Real-time 3D analysis of airborne particles produced during orthodontic composite attachment removal

2022 Research Aid Awards (RAA)

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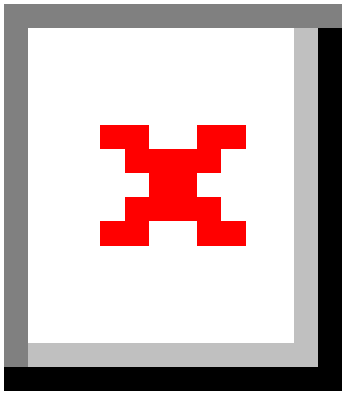
FollowUp Form

Award Information



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- *Does this Final Report provide the level of detail, etc. that you would expect, if you were the reviewer?*

Title of Project:*

Real-time 3D analysis of airborne particles produced during orthodontic composite attachment removal

Award Type

Research Aid Award (RAA)

Period of AAOF Support
July 1, 2022 through June 30, 2023

Institution
University of Washington

Names of principal advisor(s) / mentor(s), co-investigator(s) and consultant(s)
Greg Huang, Sepehr Makhsous, Igor Novosselov

Amount of Funding
$5,000.00

Abstract
(add specific directions for each type here)

Introduction and Statement of the Problem
The outbreak of SARS-CoV2 (COVID-19) and its rapid spread has led to a dramatic loss of human life and has devastated social and economic systems worldwide (WHO). Although widespread vaccination efforts are underway, multiple variants of the virus have been documented globally with mutations that allow it to spread more easily (Korber et al., 2020). The SARS-CoV2 virus is transmitted through airborne droplets, putting dental practices at increased risk of spreading the virus due to the aerosol-producing nature of many dental and orthodontic procedures (WHO). In addition to viruses, aerosols can carry bacteria and dental particulates which contain cytotoxic material such as silica and adhesive monomer (Cokic et al., 2017; Finkelstein, 2000). Continuous occupational exposure to these entities may be contributing to the increased rates of chronic respiratory diseases in dental professionals (Choudat et al., 1993; Finkelstein, 2000; Kim et al., 2002; Kuramochi et al., 2004; Nett, Cummings, Cannon, Cox-Ganser, & Nathan, 2018).

Various methods have been proposed to minimize aerosolized particles, such as supplemental extraoral evacuation and use of air-free handpieces without water supplementation (Nulty, Lefkaditis, Zachrisson, Van Tonder, & Yar, 2020). However, there is little evidence available on the effectiveness of these techniques. Current evidence is mainly focused on droplet contamination and bacterial load, rather than dental particulates (Innes et al., 2020). However, as the SARS-CoV2 virus is believed to spread via aerosols, measuring the dispersion and mitigation of particulates can serve as a surrogate for decreasing the potential for infection from the SARS-CoV2 virus and other pathogens. Thus, it is necessary to determine which methods will reduce particle production and enhance mitigation during dental and orthodontic procedures. Our plan is to simulate a common orthodontic procedure, removal of composite material. Composite is routinely used to bond orthodontic brackets, as well as to create attachments which are used to assist with tooth movement in aligner therapy. We will test all combinations of 3 different handpieces, along with 2 evacuation methods, in order to determine the most ideal method to minimize aerosol production and to maximize aerosol capture when removing composite resin.

List of Specific Aims
Aim #1: characterize the concentration, and real-time distribution of aerosolized particles produced during removal of orthodontic composite attachments bonded to upper and lower anterior teeth of printed models

mounted to an orthodontic chair. Particles will be measured at various locations, including at the particle source, operator, assistant, adjacent operatories, and adjacent walkways.

Aim #2: Investigate the effect of handpiece type (traditional air-driven, electrical, and air-free handpieces) on aerosolized particle production and dispersion when removing composite attachments bonded to upper and lower anterior teeth.

Aim 3: Investigate the effect of various evacuation systems and combinations of the evacuation systems (high-speed intraoral evacuation and high-volume extraoral scavenger) on aerosolized particle production and dispersion when removing composite from upper and lower anterior teeth.

Respond to the following questions:

Detailed results and inferences:*

If the work has been published, please attach a pdf of manuscript below by clicking "Upload a file".
OR
Use the text box below to describe in detail the results of your study. The intent is to share the knowledge you have generated with the AAOF and orthodontic community specifically and other who may benefit from your study. Table, Figures, Statistical Analysis, and interpretation of results should also be attached by clicking "Upload a file".

Yoshida Thesis Final.pdf
See attached document - Final Master's thesis

Were the original, specific aims of the proposal realized?*

Yes, the original, specific aims of the proposal were realized. The conclusions are as follows:
1. The concentration of PM2.5 particles produced during composite attachment removal is highest close to the source of the procedure and decreases with distance.
2. Using the air-free or electric handpiece when removing orthodontic composite attachments had statistically significant reductions in mean and maximum PM2.5 concentrations when compared to the conventional handpiece for most zones of the operatory. Using an air-free handpiece resulted in a predicted reduction of 48% and 72% in the operator's mean and maximum particle exposure, respectively.
3. Using any type of suction had a statistically significant reduction in the mean and maximum PM2.5 concentrations compared to no suction. Generally, using extra-oral suction (EOS) and high-volume intra-oral suction (IOS) simultaneously mitigated particles most effectively, followed by EOS only, and then IOS only. However, the differences between EOS only and IOS only were small. Using both EOS and IOS simultaneously resulted in a predicted reduction of 84% and 89% of the mean and maximum PM2.5 concentrations to the operator, respectively.

Were the results published?*

No

Have the results of this proposal been presented?*
No

To what extent have you used, or how do you intend to use, AAOF funding to further your career?*
The funding provided by the AAOF for my research has helped me realize my role in expanding the knowledge within the orthodontic field. Through my research, I have found that one of my passions is to protect the orthodontist and team members from potential occupational hazards within the clinic. This has a personal connection to me as my late father, who was an orthodontist for 26 years, passed away from lung cancer in 2019, at the age of 61. While it is hard to pinpoint the cause of his cancer, my father's passing has opened my eyes to health and safety within orthodontics. In our ever-changing field, new treatment modalities and diagnostic tools are researched thoroughly and being adopted very quickly however, the research on the exposure risk of these new techniques lags. As I begin my orthodontic career after residency, I hope to make a difference in this subject.

I am very lucky to be able to use the current AAOF award as a doorway to entering the world of orthodontic research and academia. I have had the opportunity to network with fellow researchers at the AAOF award breakfast, connect with department chairs, and gain recognition by my colleagues. I am also very thankful to have been introduced to the world of research while in residency - this has allowed me to develop my skills with the assistance of my entire department, who have taught me about research design, writing style, statistical analysis, and the process of grant submissions.

Accounting: Were there any leftover funds?
$0.00

Not Published

Are there plans to publish? If not, why not?*
Yes, we are in the process of editing my manuscript to submit to AJODO for possible publication.

Not Presented

Are there plans to present? If not, why not?*
The results were presented for my Master's thesis at the University of Washington however, they were not presented at any public lecture event. We are in the process of applying for the AAO Hellman, Sicher and Graber Research Awards for 2024 and if selected, this work may be presented at AAO 2024.

Internal Review

Reviewer comments

Reviewer Status*

File Attachment Summary

Applicant File Uploads

- Yoshida Thesis Final.pdf

Mitigation of aerosol particles during composite attachment removal

Erin Yoshida, DDS

A thesis
submitted in partial fulfillment of the
requirements for the degree of

Master of Science in Dentistry

University of Washington
2023

Committee:
Greg Huang
Bobby Cohanim
Igor Novosselov
Geoffrey Greenlee

Program Authorized to Offer Degree:
School of Dentistry, Department of Orthodontics

University of Washington

Abstract

Mitigation of aerosol particles during composite attachment removal

Erin Yoshida

Chair of the Supervisory Committee:

Greg Huang

Department of Orthodontics

Introduction: The COVID-19 pandemic brought significant public and professional attention to the aerosol-generating nature of dentistry. In orthodontics, significant amounts of aerosolized particles may be produced and spread during aligner composite attachment removal with a handpiece. Methods have been proposed to mitigate aerosols during these procedures, such as using handpieces that minimize spraying or employing various types of suction. The purpose of this study is to determine which strategies most effectively reduce aerosolized particles when removing orthodontic composite attachments.

Methods: A network of novel AeroSpec portable particle monitors was employed to record and store particulate data in real-time. 16 sensors were placed in a 3D grid system in and around a representative operatory at the UW Orthodontics Department. Composite attachments (Transbond LR) were removed from the anterior six teeth of maxillary and mandibular resin models placed in a manikin head. Particulate matter of optical diameter 2.5μm or less ($PM_{2.5}$) was measured. Three

different handpiece types were tested: conventional air-driven highspeed (StarDental), electric highspeed (BienAir), and air-free highspeed (Medidenta). Four different suction conditions were tested with each handpiece type: no suction, high-speed intraoral suction (IOS), extraoral suction (EOS), and both IOS and EOS together. Four repetitions of attachment removal with each handpiece and suction type were performed. Linear regression was used to compare average and maximum particle concentration by suction and handpiece.

Results: During removal of the composite attachments, the highest concentration of particles was observed around the operator and decreased the further the sensor was located from the source of composite removal. Linear regression for the main effect of handpiece type indicated lower $PM_{2.5}$ when electric or air-free handpieces were used compared to a conventional handpiece. Linear regression for the main effect of suction showed significant reductions when any type of suction was used compared to no suction. The simultaneous use of both IOS and EOS resulted in the greatest reduction in particulate concentrations.

Conclusion: Air-free or electric handpieces should be considered over conventional handpieces to mitigate aerosol spread. Additionally, employing IOS, EOS, or the combination of both significantly reduced the spread of particles. Using an air-free or electric handpiece, along with simultaneous use of IOS and EOS, reduced the maximum particle concentrations that the doctor was exposed to by 92 to 94 percent, compared to a conventional handpiece and no suction.

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INTRODUCTION

BACKGROUND

Occupational Exposure to Biologic Aerosols

The COVID-19 pandemic has brought significant public and professional attention to the aerosol-generating nature of dentistry. COVID-19 is caused by the highly infectious SARS-CoV-2 coronavirus and is spread by airborne droplets [1]. Dental professionals are now trying harder than ever to minimize the production and spread of these aerosols. Aerosol Generating Procedures (AGP) in dentistry can be described as "any procedure on a patient that can induce the production of aerosols of various sizes [2]." In addition to AGPs, dental professionals and team members see large numbers of patients in close contact for prolonged periods of time, increasing their risk of exposure [3,4].

Aerosols can be defined as suspensions in the air of solid or liquid particles small enough that they will remain airborne for a prolonged period of time [5]. The particles which make up aerosols can contain pathogens including bacteria and viruses, including SARS-CoV-2 [6-8]. The size of these particles ranges from ≤ 5 μm, which can remain suspended for more than an hour and can penetrate the lower respiratory tract (30% of particles ≤ 5 μm penetrate the alveolar region), to larger particles, which settle much more quickly (within seconds) and have essentially no deposition in the lower respiratory tract [5]. SARS-CoV-2 virus has been observed to have a diameter of 0.06 to 0.14 μm, so it could easily adhere to small, aerosolized particles and penetrate the lower respiratory tract if inhaled [9].

Previous research on dental AGP's has created a ranking of procedures based on contamination risk: higher risk (ultrasonic scaling, high-speed air-rotor, air-water syringe, air polishing, extractions using motorized handpieces); moderate risk (slow-speed handpieces, prophylaxis, extractions) and lower risk (water only from air-water syringe and hand scaling) [2]. While orthodontists have much fewer AGPs than general dentists and other specialists, the open bay layout of many orthodontic offices may pose an increased risk of patient-to-patient transmission of airborne pathogens [10]. Composite adhesive removal with a high-speed handpiece after bracket removal is one primary AGP orthodontists routinely perform, which has been shown to produce numerous particles in the range of 2 to 30 μm [11]. The particles produced correspond with the composition and size of the fillers and matrix of the adhesive. Clear aligner therapy, such as Invisalign, often incorporates composite resin attachments to assist with tooth movements. The volume of composite in these attachments is significantly more than the thin layer of adhesive that remains after bracket removal. Therefore, removal with a highspeed handpiece is the most practical and common method, and results in aerosolized particles [12]. In both situations above, water spray is often not used to better visualize the composite-enamel interface. However, cooling the tooth with a stream of air is common and leads to increased aerosol dispersion.

