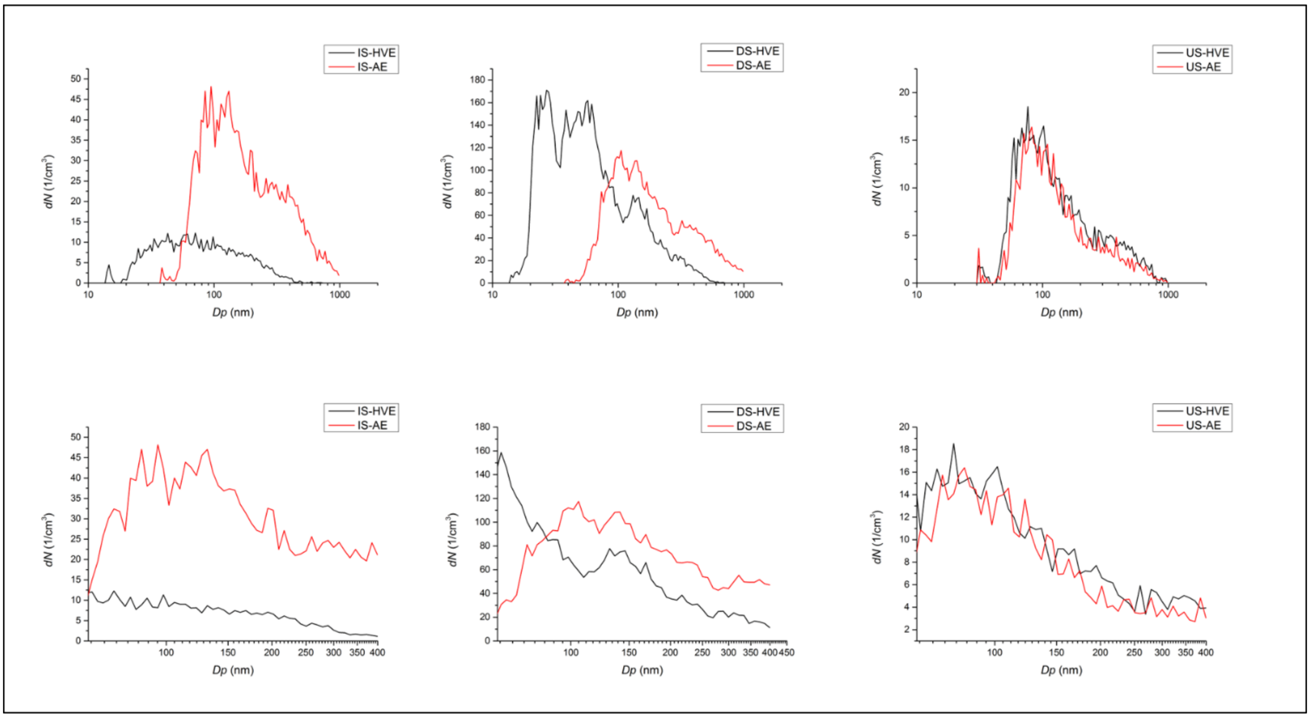

***Figure 6. Size distribution of generated water aerosol**- the effect of the applied aerosol control system within the groups defined by instrument and spray direction. dN: number concentration, Dp: particle diameter; top: TNC bottom: TNC 60-384; IS-HVE: indirect spray with high volume evacuator, IS-AE: indirect spray with aerosol exhaustor, DS-HVE: direct spray with high volume evacuator, DS-AE: direct spray with aerosol exhaustor, US-HVE: ultrasonic scaler with high volume evacuator, US-AE: ultrasonic scaler with aerosol exhaustor.*

6.1.4. Dynamics of aerosol concentration during the airing period

The results are demonstrated in **Figure 7** through the dynamics of TNC for all setups. The figure shows TNC after 5, 10 and 15 minutes of airing, from three measurements. It is readily observable in the figure that with the applied airing method, a massive drop in TNC occurred between 5 and 10 minutes for all setups. In this period, TNC dropped back to baseline or below for most of the setups, only DS-HVE remaining above baseline. TNC in DS-HVE did not completely return to the baseline even at 15 minutes. Furthermore, at 15 minutes, a minor elevation above the baseline detected in IS-AE again in one case, probably indicating that the concentration of aerosol decayed in a fluctuating manner.

