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Research article

Aerosol concentrations and size distributions during clinical dental procedures

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A R T I C L E I N F O

Keywords:
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Air turbine handpiece
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Ultrasonic scaler
Optical particle sizer

A B S T R A C T

Background: Suspected aerosol-generating dental instruments may cause risks for operators by transmitting pathogens, such as the SARS-CoV-2 virus. The aim of our study was to measure aerosol generation in various dental procedures in clinical settings.

Methods: The study population comprised of 84 patients who underwent 253 different dental procedures measured with Optical Particle Sizer in a dental office setting. Aerosol particles from 0.3 to 10 μm in diameter were measured. Dental procedures included oral examinations ($N = 52$), restorative procedures with air turbine handpiece ($N = 8$), high-speed ($N = 6$) and low-speed ($N = 30$) handpieces, ultrasonic scaling ($N = 31$), periodontal treatment using hand instruments ($N = 60$), endodontic treatment ($N = 12$), intraoral radiographs ($N = 24$), and dental local anesthesia ($N = 31$).

Results: Air turbine handpieces significantly elevated <1 μm particle median ($p = 0.013$) and maximum ($p = 0.016$) aerosol number concentrations as well as aerosol particle mass concentrations ($p = 0.046$ and $p = 0.006$) compared to the background aerosol levels preceding the operation. Low-speed dental handpieces elevated >5 μm median ($p = 0.023$), maximum ($p = 0.013$) particle number concentrations,> 5 μm particle mass concentrations ($p = 0.021$) and maximum total particle mass concentrations ($p = 0.022$). High-speed dental handpieces elevated aerosol concentration levels compared to the levels produced during oral examination.

Conclusions: Air turbine handpieces produced the highest levels of <1 μm aerosols and total particle number concentrations when compared to the other commonly used instruments. In addition, high- and low-speed dental handpieces and ultrasonic scalers elevated the aerosol concentration levels compared to the aerosol levels measured during oral examination. These aerosol-generating procedures, involving air turbine, high- and low-speed handpiece, and ultrasonic scaler, should be performed with caution.

Clinical significance: Aerosol generating dental instruments, especially air turbine, should be used with adequate precautions (rubber dam, high-volume evacuation, FFP-respirators), because aerosols can cause a potential risk for operators and substitution of air turbine for high-speed dental handpiece in poor epidemic situations should be considered to reduce the risk of aerosol transmission.

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1. Introduction

Dentistry is considered to be one of the most aerosol-generating fields in medicine, since the essential and commonly used instruments are rotatory or ultrasonic instruments, which are expected to be significantly aerosol generating. Aerosol generating procedures (AGPs) may cause a higher risk for infection via inhalation when these procedures involve manipulation of the tissue laden with pathogens capable of surviving in aerosols and infect cells in the respiratory tract [1]. However, even though multiple procedures have been listed as AGPs, the current classification is mainly based on experimental studies, expectations, and observational studies. Recently, more research regarding aerosol generation in dentistry has been performed showing a potential for aerosol reduction with high-volume suction [2, 3, 4, 5]. However, the number of studied patients has been low and there is still a clear lack of knowledge regarding the amount of generated aerosol in these procedures in real-life setting [6, 7].

It is important to base the AGP classifications on a more solid background, such as quantified data, as for example in pandemic the use of AGPs can be restricted affecting directly to patient care possibilities. At the beginning of the COVID-19 pandemic the use of air turbine handpiece and ultrasonic scaler were prohibited in most countries as dental professionals were thought to be more prone to SARS-CoV-2 infection compared to other healthcare occupational groups [8, 9, 10]. However, contrary findings were published as the pandemic evolved and dental professionals had lower SARS-CoV-2 antibody levels compared to other healthcare professionals [11] and studies indicating dental procedures do not produce much aerosol particles size smaller than 10 μm if high-volume suction or external high-volume extraction device was properly used [2, 3, 4, 5]. Additionally, personal protective equipment (PPE) in dentistry was improved when FFP-masks, face shields and hair covers were routinely recommended to use in the beginning of pandemic, and studies have been published indicating low numbers of work-related exposures in dental staff [12, 13].

During the pandemic, there has been a discussion of the aerosol definition. Generally, aerosol is defined as a mixture of solid and liquid particles suspended in air regardless of their size. In medical literature, aerosols have been defined as particles size below 5 μm [14], but under current knowledge this division is problematic and might have followed from mixing of the concept of particles capable of reaching the deeper parts of the lungs (e.g. particles <5 μm) and particles capable to stay in air and move with air flows (particles up to approximately 100 μm) depending on the environmental conditions [15, 16, 17, 18, 19]. In this paper we will follow the general aerosol definition regardless of the particle size. Still, small aerosols are important regarding the infection risk as most of the respiratory viruses have been observed mainly in particles under 5 μm [19, 20, 21].

Aerosols may be generated during dental or medical procedures but also when speaking, coughing, sneezing, or breathing [19, 22]. Saliva and mucus are surfactants that reduce the evaporation of smaller particles (<5 μm), thus protecting and extending the survival of the virus inside [23, 24]. Additionally, the oral cavity and saliva are important reservoirs of many pathogens, such as SARS-CoV-2 virus, and the significance of saliva may be underestimated in disseminating the pathogens [25]. Operating an aerosol-producing instrument in contact with the saliva and mucus of a patient with an infection, even when they are asymptomatic, risks causing pathogen-contaminated aerosols to disperse into the operating room and causing a risk to dental professionals. Therefore, exact and scientifically measured data on aerosol production during clinical dental treatment are needed.

The aim of our study was to investigate aerosol generation in various dental procedures in a clinical setting. Our aims were the following: (I) to study the quantity of aerosols generated in various dental operations; and (II) to investigate the different sizes of aerosol particles generated in various dental operations.