Infection Control and Minimizing Aerosols

Historically, surveys indicate that infection control by orthodontists has been less rigorous compared to general dentists. This is possibly due to the perceptions of less invasive procedures, younger patients, and shorter office visits [13-15]. Currently,

associations such as the ADA, AAO, and CDC recommend using standard precautions for all patients regarding infection control. These recommendations include hand hygiene, sterile instruments, clean and disinfected environmental surfaces, and the use of personal protective equipment such as masks, gloves and eyewear [16].

In addition to standard precautions, there was specific guidance for dental settings during the COVID-19 pandemic. If AGPs were necessary for patient care, the CDC suggested using four-handed dentistry and high-volume suction to capture aerosols. Intraoral high-volume suction has been reported to reduce the contamination from the operative site by up to 90 percent [8,17,18]. The use of additional portable high-efficiency particulate air (HEPA) extra-oral suction (EOS) filtration units was also suggested while patients were undergoing AGPs [16]. These filtration units have been reported to significantly reduce particle counts during in vitro dental AGPs by half to two-thirds [17,19]. Dental healthcare providers (DHCP) were instructed to use N95 respirators (or their equivalent) during AGPs to further minimize inhalation of aerosols during AGPs.

Recently, companies have started to market Electric and Air-free handpieces as alternatives to traditional air-driven dental handpieces to minimize aerosol production and/or spread. During the cutting process, all handpieces generate composite dust and debris that may be contaminated with saliva and oral microbes. This study does not directly measure the number of particles generated during cutting, but rather the number of particles that spread to surrounding areas under different conditions. In a study comparing high- and slow-speed handpieces with and without water irrigation, it was found that operators could inhale aerosolized particulates irrespective of handpiece speed or the presence or absence of water irrigation [20]. The absence of water and/or air spray

decreases aerosol dispersion however this decreases heat dissipation. This effect is often undesirable due to patient discomfort.

Occupational Exposure to Composite Dust

While the SARS-CoV-2 virus has brought significant attention to biological aerosols, occupational exposure of DHCP to the particulate components of aerosols shouldn't be ignored. Dental composites consist of inorganic filler particles, like silica treated with a silane coupling agent, in a resin-based matrix [21]. Silica nanoparticles (>100 nm) can be smaller than 10 nm, and when polymerized composite is aerosolized during dental procedures, the resultant composite dust particles can range from 7 nm up to 15 µm [21]. Chronic inhalation of composite dust is a concern for DHCP, as particles of this size can penetrate the alveoli, beyond the point where they can be removed via ciliary action and mucous secretions [22]. Inhaling small particles of any material (not just dental materials) less than 2.5 µm in size ($PM_{2.5}$) has been shown to significantly impact human health, causing conditions such as asthma, respiratory inflammation, cardiopulmonary problems, lung cancer, and general mortality [23]. Orthodontic adhesives, such as Transbond XT, have filler particles that contain silica, aluminum, and lanthanum. Chronic inhalation of particles containing silica can lead to silicosis, a progressive fibrotic lung disease [24], and can increase the risk of lung cancer by up to 30% [25].

Throughout the years, there have also been sporadic reports of clusters of dental personnel diagnosed with idiopathic pulmonary fibrosis [26] and pneumoconiosis [27]. Although occupational exposure could not be singled out as the primary cause of disease, the affected individuals reported working in dental settings and exposure to dust from

dental materials without adequate respiratory protection and dust control [26,27]. Several case reports have also identified dental personnel diagnosed with pneumoconiosis. The transbronchial lung biopsies from these individuals indicated deposition of silica particles and alginate impression powder [28,29].

Particle Measurement with AeroSpec Monitors

Particle measurement during dental AGP studies has previously been conducted with several techniques, including a single professional air monitoring unit [19,30], a single air quality monitor [17], a cascade impactor or filter followed by scanning electron microscope analysis [11,20], and splatter screen detection [10,31]. While these methods of aerosol measurement have been widely used, they do have limitations, such as the high cost of professional air-monitoring units and the inability to analyze the space-resolved distribution of aerosols. The particulate matter (PM) sensors used in this study (Fig. 1) offer a solution to these limitations, as they are relatively low-cost and compact, which allows for multiple sensors to be employed simultaneously during an AGP.

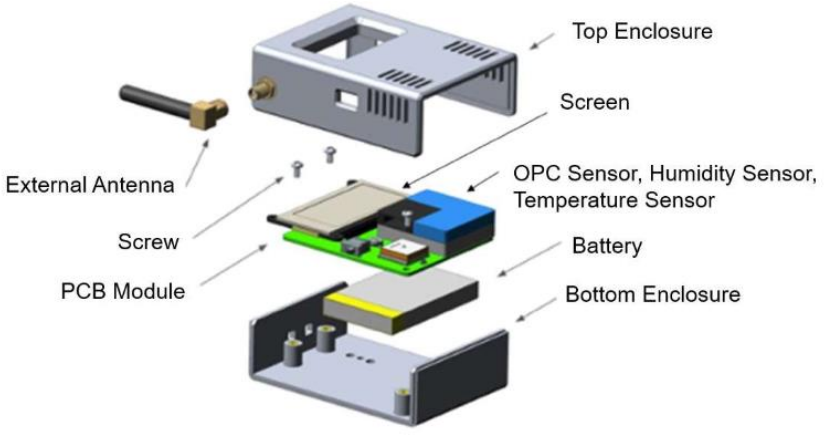


Fig. 1 Exploded view of the AeroSpec monitors used in the study[32].

The AeroSpec devices utilize Optical Particle Counters (OPCs) which rely on elastic light scattering to estimate particle concentrations with time- and space-resolved particle concentrations in the 0.3 – 10.0 µm range. Low-cost particulate matter (PM) sensors like those in the AeroSpec units have been shown to produce valid and reliable data, especially when calibrated against research-grade reference instruments [33-38]. A recent study [32] demonstrated the functionality of the AeroSpec devices when measuring real-time 3D aerosol distribution during dental procedures.

Purpose of the Study

The purpose of this study is to determine which strategies (handpiece and evacuation system) most effectively minimize the dispersion of aerosolized particles when removing orthodontic composite attachments from dental models mounted in a manikin head.

Aims

1. Characterize the concentration and real-time distribution of aerosolized particles produced during the removal of orthodontic composite attachments bonded to upper and lower anterior teeth on printed models. Particles were measured at various locations, including the operator, patient, assistant, adjacent spaces within the operatory, and adjacent operatories.
2. Investigate the effect of various evacuation systems and combinations of the evacuation systems (high-speed intraoral evacuation and high-volume extraoral scavenger) on aerosolized particle dispersion when removing composite attachments from upper and lower anterior teeth.

3. Investigate the effect of handpiece type (traditional air-driven, electrical, and air-free handpieces) on aerosolized particle dispersion when removing composite attachments bonded to upper and lower anterior teeth.

RESEARCH DESIGN AND METHODS

RESEARCH DESIGN

This in-vitro study utilized 3-D printed models placed within a manikin head with rubber cheeks to simulate clinical conditions. The in-vitro study design made it possible to standardize the size of the composite attachments, as well as the trial environment and moisture control, while also eliminating the risk of dental particulate exposure to human subjects.

Sixteen AeroSpec devices (particle measurement devices) were placed in a 3-dimensional arrangement in and around an orthodontic operatory, and real-time data on the concentration and size distribution of aerosolized particles were collected. The locations represented various zones of interest in a dental office. Three types of highspeed handpieces (conventional air-driven, air-free, and electric) were used for composite removal (Table 2) and different combinations of oral evacuation, including high-speed intraoral evacuation and extraoral suction (Table 3), were tested.

Prior to test trials, an Aerodynamic Particle Size (APS, TSI model 3321) measured the composite particle size distribution during attachment removal and immediately after attachment removal using a conventional handpiece with no suction. Composite particles produced were < 5 µm, with a median aerodynamic diameter of 1.94 µm during attachment removal and 1.19 µm at the end of attachment removal. Based on

this trial, we report data for $PM_{2.5,}$ i.e., the concentration of particles that have an optical diameter of ≤ 2.5 µm, measured in micrograms per cubic meter (µg/m³).

METHODS

Sample

Standardized rectangular attachments (4 mm long x 2 mm wide x 1 mm deep) were placed on the anterior teeth of 3D-printed resin maxillary and mandibular models. First, a thin layer of OrthoSolo™ universal sealant and bonding primer (Ormco™, Orange, CA, USA) was applied to the teeth of the resin models. Then, Transbond™ LR Light Cured Adhesive (3M™, St. Paul, Minnesota, USA) was filled into the reservoirs of the attachment templates, which were then positioned on each model and light-cured.

Apparatus and Procedures

Each AeroSpec unit measures particle counts in six size bins in the optical diameter range of 0.3 – 10.0 µm, and records mass concentration (µg/m³) at 3 levels - PM_1, $PM_{2.5}$, and PM_{10}. Original equipment manufacturer calibration was used for this study. The devices recorded and stored the particulate concentration data every 5 seconds during the testing period [32,37]. Sixteen aerosol monitors were set up in a predetermined 3D grid system in and around a representative operatory at the UW Orthodontics department. A map of the sensor placement is shown in Fig. 2. For reference, the operator was at the 12 o'clock position relative to the manikin head.

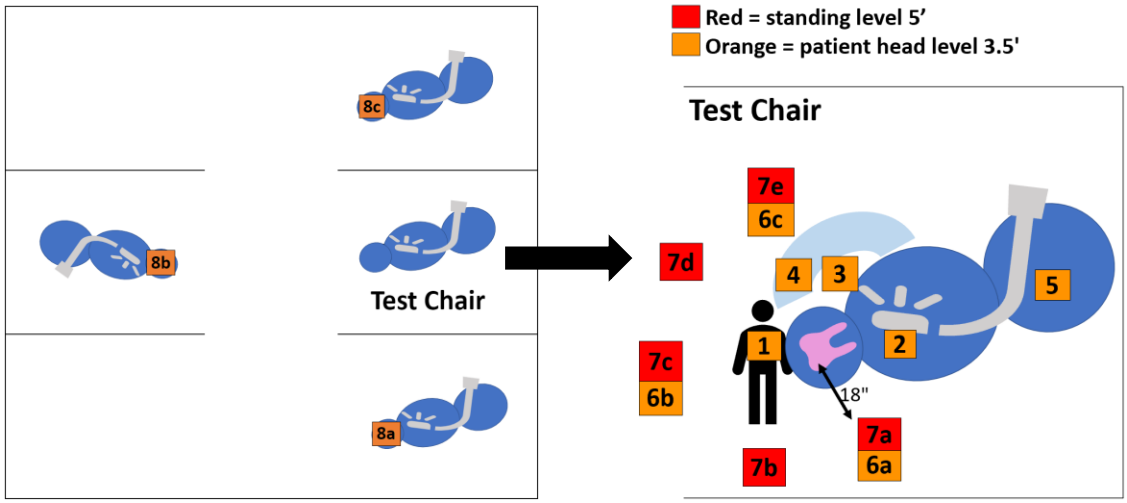


Fig. 2 (a) Map of test chair with neighboring operatories. Black lines represent partitions between operatories, which were 4.5' high, topped with plexiglass barriers which added an additional 2' of height. (b) Zoomed-in view of sensor positions within the test operatory.