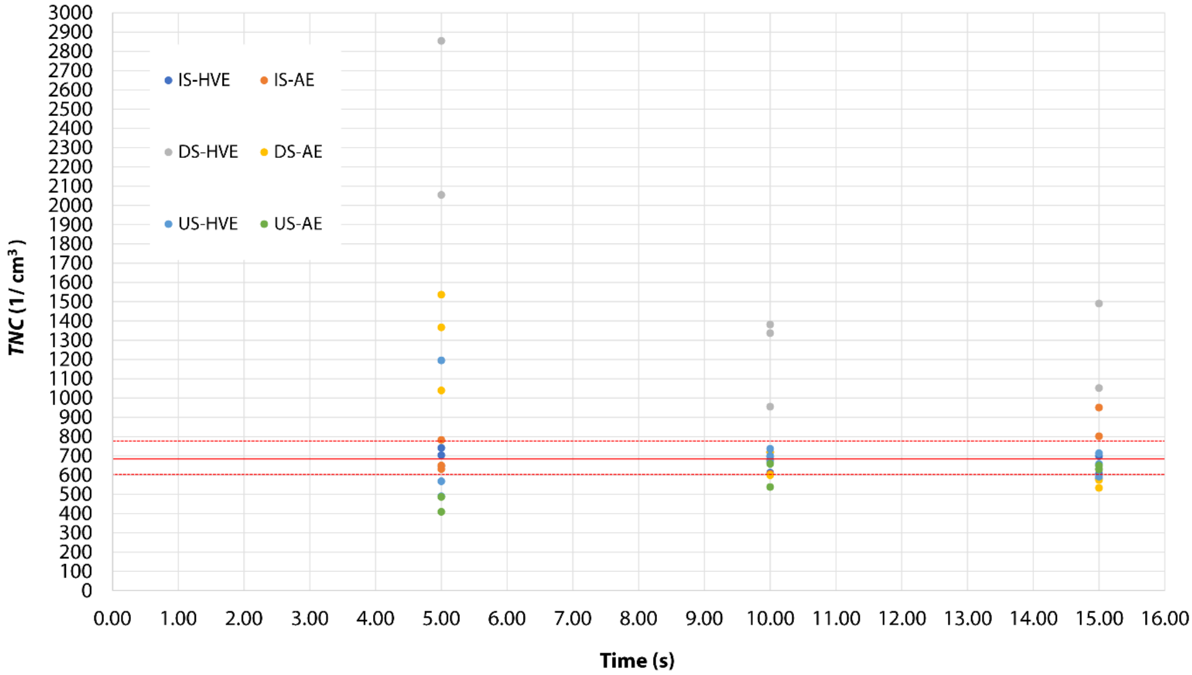

Figure 7. The dynamics of aerosol decay (TNC – total number count) during the airing period (3 measurement cycles) after each test measurement (setup). *Like the test measurements, airing measurements were carried out in triplicate. Values are given for each scenario at the end of the 5th, 10th and 15th minute of airing, corresponding to the measurement cycles. The different setups are represented by coloured dots (see legend, the conventions are the same as in Figure 1). Data for all three measurements for all three time points are shown, but please note that the dots may overlap. The solid red line represents the mean baseline level (~697/cm3), the dotted lines denote the standard deviation of the baseline mean (see also* ***Table 1****).*

6.2. Efficacy in aerosol reduction: comparison of two dental extraoral scavenger devices

6.2.1. Aerosol control: deviations from the baseline and the relative effectiveness of the tested devices

After 12 hours of airing, the following median baseline values were measured: *TNC*: 2472.51 (2239.61-2625.60) particles/cm^3; *TNC 60.4-392.4*: 1329.57 (1206.29-1383.91) particles/cm^3. These were considered as the baseline or background values, against which all other measurements were compared. The detailed descriptive statistics for the baseline and study setups are given in **Table 2**.

