A Thesis

entitled

Characterization of Aerosols and Airborne Particles in a Dental Setting

by

Niloufar Sadoughipour

Submitted to the Graduate Faculty as partial fulfillment of the requirements for the Master of Science Degree in Mechanical Engineering

Dr. George Choueiri, Committee Chair

Dr. Omid Amili, Committee Co-chair

Dr. Sorin Cioc, Committee Member

Dr. Hossein Sojoudi, Committee Member

Dr. Scott C. Molitor, Dean
College of Graduate Studies

The University of Toledo
August 2022

An Abstract of

Characterization of Aerosols and Airborne Particles in a Dental Setting

by

Niloufar Sadoughipour

Submitted to the Graduate Faculty as partial fulfillment of the requirements for the Master of Science Degree in Mechanical Engineering

The University of Toledo
August 2022

When the COVID-19 pandemic broke out, dental clinics were asked to suspend due to an elevated risk of airborne viral transmission. Dental professionals and their assistants were thought to be at a significantly high risk due to the nature of dental procedures, which result in a high number of aerosolized particles ejected from the dental equipment and oral cavity. Several recommendations were proposed by the Centers for Disease Control and Prevention (CDC) and others to safeguard dental personnel. In this study, we quantitatively examined the efficacy of those safeguards and proposed testing additional ones. To investigate the effects of mitigation strategies on aerosol control in dental practices, we first had to accurately replicate the production of aerosols under common settings in a dental operatory, and then characterize and map particle concentration under altered standard of care practices. Numerous clinical setting scenarios, including those suggested by the CDC, were executed, and their effectiveness in reducing aerosols was assessed by characterizing the rates of aerosol production procedures. The results suggest that dry drilling generates a huge amount of particles and the use of an extraoral suction unit reduces aerosols significantly. Because the study focused on aerosolized and airborne particles, these results can be used in non-clinical situations involving the spread of airborne particles from a point source in confined spaces.

To Mom & Dad,

For their endless love and scarifies.

& To my lovely brother, Aria,

For his birth to this world, he is a motivation for me.

& To my fiancé, Ali,

For his love & supporting me in all my endeavors.

Acknowledgments

First and foremost, I would like to express my sincere gratitude to my advisor and my co-advisor, Dr. George Choueiri, and Dr. Omid Amili for providing me invaluable guidance throughout this project. With their unique vision and mentorship, I learned the methodology to carry out research. Working under their supervision is a once-in-a-lifetime opportunity, and I had the privilege to be their student. Secondly, I would like to acknowledge Dr. Darya Dabiri that her constant support throughout this study shaped the present work. Also, I would like to thank Dr. Carol Wiese who helped me a lot to run the experiments. I would like to express my deep and sincere gratitude to my uncle, Dr. Vahid Andalib for his constructive suggestions and helps in the statistical analysis. I also would like to specially thank Dr. William Davis and Dr. Michael Nedley at the University of Toledo Department of Dentistry for their endless support throughout this work.

This work was financially supported by National Institutes of Health (grant number: X01 DE030405-01) through the National Dental PBRN collaborative group funding U19-DE-028717 and U01-DE-028727.

Finally, and most importantly, a huge thank you to my fiancé, Ali, my parents, Maryam & Hassan, and my little brother, Aria, without whom it was almost impossible for me to complete this thesis.

Table of Contents

List of Figures

List of Tables

List of Abbreviations

AC .... Air conditioning

AGDP .... Aerosol generating dental procedure

DHCW .... Dental health care worker

EOS .... Extraoral suction

HEPA .... High-efficiency particulate air

HVS .... High-volume suction

LA .... Lower anterior

LL .... Lower left

LR .... Lower right

MOD .... Mesio-occlusal preparation

PDA .... Phase Doppler anemometer

PM .... Particulate matter

SE .... Saliva ejector

UA .... Upper anterior

UL .... Upper left

UR .... Upper right

List of Symbols

H_0 .... null hypothesis
H_1 .... alternative hypothesis
n .... number of samples
s .... standard deviation
$\overline{S}$ .... weighted standard deviation
T .... test statistic
w_i .... weight of each value
$\overline{W}$ .... weighted average
$\overline{X}$ .... sample mean
$<>$ .... ensemble average

Greek symbols

ρ .... density
μ .... population mean
Δ_0 .... true value of μ

Chapter 1

Introduction

Aerosolized particles are classified as natural (e.g., fog, dust, and mist), anthropogenic (e.g., air pollution and smoke), and biological (e.g., bioaerosols) [2]. Bioaerosols can be generated in human airways and leave the body by coughing, sneezing, speaking, and even breathing. Bioaerosol may contain two parts, volatile and non-volatile components. Non-volatile components originating from the respiratory tract lining fluid [3], may carry viruses and bacteria that put others at risk of infection. Medical and oral health procedures also generate substantial quantities of bioaerosols; these include saliva and blood from tracheal intubation, and blood from the oral cavity, plaque and tooth debris from tooth cleanings and tooth restorations. Thus, dental staff are at particularly high risk because of the plethora of bioaerosol and splatter generating procedures [4] ubiquitous in the practice. For example, several studies have shown that the ultrasonic scalars and high-speed handpieces generate high quantities of infectious aerosols and splatter [5, 6, 7]. Because of this, the World Health Organization (WHO), the American Dental Association (ADA), and the Centers for Disease Control and Prevention (CDC) have proposed several guidelines and protocols for dental services in order to reduce the likelihood of infectious aerosol transmission [8, 9, 10]. These include effective methods of reducing the transmission of these aerosols during dental treatments, such as providing isolations [11], barriers

[12], high-efficiency particulate air (HEPA) filters [13] and extraoral suction (EOS) [14].

After reviewing the literature and guidelines, it appeared that there was not sufficient studies to characterize aerosols in a dental clinic setting while following the majority of existing procedures and guidelines. Consequently, the purpose of this research is to measure the topography of particles and aerosols generated during dental procedures and to assess the effectiveness of current approaches to reduce aerosol transmission and accumulation. The specific goals of this study are presented as follows:

- **Specific Aim 1: To quantify particle topography and size distribution.**
- **Specific Aim 2: To assess the effectiveness of guidelines for dental staff.**
- **Specific Aim 3: To investigate approaches in reducing the transmission and accumulation of aerosols.**

To achieve these objectives, we developed a methodology to comprehensively evaluate the behavior of aerosols and droplets that are commonly generated during conventional dental operations. A system consisting of an array of air particulate matter sensors was created and installed in various places in a dental operatory in order to investigate the systematic impact of various parameters. The efficacy of several measures to reduce aerosol concentration and transmission, as well as suggestions for dental clinics were assessed.

Droplets, including splatter, are water-based particles with a mean diameter greater than 10 μm. As these generally settle quickly, they are not the focal point of our investigation. Instead, we will focus on aerosols, also known as airborne nuclei, which are described as liquid or solid particles that generally have a diameter of less than 10 μm [15] and can remain suspended in the environment for extended periods of time.

The following chapter proceeds to provide background information on the characterization of bioaerosols, the generation of aerosols in dental clinics, methods to measure their size and velocity, and finally recommendations and evaluations of proposed methods of reducing aerosol concentration and transmission for dental settings. Chapter 3 represents a detailed methodology to evaluate generated dental aerosols and assess guidelines in decreasing the accumulation of these particles. The results and predictions obtained from the study are presented in chapter 4. Finally, in chapter 5, these outcomes are fully discussed and analyzed. In order to improve guidelines in dental services, this study suggests several experimental-based recommendations to keep the dental operatories safe and to reduce the likelihood of aerosol transmission throughout the clinic.

The entire work reported here has been determined as a Not Human Subjects Research (NHSR) study by the University of Toledo Internal Review Board (IRB) committee (IRBs #300694, #300818, #301018, #301231).

Chapter 2

Background

2.1 Aerosols

Aerosols are tiny particles that remain suspended in the air for extended periods of time. They are distinguished by their size and density (ρ), which determine the particle inertia and transit velocity. They are composed of particulate matter (PM), which may be in the form of either liquid and/or solid. Most bioaerosols are expelled from the body during respiratory activities including coughing, sneezing, laughing, speaking, and breathing [16, 17, 18], and they have the potential to carry pathogens that cause transmissible disease and infect individuals. The liquid parts of the aerosols and droplets may evaporate, and the solid parts remain airborne or settle on surfaces. Infectious solid or liquid aerosols could spread viruses and bacteria to other individuals, directly or indirectly. If the infectious aerosols remain airborne, they could be inhaled by individuals present in that area, which is an indirect means of disease transmission. However, if they settle down and people contact those contaminated surfaces and then touch their mouth, nose, and eyes, the spread of disease is direct. Even though both are dangerous to people, infectious airborne aerosols are the most worrisome because they are known to cause respiratory infections such as flu, tuberculosis, SARS-CoV-1, and SARS-CoV-2.