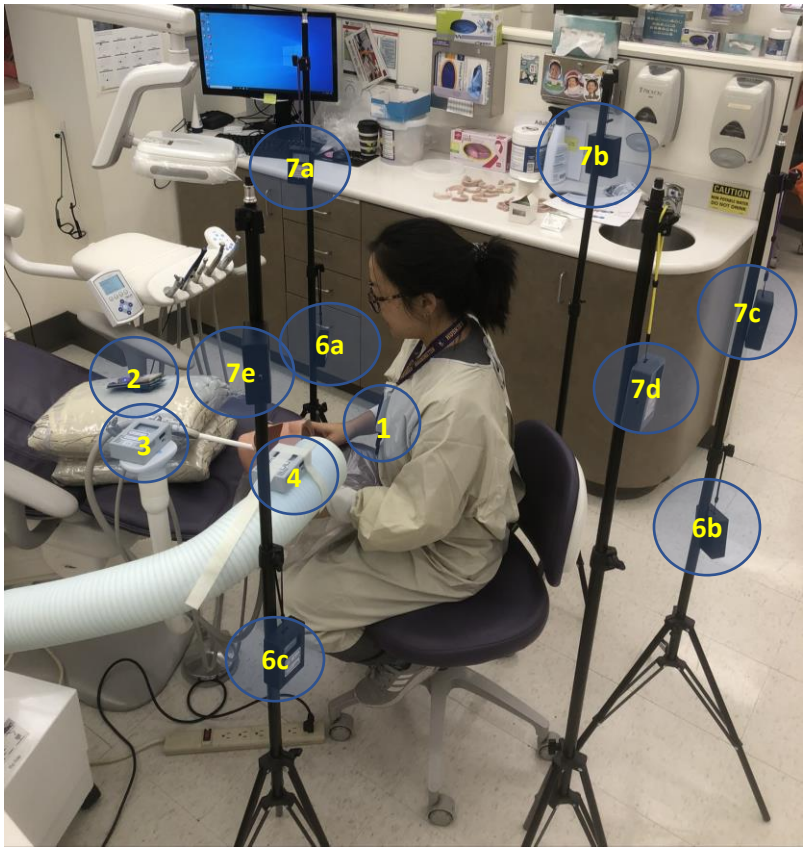


Fig. 3. Image of test chair. Visible sensors are circled and labeled.

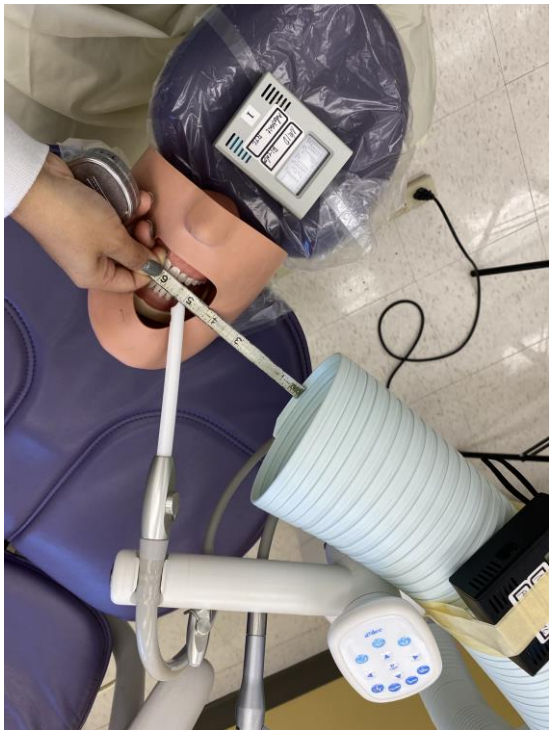
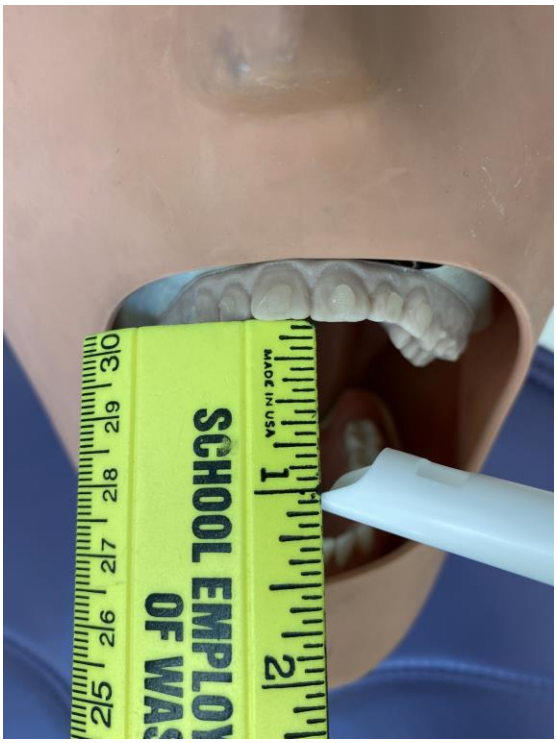
(a)  ***(b)*** 

Fig 4. Images of typodont setup with manikin cheeks in place, attached to the head of the test chair. (a) The opening of the EOS was positioned 6" away from the typodont central incisors, on the left side of the chair. (b) The IOS was placed 1" above or below the incisors during the attachment removal of the lower and upper arches, respectively.

Table 1. List of all sensor positions and descriptions.

Sensor #	Sensor Name - Location
1	Operator – Attached to lanyard around operator's neck, 6" distance below operator mouth, 6" distance above typodont
2	Patient chest – At patient chest level, 8" distance from typodont
3	Assistant – Placed on assistant control arm near suction, 8" distance from typodont
4	Top of EOS – Attached to the top of EOS suction unit, 6" distance from the orifice of the unit, 12" distance from typodont
5	Patient foot – 48" distance from typodont to foot of the chair
6a	3.5'periphery at 8:00 position – Mounted on a tripod, approximately 22" distance from typodont, 3.5 feet from the floor
6b	3.5' periphery at 12:00 position – Mounted on a tripod, approximately 30" distance from typodont, 3.5 feet from the floor
6c	3.5' periphery at 3:00 position – Mounted on a tripod, approximately 22" distance from typodont, 3.5 feet from the floor
7a	5' periphery at 8:00 position – Mounted on a tripod, approximately 36" distance from typodont, 5 feet from the floor and above 6a sensor
7b	5' periphery at 10:00 position – Mounted on a tripod, approximately 36" distance from typodont, 5 feet from the floor
7c	5' periphery at 12:00 position – Mounted on a tripod, approximately 42" distance from typodont, 5 feet from the floor and above 6b sensor
7d	5' periphery at 1:30 position – Mounted on a tripod, approximately 36" distance from typodont, 5 feet from the floor
7e	5' periphery at 3:00 position – Mounted on a tripod, approximately 36" distance from typodont, 5 feet from the floor and above 6c sensor
8a	Neighboring chair at 9:00 position – placed on chair head with chair reclined, approximately 10' distance from typodont
8b	Neighboring chair at 12:00 position – placed on chair head with chair reclined, approximately 6' distance from typodont
8c	Neighbor chair at 3:00 position – placed on chair head with chair reclined, approximately 10' distance from typodont

Note: Operator at 12 o'clock relative to manikin head.

The operatory has dimensions of approximately 10 ft wide by 10 ft deep, separated from adjacent units by walls 4.5 ft high topped with 2 ft plexiglass barriers. One side of the operatory opens to a walkway 5 ft wide, which directly connects it to the unit across.

To minimize external factors that might affect the results, standardized conditions were maintained. All windows and doors were closed, and the ventilation in the room was operating at a constant low volume. No other clinical activities occurred during or 24

hours prior to the experiments. There was no movement of any equipment or personnel in the orthodontic clinic other than the minimal movement of the operator, during the duration of each trial.

Table 2. Description of each highspeed handpiece type used for this study, including maximum speed, power, and additional information.

	Conventional	Electric	Air-Free
Handpiece Brand/Name	StarDental 430 SW high-speed handpiece	BienAir CA 1:5 high-speed handpiece	Medidenta Air Free 90 Titan high-speed handpiece
Max Speed (rpm)	430,000 (no load)	200,000	400,000 (no load)
Power	14 watts	~55-65 watts	18 watts
Operating air pressure	30-32 psi	N/A	35-40 psi
Additional information		0.70 Ncm torque	Exhaust air vents near the connection to hose, away from cutting field
			

Table 2 describes the three different handpiece types which were used and their specifications. Note that the maximum speed for both the conventional and air-free handpieces are 400,000 rpm or greater. However, when placed under a load, these handpieces typically cut at 180,000-200,000 rpm. To match the speed for each handpiece type as closely as possible, all three were used at maximum speed, depressing the foot pedal fully. Both the conventional and air-free handpiece use compressed air to turn the

turbine which turns the bur. The conventional handpiece exhausts this air at the area of the head of the handpiece, while the air-free handpiece exhausts this air toward the rear of the handpiece where it connects to the air/water hose. The conventional and electric handpieces also release chip air from the head during operation for cooling the field. This is air supplied through the handpiece from a dedicated line to cool the field. Chip air was set to the lowest setting and water coolant was turned off for all handpieces. The air-free handpiece does not provide a line for chip air, and therefore does not blow any air onto the field. Table 3 describes the two evacuation systems used in this study.

Table 3. Description of the two evacuation systems used in this study, including air flow rate, evacuator opening size, and additional information.

	High-speed evacuation (HSE)	**Extra-oral Suction (EOS)**
Brand/Name	Adec dental chair assistant arm HVE opening	Dent AirVac DAV VII Turbo+ Oral Aerosol Evacuation System
Air flow rate	12 cfm	770 cfm
Opening size	0.435 in	5 in
Additional information		4 stage filtration system: moisture intake liner, prefilter, HEPA filter (0.3-micron rating), granulated carbon filter
		

The following list describes the different conditions used during composite attachment removal:

1. Air-driven handpiece with no evacuation
2. Air-driven handpiece with high-speed intraoral evacuation
3. Air-driven handpiece with EOS
4. Air-driven handpiece with high-speed intraoral evacuation and EOS
5. Electric handpiece with no evacuation
6. Electric handpiece with high-speed intraoral evacuation
7. Electric handpiece with EOS
8. Electric handpiece with high-speed intraoral evacuation and EOS
9. Air -free handpiece with no evacuation
10. Air-free handpiece with high-speed intraoral evacuation
11. Air-free handpiece with EOS
12. Air-free handpiece with high-speed intraoral evacuation and EOS

All trials were performed for both the maxillary and mandibular arches oriented in the typodont/manikin head and mounted on the orthodontic chair head. For the first three minutes of each trial, composite attachments located on the facial surfaces of the maxillary anterior six teeth were removed. This was followed by a two-minute pause, to allow particle concentrations to return to baseline. During the next three minutes, the composite attachments located on the facial surfaces of the mandibular anterior six teeth were removed similarly. Again, this was followed by a two-minute pause to allow particle concentrations to return to baseline. For periods using only IOS or no suction, additional pause time was allocated with the EOS turned on to allow particle concentrations to reach baseline levels. For Trials 1 and 2, pause times varied from 30 seconds to 1 minute, based on the time needed for the operator to prepare for the next trial. For Trials 3 and 4, the pause time was standardized at 1 minute when IOS only was used, or 2 minutes when no suction was used. The #7901 carbide finishing bur (Komet) was used to remove the composite in all trials. Burs were replaced for each new trial.

Table 4. Timing schedule used for trials 3 and 4. The numbers in the first column represent handpiece types (1: conventional handpiece, 2: electric handpiece, 3: air-free handpiece). The order of handpiece use for each suction combination was randomized for each of the 4 trials using a random sequence generator.

Both	**Attachment removal upper arch (6 teeth)**	**Pause**		**Attachment removal lower arch (6 teeth)**	**Pause**	
3	3 min	2 min		3 min	2 min	
1	3 min	2 min		3 min	2 min	
2	3 min	2 min		3 min	2 min	
EOS	Attachment removal upper arch	Pause		Attachment removal lower arch	Pause	
1	3 min	2 min		3 min	2 min	
3	3 min	2 min		3 min	2 min	
2	3 min	2 min		3 min	2 min	
IOS	Attachment removal upper arch	Pause	Turn on EOS	Attachment removal lower arch	Pause	Turn on EOS
2	3 min	2 min	1 min	3 min	2 min	1 min
1	3 min	2 min	1 min	3 min	2 min	1 min
3	3 min	2 min	1 min	3 min	2 min	1 min
No Suction	Attachment removal upper arch	Pause	Turn on EOS	Attachment removal lower arch	Pause	Turn on EOS
1	3 min	2 min	2 min	3 min	2 min	2 min
2	3 min	2 min	2 min	3 min	2 min	2 min
3	3 min	2 min	2 min	3 min	2 min	2 min

One operator (EY) removed the orthodontic composite attachments and sat in the 12 o'clock position relative to the manikin head mounted on the dental chair. The high-speed intraoral suction tip was positioned 1 inch away from the central incisors of the typodont, directed from below during the attachment removal of the upper arch (Fig. 4a). During the attachment removal of the lower arch, the IOS was positioned 1inch above the mandibular central incisors. The EOS unit was positioned in the three o'clock position relative to the manikin head, 6 inches from the typodont (Fig. 4b). When not used, the EOS unit remained in the same position.