2. Materials and methods

2.1. Study subjects and operation rooms

The study population comprised 84 patients: 54 females (64.3 %) and 30 males (35.7 %). The mean age of participants was 53.3 (15.9) years. All the patients attended a specialist clinic at the Unit for Specialized Oral Care in the Metropolitan area and Kirkkonummi, Department of Social Services and Health Care, City of Helsinki in Helsinki, Finland between July 2020 and January 2021. No minors were recruited, and all subjects gave written consent before participation. Presumably, no COVID-19 patients were included in the study, because the patients were screened beforehand and if the patient was exposed to SARS-CoV-2 virus or had symptoms linked to SARS-CoV-2 virus etc. the appointment was postponed. However, this information was not laboratorically confirmed. The study was conducted according to the guidelines of the Declaration of Helsinki and the study design was approved by the local ethical committees of Helsinki University Hospital and the City of Helsinki (HUS/1701/2020, HUS/1450/2020, HEL 2020–007596 T 13 02 01). Three experienced dentists performed procedures in six different dental operation rooms (ORs) at the clinic. The incoming air change rate varied from 38 to 175 dm^3/s and exhaust rate varied from 35 to 285 dm^3/s in different ORs. The room temperature varied between 21 and 23 degrees Celsius. All other operating rooms except room 6 in floor 3 had one window, room 6 in floor 3 had no window. All operating rooms had one door. Measurements of ORs and information on air condition and ventilation are presented in Supplement 1.

2.2. Clinical oral and dental procedures

Dental procedures included oral examinations (check-up or control visit, regular dental examination, comprehensive periodontal or endodontic examination/evaluation), restorative procedures with high-speed and low-speed handpieces (air turbine handpiece, high-speed dental handpiece, low-speed dental handpiece), ultrasonic scaling, periodontal treatment using hand instruments, endodontic treatment (low-speed dental handpiece, endodontic hand instruments), intraoral radiographs, and dental local anesthesia (injection, mandibular nerve block, superficial gel for topical anesthesia). Intraoral evacuators were used during procedures. Both high-volume suction with drills and ultrasonic scalers and low-volume surgical suction with hand instruments and surgical procedures were used.

The patient samples were collected during normal clinical work, thus all routinely used aerosol prevention strategies were used such as pre-procedure mouth wash, high volume suction, tightened infection control between patients and patient screening before treatment to prevent pathogenic aerosol spreading during COVID-19 pandemic.

2.3. Measurement of aerosol particle concentrations

Aerosol particle concentrations emitted during different various dental procedures were measured with an Optical Particle Sizer (OPS) TSI Model 3330. The OPS device is a portable spectrometer that measures particle concentrations and particle size distribution utilizing single particle counting technology. OPS measures aerosol particles ranged from 0.3 to 10 μm in 16 user-adjustable size channels. The OPS device was placed vertically at the same level as the head of the patient during the procedures (Supplement 1). The distance of the OPS device from the top of the head of the patient was approximately 50 cm when the patient was in a horizontal position in the dental chair.

The raw data gathered from 16 size channels with the OPS device was connected to the time stamp of every dental procedure with 10 s accuracy. The timetable of the various dental procedures was documented on paper during the therapy, and after each day the raw data of measurements and procedure log were input to Excel. The measurement with the

OPS device was continuous, and the device was on the whole day, measuring fallow times until the next patient's measurement started. The background values preceding the procedures were measured just as the procedures were. The background was measured in a 1-minute preceding operation and there were no breaks in measurements between background and procedure measurements. The background values varied during the day if the clearance of aerosol production after previous patient was not ready. The windows were closed during measurements and opening doors was avoided when possible. The particle concentrations were divided into <1 μm, 1–5 μm and >5 μm size groups and total concentration, because the particle deposition efficiency in the lungs for example is dependent on particle size. Thus, the sub-micron particle category is interesting to investigate too. The data was further analyzed and median and maximum particle concentrations in these four classes during the procedures were registered. When calculating the maximum values of a given procedure, outliers were excluded.

The particle mass concentrations were also determined to estimate the effect of aerosol particles larger than 5 μm, whose number concentrations are otherwise low. The particle volume concentrations were first calculated assuming that aerosol droplet takes the volume of the sphere, where the lower and upper boundaries of the OPS size channels were used to calculate the diameter of the particle. Volume size distributions were converted to mass size distributions by assuming a particle density of 1 g/cm^3.

2.4. Statistical analysis

The aerosol levels exhibited a skewed distribution, thus medians and interquartile ranges (IQR) were calculated. Both median and maximum values were calculated. When calculating maximum values, the outliers were excluded, and the median of maximum values were calculated. Statistical differences were calculated with non-parametric Mann-Whitney test or Kruskall Wallis test. The statistical analysis was performed with SPSS version 27.

The minimum number of procedures in each class was 6. A similar design has also been used in previous studies [26, 27].

3. Results

A total of 253 different procedures measured in six different rooms were included. Table 1 presents the characteristics of the patients and procedures performed. The median lengths of different operation groups were calculated (Table 1) and the longest operation was periodontal treatment performed manually, median length being 21.3 min, whereas the shortest operation was intraoral X-ray, with a median length of 1.2 min.

Figure 1 shows examples of how aerosol levels vary during different dental procedures. The use of air turbine and dental hand pieces and restauration by composite filling (1A), periodontal treatment with ultrasonic scaler and with hand instruments (1B), and root canal treatment (1C) are presented.

Table 2 presents particle concentration compared to the background in studied procedures. Air turbine handpiece significantly elevated <1 μm particle concentrations and total particle concentrations compared to background aerosol levels preceding operation (Table 2 and Figure 2). Additionally, the maximum concentrations were correspondingly elevated for <1 μm and total particle concentrations when using air turbine handpiece (Table 2). When calculating the particle mass concentrations, the elevation of <1 μm particle mass concentrations was observed during the use of air turbine (Table 3). However, the increase in total particle mass concentration was not significant.