Table 2. Descriptive statistics of the results by parameter and setup. *Aerosol control: this is a multiplier calculated as $median_{test\ setup}/median_{baseline}$ and is used to characterize the efficiency of aerosol control in the given setup. The lower the value, the lower the elevation compared to baseline and the more efficient the control.

TNC (particles/cm³)					
	N	**Median**	**Minimum**	**Maximum**	**Aerosol control***
BASELINE	30	2472.51	2239.61	2625.60	N/A
NO EOS	30	44043.85	18225.03	142091.45	17.81
EOS A	30	34025.21	21402.18	149811.30	13.76
EOS B	30	14801.07	11363.21	45547.91	5.99
TNC 60.4-392.4 (particles/cm³)					
	N	**Median**	**Minimum**	**Maximum**	**Aerosol control***
BASELINE	30	1329.57	1206.29	1383.91	N/A
NO EOS	30	7866.24	5069.73	13947.97	5.92
EOS A	30	2714.33	1597.20	4672.17	2.04
EOS B	30	3174.18	1552.06	4407.94	2.39

Regarding *TNC*, the Kruskal-Wallis test indicated a significant overall variance (H=80.8, df=3, $p < 0.001$). The post-hoc test indicated that the elevation compared to baseline was significant in all three test setups at $p < 0.001$. Furthermore, the elevation measured for EOS A was not significantly different from NO EOS (p= 0.761), but it differed significantly from EOS B ($p<0.05$). EOS B also differed significantly from NO EOS ($p< 0.05$). Thus, in this size range, EOS B allowed the most efficient aerosol reduction also with the smallest dispersion of the three study setups.

Regarding *TNC 60.4-392.4*, the Kruskal-Wallis test indicated a significant overall variance (H=100.43, df=3, $p < 0.001$). Tukey's HSD indicated that the elevation compared to baseline was significant in all three test setups at $p < 0.001$. Furthermore, the elevation measured for EOS A was not significantly different from EOS B (p= 0.900), but both setups allowed a significantly greater reduction of particle counts than NO EOS at $p < 0.001$. In this size range, the efficiency of EOS A and EOS B was comparable, and both were superior to NO EOS. **Figure 8** summarizes the above results.