Four repetitions of each combination of handpiece type (air-driven, electric, air-free) and evacuation method (none, high-speed suction, EOS, both) were performed, with the order of the handpieces randomized for each trial. Trials 1 and 2 were completed on the same day, and Trials 3 and 4 were completed on a different day.

Statistical Analysis

The data collected from all AeroSpec sensors was $PM_{2.5}$ concentrations (particulate matter of optical diameter 2.5µm or less, measured in micrograms per cubic meter (µg/m³)), acquired every 5 seconds for all experiments. Data were restricted to a 5-minute period (3 minutes of attachment removal and 2 minutes pause) for each suction, handpiece, and arch combination. The 5-minute period was used instead of the 3-minute attachment removal period because the particle concentrations sometimes rose after the 3-minute attachment removal period ended, due to the time needed for the particles to disperse to more distant sensors. Due to the exponential scattering of recorded values, 1 was added to the $PM_{2.5}$ concentrations and then values were logarithmically transformed (base 10) for statistical analysis. This allowed for the description of trends on a linear scale. The mean and maximum particle concentration was computed for each sensor, suction, handpiece, and arch combination. Then the mean of the means and mean of the maximum particle concentrations were computed for eight sensor Zones, based on sensor position, as well as similarity of measurements.

ZONE 1: Sensor 1 (Operator)

ZONE 2: Sensor 2 (Patient's chest)

ZONE 3: Sensor 3 (Assistant)

ZONE 4: Sensor 4 (Top of EOS)

ZONE 5: Sensor 5 (Foot of Patient)

ZONE 6: Sensors 6a, 6b, and 6c (3.5-foot-high operatory periphery)

ZONE 7: Sensors 7a, 7b, 7c, 7d, and 7e (5-foot-high operatory periphery)

ZONE 8: Sensors 8a, 8b, and 8c (Head of adjacent chairs, 3.5-foot-high level)

Summaries (mean, standard deviation [SD], median, interquartile range [IQR], minimum and maximum) were created for the mean and maximum particle concentrations (log base 10) by suction, handpiece, arch, and trial for each Zone and sensor.

Linear regression was used to compare the log (base 10) particle concentrations by suction, handpiece, and arch separately for each Zone. The linear regression model included the main effects for suction (both, EOS, IOS and none), handpiece (conventional, electric, and air-free), and arch (lower and upper). To account for an overall effect of a trial (i.e., to "normalize for trial"), a main effect for trial (four trials, 1, 2, 3, and 4) was included in the regression model. As an attempt to control for carryover effects, the log (base 10) starting (first) particle concentration of the 5-minute period was included as a covariate in the regression model. For Zones 6, 7, and 8, which include multiple sensors, the mean starting particle concentration is based on the mean starting particle concentration for the multiple sensors.

First, testing was done for the main effect of suction, handpiece, and arch, regardless of whether there was a significant interaction with the trial or between suction,

handpiece, and arch. Pairwise post-hoc testing was performed using the Tukey method to adjust for the multiple testing.

To describe the regression results, the predicted (least squares) means and 95% confidence intervals are reported and displayed by suction, handpiece, and arch. All values were converted from log (base 10) values to original particle concentrations for easier interpretation. The predicted mean is the average or maximum particle concentration averaged over all the other effects in the model during the 5-minute period. For example, the predicted means by suction would be comparing the average particle concentration for each suction using the average value for trial, handpiece, arch and starting particle concentration.

Additional comparisons assessed differences by trial, as well as tests for two-way interactions between trial, suction, handpiece, and arch. If there was a significant interaction (p-value < 0.05), predicted means are reported to describe the interaction. Regardless of the statistical significance of the interaction between suction and handpiece, the effect of handpiece by suction was reported because of potential for carryover effects. The order of the suction is the same for all trials (Both, EOS, IOS, and None). Hence, differences between handpieces could impact more by carryover effects for IOS and None compared to Both and EOS.

FACILITIES

Data collection took place in the clinical operatories in the Department of Orthodontics at the University of Washington. All statistical analyses were completed by a biostatistician at the University of Washington.

RESULTS

CONCENTRATION AND REAL-TIME DISTRIBUTION OF COMPOSITE PARTICLES

Figure 5 is a pictogram illustrating the timing intervals and color-coding used for the graphs in Figures 6-9, which show actual sensor data for four Zones from one representative trial out of the 4 trials that were conducted for the study. Figure 6 represents the operator sensor (Zone 1), Figure 7 represents the assistant sensor (Zone 3), Figure 8 represents the 5-foot-high periphery of the operatory (Zone 7), and Figure 9 represents the three adjacent chairs (Zone 8).

The peach lines indicate periods when the air-free handpiece was used, the blue lines indicate electric, and the green lines indicate conventional. Dark shaded areas denote the 3-minute attachment removal period and light shaded areas denote the 2-minute period of clearance (pause). White spaces denote extra suctioning time after the 2-minute period. Dark lines are locally weighted scatter plot (LOESS) smooths based on a 5-minute interval consisting of the 3-minute attachment removal period and the 2-minute period after attachment removal. Each graph, from left to right, represents the timeline for the readings in a specific Zone during the course of one trial.

The trials start with both IOS and EOS being used. This is followed by EOS only, then by IOS only, and then neither suction. The scale used was log10, indicated on the left-hand side of each graph. On the right-hand side, the log10 values are converted back to the original concentrations.

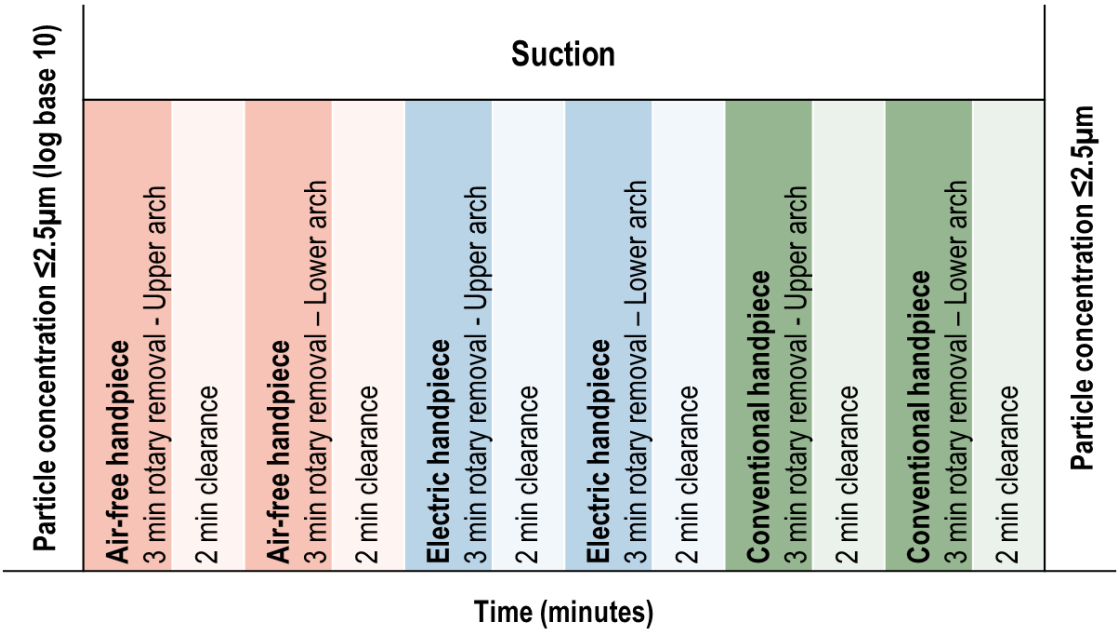


Fig. 5. Guide showing the timing intervals and color coding for each handpiece type. Note this sequence is repeated for each suction condition. Dark shaded areas denote the 3-minute attachment removal period and light shaded areas denote the 2-minute pause. Log10 values on left, original values on the right.

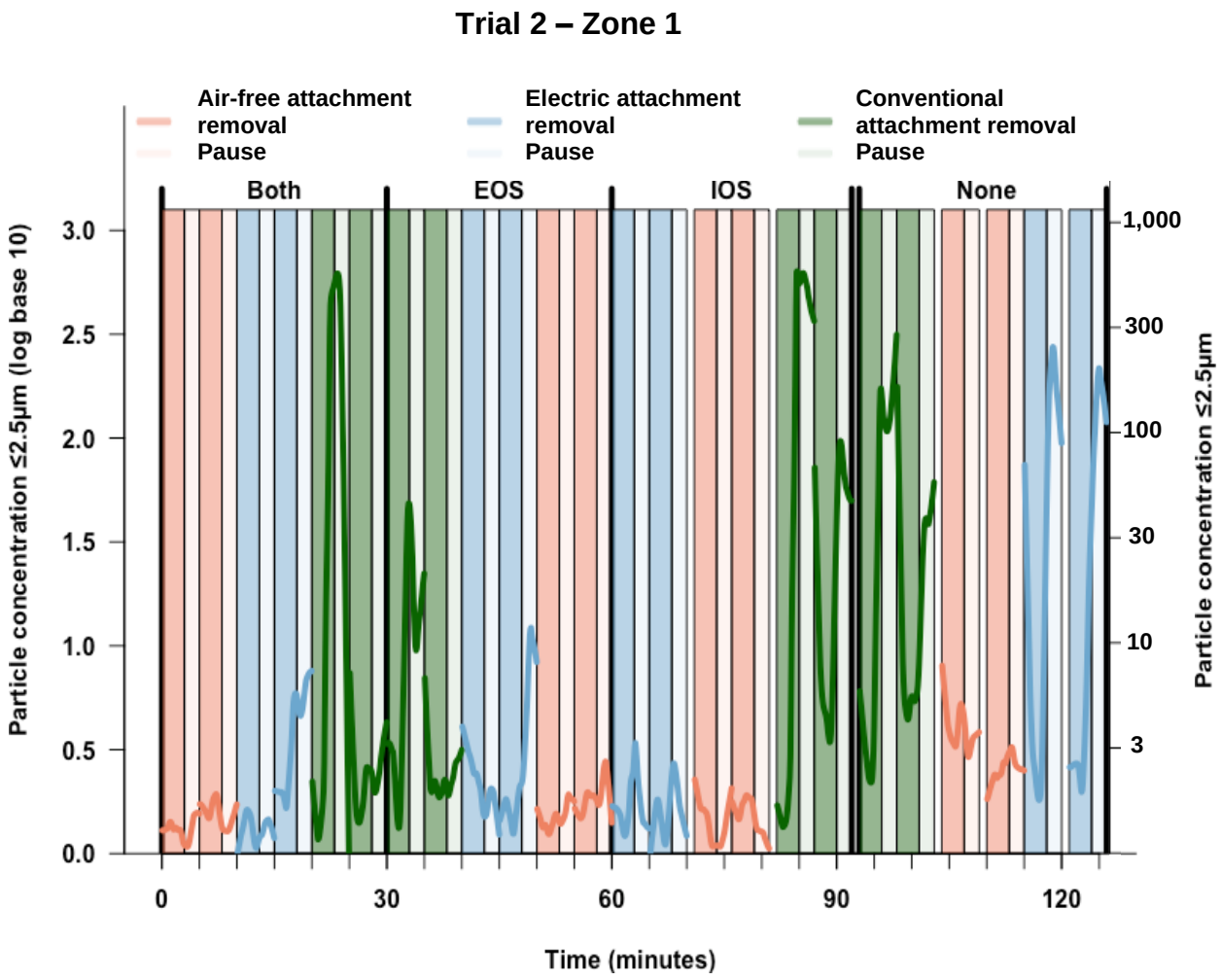


Fig. 6. Zone 1 sensor (Operator) $PM_{2.5}$ measurements during Trial 2.