Low-speed dental handpiece elevated >5 μm maximum particle concentrations, > 5 μm particle mass concentrations, as well as maximum total particle mass concentrations (Table 3). High-speed dental handpiece did not significantly elevate any size class of particle, total particle, or particle mass concentrations when compared to preceding background concentrations (Tables 2 and 3 and Figure 2), but a significant elevation in particle concentration was seen when comparing high-speed dental handpiece to the aerosol levels produced during oral examination. Additionally, ultrasonic scaler slightly elevated >5 μm maximum particle concentrations (Table 2) and >5 μm maximum particle mass concentrations (Table 3). Intraoral X-ray did not elevate any class of aerosol particle concentrations (Tables 2 and 3).

When comparing the aerosol levels produced in different dental procedures, the levels of median <1 μm, 1–5 μm, >5 μm and total concentration differed significantly between all groups, calculated by non-parametric Kruskall Wallis test. The concentrations were highest when using an air turbine handpiece, but the low-speed dental handpiece, high-speed dental handpiece, and ultrasonic scaler also elevated aerosol levels compared to the levels during oral examination.

The half-life for particle concentration was determined for 22 drilling operations including both use of air turbine handpiece and low-speed dental handpiece (see Supplement 2 Eqs. (1) and (2)). The median half-life was 21.7 min (range 8.5–47.9 min), and similar in all rooms (Rooms 4A's and 4B's, see Supplements) where suitable cases were analyzed. This is due to ventilation rates being similar in these rooms, with Air Change Rate (ACR) varying between 2.76 and 6.19 h^{-1}. The actual fallow time follows a rather subjective choice of what concentration levels should be considered risky. If the risky concentration level is considered equal to the background concentration, then for air turbine, or data suggest that the fallow time would be approximately 98.5 min (maximum concentration of generated aerosols = 1.6 cm^{-3}, see Table 4; background aerosol concentration = 1.37 cm^{-3}, see Table 2).

18 dental procedures with significant peaks in the time series of particle number concentrations were observed during the measurement

Table 1. Characteristics of the study subjects and the dental procedures performed.

	Dental handpieces*	Periodontal operations**	Oral examination	Other dental operations***
Number of measured procedures	44	91	52	66
Number of patients	28	48	52	46
Females (%)	24 (55 %)	52 (57 %)	30 (58 %)	40 (61 %)
Age (mean, SD)	62.2 (13.8)	51.9 (14.3)	51.1 (17.9)	47.6 (15.2)
Length of procedure (min, median, IQR)	4.3 (2.2–7.7)	13.0 (5.0–26.26.9)	12.7 (6.9–19.5)	1.6 (1.0–3.2)
Number of operation rooms measured	6	5	6	5
Procedure done/ diagnosis (ICD-code)	K02.1 (dentin caries)	K05.30 (chronic periodontitis) and K05.31 (chronic severe periodontitis)	K05.30 (chronic periodontitis) and K05.31 (chronic severe periodontitis), K02.1 (dentin caries), K04.5 (apical periodontitis) and K04.0 (pulpitis)	K05.30 (chronic periodontitis) and K05.31 (chronic severe periodontitis), K02.1 (dentin caries), K04.5 (apical periodontitis) and K04.0 (pulpitis)

* Dental handpieces include air turbine handpiece, low-speed dental handpiece, and high-speed dental handpiece.