2.2 Natural Bioaerosol Production

Breathing is one of the primary natural sources of bioaerosols from humans. Exhalation removes gases like carbon dioxide, but it also releases solid and liquid particles from the body. As shown in Figure 2-1 (b) the airway closes after a deep breath out. Inhalation results in the reopening of the airway and the formation of a film of respiratory tract lining fluid across the airway. When the airway fully opens, the film stretches, ruptures, and droplets form [19, 20, 21]. If we breathe more deeply and quickly, more film rupture occurs, more aerosols are generated, and spill out during our breathing [22]. On the other hand, when a person sneezes or coughs, the airway walls shake from the turbulence and dynamic compression. Respiratory tract lining fluid droplets are produced in the airways and are expelled from the body as a result of this vibration [23] as represented in Figure 2-1 (a). Recent studies have investigated the size of these bioaerosols and found that exhaled particles vary in size from 0.3 to 0.9 μm [24, 25], whereas sneezed and coughed particles are between 1 and 16 μm [19, 26].

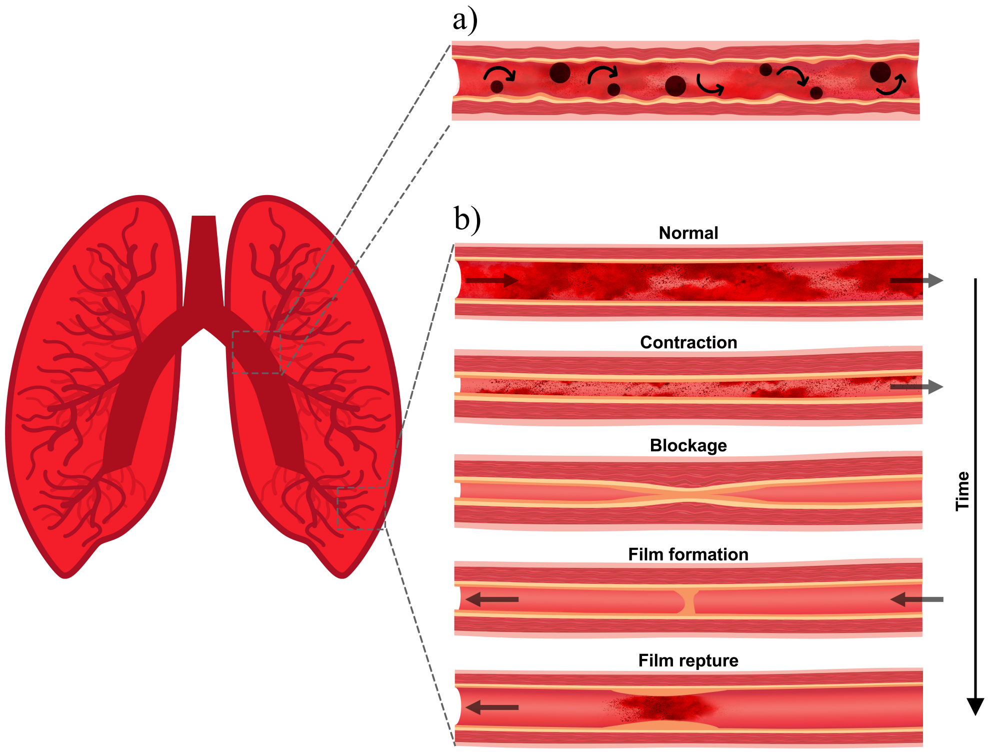


Figure 2-1: Aerosol formation in human airway. (a) Aerosols generated as a result of turbulence during coughing and sneezing. (b) Film droplet formation during breathing in small airways. Arrows pointing to the right show exhalation and left ones show inhalation. This schematic is an illustrative reproduction of the work by Johnson et al. [22].

2.3 Aerosols in Dental Settings

In dental operatories, the transmission of microorganisms can take place either directly, through contact with pathogens that are present on the surfaces of dental instruments and dental providers, or indirectly, through splatter and aerosols. Bacterial colonies on the surfaces of dental equipment have been identified as primary pathogens responsible for a variety of operator related disease transmissions [2]. When they are aerosolized by aerosol generator dental procedures (AGDP), tissue, blood, plaque, and saliva, all of which can contain bacteria and viruses, become airborne and can result in indirect disease transmission. This places dentists and their assistants at high risk of contracting respiratory diseases because of how close they work to a patient's oral cavity (30 to 60 cm away). Because of this heightened risk, in the most recent pandemic (COVID-19), dental services were initially suspended [27, 10, 28]. After suspensions were relaxed, stringent guidelines were suggested, such as not using cooling water sprays during drilling procedures. The efficacy of these measures will be evaluated in our study.

The most common aerosol generating dental procedures involve the use of high-speed handpieces [29, 30, 31], and ultrasonic scalars.

2.3.1 Air Turbine/High-Speed Handpieces

Air turbine handpieces are essential devices for routine dental procedures. They come in a variety of designs, but all have the purpose of imparting high-speed rotary action. To this effect, compressed air is used to power a turbine that is located inside the head of the handpiece. The speed of these devices is in the range of $250,000 - 400,000$ revolutions per minute (rpm) [7]. Therefore, in order to bring down temperatures that can be created at the drilling site due to friction, water and pressurized air are combined and then directed towards the tooth surface. This high-speed spray can combine with saliva and blood, aerosolizing them and spreading them throughout the operatory. The high-speed handpiece has been the subject of a number of studies, all of which have come to the conclusion that it is a major source of aerosols [7, 32].

2.3.2 Ultrasonic Scalar

An ultrasonic scalar is a typical dental instrument used by dental hygienists to clean teeth. While in use, a spray of water is released from the working tip, which is comparable to that of a high-speed handpiece. To eliminate calculus deposits, the ultrasonic scalar employs high-frequency vibrations and water as an ultrasonic energy channel. Therefore, it has been determined to generate a significant amount of aerosol and spatter contamination and is categorized as one of the dental devices with a high risk of disease transmission in a dental clinic [29, 33].

2.4 Aerosol Characterization

The density and size distribution of an aerosol have a significant impact on its behavior. In spite of the fact that these particles may not always take the form of spheres, the mean diameters are nevertheless utilized to determine their size, which may vary from 0.001 to 100 μm. The smallest particles stand in for nuclei, which are made up of a very tiny number of molecules; the largest of these particles would be comparable in size to extremely fine sand. The path that these droplets will take is influenced by inertia, gravity, and evaporation. Larger aerosols, which have more mass, have a greater chance of falling down with a ballistic trajectory [34] rather than evaporating, and as a result, they are more likely to contaminate surfaces. While smaller ones evaporate in a matter of seconds [35] before they can settle down. As a result, the small particles or droplet nuclei, remain airborne and have the potential to float in the air for hours or even days, allowing them to be carried across long distances [36]. Thus, the risk of particle transmission to individuals increases in indoor environments such as offices, elevators, and classrooms.

It has been highlighted by the researchers that although breathing generates aerosols at a far slower rate than other activities, it is a continuous activity and possibly creates more particles daily than episodic actions like sneezing and coughing [37, 38]. A droplet nucleus has the capacity to contain several viruses. Some respiratory diseases, such as the SARS-type, can be spread by a single virus [39]. Hence, droplet nuclei play a critical role in the transmission of respiratory infections.

As most aerosols comprise a variety of particle sizes, the distribution of number of particles per size and mass of particles per size are used to characterize them. The whole aerosol size range is divided into a series of consecutive size intervals, and the number of particles in each interval is calculated to generate the size distribution. In order to compare the contents of intervals with various widths, it is common to divide the number of particles in an interval by the width of the size interval. In other words, it tells us how many particles there are in a certain interval of size, such as count per μm.

2.5 Aerosol Measurement Methods

Aerosol size and concentration are significant factors in determining the likelihood of disease transmission. The inhalation of droplet nuclei (due to their small size) allows these particles to penetrate into the respiratory system and go more deeply into the lungs, where they cause a wide range of serious diseases [40]. Therefore, it is essential to identify the size of the aerosol. Several approaches have been utilized by researchers to measure the size and concentration of aerosols, and these will be described in the following.

2.5.1 Aerodynamic Particle Sizer

Aerodynamic Particle Sizers (APS) measure particle size using the concept of inertia. Particles travel between two laser beams, and a photodetector collects the scattered light. By monitoring the time delay between pulses created when particles travel through the lasers, particle velocity and diameter may be determined. APS can often distinguish particles between 0.3 and 20 μm. Several studies used APS to measure aerosol size and concentration for a variety of breathing exercises. The findings demonstrated that voiced activity created more particles than whispered activity, indicating that vocal cord vibration produces particles [41].

2.5.2 Exhaled Breath Condensate

In 1980, the exhaled breath condensate (EBC) equipment was first described for the study of lung disease. EBC collects non-volatiles from exhale breaths that have been condensed through cooling [42]. Collected components include small quantities of lipids and proteins derived from the respiratory tract lining fluid and also contain many potential biomarkers for airway inflammation and oxidative stress originating from the respiratory tract lining fluid. EBC tests struggled with reproducibility, prompting more effective methods to analyze and quantify exhaled non-volatile compounds.