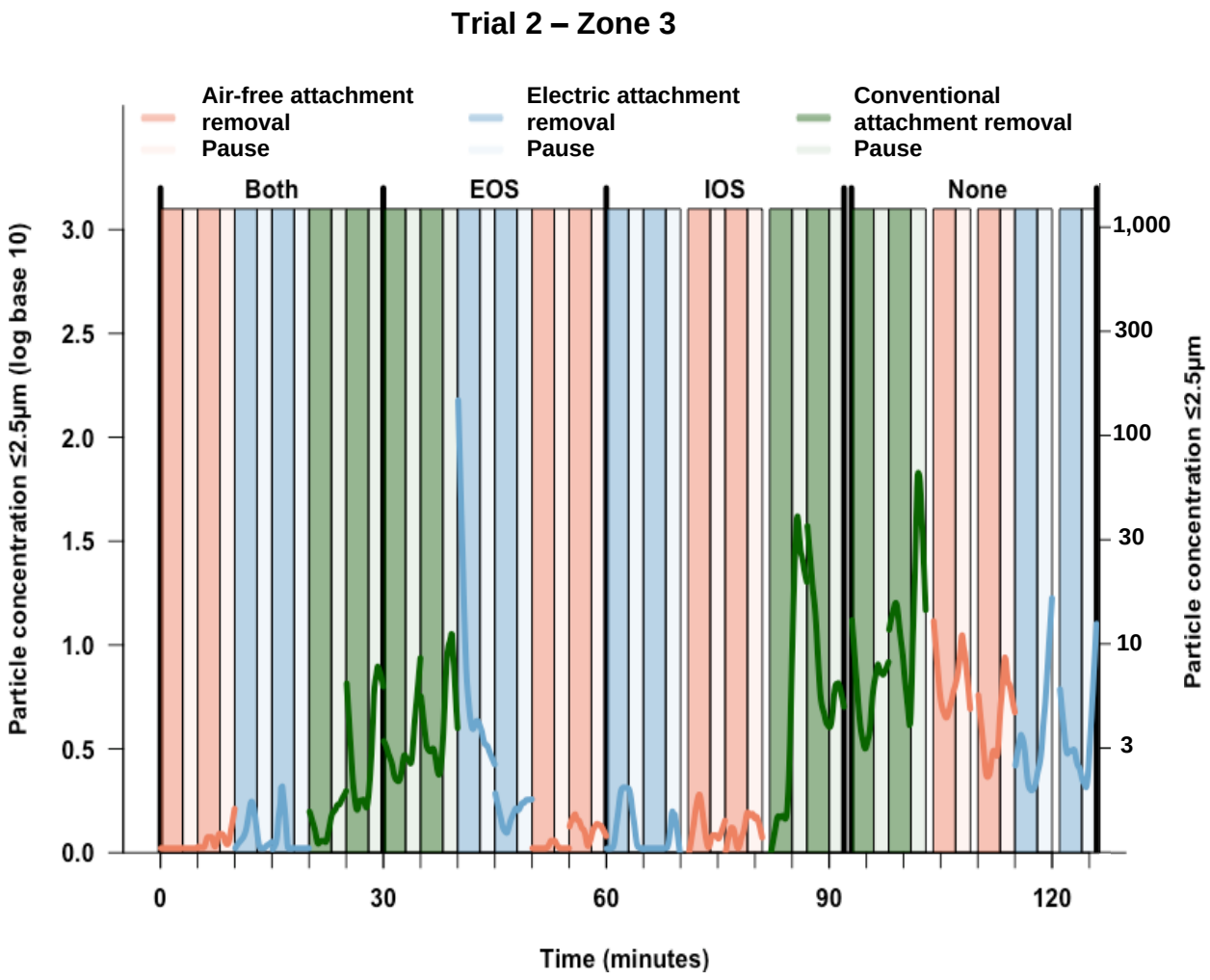


Fig. 7. Zone 3 sensor (Assistant) $PM_{2.5}$ measurements during Trial 2.

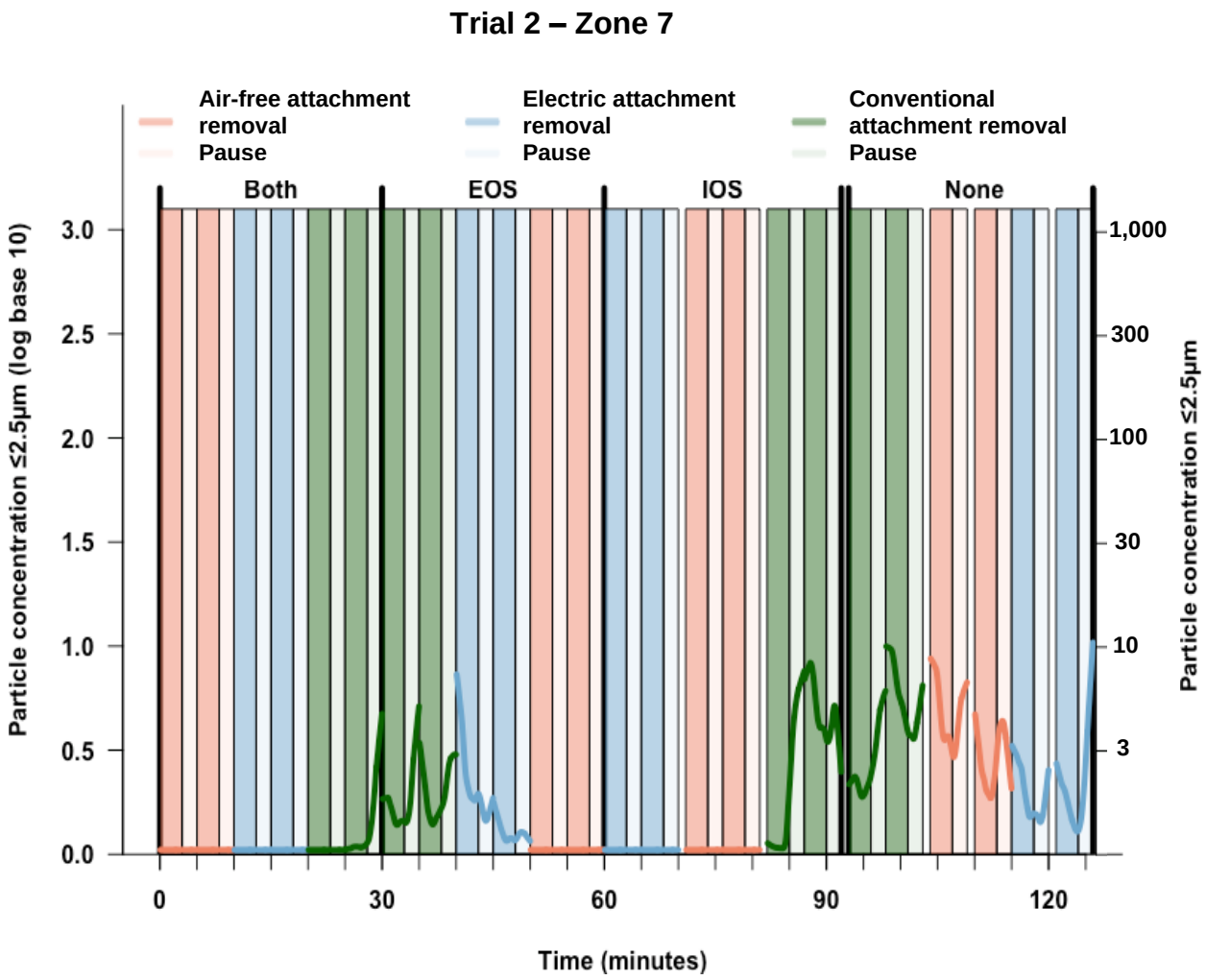


Fig. 8. Zone 7 sensors (5' high periphery) averaged $PM_{2.5}$ measurements during Trial 2.

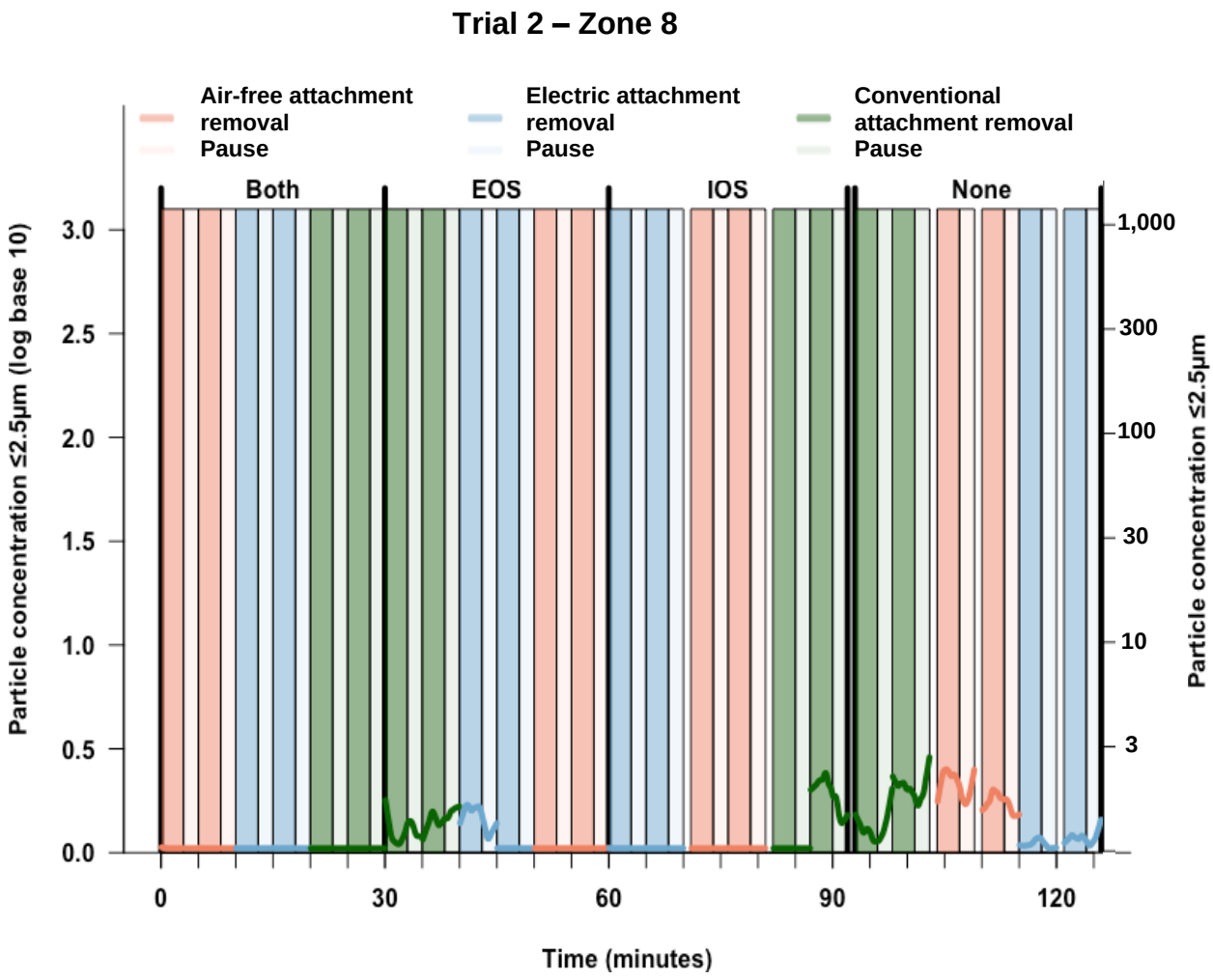


Fig. 9. Zone 8 sensors (Adjacent chairs) averaged $PM_{2.5}$ measurements during Trial 2.

Overall, the graphs indicate that for this trial, the baseline level of particulates 2.5 µm or smaller was very close to zero in all locations. During the attachment removal periods, the levels for both air-free and electric handpieces remained relatively low (less than 3), unless no suction was employed.