** Periodontal operations include ultrasonic scaler and manual periodontal treatment.

*** Other dental operations include local and topical anesthesia, intraoral X-ray and root canal treatment.

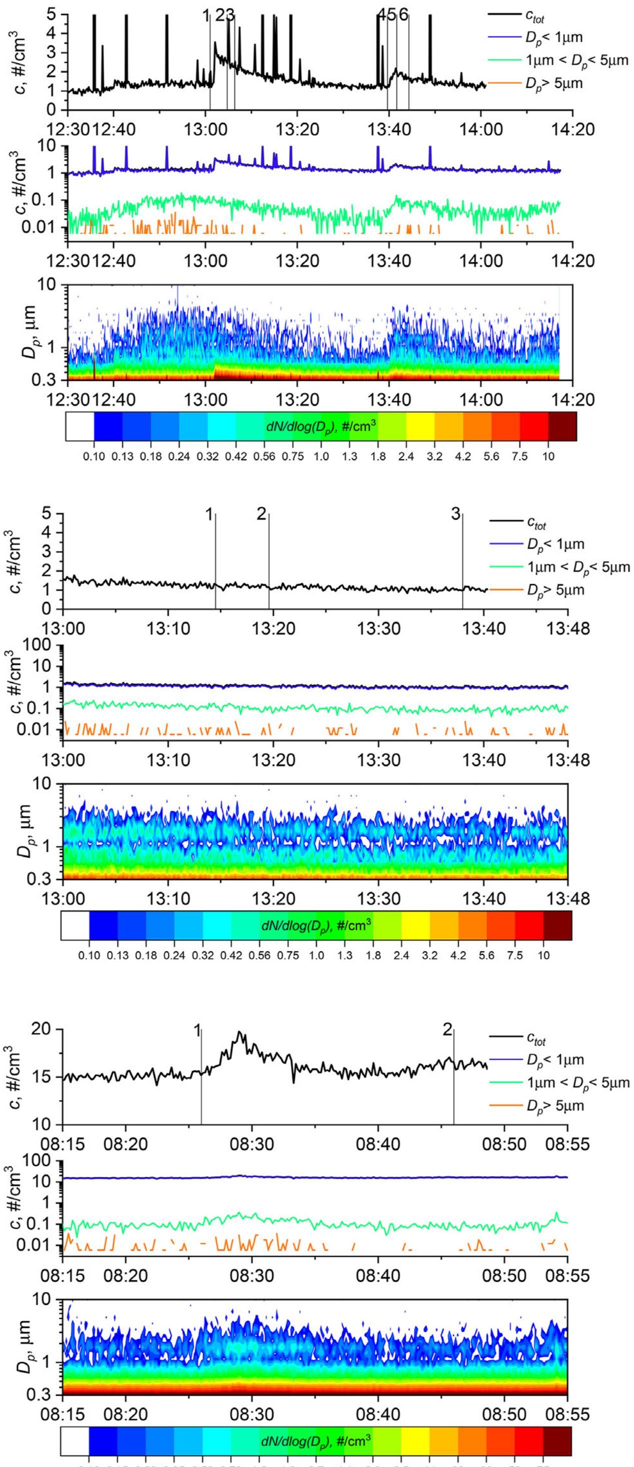

Figure 1. Example timelines of measured dental procedures. 1A. Dental handpiece 1B. Periodontal treatment 1C. Root canal treatment. For each procedure 1A-1C.: Upper panel: total particle concentration. Middle panel: particle concentrations in discrete size bins. Lower panel: continuous particle size distribution. In the upper panels, the main phases of the procedures are indicated: 1A. Dental handpiece: (1) Air-turbine d.17 begins (2) Air-turbine d.17 ends, rose-drill begins (3) Rose-drill ends (4) Air-turbine d.14 begins (5) Air-turbine d.14 ends, rose-drill begins 6) Rose-drill ends. 1B. Periodontal treatment: (1) Depuration with ultrasound G6-tip begins (2) Depuration with ultrasound ends, depuration with hand held instruments begins (3) Depuration with hand held instruments ends. 1C. Root canal treatment: (1) Treatment begins (2) Treatment ends.

period. Particle emission rates were quantified for the three size ranges (<1 μm, 1–5 μm, >5 μm) and the total particle number concentration of each peak, taking into account the influence of indoor particle loss rates and contributions from outdoor air (PλO). The quantification method was based on the Indoor Aerosol Model [28], using the single-parameter approach [29, 30, 31]. Mean and standard deviation (SD) of the results are shown in Table 4 and Figure 3. A detailed description of the method can be found in Supplement 3. Particle emission rates were quite high in 1–5 μm and >5 μm size groups which reflects quick change in concentrations (Table 4 and Figure 3) even though the particle concentration range is small (Table 2).

4. Discussion

This study investigated aerosol generation in a dental office setting during 253 clinical procedures performed on 84 patients. The major finding was that the air turbine handpiece generated high levels of <1 μm particles and the highest total particle concentration when compared to other commonly used instruments. This corroborates with other studies [32, 33]. Furthermore, dental procedures utilizing high- and low-speed dental handpieces or ultrasonic scalers elevated the aerosol levels compared to the aerosol levels measured during oral examination. The higher rotational speed in dental handpieces has been associated earlier with higher aerosol generation even though the evidence is scarce [6], which is supported by this study when considering aerosol concentrations compared to oral examination and with background concentrations subtracted.

This present study examined aerosol particle number concentrations and particle mass concentrations, which describe different aspects: increase in particles is seen in total particle number concentration, whereas increase larger particles is noted in total particle mass concentration. In this study air turbine handpiece increases significantly the number of small aerosol particles. Smaller particles drift more deeply into the airways and lungs [34, 35], and smaller particles (particle size below 5 μm) contain more virus replicas than larger particles [35], thereby smaller particles can cause potentially more severe disease than larger particles.

Dental professionals are at increased risk of airborne viruses due to the aerosol- and splatter-generating procedures that are unavoidable in dentistry [7]. Additionally, dental professionals are exposed to patient-borne aerosols from upper airways in close contact with maskless patients during dental visits, even without aerosol-generating procedures [19, 22, 36]. Ultrasonic scalers generate a wide range of aerosols and large splatter (37 Both aerosols and splatter can be mitigated by using high-volume suctions and extraoral evacuation systems) [37, 38]. Aerosols of the spray mist have been shown to be effectively reduced by means of high-volume evacuator with an evacuation rate of ≥300 l/min [39]. A recent simulation study using ϕ6-bacteriophage as a surrogate for SARS-CoV-2 showed that aerosolization of the virus in dental clinics can be significantly reduced by using high-volume aspiration [40]. Results of this study also support the role of high-volume evacuators in reducing aerosols, as they were routinely used in this study simultaneously with air turbine, dental handpieces, and ultrasonic scaler.

In this study the air turbine was a significant aerosol-generating instrument, whereas high-speed and low-speed dental handpieces as well as ultrasonic scalers could also be classified as aerosol-generating instruments, but they produced less aerosols than we expected. As can be seen in Tables 4 and 7 out of 8 air turbine procedures showed significant peak in particle number concentration, while this ratio was 2/30 and 3/6 for low-speed and high-speed dental handpieces, respectively. Furthermore, the mean particle number emission rate for the procedure was about 5.2×10^7 (# min^{-1}), which can represent the typical emission rate of this procedure. Although the emission rates for low-speed and high-speed dental handpieces appear quite high, they only show the potential for high particle emission due to the limited number of cases observed here. The root canal treatment, 6 out of 12 cases were observed

Table 2. Medians and max values compared to background.