2.5.3 Anderson Cascade Impactors

An Anderson style cascade impactor or a cascade sampler impactor can be used to measure the size distribution of non-volatile aerosolized particles. Particles of varying sizes are separated by passing air through a series of stages with the help of a vacuum pump. On the first collecting plate, larger particles accumulate, while smaller particles move to the next size step. The number of steps varies, but is normally between 6 and 8, and could measure particle sizes in the range of 10 nm to 10 μm [43].

2.5.4 Droplet Deposition Analysis

Droplet deposition analysis (DDA) uses optical or electron microscopes to measure the size of droplets deposited on a surface using a substrate that retains traces of the deposited droplets. If a trace is measured by a reticle, the original droplet's size may be calculated correspondingly. This method is often more accurate for measuring droplets with a diameter of $10\mu m$ or more. Several dentistry-related studies utilized this method and their results show that the most contaminated areas are on the practitioner and the assistant [44, 45, 46].

2.5.5 High-speed Imaging

Several studies employed a high-speed camera to detect generated aerosols during dental procedures. Images were analyzed to track the trajectory of aerosols and also to measure the concentration and velocity of the particles. Their results demonstrated that they could measure aerosols less than 0.56 μm in diameter, which initially traveled at 1 m/s. Also, they mentioned that a high concentration of the particles is produced immediately after starting the high-speed handpiece [47].

2.5.6 Interferometric Mie imaging (IMI) and Particle Image/ Tracking Velocimetry (PIV/ PTV)

Interferometric Mie Imaging (IMI) is an out-of-focus imaging technique for illuminating particles with a laser light sheet [48]. It may be utilized simultaneously with particle imaging/tracking velocimetry (PIV/PTV), which uses Mie scattering to determine instantaneous flow field velocity by lighting particles in a laser sheet and comparing precisely timed picture pairs, to identify tiny droplets with low or medium density. Depending on the particle size range and imaging settings, the pictures may also be used to measure the size of particles.

Several studies used IMI to measure the size distribution and velocity of droplets during speaking and coughing. The findings indicate that the majority of particle sizes fall within the range of $0.5 - 1$ μm. Using PIV, the average velocity of these particles was determined to be $11.7m/s$ and $3.1m/s$ for coughing and speaking, respectively

[26, 49, 50].

2.5.7 Laser Diffraction Particle Size Analyzer

Mie's concept of light scattering is used in laser diffraction to determine the particle size distribution. This is achieved by measuring the precise fluctuations in the intensity of light scattered as a laser beam passes through a sample of dispersed particulate matter. The laser beam reflects light dispersed from big particles at tiny angles, while light scattered from small particles is reflected at large angles. The data on the angular scattering intensity is then examined using Mie theory to identify the size of the particles responsible for producing the scattering pattern. The size of the aerosolized particles that are that expelled from a cough has been measured using a laser diffraction instrument, and the results fall in the range of $0.1 - 900$ μm of which 97% of the particles have a diameter smaller than 1 μm [51].

2.5.8 Optical Particle Counters

An optical particle counter (OPC) works based on the principle of light scattering. It utilizes a focused LED or a laser to illuminate particles in a stream of air (driven either naturally, via convection or gravity, or mechanically via a pump or fan). Light scattered by the particles is picked up by a photodetector and its patterns and intensity are utilized to determine the particle count and size. Often, OPCs report concentrations in units of $\mu g/cm^3$, however this value is simply an approximation based on the perceived density of particles being measured. OPCs are typically used as particulate matter (PM) environmental sensors. Several studies have used PM sensors to measure aerosols in dental settings before and after utilizing several parameters to decrease the amount of the particles [52, 53]. Their results indicated that dental aerosols are larger than 0.3 μm. They also stated that particle concentration was increased within $0.5m$ of the source [7]. This type of sensors was utilized in present work.

2.5.9 Digital In-line Holography

Digital in-line holography gathers three-dimensional data from an image using a camera and a coherent laser light. The particles scatter laser light as waves, and the camera captures the wavefront that the particles disperse. A few studies used digital in-line holography to measure the size and speed of the generated aerosols during a dental procedure. They concluded that 99% of the generated particles have a diameter in the range of $12-200$ μm. Furthermore, more than 65% of the generated droplets and aerosols had a velocity of < 1 m/s [54].

2.5.10 Phase Doppler Anemometer

Characterizing the particle size and velocity in a small measurement volume can be done with the use of a phase Doppler anemometer (PDA). The laser emits two coherent laser beams, which then intersect with one another at a single point. The intersection creates a volume due to the Gaussian distribution of the laser beams, which is in the shape of an ellipsoid as indicated in Figure 2-2. When a particle flows through the measurement volume, it scatters light, which is picked up by a receiving probe. After that, photo detectors take the signal from the dispersed light and turn it into information about the velocity and temporal concentration of the particles. By comparing the Doppler signals obtained from the different detectors, the size of the particles could be estimated [55].

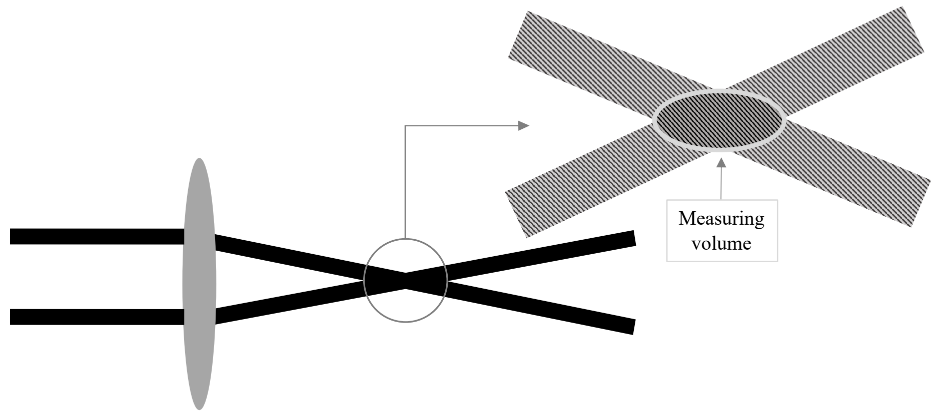


Figure 2-2: Measuring volume created by intersecting two laser beams of PDA. The photo detector, captures scattered light from particles which pass through the measuring volume.

2.5.11 Summary of Measurement Methods

Figure 2-3 summarizes the results of a wide range of studies that used different aerosol characterization tools. It can be seen that while there are overlaps, different instruments perform better in specific ranges. Unsurprisingly, the size distributions of bioaerosols reported in the studies we reviewed happen to coincide with the limited measuring capabilities of the instruments used. While this puts some of the reported conclusions into question, it also gives some prospective of the breadth of the subject matter and the importance of contributing to this type of research.

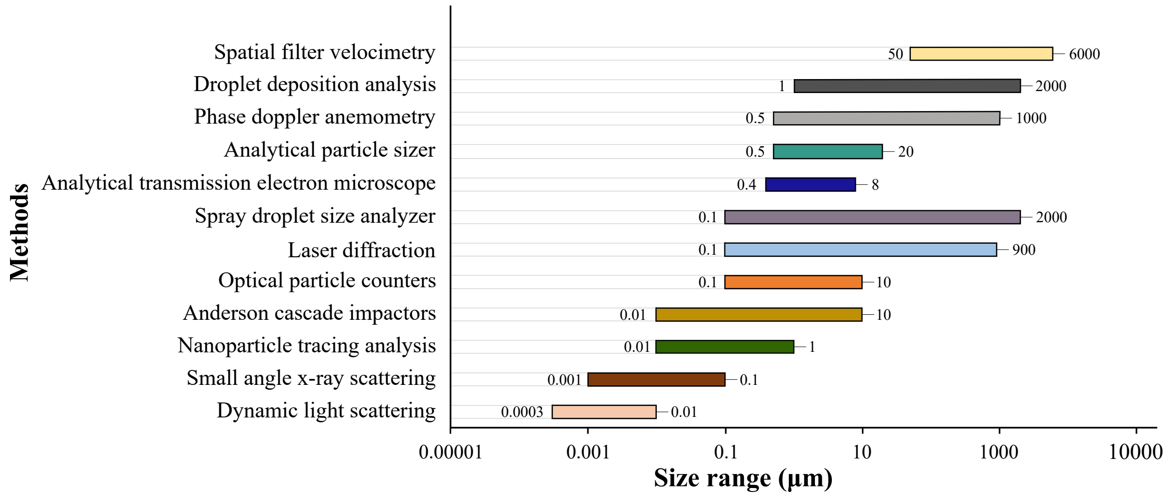


Figure 2-3: Summary of particle/aerosol measurement tools reviewed in this chapter.

2.6 Minimizing Dental Aerosols

Two typical dental instruments that disperse dental aerosols are high-speed handpieces and ultrasonic scalars. Saliva, blood, respiratory lining fluid, and tooth particles are all potential infection carriers in dental aerosols. Therefore, it is crucial to reduce the number of droplets and aerosols in the space of the operatory.