During the 2-minute intervals of pause, we expected particle concentrations to return to baseline. This was usually observed when the air-free or electric handpieces were used, and any type of suction was employed. However, in trials that involved the conventional handpiece or no suction, the particle concentrations usually did not return to

baseline. This “carry-over” effect resulted in higher starting particle concentrations when the next recording period began.

The concentration of particles was the highest in Zone 1 (operator), which included the sensor most closely positioned to the typodont during attachment removal. The peaks in particle concentration ranged from about 10 µg/m³, up to over 600 µg/m³ when the conventional handpiece was used. The further away the sensors were positioned from the typodont, the lower the recorded particle concentrations were. Of the four graphs shown, Zone 2 (assistant) showed the second highest particle concentrations, with peaks ranging from 10-100 µg/m³. Zone 7 (5’ periphery) had much lower peaks, ranging from approximately 3-10 µg/m³, and Zone 8 (adjacent chairs) had the lowest peak particle concentrations, which stayed below 3 µg/m³.

A lag in the time from attachment removal to increased measurements at the sensors appeared to be dependent on the distance from the source of attachment removal. Zone 1 had the shortest amount of lag time, and this was most evident when the conventional handpiece was used (Fig 6). When both suctions were on, we saw the particle concentration for the conventional handpiece rapidly increasing about 1 minute after attachment removal began in the upper arch. The amount of lag time for Zones 3 and 7 was 2-3 minutes, as the graphs only started to peak towards the end of the attachment removal period (Fig 7). For Zone 8, the lag time was at least 3-5 minutes, as the peaks in the graph appeared to be delayed by a whole cycle of attachment removal and pause. For example, the peak corresponding to attachment removal in the upper arch with the conventional handpiece using just IOS occurred during the time attachment removal was performed on the lower arch (Fig 9).

EFFECT OF HANDPIECE TYPE ON PARTICLE PRODUCTION

Table 5 presents the predicted mean and maximum particle concentrations for each handpiece by Zone. In Zone 1, the air-free handpiece produced significantly lower predicted mean and maximum values than the conventional handpiece. In Zone 2, only the predicted mean for the electric handpiece was significantly lower compared to the conventional handpiece. Zones 3, 5 and 6 showed that both air-free and electric handpieces produced lower predicted mean and maximum concentrations compared to the conventional handpiece. Zone 4 exhibited significantly lower predicted maximum concentrations for the air-free and electric handpiece. Zone 8 had a significantly lower predicted maximum concentration for the air-free handpiece than the conventional handpiece.

The conventional handpiece most frequently produced the highest predicted mean and maximum particle concentrations, while the air-free and electric generally had lower values. For the operator (Zone 1), using an air-free handpiece compared to a conventional handpiece resulted in an 48% reduction in mean particle concentration, and a 72% reduction in maximum particle concentration.

Table 5. The predicted means and maximums for PM≤2.5 in μg/m³ for each handpiece by Zone, and percent reduction compared to Conventional Handpiece.

Zone	**Air-free Handpiece** Predicted mean (95% CI), % reduction Predicted max (95% CI), % reduction	**Electric Handpiece** Predicted mean (95% CI), % reduction Predicted max (95% CI), % reduction	**Conventional Handpiece** Predicted mean (95% CI) Predicted max (95% CI)
1* Operator	4.2[a] (3.2 – 5.6), 48%	5.4[ab] (4.1 – 7.1), 33%	8.1[b] (6.2 – 11.0)
	57.5[a] (33.1 – 102.3), 72%	112.2[ab] (64.6 – 195.0), 45%	204.2[b] (114.8 – 363.1)
2*** Patient Chest	3.7[ab] (3.1- 4.5), 27%	3.5[a] (3.0 – 4.3), 31%	5.1[b] (4.2 – 6.0)
	26.3[a] (17.8 – 38.9), 42%	29.5[a] (20.0 – 43.7), 35%	45.7[a] (30.9 – 67.6)
3* Assistant	2.6[a] (2.2 – 3.1), 30%	2.8[a] (2.3 – 3.2), 24%	3.7[b] (3.2 – 4.5)
	16.6[a] (11.0 – 25.1), 65%	18.6[a] (12.3 – 28.2), 60%	46.8[b] (30.9 – 70.8)
4** Top of EOS	2.5[a] (2.0 – 3.2), 29%	2.7[a] (2.1 – 3.4), 23%	3.5[a] (2.8 – 4.4)
	19.1[a] (11.2 – 32.4), 64%	19.1[a] (11.5 – 31.6), 64%	52.5[b] (31.6 – 89.1)
5* Patient Foot	2.8[a] (2.4 – 3.4), 39%	2.4[a] (2.0 – 2.8), 48%	4.6[b] (3.9 – 5.4)
	13.1[a] (8.9 – 19.5), 62%	9.5[a] (6.5 – 13.8), 72%	34.4[b] (23.4 – 51.3)
6* 3.5-Foot Periphery	2.2[a] (1.9 – 2.5), 19%	1.9[a] (1.7 – 2.1), 30%	2.7[b] (2.4 – 3.0)
	11.2[a] (8.7 – 14.8), 40%	7.9[a] (6.2 – 10.2), 58%	18.6[b] (14.8 – 23.4)
7 5-Foot Periphery	2.3[a] (2.1 – 2.5), 4%	2.1[a] (1.9 – 2.3), 13%	2.4[a] (2.2 – 2.6)
	9.6[a] (7.8 – 11.7), 23%	10.4[a] (8.5 – 12.6), 16%	12.4[a] (10.5 – 14.8)
8** Adjacent Chairs	2.1[a] (1.9 – 2.3), 0%	2.1[a] (1.9 – 2.3), 0%	2.1[a] (1.9 – 2.3)
	4.1[a] (3.5 – 4.8), 28%	4.5[ab] (3.9 – 5.2), 21%	5.7[b] (4.9 – 6.6)

* Indicates overall significance in the Zone for the main effect of handpiece (P<0.05) for mean and maximum particle concentration

** Indicates overall significance in the Zone for the main effect of handpiece (P<0.05) only for maximum particle concentration

*** Indicates overall significance in the Zone for the main effect of handpiece (P<0.05) only for mean particle concentration

[ab] Within a row, means and maximums without a common superscript differ (P<0.05)

Effect of evacuation system on particle production

Based on the linear regression analysis, the predicted mean and maximum particle concentrations for the main effect of suction indicate statistically significant relationships between the type of suction used during composite attachment removal and particle concentration for almost all Zones (Table 6). The only exception was Zone 8 (adjacent chairs), which only had significance for the predicted maximum concentrations, but not the mean concentrations.

Table 6. The predicted means and maximums for PM≤2.5 in μg/m³ for each suction condition by Zone and percent reduction compared to no suction.

Zone	**Both Suctions** Predicted mean (95% CI), % reduction Predicted max (95% CI), % reduction	**Extra-oral Suction (EOS)** Predicted mean (95% CI), % reduction Predicted max (95% CI), % reduction	**Intra-oral Suction (IOS)** Predicted mean (95% CI), % reduction Predicted max (95% CI), % reduction	**No Suction** Predicted mean (95% CI) Predicted max (95% CI)
1* Operator	2.4[a] (1.7 – 3.3), 84%	4.0[a] (2.9 – 5.5), 74%	7.4[b] (5.4 – 10.2), 51%	15.1[c] (11.0 – 20.9)
	34.7[a] (18.2 – 66.1), 89%	93.3[ab] (50.1 – 177.8), 70%	144.5[bc] (75.9 – 269.2), 54%	316.2[c] (166.0 – 602.6)
2* Patient Chest	2.3[a] (1.9 – 2.9), 77%	2.7[a] (2.2 – 3.4), 74%	4.1[b] (3.4 – 5.1), 60%	10.2[c] (8.1 – 12.9)
	9.2[a] (5.9 – 14.8), 95%	15.5[a] (9.8 – 24.5), 91%	45.0[b] (28.8 – 70.8) 75%	181.6[c] (112.2 – 295.1)
3* Assistant	1.8[a] (1.5 – 2.2), 73%	2.3[ab] (1.9 – 2.8), 65%	2.9[b] (2.5 – 3.5), 56%	6.6[c] (5.5 – 7.9)
	8.6[a] (5.2 – 13.8), 89%	18.8[ab] (11.7 – 30.2), 75%	19.2[b] (18.2 – 44.8), 74%	75.2[c] (46.5 – 123.0)
4* Top of EOS	2.0[a] (1.5 – 2.5), 67%	2.0[a] (1.5 – 2.6), 67%	2.9[a] (2.3 – 3.8), 52%	6.0[b] (4.6 – 7.8)
	15.8[a] (8.7 – 28.8), 78%	17.0[a] (9.3 – 30.9), 76%	26.9[ab] (14.8 – 49.0), 62%	70.8[b] (38.0 – 131.8)
5* Patient foot	2.2[a] (1.8 – 2.8), 61%	2.5[a] (2.1 – 3.1), 55%	2.9[a] (2.5 – 3.7), 48%	5.6[b] (4.5 – 6.9)
	7.9[a] (4.9 – 12.6), 80%	12.7[a] (7.9 – 20.0), 68%	17.5[ab] (11.2 – 27.5), 56%	39.4[b] (24.0 – 64.6)
6* 3.5-Foot Periphery	1.7[a] (1.5 – 1.9), 47%	2.0[ab] (1.8 – 2.3), 38%	2.2[b] (1.9 – 2.5), 31%	3.2[c] (2.9 – 3.6)
	6.4[a] (4.6 – 8.7), 71%	10.0[ab] (7.2 – 13.8), 55%	13.9[bc] (10.7 – 18.2), 38%	22.3[c] (17.0 – 28.8)
7* 5-Foot Periphery	1.9[a] (1.7 – 2.1), 39%	2.1[a] (1.9 – 2.4), 32%	2.2[a] (2.0 – 2.4), 29%	3.1[b] (2.8 – 3.4)
	7.3[a] (5.6 – 9.5), 62%	8.6[a] (6.8 – 11.0), 56%	10.9[a] (8.9 – 13.5), 44%	19.4[b] (15.8 – 23.4)
8** Adjacent chairs	2.1[a] (1.9 – 2.4), 9%	1.9[a] (1.7 – 2.2), 17%	2.0[a] (1.8 – 2.2), 13%	2.3[a] (2.1 – 2.6)
	3.7[a] (3.1 – 4.4) 46%	3.9[ab] (3.2 – 4.6), 43%	5.1[b] (4.4 – 6.0), 26%	6.9[c] (6.0 – 8.1)

* Indicates overall significance in the Zone for the main effect of suction ($P<0.05$) for mean and maximum particle concentration

** Indicates overall significance in the Zone for the main effect of suction ($P<0.05$) only for maximum particle concentration

[abc] Within a row, means and maximums without a common superscript differ ($P<0.05$)

In general, using both suctions, compared to no suction, resulted in the lowest mean and maximum particle concentrations for all Zones, except in Zone 8 for predicted

mean. Compared to just EOS, using both suctions did not produce a significant difference in particle concentrations for any Zone. EOS only rarely produced significantly lower particle concentrations compared to IOS only. The exceptions were in Zones 1 and 2. In all Zones, using IOS produced a lower particle concentration in at least one of the predicted mean or maximum values, compared to no suction. For the operator (Zone 1), the simultaneous use of both suctions compared to no suction resulted in an 84% reduction in mean particle concentration, and an 89% reduction in maximum particle concentration.

Other Comparisons

Table 7 presents the reduction in particle concentrations when simultaneously accounting for both handpiece and suction in Zone 1 (operator). Percent reduction was based on the predicted mean and maximum values for the conventional handpiece with no suction. With all handpieces, the greatest reductions were seen when both suctions were employed. The next highest reductions were generally seen across all handpieces when EOS was used, followed by IOS. The greatest reductions for the maximum predicted $PM_{2.5}$ values were 92% and 94% when achieved by using both suctions and the air-free and electric handpieces, respectively.

There were two combinations of handpiece and suction had greater predicted maximum values compared to the conventional handpiece with no suction, resulting in a negative percent reduction. This was the case for the conventional handpiece with only IOS and the electric handpiece with no suction.