Procedure		<1 μm particle concentration, particles/cm^3	1–5 μm particle concentration, particles/cm^3	>5 μm particle concentration, particles/cm^3	Total particle concentration, particles/cm^3
		Median (IQR)			
Air turbine handpiece (N = 8)	Background	1.24 (1.18–2.20)	0.09 (0.04–0.11)	0 (0–0.007)	1.37 (1.25–2.24)
	Median	3.29 (1.83–4.27)	0.10 (0.06–0.27)	0.003 (0–0.006)	3.40 (1.94–4.50)
	Maximum	3.66 (2.20–5.50)	0.10 (0.06–0.24)	0.006 (0–0.03)	3.77 (2.28–5.76)
	P-value*	0.013	NS	NS	0.021
	P-value**	0.016	NS	NS (p = 0.065)	0.012
Low-speed dental handpiece (N = 30)	Background	2.63 (1.18–10.89)	0.07 (0.03–0.12)	0 (0–0.002)	2.74 (1.22–11.02)
	Median	2.59 (1.23–10.68)	0.06 (0.04–0.09)	0 (0–0)	2.71 (1.25–10.8)
	Maximum	2.87 (1.45–12.68)	0.07 (0.05–0.12)	0.006 (0–0.006)	3.00 (1.53–12.75)
	P-value*	NS	NS	0.023	NS
	P-value**	NS	NS	0.013	NS
High-speed dental handpiece (N = 6)	Background	1.32 (0.82–1.52)	0.05 (0.01–0.07)	0 (0–0.002)	1.37 (0.84–1.57)
	Median	1.40 (1.16–3.24)	0.05 (0.01–0.17)	0 (0–0.02)	1.47 (1.17–3.41)
	Maximum	1.81 (1.32–4.22)	0.06 (0.04–0.24)	0.003 (0–0.03)	1.90 (1.35–4.44)
	P-value*	NS	NS	NS	NS
	P-value**	NS (p = 0.055)	NS	NS	NS (p = 0.055)
Ultrasonic scaler (N = 31)	Background	3.32 (1.19–7.56)	0.03 (0.02–0.14)	0 (0–0)	3.37 (1.28–7.56)
	Median	3.32 (1.20–7.56)	0.03 (0.01–0.11)	0 (0–0)	3.39 (1.22–7.56)
	Maximum	3.65 (1.42–7.79)	0.05 (0.03–0.13)	0 (0–0.006)	3.75 (1.43–7.80)
	P-value*	NS	NS	NS	NS
	P-value**	NS	NS	0.015	NS
Periodontal treatment, manual (N = 60)	Background	2.21 (1.24–4.88)	0.05 (0.02–0.09)	0 (0–0.005)	2.33 (1.30–5.10)
	Median	2.07 (1.14–4.06)	0.03 (0.01–0.05)	0 (0–0)	2.11 (1.14–4.15)
	Maximum	2.54 (1.43–4.92)	0.05 (0.03–0.11)	0.006 (0–0.006)	2.69 (1.47–5.08)
	P-value*	NS	0.018	<0.001	NS
	P-value**	NS	NS	<0.001	NS
Local and topical anesthesia (N = 31)	Background	2.43 (1.74–6.79)	0.05 (0.02–0.10)	0 (0–0.006)	2.63 (1.78–7.03)
	Median	2.45 (1.66–6.86)	0.06 (0.02–0.08)	0 (0–0.006)	2.52 (1.73–6.79)
	Maximum	2.50 (1.76–7.31)	0.05 (0.03–0.09)	0.006 (0–0.01)	2.62 (1.79–7.38)
	P-value*	NS	NS	NS	NS
	P-value**	NS	NS	0.019	NS
Oral examination (N = 52)	Background	3.58 (1.35–9.38)	0.07 (0.04–0.10)	0 (0–0.006)	3.61 (1.41–9.51)
	Median	3.18 (1.21–9.49)	0.05 (0.03–0.07)	0 (0–0)	3.44 (1.37–9.74)
	Maximum	4.11 (1.52–9.87)	0.08 (0.04–0.14)	0.006 (0–0.01)	4.22 (1.62–9.93)
	P-value*	NS	0.046	<0.001	NS
	P-value**	NS	NS	0.001	NS
Intraoral X-ray (N = 24)	Background	10.47 (6.49–14.82)	0.05 (0.03–0.07)	0 (0–0)	10.46 (6.56–14.91)
	Median	9.89 (3.42–12.83)	0.05 (0.03–0.07)	0 (0–0)	10.02 (5.96–13.16)
	Maximum	10.41 (6.25–14.36)	0.06 (0.04–0.1)	0 (0–0.01)	10.47 (6.40–14.48)
	P-value*	NS	NS	NS	NS
	P-value**	NS	NS	NS	NS
Root canal treatment (N = 12)	Background	15.65 (10.19–20.68)	0.06 (0.04–0.08)	0 (0–0)	15.74 (10.27–20.60)
	Median	13.19 (7.30–20.51)	0.07 (0.03–0.11)	0 (0–0)	13.44 (7.42–20.82)
	Maximum	17.54 (11.82–23.14)	0.13 (0.06–0.45)	0.003 (0–0.02)	17.81 (11.94–23.36)
	P-value*	NS	NS	NS	NS
	P-value**	NS	0.04	0.019	NS

P-value* for median compared to background.
P-value** for maximum compared to background.
Statistical significance tested with non-parametric Mann-Whitney test. NS refers to non-significant.
Maximum values are presented as medians of maximum values.

with relative high particle number emission, root canal treatment utilizing also handpieces with emission rate about 1.5×10^7 (# min^{-1}). If a rubber dam shield cannot be used with the air turbine handpiece, the high-speed dental handpiece could be considered as a safer and less aerosol-generating option if aerosol production needs to be avoided during the pandemic, as has also been suggested elsewhere [40].

This study also noticed that the high aerosol levels produced after drilling take a long time to decline to the level of the background. As shown in Table 4, the mean indoor particle loss rates for total particle concentration after the significant peak caused by the handpiece procedures were 0.031–0.035 min^{-1}. And the median half-life for particle concentration after simultaneous use of air turbine and low-speed dental