2.6.1 Saliva Ejectors, High-Volume Suction and Extraoral Suction

Saliva ejectors (SE), high-volume suctions (HVS), and extraoral suctions (EOS) are employed to minimize these aerosols and droplets during dental procedures. The SE is not powerful enough to remove a significant quantity of particles [56]. It has been recommended by the CDC that HVS and EOS be used to reduce aerosols by $93\% - 96\%$ [9, 57, 58]. Several studies have been done on the effect of EOS on aerosol dispersion during dental treatments. Their results showed that EOS is an effective and low-cost device for reducing generated aerosols while using ultrasonic scalars and high-speed handpieces [45, 53, 14]. Also, HVS has a great impact on reducing aerosols, especially if used by an assistant during dental treatments [44, 14].

2.6.2 High-Efficiency Particulate Air Filters

Aerosols could also circulate between open operatories via natural air currents [59, 60]. As the air quality of the dental clinic plays a critical role in infection rates, one easy and cost effective way to reduce the transition of aerosols is air filtration using high-efficiency particulate air (HEPA) filters. A HEPA filter can trap 99.97% aerosols smaller and larger than 0.3 μm [61]. Portable air purifiers with HEPA filters not only trap particles, but also deliver clean air to the environment. The CDC recommended using portable air purifiers equipped with HEPA filters in high-risk areas [61]. Although at the start of the COVID-19 pandemic, the CDC has not specifically recommended the usage of HEPA filters for dental clinics, several studies have suggested that these portable air purifiers are very effective [62, 63, 64]. Chen et al.(2010) [65] suggested that further studies should be done on the effect of portable HEPA filters on the dispersion of aerosols and droplets in dental clinics. Their work also proposes that the position of the air purifier is important in reducing exposure to dental practitioners.

2.6.3 High-Speed Handpiece

As described in section 2.3.1, water coolant is mixed with the pressurized air in the head of the high-speed handpieces and sprayed on the surface of the tooth. This water spray results in dispersing aerosols which can be contaminated with biological matter. There are other types of handpiece in which the spray is not premixed with compressed air. A few studies have been done to compare the effects of different high-speed handpieces on the rate of aerosol generation, and they recommended using handpieces which do not premix water to reduce the concentration of aerosols [7]. Also, another study showed that high-speed contra angle handpieces generated 97% less particles than air turbine handpieces [66]. Furthermore, since the onset of the COVID-19 pandemic, a new four-sprayer high-speed handpiece was released with the aim of reducing aerosolized particle transfers that was tested in this work.

2.6.4 Rubber Dam

A Rubber dam is a dental isolation which is recommended to reduce the production of contaminated aerosols [67, 68, 11]. The use of a rubber dam without HVS increases the average size of the particles, so it is important to note that the rubber dam should be used with HVS and EOS [68, 69].

2.6.5 Isolation

According to the findings of certain studies, the use of supplementary suction in an open-space dental clinic is not nearly as successful as the installation of space separating barriers in preventing the transmission of aerosols to other areas of the clinic [47]. In another study, the researchers isolated the patient from the dental staff by placing a barrier around the patient. The barrier had two gaps in it so that the practitioner and their assistant could operate through it. According to the findings, the barrier was successful in capturing a significant quantity of both the aerosols and the splatters [12].

Chapter 3

Materials and Methods

This chapter is devoted to the materials and methodologies that we used in this study. Beginning with the experimental setup and proceeding to the instruments. Finally, details about experimental procedures and statistical analysis methods used are provided.

3.1 Experimental Setup and Instruments

The experimental setup (Figure 3-1) consists of 35 particulate matter (PM) sensors (details about sensors and their positioning are provided in section 3.1.7) in a closed dental operatory with dimensions of 3.0 m $\times$ 3.5 m $\times$ 2.5 m (width, length, and height, respectively), located at the University of Toledo's Department of Dentistry. A protractor with a radius of 40 inches was placed under a dental chair, and the PM sensors were positioned around this protector systematically. The operatory included a portable dental cart (section 3.1.1), a mannequin equipped with a typodont (Youya Dental TM-022 with 32 removable teeth), restoration treatment instruments (section 3.1.2), an extraoral suction unit (section 3.1.3), and a HEPA filtered air purifier (section 3.1.4).

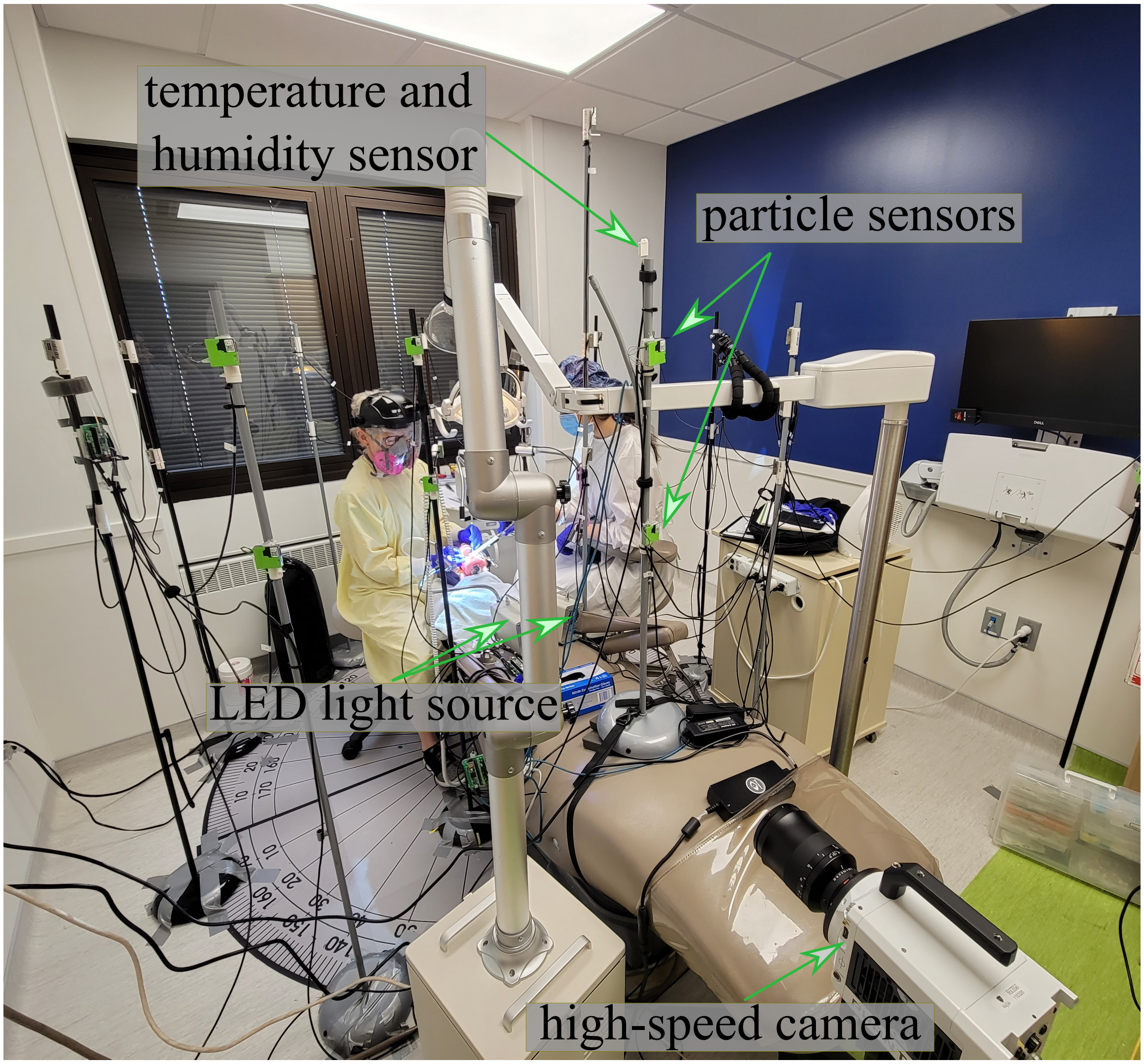


Figure 3-1: Experimental setup consists of 35 particulate matter sensors and a high-speed camera for aerosol measurement.

3.1.1 Dental Unit

A portable dental unit (ASI model 90-2021) was used to provide dental treatments throughout the experimentation process (Figure 3-2). It is equipped with an air-water syringe and two air-driven handpiece receptacles; one high-speed and the other one low-speed. The air compressor provides power to the handpieces as well as pressurizes the water system. A high-volume suction (HVS) and a saliva ejector (SE) are connected to an internal vacuum pump. During the studies, the HVS was utilized to remove water and tooth particles from the dental mannequin's mouth.

Figure 3-2: Portable dental unit consists of a water system, a suction system and an air compressor to pressurize water and air.

3.1.2 High-speed Handpieces

In order to conduct the experiments in a realistic manner, we used an intubation mannequin fitted with a typodont (Youya Dental TM-022 with 32 removable teeth). Two types of high-speed handpieces were utilized to carry out dental procedures, one was a single-sprayer (Precision-Torque 2, Henry Schein Inc.) which has one hole to spray water during the dental treatments, and the other was a four-sprayer (Maxima Pro 2S, Henry Schein Inc.) which has four set of water spray holes. Figures 3-3 (a) and (b) show an image of a single-sprayer and four-sprayer high-speed handpiece, respectively. Besides high-speed handpieces, two types of dental burs were used.