Table 7. The predicted means and maximums in Zone 1 for PM≤2.5 in μg/m³ for each suction condition by handpiece, and percent reduction compared to the conventional handpiece with no suction.

Handpiece	Both Suctions Predicted mean (95% CI), % reduction Predicted max (95% CI), % reduction	Extra-oral Suction (EOS) Predicted mean (95% CI), % reduction Predicted max (95% CI), % reduction	Intra-oral Suction (IOS) Predicted mean (95% CI), % reduction Predicted max (95% CI), % reduction	No Suction Predicted mean (95% CI), % reduction Predicted max (95% CI), % reduction
Air-Free Handpiece	2.0 (1.1 – 3.5), 87%	3.4 (2.0 – 5.8), 78%	5.0 (2.9 – 8.6), 68%	9.9 (5.8 – 17.0), 36%
	22.9 (7.4 – 70.8), 92%	54.5 (17.9 – 154.9), 81%	51.3 (17.3 – 151.4), 82%	186.2 (64.1 – 549.5), 34%
Electric Handpiece	2.1 (1.2 – 3.6), 86%	3.0 (1.8 – 5.2), 81%	6.4 (3.7 – 11.0), 59%	21.4 (12.4 – 36.8), 38%
	18.2 (6.0 – 55.0), 94%	89.1 (30.4 – 263.0), 68%	173.8 (59.6 – 512.9) 38%	575.4 (191.9 – 1698.2), -104%
Conventional Handpiece	3.4 (2.0 – 5.9), 78%	6.0 (3.5 – 10.4), 61%	12.6 (7.3 – 21.7), 19%	15.5 (9.0 – 26.8)
	102.3 (34.3 – 302.0), 64%	177.8 (59.8 – 524.8), 37%	331.1 (110.9 – 977.2), -17%	281.8 (95.3 – 851.1)

Linear regression was performed for the main effect of arch, and no significant difference in the predicted log10 mean and maximum particle concentrations were found for all Zones.

Tests for two-way interactions with trial for suction, handpiece, and arch, as well as interactions between suction, handpiece and arch were performed, and there were significant interactions in all Zones (Table 8). Significant interactions between trial and handpiece were found for nearly all Zones. The air-free handpiece had significantly lower mean and maximum predicted values in Trial 2 compared to Trials 1, 3, and 4. Figure 6 shows the Zone 1 interactions between the handpiece and arch. The upper arch had more variation in predicted mean and maximum values than the lower arch, with the air-free handpiece having significantly lower values and the conventional handpiece having significantly higher values.

Table 8. Significant (P<0.05) two-way interactions in each Zone.

Zone	Two-way interactions with trial	Two-way interactions between suction, handpiece, and arch
1 Operator	Mean – Trial: Handpiece Max – Trial: Handpiece	Mean – Handpiece: Arch Max – Handpiece: Arch
2 Patient chest	Max – Trial: Handpiece	Mean – Suction: Handpiece Max – Suction: Handpiece
3 Assistant	Mean – Trial: Handpiece Max – Trial: Handpiece	None
4 Top of EOS	Max – Trial: Handpiece	None
5 Patient foot	Mean – Trial: Handpiece Max – Trial: Handpiece	None
6 3.5-Foot Periphery	Mean – Trial: Handpiece Max – Trial: Handpiece	Mean – Suction: Handpiece
7 5-Foot Periphery	Mean – Trial: Handpiece Max – Trial: Handpiece	Mean – Handpiece: Arch, Suction: Handpiece Max – Handpiece: Arch
8 Adjacent chairs	None	Mean – Suction: Handpiece Max – Suction: Handpiece

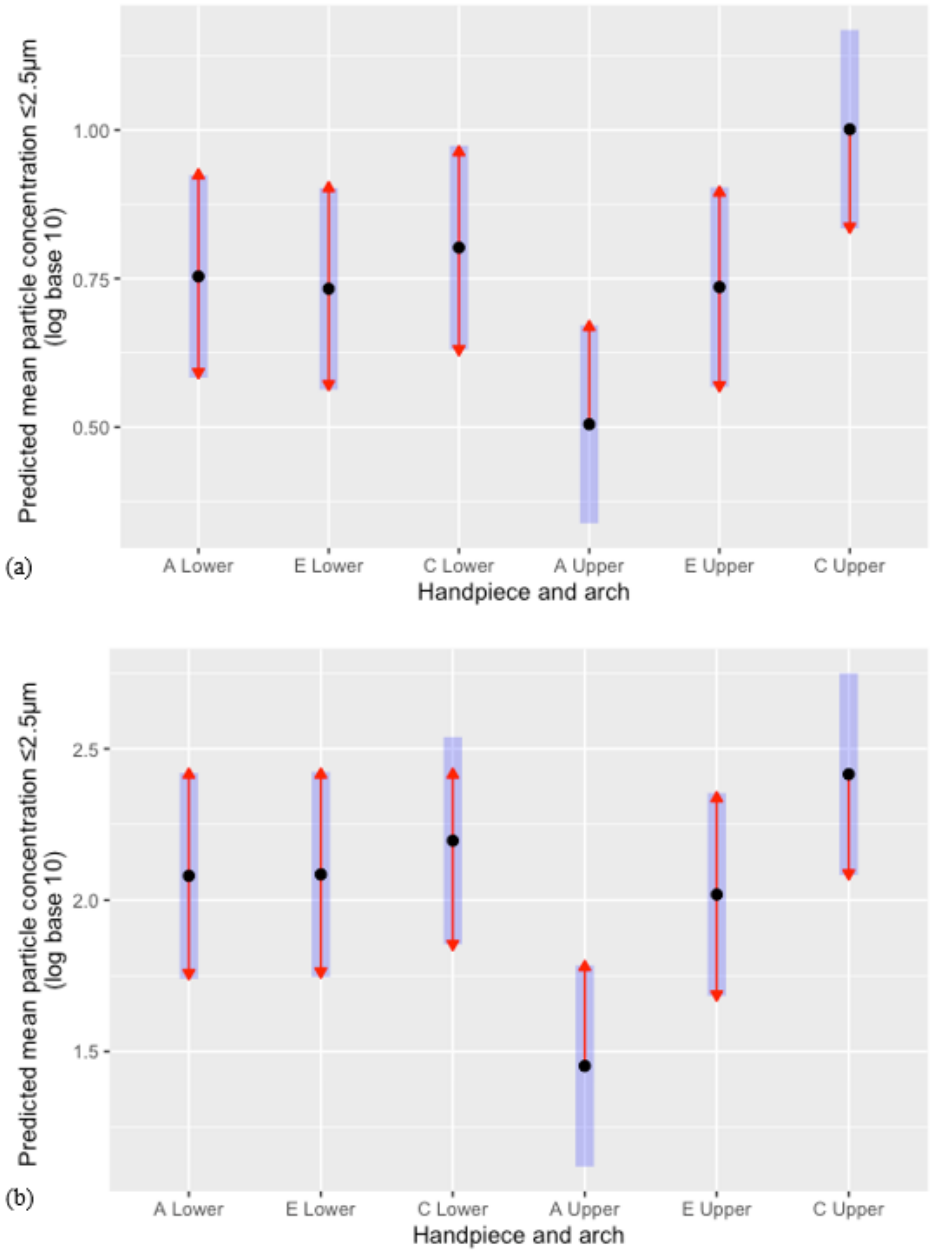


Fig. 10. Zone 1 differences by handpieces varied by arch.
(a) Predicted means. (b) Predicted maximums.

DISCUSSION

HAZARDOUS $PM_{2.5}$ EXPOSURE DURING AGPS

The findings from this study provide us with insights on the relative $PM_{2.5}$ exposure of individuals in an orthodontic clinic during AGPs. When removing composite aligner attachments with a handpiece, the concentration of $PM_{2.5}$ increased from a baseline of 0 µg/m³ to over 600 µg/m³. These values were highest near the source of aerosol production and decreased further away from the source. Figure 11 outlines the Environmental Protection Agency's (EPA) AQI categories and values based on 24-hour average $PM_{2.5}$ concentration. It is important to note that while an individual's total 24-hour $PM_{2.5}$ exposure may be good or moderate, brief exposure to high concentrations can decrease lung function, aggravate asthma, and trigger respiratory symptoms, especially in children [39].

AQI Category	AQI Value	24-hr Average $PM_{2.5}$ Concentration (µg/m³)
Good	0 - 50	0 - 15.4
Moderate	51 - 100	15.5 - 40.4
USG	101 - 150	40.5 - 65.4
Unhealthy	151 - 200	65.5 - 150.4
Very Unhealthy	201 - 300	150.5 - 250.4
Hazardous	301 - 500	250.5 - 500.4

Fig. 11. United States Environmental Protection Agency (EPA) AQI categories and values based on 24-hr average $PM_{2.5}$ concentration[40]. USG indicates unhealthy for sensitive groups.

It is clear that $PM_{2.5}$ levels increase to hazardous levels near the source of aerosol production (Zone 1), as the maximum predicted $PM_{2.5}$ in this zone was 316 μg/m³ when no suction was used. This primarily impacts the operator and the patient, as they are closest during AGPs. Special attention should be paid towards the operator, who may be performing AGPs for extended periods of time, on several patients in a row. When IOS or EOS is used, the predicted maximum $PM_{2.5}$ levels are lowered by 54% and 70% respectively, however these are still levels considered unhealthy by the EPA. Using both suctions is able to reduce the predicted maximum $PM_{2.5}$ by 89%, to a moderate level, which can still impact health over time [23,41].

For an assistant who would be positioned near Zone 3, the maximum predicted $PM_{2.5}$ ranged from approximately 9 μg/m³ when both suctions were on, to approximately 19 μg/m³ when only IOS was used. Their $PM_{2.5}$ exposure falls into the moderate level.

For personnel who may be walking past the operatory, or parents who may be in the periphery of the operatory (Zone 7), the maximum predicted $PM_{2.5}$ ranged from approximately 7 μg/m³ when both suctions were on to 19 μg/m³ when no suction was on. Although this overall exposure is low, it is still important to remember that particles are spreading into the periphery of the operatory, and they can potentially carry bacteria and viruses such as SARS-CoV-2.

Finally, for patients sitting in chairs adjacent to where an AGP is being performed (about 6-10 feet away in our clinic), predicted maximum $PM_{2.5}$ concentrations were 10 μg/m³ at most, even when no suction was used. This finding suggests that social distancing guidelines recommended by the CDC of staying 6 feet apart is relatively effective at reducing the spread of aerosols, at least in our clinic layout.

METHODS OF MINIMIZING $PM_{2.5}$

To minimize particles, several strategies may be employed. First, particle generation could be minimized. However, for aligner attachments, the entire attachment is usually removed with a highspeed rotary instrument, which will always result in particle creation. Second, these particles may be spread less if air or water spray is not used. While water and/or air spray from handpieces help to cool the field, they enhance the spread of particles. Finally, the particles that are generated can be removed, using various types of suction devices.

Handpiece

Studies have compared high-speed and slow-speed air-rotor handpieces with and without water coolant and found that high-speed air-rotor handpieces with water irrigation produced the highest concentration of particulates [18,20]. The large size of aligner attachments compared to the thin layer of adhesive for bonding orthodontic brackets makes removal with a high-speed handpiece the only viable to way remove attachments. This study found that electric and air-free handpieces generally resulted in lower mean and maximum concentrations of particles compared to the conventional air-driven handpiece. These reductions in maximum concentrations were in the 40% to 70% range in the zones closest to the source of aerosol production. We speculate that all 3 handpieces created similar amounts of particles as the attachments were removed, but the presence and amount of exhaust air and chip air from each handpiece likely impacted particle dispersion. The conventional handpiece, with exhaust air at the head and the strongest stream of chip air consistently exhibited the highest $PM_{2.5}$ values. The electric

handpiece had no exhaust air and a much lighter stream of chip air, and the air-free handpiece had exhaust air at the site of the connector and no chip air, resulting in the lowest particulate measurements.