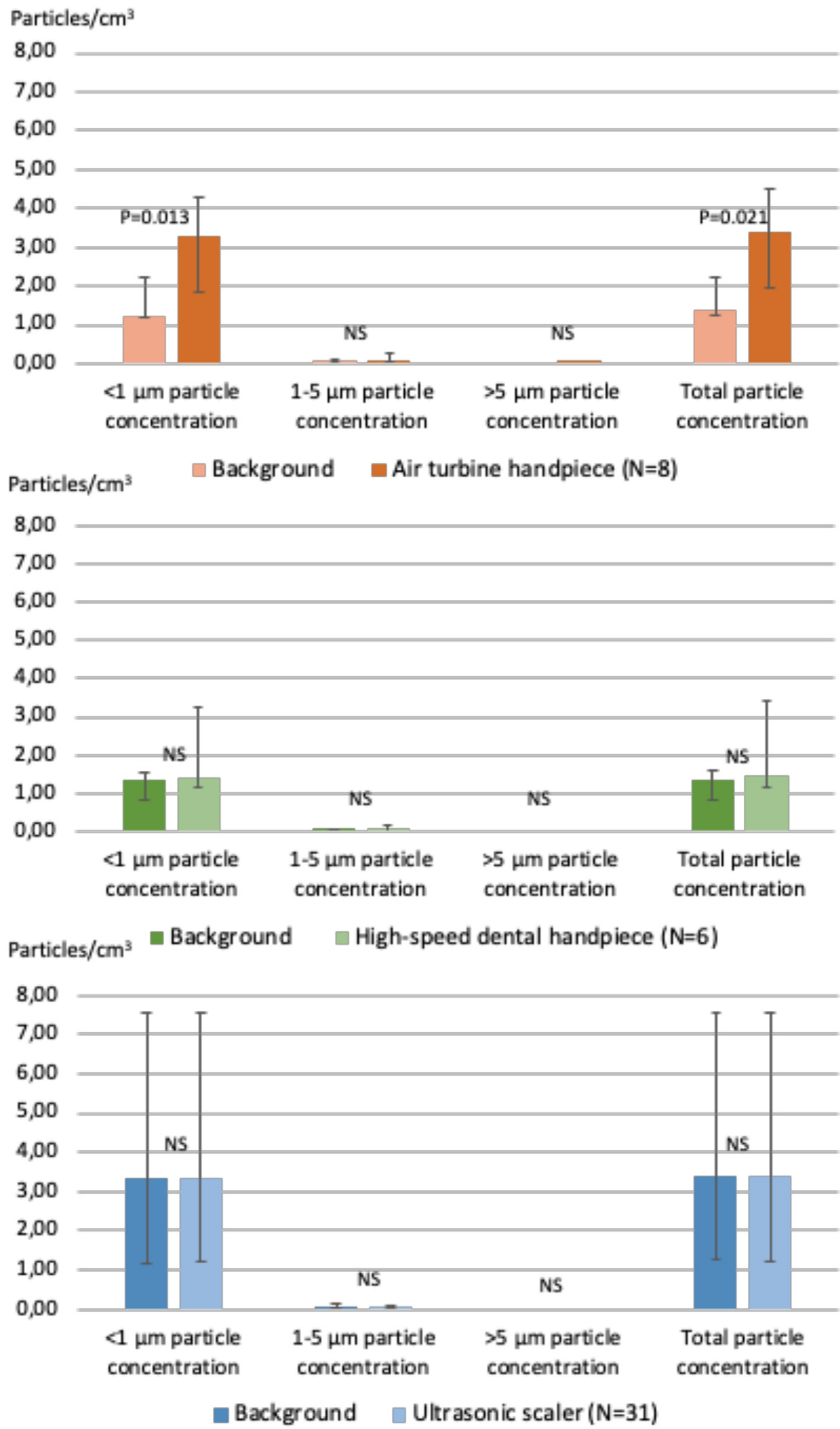

Figure 2. Medians and interquartile ranges of particle concentration medians in different particle size groups during air turbine handpiece, high-speed dental handpiece and ultrasonic scaler. Statistically significant p-values presented. NS refers to non-significant.

handpiece was approximately 20 min, which is a notably longer time than the period needed to prepare the operation room for the next patient would routinely be. At our clinic the ventilation was not good, with ACH varying between 2.76 and 6.19 h^{-1}, and the first tool to shorten the half-life and fallow time is to ensure good ventilation in operating rooms. If ventilation and air condition cannot be optimized, keeping a window open and acquiring a cross-draught in the operating room could be considered. It should further be noticed, that in addition to half-life, the

Table 3. Particle mass concentrations compared to background.