Carbide burs for occlusal preparation and mesio-occlusal preparation (MOD) and diamond burs for crown preparation (section 3.2). Figures 3-4 (a) and (b) represents carbide burs and diamond burs.

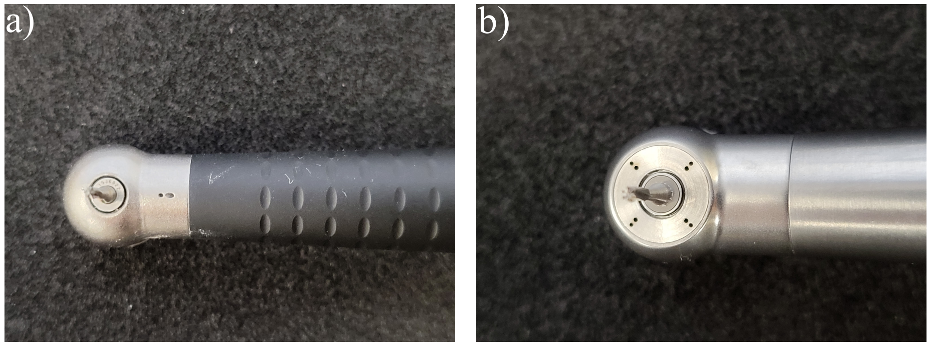


Figure 3-3: a) Single-sprayer high-speed handpiece, b) four-sprayer high-speed handpiece.

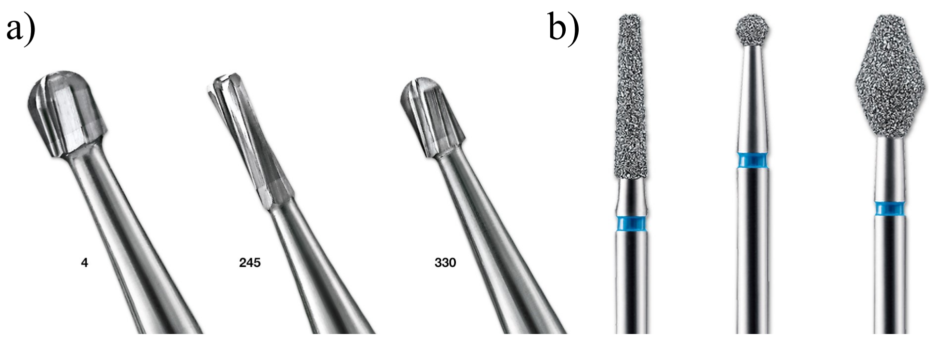


Figure 3-4: a) Carbide burs [70], b) Diamond burs [71]

3.1.3 Extraoral Suction

An extraoral suction (EOS) unit (UNIVAC E100, Unicore Dental Supply) was utilized during several dental treatment procedures. It is equipped with a HEPA filter with 99.97% efficiency to remove aerosols and particles larger than 0.3 μm. EOSs were introduced in recent years as a work area targeted vacuum unit. The nozzle was positioned in front of the mannequin mouth, as shown in Figure 3-6 (b).

This unit has a suction flow rate of 72 CFM.

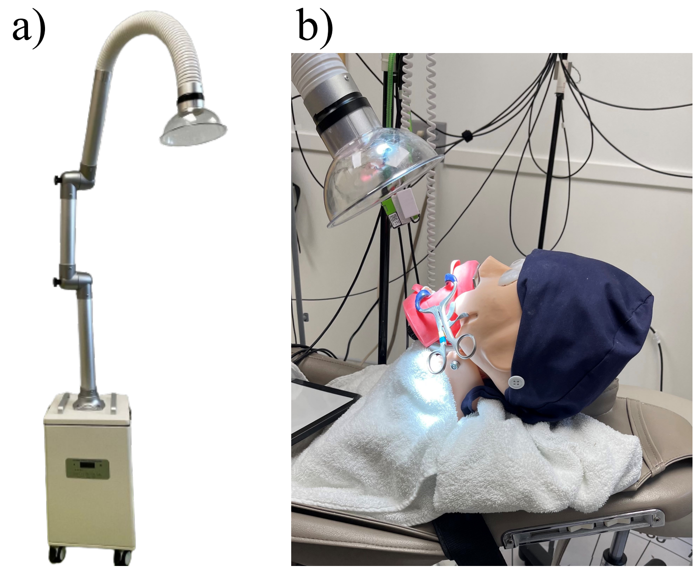


Figure 3-5: a) UNIVAC E100 extraoral suction unit b) Position of extraoral suction nozzle on top of the mannequin mouth during procedures.

3.1.4 HEPA Filtered Air Purifier

To examine the effect of air quality management on particle concentration, we used a portable HEPA filtered air purifier (Holmes aer1, Sunbeam Products Inc.). The air purifier was positioned such that the suction side was facing the practitioner and the blowing side was facing the door. This unit has an air flow rate of 91 CFM.

Figure 3-6: HEPA filtered air purifier.

3.1.5 Dental Isolation Devices

Depending on the procedure, isolation devices such as rubber dams and dental isolation were used. A rubber dam is a latex sheet that is placed over the patient's mouth, which a hole is cut so that the dentist may operate on the tooth that is meant to be treated, as seen in Figure 3-7. It is more commonly used for children and improves patient safety by avoiding small dental debris from being swallowed. It also improves the safety of the dentist and their assistant by reducing the spread of potentially infectious saliva and blood.

Figure 3-7: Adjusted rubber dam on the typodont to perform a dental procedure.

A dental isolation device (Dryshield DS-SUS-400) is utilized instead of HVS, SE, tongue guards, and oral pathway protectors. It is connected to the HVS port of the dental unit and then adjusted in the patient mouth as shown in Figure 3-8.

Figure 3-8: Dental isolation connected to HVS.

3.1.6 Dental Chair Positions

Position of the patient in also examined in this study to confirm if it has any effect on particle concentration. Figures 3-9 (a) and (b) represent supine and semi-supine positions of the dental chair, respectively. Both positions were set by dental practitioners to a common patient position in reality.

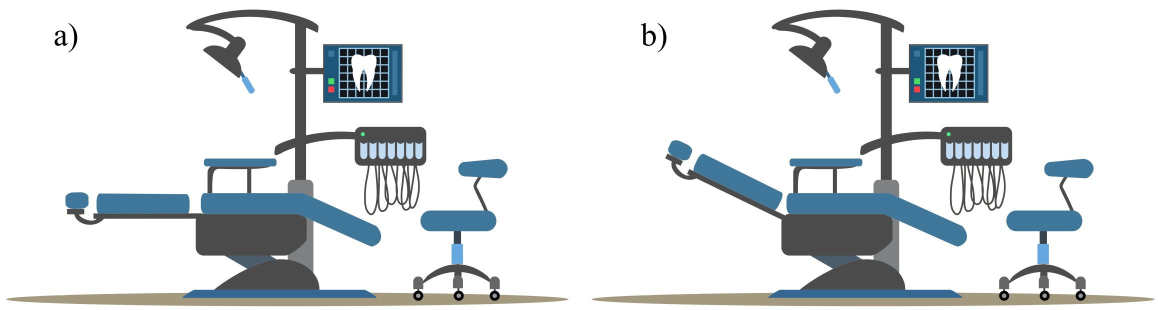


Figure 3-9: a) Supine position, b) Semi-supine position.

3.1.7 Environmental Sensors

Thirty-five Sensirion particulate matter (PM) sensors (SPS30, Sensirion AG, Switzerland) were installed in the dental office to characterize the presence, transport, accumulation, and dissipation of aerosols produced during routine dental treatments. These sensors are a kind of laser based optical particle counter (see section 2.5.8) with a reported uncertainty of $\pm 25\ \mu g/cm^3$ for PM10 mass concentration and $\pm 100\ count/cm^3$ for PM10 number concentration under factory calibration. While these are amongst the better PM sensors on the market, for our study, we opted to validate the sensor outputs with a phase Doppler anemometer, which is described in section 3.1.8 as to not rely on the high specification sheet uncertainty.

In both indoor and outdoor environments, such particulate matter sensors offer a broad range of use in detecting air quality [72, 73, 74]. The aerosol data is allocated into five channels: PM 0.5, PM 1.0, PM 2.5, PM 4.0, and PM 10.0. These channels detect particles up to their nominal size. For example, PM 2.5 refers to particles up to 2.5 μ in diameter. This is considered amongst the more dangerous aerosol sizes owing to its ability to penetrate deeply into human lungs [75]. Only data from the PM 10.0 channel are given in this study since it encapsulates data from all the other channels. Sensors were programmed using Python (Section 3.1.9) to read real time particle concentration at a frequency of approximately 1 Hz.