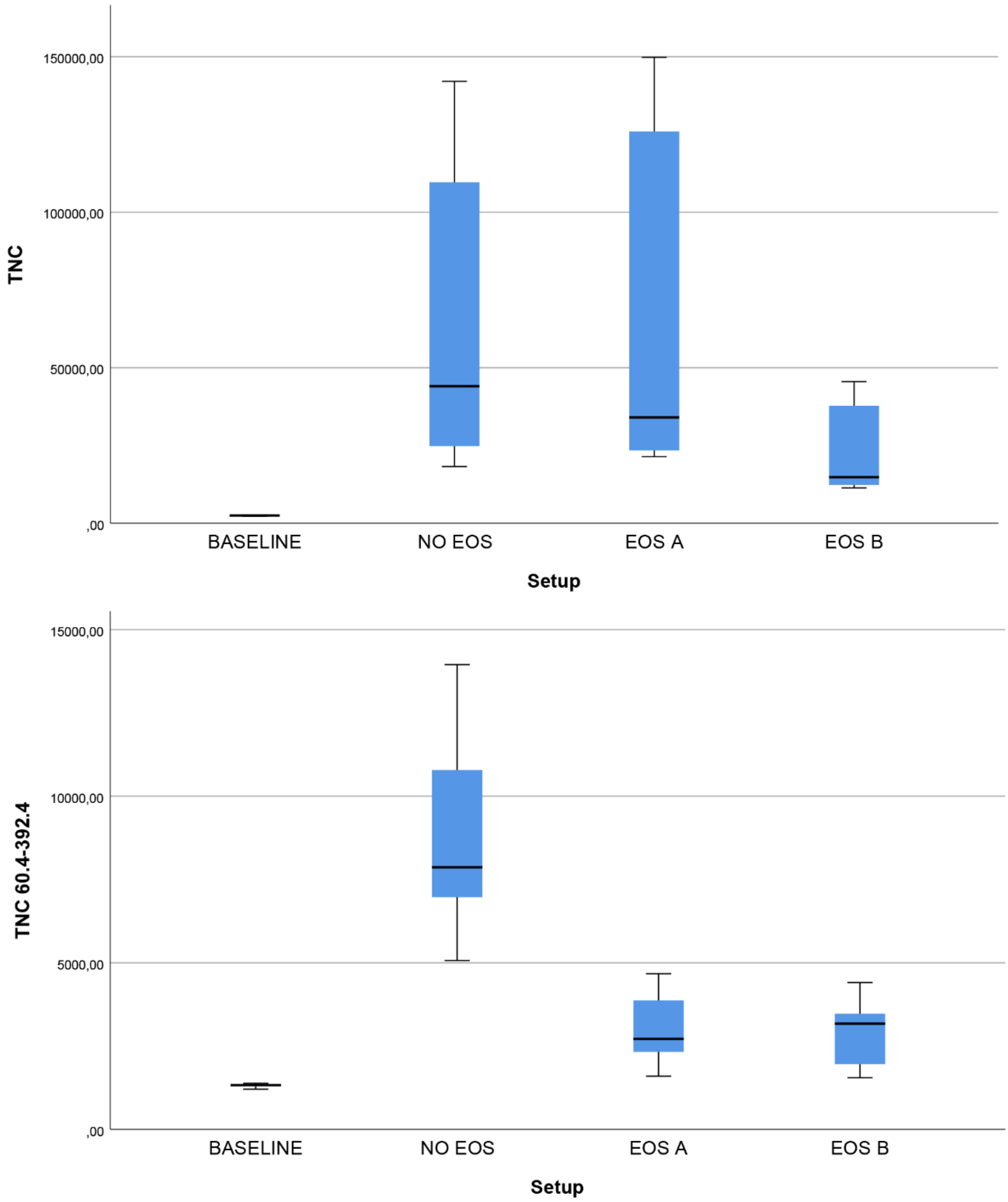

Figure 8. Top: TNC (particles/cm³). Bottom: TNC 60.4−392.4 (particles/cm³) – box plot comparison of the setups*. The lower margin of the boxes represents the 25th percentile. The line within the boxes marks the median, and the upper margin of the boxes indicates the 75th percentile. The error bars (whiskers) above and below the boxes denote the 90th and 10th percentiles, respectively.*

6.2.2. Number concentrations and particle sizes

Figure 9 shows number concentrations by particle size for the entire measurement range of the spectrometer and for the narrower critical range. As for the full range, the number concentrations for NO EOS and EOS A were quite similar over a wide range of particle sizes. In fact, the number concentrations were somewhat higher for EOS A between 9.31 and 34 nm for EOS A, however, the TNC count was still slightly lower than for NO EOS. As for the critical range, both EOS devices were superior to NO EOS in aerosol reduction, over the entire range. For EOS A, there was also a slight shift toward smaller particle sizes, which shows as peaks at 10.8 and 16.5 nm in the figure. When analyzing the whole spectrum, these peaks add much to the amount of produced aerosol, which explains why the results for EOS A were so like NO EOS.