After all trials were completed, it was noted that the air-free handpiece used for Trials 3 and 4 was missing a small metal plug, which allowed a small amount of air to be vented away from the field (see Appendix 2.) This may have contributed to the significant two-way interactions detected between handpiece and trial number, as the particle concentrations were higher for the air-free handpiece in Trials 3 and 4 than in Trial 2. Had the air-free handpiece not been missing the small plug in Trials 3 and 4, we may have seen a more significant difference in the predicted mean and maximum $PM_{2.5}$ concentrations. However, the electric handpiece also displayed higher aerosol concentrations in Trials 3 and 4, and it was the identical handpiece.

Suction

With regards to suction, our findings concur with other studies that report utilizing any suction reduces particle concentrations compared to no suction [17,19,42,43]. Other studies tested the individual effects of IOS and EOS compared to no suction. IOS can most effectively remove aerosols at the site of production, but for various reasons, it cannot always be perfectly positioned. This study is a good example of that, as the position of the IOS was fixed during each trial, 1 inch below the central incisors, even as attachment removal was occurring on neighboring anterior teeth. EOS, on the other hand, is a large volume scavenger that generally creates an airflow above the patient's head toward the orifice. This generally seems to be as effective, or possibly more effective,

than IOS, based on our data. The current study additionally tested the combination of both IOS and EOS. We found that using both IOS and EOS together reduced particle concentrations more than using either alone. These reductions in maximum concentrations were in the range of 70% to 90% in the zones closest to the source of aerosol production. These findings lead us to suggest using both IOS and EOS together when possible, during attachment removal.

Analysis by handpiece and suction together (Table 7) allowed us to compare combinations of suction and handpiece types in Zone 1. Compared to the conventional handpiece with no suction, using both suctions with the air-free or electric handpiece reduced the predicted maximum $PM_{2.5}$ concentrations by 92% and 94%, respectively. It is important to note that removing particles close to the source also prevents them from diffusing to other areas of the office.

Other Methods

Wearing proper PPE during AGPs remains the simplest way to decrease individual exposure to dental aerosols. While surgical masks have high filtration efficiency and are effective at blocking large-particle droplets and sprays, their loose fit on the face allows air to bypass directly to the nose and mouth [44]. Therefore, fit-tested N95 respirators are the gold-standard when it comes to minimizing respiratory exposure when AGPs are performed in the dental clinic. They offer robust protection against small particles and are named for their 95% efficacy at blocking particles as small as 0.3 µm. While suction devices and specific handpieces can be used to reduce $PM_{2.5}$ concentrations overall, the added protection of the N95 respirator will protect personnel

from being exposed to variations and peaks in particle concentration that may occur as procedures are performed. Each aerosol mitigation technique should be additive. Based on this study, an air-free or electric handpiece might be expected to reduce mean aerosol exposure to the operator by 48%, compared to a conventional handpiece. From the 52% of aerosols that are produced, using both an EOS and IOS could further reduce the mean aerosol exposure to the operator by 84%. This reduces the aerosols to about 8% of that when not suction is used. The use of an N95 mask would then filter out 95% of the 8%, effectively reducing the operator's exposure to less than 0.5% of the exposure if no mitigation effects were used.

Future Use of Portable PM Devices

Currently, this study is the first to employ a network of portable sensors to measure $PM_{2.5}$ concentrations during orthodontic composite attachment removal with a handpiece. In addition to the use of the novel sensor network, this study also is the first to test combinations of three dental handpiece types with four different suction conditions. The method of using multiple PM sensors to measure real-time particulate data has gained increasing attention due to the COVID-19 pandemic and has been employed by others in various dental and medical settings to spatially analyze particle production and distribution [32,37,42].

While having a dozen PM devices set up in a clinic operatory at all times is not practical, future applications of this device can be similar to that of personal radiation dosimeters [45]. The PM device can be worn by the operator and assistant throughout the day to provide real-time $PM_{2.5}$ concentration readings. It could even be programmed to

warn the wearer if the concentration exceeds a certain level. This would then signal personnel to consider strategies to reduce particulates.

Other Considerations

The period observed during this study included three minutes of attachment removal and a two-minute pause for both upper and lower arches. Sampling even during the waiting period was necessary because of the lag in the time it took for sensors to record peaks after attachment removal started, as shown in Figures 6-9. Due to the passive sampling of air by the AeroSpec monitors, the farther away from the source of attachment removal the sensor was positioned, the longer the lag time. For the sensors in Zone 8, the lag time appeared to be longer than 3 minutes, suggesting that more time could have been allocated to allow particle diffusion, as well as return to baseline.

A result of including the entire five-minute period in our analysis was the large differences in the mean and maximum predicted values, presented in Tables 5 and 6. Predicted mean values were much lower, as they accounted for periods of attachment removal of composite, as well as periods of clearance.

One consideration not explored in this study is the cooling mechanism used by each handpiece. For conventional and electric handpieces, chip air, a dedicated air line for the purpose of cooling the field, is typically employed during attachment removal. Some delivery systems allow chip air to be completely turned off, but our units only allow reducing, but not eliminating, chip air. In addition, conventional handpieces usually vent exhaust air at the head of the handpiece. The air-free handpiece does not have chip

air, and although air is used to turn the turbine, exhaust air is vented close to the connector and away from the field. Thus, air-free handpieces have no mechanism to cool the field during operation. It was noted during the experiment that the air-free handpiece tended to produce more heat than the conventional or electric handpieces. In a clinical situation, the high temperatures might cause patient discomfort if the same attachment were removed without interruption. Therefore, an operator might choose to remove a group of attachments, moving from one to another, gradually removing the adhesive from each one, to prevent overheating.

LIMITATIONS

A limitation of this study is its in-vitro nature. Removal of attachments from a typodont is different from with the same procedure in patients. However, this study design allowed us to standardize many factors that would introduce environmental bias in a patient-based study. These include the number and size of orthodontic attachments to be removed, moisture-control, and patient movement/breathing/coughing.

The generalizability of our study is somewhat limited by the specific setting, attachment removal technique, handpieces, suction devices, and composite material. However, all were representative of methods and equipment that are commonly used and commercially available.

While we did attempt to standardize many of the conditions of our study, it was impossible to control the outside air quality. Differences in the air quality based on the day and/or time of day could have impacted the starting particle concentrations. In addition, the exact handpiece units were not always standardized between the trials. The

same electric handpiece was used for all trials. However, the conventional and air-free handpieces used for Trials 1 and 2 were different from those used in Trials 3 and 4.

It is important to note that the AeroSpec PMs measure the scatter of light from the particles, which is a surrogate for estimating particle concentration. AeroSpec devices are calibrated using a much more precise particle measurement device, but there may be small variations in the particle measurement data from sensor to sensor.

Finally, as mentioned, the presence of carry-over effects from one handpiece type to another was a significant limitation. It would have been ideal to wait for all sensor readings to return to baseline between attachment removal trials to minimize carry-over effects. However, due to timing constraints and the operator's inability to see all sensor's readings from one position, this was not possible.

CONCLUSIONS

1. The concentration of $PM_{2.5}$ particles produced during composite attachment removal is highest close to the source of the procedure and decreases with distance.
2. Using the air-free or electric handpiece when removing orthodontic composite attachments had statistically significant reductions in mean and maximum $PM_{2.5}$ concentrations when compared to the conventional handpiece for most zones of the operatory. Using an air-free handpiece resulted in a predicted reduction of 48% and 72% in the operator's mean and maximum particle exposure, respectively.
3. Using any type of suction had a statistically significant reduction in the mean and maximum $PM_{2.5}$ concentrations compared to no suction. Generally, using EOS and IOS simultaneously mitigated particles most effectively, followed by EOS only, and then IOS only. However, the differences between EOS only and IOS only were small. Using both EOS and IOS simultaneously resulted in a predicted reduction of 84% and 89% of the mean and maximum $PM_{2.5}$ concentrations to the operator, respectively.
4. Using both EOS and IOS, along with an air-free or electric handpiece, reduced aerosols by 92% to 94%, respectively, compared to no suction and a conventional handpiece.

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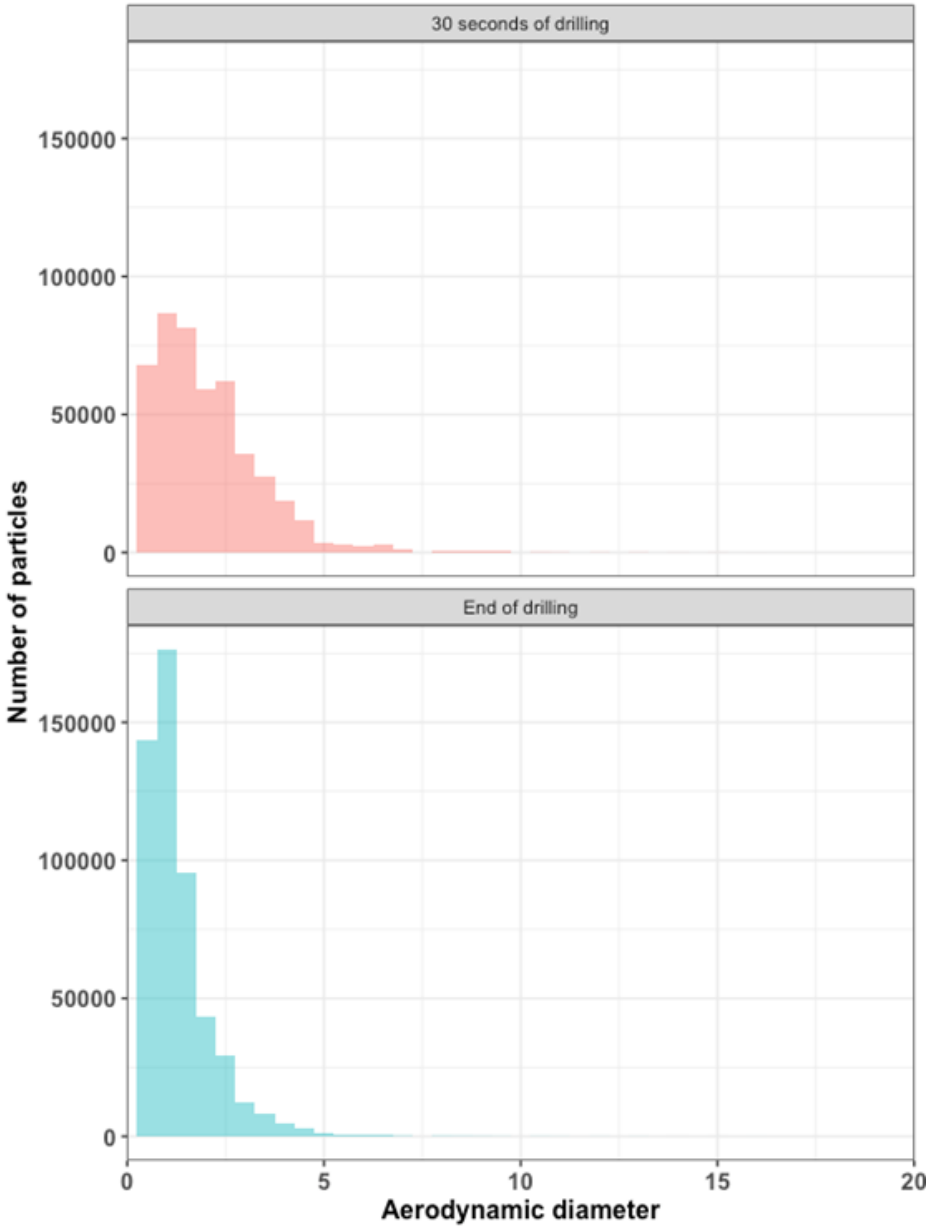
APPENDICES

APPENDIX 1. HISTOGRAMS OF PARTICLE SIZE DISTRIBUTION



Composite particles were measured by the Aerodynamic Particle Sizer (TSI APS 3321) at 30 seconds of attachment removal and at the end of attachment removal. The median diameter was1.94 µm during attachment removal and 1.19 µm at the end of attachment removal.

APPENDIX 2. AIR-FREE HANDPIECE USED IN TRIALS 3 AND 4.

On the left is a properly operating air-free handpiece and on the right is the air-free handpiece that was used for trials 3 and 4. The arrow points to a hole which was venting air during attachment removal, which should normally be plugged with a metal piece as shown by the handpiece on the right.