For the purpose of a precise sensor arrangement, a protractor with a radius of $40''$ was placed under the dental chair to position the sensors systematically in three circles with different diameters, as shown in Figure 3-10. The first circle consisted of three sensors located above the mannequin in the close vicinity of the practitioner and the assistant. The second circle consisted of a total of six sensors at two heights: three sensors at a sitting height of $46''$ from the floor and three sensors at a standing height of $61''$ from the floor. The third circle consisted of a combination of 18 sensors at the same two heights. In addition, one sensor was mounted near the inflow air conditioning vent at a height of $83''$ and five others were mounted at farther distances with respect to the center of the setup. Furthermore, during the experiments, one sensor was attached to the forehead of the practitioner and one to the assistant, making the total number of sensors 35. In addition to PM sensors, the setup included a DHT-22 sensors to monitor the temperature in range of $0 - 50°$C with an accuracy of $\pm 2°$C and the humidity in range of $2 - 80\%$ with an accuracy of 5%.

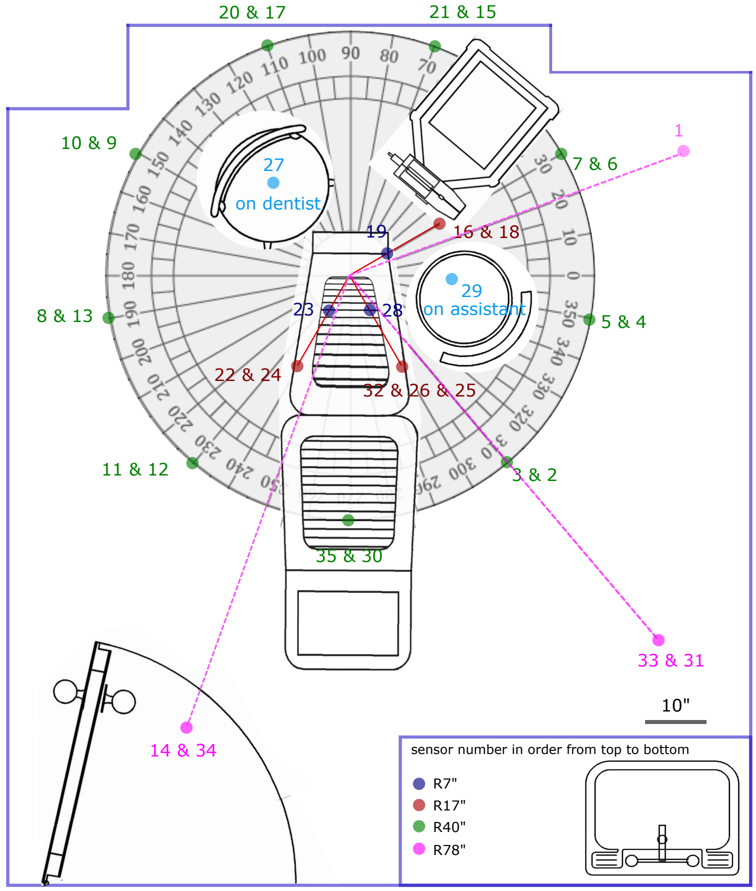


Figure 3-10: Operatory layout with sensor positions.

3.1.8 PM Sensors Validation

To validate PM sensors, an experiment was done to compare the sensor's findings with those from a phase Doppler anemometer (PDA). A Sensirion sensor was placed within a closed box which had clear access for using a PDA. A mannequin with a removable typodant was placed inside the box and when the PDA laser was turned on, drilling teeth started to generate tooth particles. Figure 3-11 displays concentration of PM10 aerosol particles within the box detected by PDA and the Sensirion sensor. The PDA measures the particle counts over time ($count/s$) and the PM sensors measure the particle count in a volume ($count/cm^3$). To compare the results, we needed to find the measured particle count per volume for PDA as well, which is calculated using equations 3.1 and 3.2. In this equation, v is the particle's velocity measured by PDA, and A is the orthogonal area of the PDA measuring volume. The figure reveals that the concentration of aerosol particles measured by the Sensirion sensors was well matched to those from the PDA, thus giving us more confidence in the reported results.

$$Q(\text{cm}^3/\text{s}) = v(\text{cm/s}).A(\text{cm}^2) \tag{3.1}$$

$$PM10_{PDA}(\text{count/cm}^3) = \#_{PDA}(\text{count/s})/Q(\text{cm}^3/\text{s}) \tag{3.2}$$

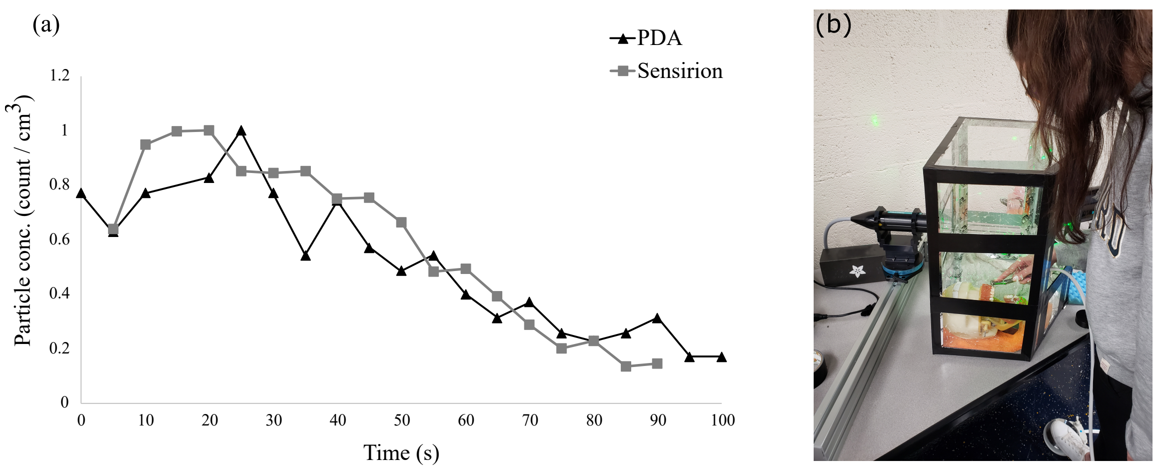


Figure 3-11: (a) Validation of the PM sensor using PDA during an experiment. (b) An image of the experiment.

3.1.9 Data Acquisition

Each PM sensor was attached to a Teensy microcontroller (Teensy 4.1, PJRC Portland, Oregon, USA) to monitor and identify aerosol particles. A total of 35 sensors required the usage of a total of five Teensy boards, and eventually all of them were connected to a single Teensy, which acted as a hub. Because of this, each Teensy was coded using the Arduino IDE to write data acquired by sensors at a rate of 1 Hz, (code available in Appendix A.1) and the Teensy hub had its own code to receive data from each Teensy concurrently (Teensy hub code is available in Appendix A.2). Figure 3-12 shows the connection of 7 PM sensors to a microcontroller. An SQlite database was then created using Python to store the acquired data, which is available in Appendix B.1. This data was later analyzed statistically and stored in a SQLite database (Appendix B.2) and finally analyzed and plotted (Appendix B.3).

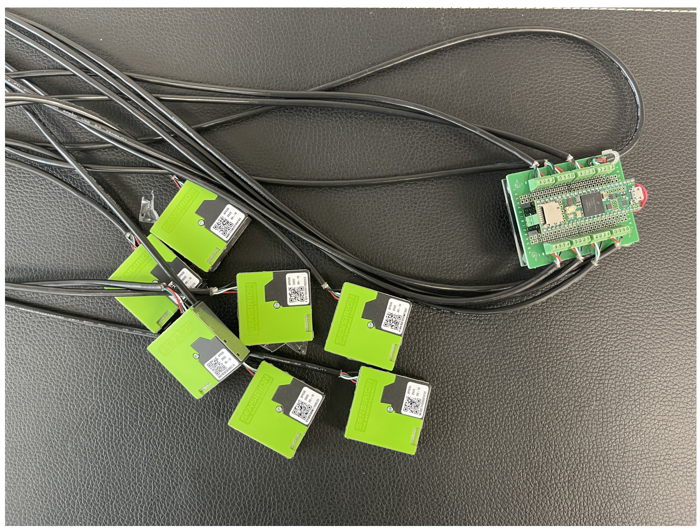


Figure 3-12: Connection of PM sensors to a microcontroller.

For certain experiments, a high-speed camera was also used to identify larger particles and splatter in addition to their trajectories. The experiments were also documented using a GoPro Hero 8 camera, which was attached to the dental assistant.

3.2 Experimental Procedures

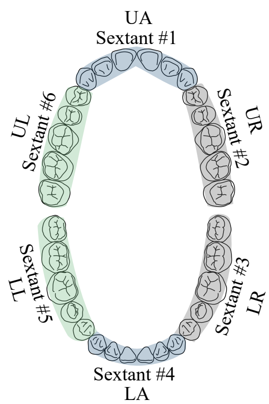
A dental mannequin was attached to a dental chair's headrest in a typical working position. Replaceable typodonts held 32 removable teeth fixed in the jaw of the mannequin head. Dental operations were mimicked by placing the operator at the 9-12 o'clock position, while the assistant was at the 1-3 o'clock. Restoration treatments, including a 1- and 2-minute surface drilling and a 5-minute complete crown preparation, were all mimicked by a dentist (Drs. Carol Wiese and Darya Dabiri). The typodont was split into sextants, as indicated in Table 3.1, and each sextant was prepared according to these three dental procedures. A 557-carbide bur was used to do an occlusal preparation for one minute on sextants #2, #3, #5, and #6 (upper right: UR, lower right: LR, upper left: UL, and lower left: LL, respectively). On the same tooth, a 2-minute mesio-occlusal-distal (MOD) preparation was then completed. Finally, diamond burs were used to prepare the tooth for a crown installation using wheel, chamfer, flame, and football burs. In sextants #1 and #4, (upper anterior: UA, and lower anterior: LA), a 557-bur was used to create an endodontic access opening on the lingual surface(s) for 1-minute and then mesial, facial lingual surfaces were done for 2-minutes. Finally, a 5-minute preparation of the anterior area for the crown installation utilizing chamfer, flame and diamond burs was conducted.