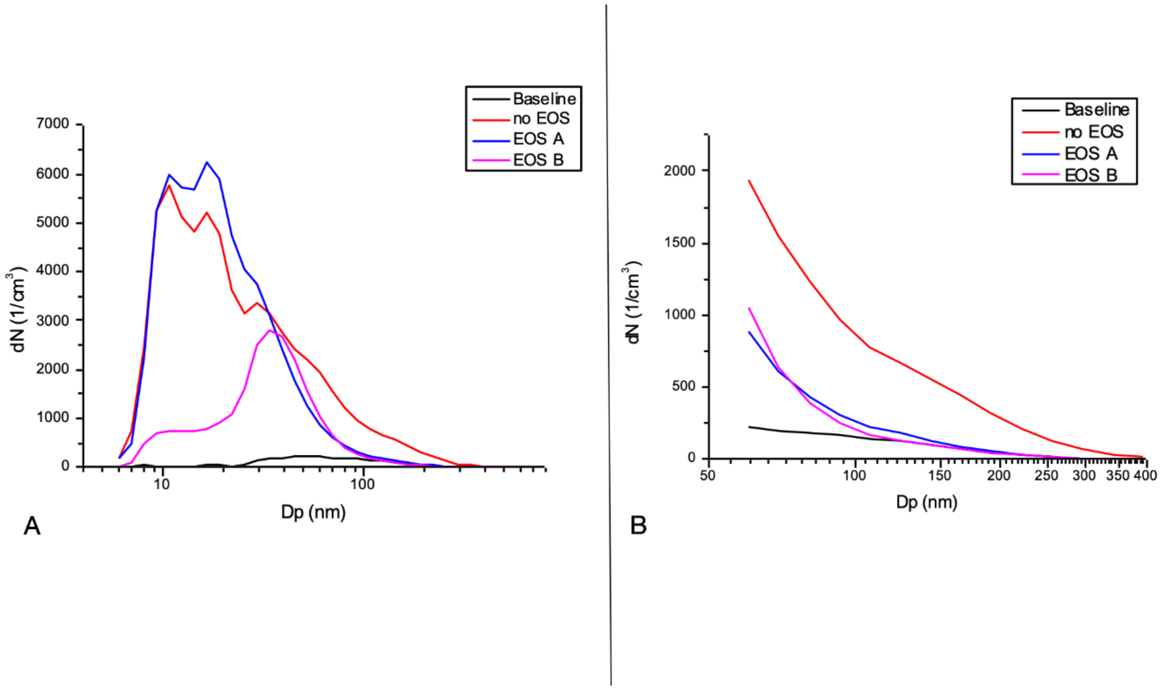

***Figure 9. Size distribution of the generated water aerosol for the baseline measurements and the study setups**. **A)** Size distribution of generated aerosol for the entire measurement range of the spectrometer (5.6−560 nm). **B)** Size distribution of generated aerosol in the critical spectrum (60.4−392.4 nm). dN, number concentration (diameter); Dp, particle diameter.*

7. Discussion

The results of the first study allow a quantitative characterization of the generated water aerosol in the whole measuring range of the spectrometer and specifically in the range that is relevant in terms of virus spread. The data do not allow conclusions either regarding the circumstances in which the individual particles were formed or the changes they underwent during their spread. The analysis of such fine changes is beyond the scope of this study, as it is highly unlikely that in the given setting, they could considerably influence the results. However, this a limitation of the study beyond doubt, as are its in vitro nature, and the small number of repeated measurements. All these limitations make the study exploratory in nature.

The aim was to determine in a clinically relevant way what aerosol particle concentrations two typical dental instruments featuring air spray generate and how efficiently these concentrations are controlled by two widespread control devices, as such quantitative measurements were lacking. To interpret the results correctly, one must understand that in real-life dentistry, the spray is never exclusively directed inward or outward, rather, the instrument alternates between these positions, and even that with breaks. Direct and indirect mark the endpoints of a spectrum, so the results define the range in which concentration changes may take place during various treatments performed with the studied instruments and controlled with the studied control systems.

Regarding the setups, we hypothesized that both the instrument/ its use and aerosol control would be significant determinants of aerosol concentration.