Procedure		$<PM_1 < 1$ μm particle mass concentration, μg/m^3	PM_1-PM_5 1–5 μm particle mass concentration, μg/m^3	$>PM_5 > 5$ μm particle mass concentration, μg/m^3	Total PM Total particle mass concentration, μg/m^3
		MEDIAN			
		Median (IQR)			
Air turbine handpiece (N = 8)	Background	0.04 (0.03–0.05)	0.30 (0.11–0.58)	0 (0–1.43)	0.40 (0.14–2.17)
	Median	0.06 (0.04–0.12)	0.40 (0.21–1.03)	0.16 (0–0.97)	1.01 (0.25–2.59)
	Maximum	0.07 (0.05–0.16)	0.44 (0.32–0.85)	1.31 (0–3.73)	1.81 (0.58–4.62)
	P-value*	0.046	NS	NS	NS
	P-value**	0.006	NS	NS	NS (p = 0.074)
Low-speed dental handpiece (N = 30)	Background	0.06 (0.03–0.21)	0.27 (0.07–0.43)	0 (0–0.08)	0.39 (0.16–0.93)
	Median	0.06 (0.03–0.21)	0.19 (0.08–0.38)	0 (0–0)	0.31 (0.17–0.60)
	Maximum	0.06 (0.04–0.22)	0.25 (0.10–0.62)	0.32 (0–0.94)	0.93 (0.46–1.60)
	P-value*	NS	NS	0.021	NS
	P-value**	NS	NS	0.022	0.013
High-speed dental handpiece (N = 6)	Background	0.03 (0.02–0.04)	0.16 (0.04–0.40)	0 (0–0.08)	0.28 (0.06–0.47)
	Median	0.03 (0.02–0.10)	0.11 (0.01–1.06)	0 (0–2.98)	0.15 (0.04–4.11)
	Maximum	0.05 (0.02–0.13)	0.22 (0.11–1.44)	0.48 (0–5.74)	0.76 (0.27–7.14)
	P-value*	NS	NS	NS	NS
	P-value**	NS	NS	NS, p = 0.06	NS
Ultrasonic scaler (N = 31)	Background	0.06 (0.03–0.13)	0.09 (0.04–0.48)	0 (0–0)	0.25 (0.07–0.77)
	Median	0.06 (0.02–0.12)	0.07 (0.02–0.45)	0 (0–0)	0.17 (0.08–0.53)
	Maximum	0.07 (0.03–0.13)	0.25 (0.12–0.48)	0 (0–0.96)	0.45 (0.2–1.63)
	P-value*	NS	NS	NS	NS
	P-value**	NS	NS, p = 0.079	0.018	0.034
Periodontal treatment, manual (N = 60)	Background	0.04 (0.03–0.09)	0.15 (0.03–0.37)	0 (0–0)	0.22 (0.09–0.81)
	Median	0.04 (0.02–0.08)	0.04 (0.01–0.15)	0 (0–0)	0.12 (0.05–0.21)
	Maximum	0.05 (0.03–0.10)	0.23 (0.08–0.43)	0.47 (0–2.30)	0.94 (0.20–2.48)
	P-value*	NS	0.004	<0.001	<0.001
	P-value**	NS	0.048	<0.001	0.001
Local and topical anesthesia (N = 31)	Background	0.05 (0.04–0.12)	0.19 (0.06–0.52)	0 (0–0.32)	0.27 (0.12–1.16)
	Median	0.05 (0.04–0.12)	0.15 (0.03–0.37)	0 (0–1.15)	0.25 (0.13–1.60)
	Maximum	0.05 (0.04–0.12)	0.17 (0.08–0.51)	0.62 (0–3.50)	1.31 (0.16–3.63)
	P-value*	NS	NS	NS	NS
	P-value**	NS	NS	0.018	0.045
Oral examination (N = 52)	Background	0.09 (0.03–0.16)	0.34 (0.16–0.46)	0 (0–2.05)	0.63 (0.31–2.35)
	Median	0.06 (0.03–0.16)	0.13 (0.07–0.26)	0 (0–0)	0.23 (0.14–0.40)
	Maximum	0.10 (0.04–0.17)	0.30 (0.16–0.63)	2.06 (0–2.94)	2.32 (0.66–3.84)
	P-value*	NS	<0.001	<0.001	<0.001
	P-value**	NS	NS	<0.001	0.004
Intraoral X-ray (N = 24)	Background	0.18 (0.12–0.25)	0.17 (0.05–0.25)	0 (0–0)	0.38 (0.27–0.80)
	Median	0.17 (0.06–0.23)	0.12 (0.05–0.22)	0 (0–0)	0.30 (0.20–0.53)
	Maximum	0.18 (0.06–0.24)	0.15 (0.10–0.29)	0 (0–2.54)	0.46 (0.27–3.06)
	P-value*	NS	NS	NS	NS
	P-value**	NS	NS	NS	NS
Root canal treatment (N = 12)	Background	0.31 (0.18–0.36)	0.22 (0.05–0.46)	0 (0–0)	0.48 (0.32–0.88)
	Median	0.23 (0.11–0.35)	0.13 (0.05–0.22)	0 (0–0)	0.40 (0.21–0.62)
	Maximum	0.35 (0.23–0.47)	0.51 (0.22–1.25)	0.48 (0–2.54)	2.32 (0.64–3.39)
	P-value*	NS	NS	NS	NS
	P-value**	NS	NS	0.018	0.015

P-value* for median compared to background.
P-value** for maximum compared to background.
Statistical significance tested with non-parametric Mann-Whitney test. NS refers to non-significant. PM refers to particulate matter.

fallow time is a function of the absolute concentration generated by the procedure. Therefore, the fallow time for air turbine is higher than for handpiece-procedures.

In a recent study, salivary microbes were found in aerosol microbiomes irrespective of what type of dental aerosol-generation procedure was measured [12]. The writers stated that this observation supports the perception that the water or the irrigant fluid used during aerosol-generating procedure forms the major portion in dental aerosols [12], with water or irrigant diluting the saliva even 200-fold [41]. Previously, some waterborne infections such as legionellosis and pneumonia have been transmitted from dental unit water lines [42, 43]. In our study we observed aerosol production at maximum values during root canal

Table 4. Particle loss rates, contributions from outdoor air (PλO), and emission rates from dental procedures with significant peaks in particle number concentration.

Procedure	Particle size range	Particle loss rate (min^{-1})		PλO (# cm^{-3} min^{-1})		Emission rate (# min^{-1})	
		mean	SD	mean	SD	mean	SD
Air turbine handpiece (N = 7)	<1 μm	0.034	0.009	0.049	0.031	6.07E+07	4.77E+07
	1–5 μm	0.059	0.005	0.002	0.002	3.07E+07	3.13E+07
	>5 μm	0.062	0.042	0.000	0.000	6.32E+06	3.80E+06
	Total (0.3–10 μm)	0.032	0.008	0.049	0.028	5.15E+07	3.36E+07
Low-speed dental handpiece (N = 2)	<1 μm	0.031	0.013	0.206	0.177	1.24E+08	1.68E+08
	1–5 μm	0.087	0.035	0.003	0.003	9.18E+07	1.09E+08
	>5 μm	0.075	0.037	0.001	0.000	5.75E+06	2.02E+06
	Total (0.3–10 μm)	0.031	0.013	0.206	0.177	1.25E+08	1.72E+08
High-speed dental handpiece (N = 3)	<1 μm	0.036	0.010	0.029	0.015	1.30E+08	7.35E+07
	1–5 μm	0.035	0.006	0.001	0.001	1.31E+08	2.14E+08
	>5 μm	0.075	0.067	0.001	0.000	3.38E+07	5.25E+07
	Total (0.3–10 μm)	0.035	0.011	0.031	0.017	1.29E+08	8.29E+07
Root canal treatment (N = 6)	<1 μm	0.023	0.014	0.221	0.105	1.38E+07	1.06E+07
	1–5 μm	0.077	0.039	0.004	0.003	2.28E+07	2.08E+07
	>5 μm	0.065	0.035	0.000	0.000	1.25E+07	8.85E+06
	Total (0.3–10 μm)	0.022	0.012	0.211	0.101	1.50E+07	1.15E+07