We attempted to do all of the procedures as realistically as possible. A high-volume suction (HVS) was used to remove the water content from the mouth during each treatment. The dental assistant (who is the present examiner) utilized HVS as if operating on a human patient with great attention during operations. Various factors influenced how each treatment was carried out, including whether an extraoral suction machine was used, if an air purifier was used, and if the procedure was done in a close-door or an open-door room. Each of the sextants was subjected to various processes and experimental settings as shown in Table 3.1. When no dental procedures were taking place in a given space, the PM sensors indicated that the concentration of particles in the air was at or below 7 $particles/cm^3$. Consequently, we began each experiment when the readings from all PM sensors were below this threshold in order to ensure maximum consistency across measurements. Prior to beginning a new procedure, we waited until the particle count dropped to below this predetermined threshold utilizing by an air purifier. In order to establish the experiment to experiment variations, and to average out any potential bias caused due to human effects, the base case measurements were repeated six times, while others were performed 1-3 times.

In this study, the position of the mannequin on the dental chair was supine during the majority of experiments. However, for certain individuals, it is not practical to do dental treatments in the supine position. Hence, to assess the effect of the patient position on the concentration of the generated particles, the mannequin position was set to semi-supine in some instances.

Most of the guidelines suggest dental staff keep the operatory door closed during dental treatments [76, 77, 27, 78]. However, there are a few studies on aerosol transmission in a closed door versus open door operatories. Shahdad et al. (2020) [79] compared aerosol concentration in a closed and open operatory during AGDPs and concluded that the frequency of contamination is less in an open operatory than in a closed one.

Table 3.1: All parameters were investigated for all six sextants and for three dental procedures depending on the parameter (occlusal preparation for 1-minute, MOD for 2-minute, and crown preparation for 5-minutes). A combination of stared parameters (*) form the base case.



Tooth Sextant	Parameters Group		Dental Procedure		
	Patient simulator	Supin*	1 min	2 min	5 min
		Semi-supine	1 min	2 min	5 min
	High-speed hanpiece	single sprayer*	1 min	2 min	5 min
		Four sprayer	–	–	5 min
	Dental accessories	Rubber dam	1 min	2 min	–
		Dry-shield	1 min	2 min	5 min
	Modification of standard of care	Wet drilling*	1 min	2 min	5 min
		Dry drilling	1 min	2 min	–
		Open room*	1 min	2 min	5 min
		Close room	1 min	2 min	5 min
		Air purifier	–	–	5 min
		Extraoral suction	–	–	5 min

3.3 Statistical Methods

To elucidate the effectiveness of the various recommendations at reducing bioaerosals, a suitable statistical approach had to be determined. Due to the inherently small sample size, the variability within each procedure, and the temporal variation of the aerosol concentrations during each procedure, we determined that the independent sample t-test was the most appropriate approach. Using this statistical hypothesis testing, we are able to make inferences about unknown parameters in the study and to determine if there is any significant relations between parameters [80, 81]. For this approach, one must define the null hypothesis H_0, which is the hypothesis that there is no significant difference between a specified reference population, and observed difference in a second population being tested. The independent sample t-test is described in the following.

One can use a t-test in case the sample size is small, the population standard deviation is unknown, which often happens in practice, and the data follows a normal distribution. A non-parametric testing can be applied if the normality assumption is violated. Assuming the aforementioned conditions hold, we use a one-sample t-test for comparing a single group mean with a specified value ($H_0 = \mu_0$) with the test statistic as below

$$T = \frac{\overline{X} - \mu}{s/\sqrt{n}}. \tag{3.3}$$

where $\overline{X}$ is sample mean, μ_0 is target value under the H_0, s is sample standard deviation and n is sample size. Under the null hypothesis H_0, sampling distribution of the statistic T above has a t distribution with $n-1$ degrees of freedom (df). Depending on the direction of the alternative hypothesis H_1, we can make decision on either rejecting or accepting the H_0 at significance level of α, accordingly. $t_{\alpha,df}$ is a critical value under the t_{curve} with a specified degree of freedom to the right of $t_{\alpha,df}$ which is demonstrated in Figure 3-13. For example, $t_{0.05,8}$ is the critical value corresponding to upper tail probability of $\alpha = 0.05$ of the t distribution with $df = 8$. Also, $-t_{\alpha,df}$ is the critical value corresponding to lower tail probability of $\alpha = 0.05$ of the t distribution. Possible alternate hypotheses are as below

$$H_1 : \mu > \mu_0$$

$$H_1 : \mu < \mu_0$$

$$H_1 : \mu \neq \mu_0$$

For example, if the alternate hypothesis is $H_1 : \mu > \mu_0$, we reject H_0 at level of α if $T > t_{(\alpha,df=n-1)}$.

Now, if comparison involves two independent groups, and assuming the conditions above hold, we use two-independent samples t-test to test the hypothesis $H_0 : \mu_x -$

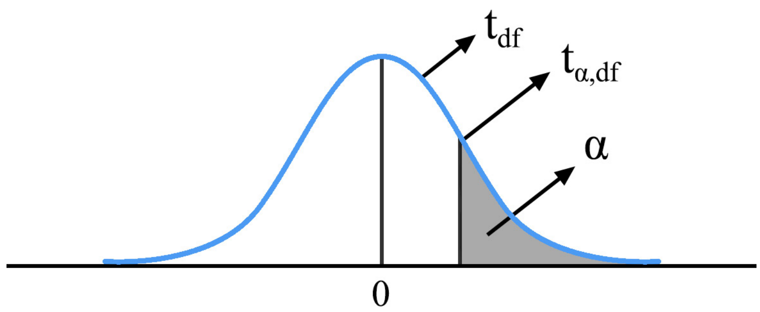


Figure 3-13: Critical value of t distribution with degree of freedom df corresponding to α.

$\mu_y = \Delta_0$. To do so, the test statistics is calculated under the H_0 and is given by

$$T = \frac{\overline{x} - \overline{y} - \Delta_0}{\sqrt{\frac{s_x^2}{n_x} + \frac{s_y^2}{n_y}}}. \tag{3.4}$$

where $\overline{x}$ and $\overline{y}$ are the average of the samples in group x and y, respectively; and s_x^2 and s_y^2 show the variance of the samples for the corresponding populations. The number of samples for group x is represented by n_x and for y is represented by n_y. Under the H_0, the above test statistic has t distribution with df equal to equation 3.5. The nearest integer to df is used

$$df = \frac{\left(\frac{s_x^2}{n_x} + \frac{s_y^2}{n_y}\right)^2}{\frac{(\frac{s_x^2}{n_x})^2}{n_x - 1} + \frac{(\frac{s_y^2}{n_y})^2}{n_y - 1}}. \tag{3.5}$$

Different alternative hypotheses for the two-sample t-test are

$$H_1 : \mu_x > \mu_y$$

$$H_1 : \mu_x < \mu_y$$

$$H_1 : \mu_x \neq \mu_y$$

For example, if the alternate hypothesis is $H_1 : \mu_x - \mu_y > \Delta_0$, we reject H_0 at a level of α if $T > t_{(\alpha,df)}$. In this case, the P-value is $P(t > T)$, where t is the t distribution random variable with degrees of freedom df. If the alternate hypothesis is $H_1 : \mu_x - \mu_y < \Delta_0$, P-value is $P(t < -T)$. Appendix C provides critical values of the t distribution value [1].

Chapter 4

Results

The major focus of this research was to identify potential strategies for decreasing the spread and accumulation of aerosols in a dental office. Therefore, in the first half of this chapter, an explanation of the *base case* will be provided. This represents typical scenarios in which dental procedures are conducted on different sextants as well as what happens if we do not employ HVS. The second part of this study examines the effects of several aerosol mitigating strategies as compared to the *base case*.

4.1 Base case

The first set of studies were carried out in an open-door operatory room. The mannequin head was positioned in the conventional supine position, and a single-sprayer high-speed handpiece was employed to mimic the common dental treatments. The term "base case" refers to the fact that no supplementary equipment, such as a rubber dam, dental isolation device, extraoral suction unit, or air purifier, etc was used. Following the procedure outlined in section 3.2, each sextants UR, LR, UL, and LL (Table 3.1) in the posterior area was drilled for one minute as the occlusal preparation, two minutes as the MOD preparation, and five minutes for the crown preparation. In the anterior area of sextants, UA and LA (Table 3.1), a one-minute process was performed to open the endodontic access. This was then followed by a two-minute restoration on the mesial, facial, lingual surfaces of the tooth, and finally, a five-minute procedure was performed to prepare the tooth for the crown process. To average out any potential bias from the human experimenters, we repeated this "base case" experiment six times. The base case parameters are stated in the Table 3.1.