The results partially support the hypothesis. The type of dental instrument and its way of use was indeed a key factor in aerosol generation. Scaler generated the least aerosol, followed by turbine with indirect spray, and turbine with direct spray. This was somewhat surprising, as earlier studies [42, 43] suggested that by producing 3 times more bioaerosol, the ultrasonic scaler was the most problematic instrument in the dental setting in this respect.

The applied aerosol control system was not a significant factor in any of the setups, except for indirect high-speed turbine, where HVE was the most efficient method. It must be noted, though, that in the direct turbine setups, AE resulted in markedly lower concentrations. Statistical significance could not be established, but it might easily be a result of the low number of measurements, as the effect is obvious. While the results do not allow strong conclusions about the effect of in-treatment aerosol control, they strengthen the hypothesis that specific types of aerosol control might be better suited for specific settings. This points to the necessity of further studies in this direction.

Regarding the effect of airing between treatments, we hypothesized that a conventional method of airing would be sufficient to reduce aerosol concentration to safe levels in a clinically reasonable timeframe. This was true for all setups, except for DS-HVE (which, as said, is never used exclusively during any treatment). Based on the results, a safety airing period of at least 15 minutes is recommendable between two treatments. This time window can elongate the dental treatment, but its importance is inevitable in terms of infection control. The properly planned dental schedule should involve the minimum time of airing, to keep the aerosol concentration on the minimal level between treatments. By the application of more advanced airing methods (such as a built-in ventilation unit) shorter periods may be achievable. [44] Adding other circumstances i.e., air temperature and relative humidity of the room, a complex ventilation protocol can be set up, to reduce possible transmission. [45]

As dental professionals, personal protection with different shields and masks is a solid component of everyday dentistry. These layers of protection make the aerosol particle size less important for us, however their presence is an existing hazard for the patient and the dental team when there is reduced amount of protection between two treatments. The presence of the aerosol is given during and after certain dental interventions posing a risk of exposure, and our two main options to decrease the potential of viral/bacterial infection are the between-treatment airing and the use of high-volume suction during the whole treatment when aerosol production occurs.

After understanding the amount of aerosol for each type of water spray producing instrument and the limitations of the conventional suction systems, a consecutive study was necessary to be undertaken. A rising amount of different high-volume suction systems (EOSs) has appeared on the market, due to the pandemic. Their efficacy has never been compared, only their superior suction capacity over the general HVE method was proven. While some studies suggested that their use is not absolutely necessary for good aerosol control [46], there is an agreement in the literature that they are efficient and increase the safety of the dental operatory. [47-51]

With the help of the second study two commercially available EOSs were compared in terms of their efficacy in aerosol control.

In the second study somewhat higher aerosol concentrations were detected compared to the earlier study, carried out in the same operatory. [41] One reason for this could be that in the 2nd study, a more advanced spectrometer was applied, which resulted in a larger amount of more precise data. Another reason could be the different baseline aerosol concentrations. The baseline values were more than three times higher on average in both the full and the critical range than in the previous study, even though the operatory was prepared the same way as before. This shows that there are several, probably uncontrollable factors that determine baseline aerosol. So that the efficacy of the tested systems (or any aerosol control system for that matter) should not be judged based on absolute values, rather the degree to which each system can reduce aerosol concentration.

It has been reported earlier that FFP masks offer somewhat reduced protection against aerosol contamination below 384 nm [8]. It is also known that the SARS-CoV-2 virus may attach to aerosol particles of various sizes, resulting in combined particle sizes from 60 nm to approximately 300 nm [25]. Thus, to get relevant results both in terms of SARS-CoV-2 and the relative deficits of FFP mask protection, we concentrated on the 60-384 nm critical range in our previous study [41].