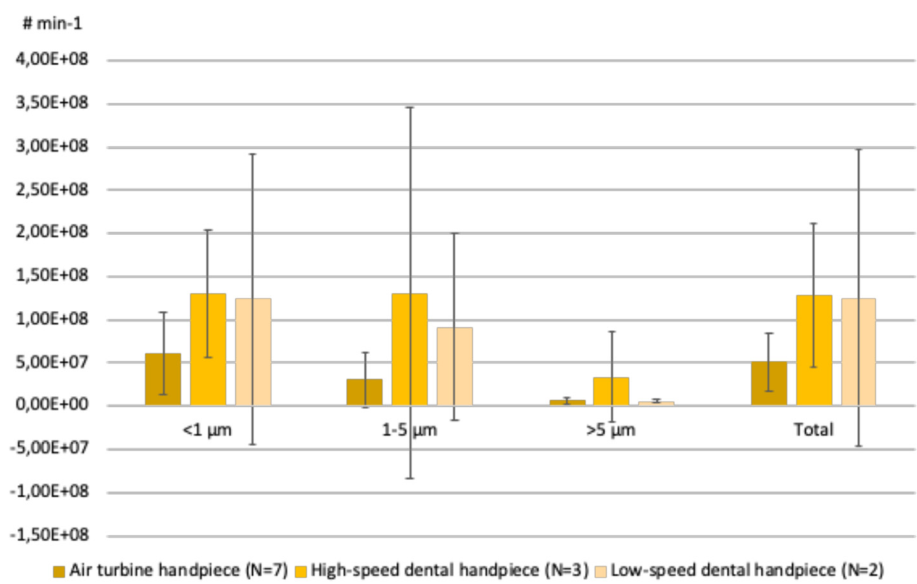

Figure 3. Mean emission rates and standard deviations in different particle size groups during air turbine handpiece, high-speed dental handpiece and low-speed dental handpiece.

treatment reflecting the major load of irrigant fluid in dental aerosols. Additionally, during topical and local anesthesia some minor differences in aerosol levels were observed, which can be explained by the simultaneous use of an air-water syringe.

There are several limitations in this study. This study deals with aerosol levels that are mainly composed of water or irrigant from the drills or ultrasonic scaler, and this study did not measure whether the aerosols contained viruses or other microbes. We cannot provide any estimate on the infectivity of these aerosols; however, we recommend that every dental aerosol-generating procedure should be concerned with precautions because of the potential risk for pathogens. In addition, the measurements were performed in six different operation rooms, which had slightly different ventilation and air conditions as well as different air volumes. This was taken into account by measuring the background levels immediately before each procedure and by adjusting the background levels to the results. In addition, our emission rate analysis took into account the room size. The remaining variability is related to the statistical distribution of the emissions [44], and other artifacts such as the spatial distribution of the emitted aerosols while being transported from the source to the receptor (instrument). The position and distance have direct effect on the aerosol's dispersion. There were naturally high background aerosol levels at our clinic, built in the late 1970s and not originally designed with surgery-level ventilation. Thus, smaller changes in overall aerosol concentrations may have been underestimated due to the high background aerosol concentrations. Aerosol levels in this study were measured using only one measurement device designed for measuring concentration not total amount of aerosol during the day. To be more specific and thorough, a more comprehensive aerosol measurement setup should be utilized to find out e.g. the size distribution up to 100 μm.

The strengths of this study is large sample size with actual patients in routine clinical situations. In this study we measured a great variety of dental procedures, which also enables comparison between different procedures. This data was collected in real clinical situations, in which dental instruments and high-volume evacuators are routinely used, thus the estimation of real aerosol generation can be evaluated.

In the early phase of the COVID-19 pandemic, aerosol and droplet generation by dental procedures was immediately highlighted, and urgent guidelines for the reduction of aerosol and droplet production were recommended to oral-health providers [45, 46, 47, 48]. Then, however, specific and certified scientific data on aerosol generation during various dental procedures were missing, and the recommendations were based on conceivable logic, but also out of an abundance of caution during the rise of the novel coronavirus. Recommendations regarding the use of air turbine handpiece, air spray, and ultrasonic scaler as well as on pre-procedural mouth rinses, fallow time, and personal protective equipment were given in detail, and dental operators followed them all around the world. In the future, studies addressing the exposure risk for detectable dental pathogens during these procedures are needed. Different samples from simulation studies and samples from real patients with different sampling methods are needed to combine straight patient samples (i.e. saliva) to different collection methods to investigate RNA and infective viruses. The studies should be further conducted to investigate not only SARS-CoV-2 virus but also other respiratory or mucosal viruses and pathogens, which can potentially generate a risk for dental professionals.

In conclusion, this study observed the highest aerosol production when using an air turbine handpiece mostly in particle size <1 μm. Additionally, high- and low-speed dental handpieces and ultrasonic scalers elevated the aerosol levels significantly compared to the aerosol levels measured during oral examination. The aerosol-generating dental instruments, especially air turbine, should be used with adequate precautions (rubber dam, high-volume evacuation, FFP-respirators), because dental aerosols can cause a potential risk for operators. Additionally, substitution of air turbine for high-speed dental handpiece in poor epidemic situations should be considered to reduce the risk of aerosol transmission.

Declarations

Author contribution statement

Laura Susanna Julia Lahdentausta, PhD: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Saku Lauretsalo; Verneri Korkee; Jiangyue Zhao; Tareq Hussein: Analyzed and interpreted the data; Wrote the paper.

Sini Nyman: Performed the experiments; Wrote the paper.

Enni Sanmark; Lotta Oksanen; Nina Atanasova: Conceived and designed the experiments; Wrote the paper.

Antti Hyvärinen: Conceived and designed the experiments; Analyzed and interpreted the data; Contributed materials, analysis tools or data; Wrote the paper.

Susanna Paju: Conceived and designed the experiments; Performed the experiments; Contributed materials, analysis tools or data; Wrote the paper.

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Data availability statement

Data will be made available on request.

Declaration of interest's statement

The authors declare no conflict of interest.

Additional information

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