The results show that EOS devices can differ in their aerosol-reduction efficacy and the particle size range in which they are most efficient. In the full particle size range of the spectrometer, only EOS B could achieve significant aerosol reduction, but in the critical 60.4-392.4 nm range, both devices achieved significant reduction. At the same time, neither of the devices could reduce aerosol counts to an extent to make the difference from the NO EOS setup non-significant. It must be seen, however, that the variance of the baseline values was extremely narrow, so statistically non-significant should by no means be interpreted as practically non-significant. As the aerosol control multipliers show, total number concentrations in the 60.4-392.4 nm range were approximately two times the baseline with both EOS A and EOS B, while without any EOS device, approximately six times higher values were measured.

These results corroborate the findings of Nulty et al. who concluded that extra-oral suction can be a useful means of mitigating the risk of SARS-CoV-2 infection in a clinical context [52]. The authors used an industrial particle counter, and their findings indicated a significant decrease in the number of aerosol-counts when using an EOS device in different clinical setups and with different operators. However, it was an obvious weakness of their study that the aerosol source was not standardized, which introduced uncontrolled and potentially confounding variables, such as the intensity and direction of the aerosol spray. Furthermore, their measurement distance was 42 cm, which is larger than the usual working distance under PPE (personal protective equipment). Finally, they used a particle counter with a lower detection limit of 300 nm, so the results allow limited conclusions regarding an actual SARS-CoV-2 scenario. Despite all these limitations, it can be concluded correctly that an external high-volume suction device may potentially diminish the risk of transmission of viral particulate.

Graetz and colleagues also concluded that the use of an EOS device significantly reduced the number of generated particles during different aerosol-generating procedures [53]. The lower detection limit of the sampling device used in their study was 100 nm, which is much more optimal for SARS-CoV-2- relevant conclusions than the 300 nm limit of the Nulty group, even if it misses a fraction of the spectrum of interest (from 60 nm up) [25, 52]. A further limitation was the relatively short (2-minute) sampling time, which might have contributed to the low measured values. Finally, sampling took place at 35 cm above the mannequin head, the same level as the EOS ending. Assuming that sampling should take place at approximately the level of the operator's head, such fails to correspond to most manufacturers' instructions which usually suggest that the ending of the device should be closer to the patient than the operator.

It must be noted, though, that there is a lack of consensus about the optimal use of EOS devices in many respects. For instance, even the manufacturers are not consistent about the distance that allows maximum protection and minimal interference with the treatment. The distance we used (20 cm) is quite close to the patient within the suggested range of 15-40 cm. In most real-life treatment scenarios, such a short distance would lead to a situation where the operator would see the treatment area through the transparent ending of the device most of the time. On one hand, the ending functions as an extra layer of physical protection in this situation, but on the other hand, it is also an extra layer of visual hindrance, especially if the operator is wearing protective equipment (such as a shield). Skilled and experienced operators might still be able to work properly under such circumstances, but even then, looking at the treatment area through multiple layers of plastic is hardly the optimal approach to patient treatment. The question of optimal distance is indeed one that needs to be addressed in further studies or a review of studies once enough data have been gathered. These measurements are especially distance-sensitive: the farther the device, the less efficient the suction is. Therefore, the results of this study are to be interpreted as valid for scenarios when the ending of the device is positioned at a short distance from the aerosol source.

The other major inconsistency can be noticed in the literature, is the position of the EOS device. Certain studies place the extraoral suction machine at 9:00 position, meaning the suction comes from the right side of the patient's head so that offers a completely different aerosol spreading and control. [43] However, the dental team is exposed from another angle, there is no data available in the literature of the comparison of aerosol spreading when the EOS devices are in different position.

The quantitative characterization of the generated water aerosol and its depression with two commercially available EOS devices does not allow conclusions either regarding the circumstances in which the individual particles were formed or the changes they underwent during their spread, nor do they inform about the real viral load of a possible scenario. The analysis of such fine changes is beyond the scope of our study, and it is unlikely that they could considerably have influenced our results. However, these are limitations to this study, as are its *in vitro* nature and that the data may be influenced by the all-time aerosol content of the environment to a considerable extent. All these limitations make the study exploratory in nature.

It might appear as a limitation that we did not consider the effect of air movement. It has been demonstrated that air conditioning may contribute to the transmission of SARS-CoV-2 and the movement of persons might also influence the spread of the aerosol. [54] However, the study setup was designed especially for the comparison of two EOSs under controlled conditions, and air movement was a controlled variable (i.e., the measurements were done with closed doors, closed windows, no air conditioning and preventing any significant air movement). Minor disturbances, such as the hand movements of the person operating the spectrometer, should be potential confounders in real life. Therefore, this factor was not taken into consideration.

The use and efficacy of EOS devices in dental settings are still a matter of debate in the literature. We tested the aerosol-reducing efficacy of two commercially available extraoral scavenger devices during modeled dental treatment in a setup, based on our initial study. After proving that basic dental interventions with different instrument angles generate high aerosol load, a consecutive study design was necessary to be find the 'most effective' method in aerosol reduction. In the SARS-CoV-2- relevant particle size range, both devices managed to reduce the aerosol load to a statistically significant extent as compared to the scenario when only a high-volume evacuator and a saliva ejector (and no EOS) were used. Within the limitations of our study, the results support the assumption that EOS devices for aerosol reduction increase safety in the dental operatory.

8. New findings

- We can state that the type of dental instrument and its way of use is a key factor in aerosol generation. Ultrasound scaler generates the least aerosol, followed by turbine with indirect spray, and turbine with direct spray, meanwhile the type of aerosol control system is not a significant factor. HVE has the best controlling capacity in most of the situations.

- The efficiency of airing between two treatments and recommendable airing time, the results suggest that 10 minutes of airing reduces aerosol concentration to a safe level in most typical treatment scenarios (with doors and windows open and using a commercially available standard fan).

- However, if during the intervention a high amount of aerosol could get in the air directly, it is recommended that at least a 15-minute airing break be observed. Advanced airing methods (e.g. a built-in ventilation unit) may shorten this period.

- EOSs allow a significantly greater reduction of particle counts and aerosol load compared to the setup when no EOS is in use. In the SARS-CoV-2- relevant particle size range, both examined devices can manage to reduce the aerosol load to a statistically significant extent as compared to the scenario when only a high-volume evacuator and a saliva ejector (and no EOS) is used.

- Our results support the assumption that EOS devices for aerosol reduction increase safety in the dental operatory.

9. Summary

The pandemic made healthcare professionals realise that the importance of PPE should come into prominence. The emerging number of airborne infections and the continuous need of dental intervention in acute situations raised new questions and solutions regarding aerosol control possibilities.

Based on earlier experiments, the type of aerosol producing handpiece and the angle of application – so that the direction of the water-spray – seemed to be significant factors waiting for clarification. The amount of aerosol -mingling with /separated from the oral flora is a severe risk factor when talking about contagion. The most commonly used instruments are the ultrasound scaler and the high-speed turbine with copious amount of water cooling – as a pathway of infection. The efficacy of conventional suction is questionable in these cases and the use of rubber dam isolation can be controversial in certain positions.

Our research focused on the efficacy of different extraoral suction methods, the extent, and the particle size distribution of the aerosol during specific dental treatments. The other perspective was to define the minimum necessary time of airing after dental interventions when aerosol occurs. The up-graded research focused on the significance of extra oral scavenger devices to reduce the aerosol load.

The results highlight the importance of careful planning during the dental treatment regarding the choice of the instrument, suction alternatives and airing of the dental surgery between two treatments. High volume evacuators provide the best aerosol reduction, however the position and the type of the aerosol producing instrument has a significant effect on this. The minimum recommended time of airing to reach the baseline concentration of the aerosol between 2 treatments is 15 minutes. EOSs can significantly reduce the aerosol concentration in the working zone, which can have a serious effect on the safety of the whole dental team and the patients as well.

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