According to what is described in section 3.1.7, we placed 35 PM sensors in the room that recorded the concentration of the aerosols. Using the data, that was collected by the sensors, we were able to create a 2D map showing the distribution of the particle concentration. At the beginning of each experiment, the practitioner and the assistant were exposed to a high concentration of the particles. These hot-spots were not confined to the immediate area around the patient, but were instead moving from one location to another, demonstrating the complex fluid dynamics of the cloud of particles. Figures 4-1 (a), (b), and (c) show an example of particle migration recorded by sensors at standing height in 5 seconds. In the region close to the practitioner, the assistant, and the patient simulator, the concentration of particles was found to be very high. However, as time passed, this concentration transferred to other regions as well.

In order to report the data, the median of the particle concentration from all 35 sensors is computed at each time step for each process. Figure 4-1 (d) shows the logarithmic concentration of the particles in the room as measured by all 35 sensors throughout the 5-minute base case treatment performed on a tooth located in the lower right sextant. The experiment started when the sensors showed less than 7 $particles/cm^3$ in the room, which is shown by the horizontal blue dashed line in the Figure. The black solid line represents the median value of the particle concentration taken by all of the sensors. The Figure also shows how long it take for particle concentration to go back to its initial value of 7 $particles/cm^3$. Three vertical dashed line show the time for each of the particle maps, which are presented at times 3'51", 3'53", and 3'55", respectively.

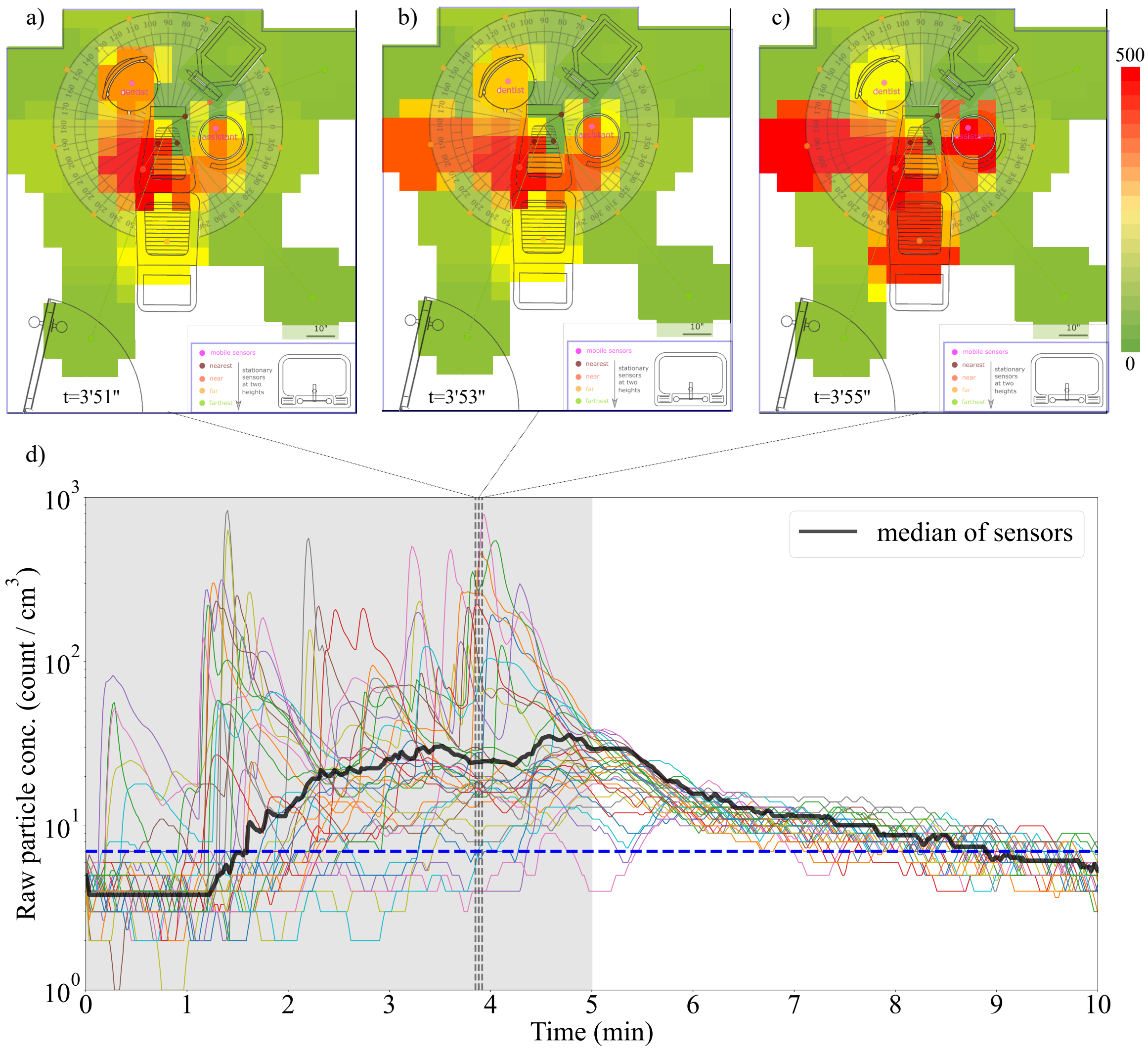


Figure 4-1: A sample of particle concentration over time measured by all the sensors during a 5-minute procedure. Figures (a), (b), and (c) show particle transition at t=3′50″, t=3′53″, t=3′55″, respectively. Figure (d) shows measured particle concentration by 35 sensors. Median of particle concentration from all sensors is presented by a black line. Vertical dashed gray lines show the time at which each particle concentration map is extracted in the above panels. The horizontal blue line shows the room's maximum particle concentration without any dental procedure in progress.

Figure 4-2 shows the base case results for six repetitions during a 5-minute crown preparation. Each gray line represents the median of 35 sensors for each repetition. It should be noted that in the case of UA (bottom-center plot in Figure 4-2), there appears to be one divergent case in which particles were found to be quite high as compared to other repetitions. This can be a result of several factors; for example, if the HVS was not positioned properly, or if the the procedure was not repeated exactly. In practice, such events are to be expected, which is why we repeated the base case 6 times.

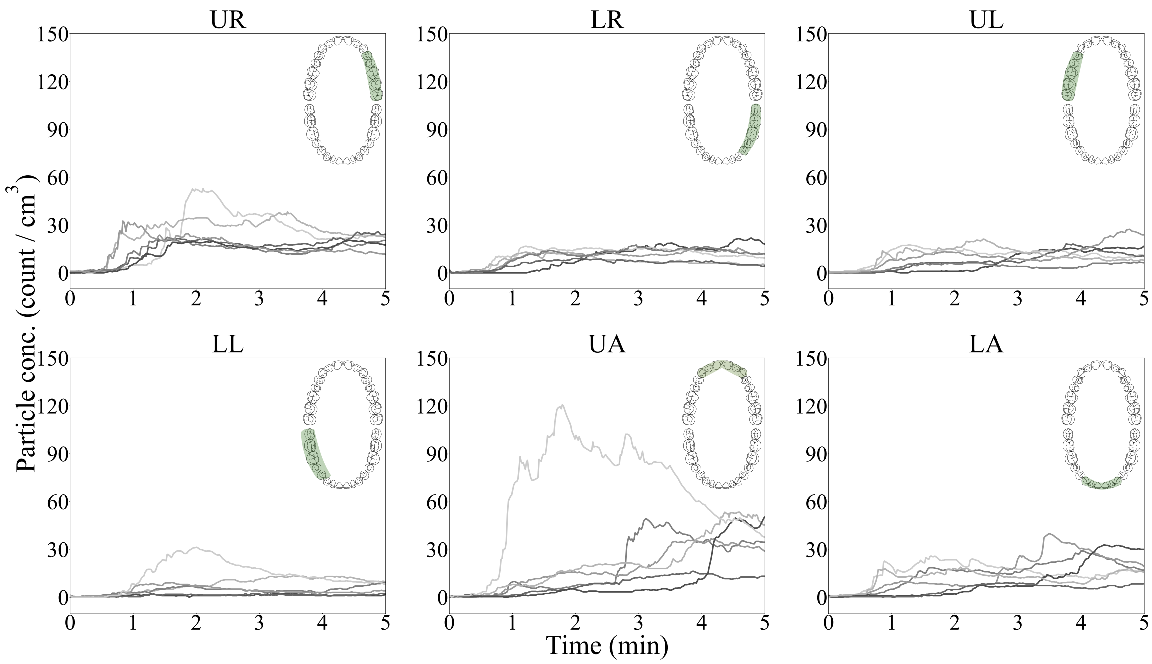


Figure 4-2: Particle concentration plots for six sextants during a 5-minute crown preparation. Each gray line represents median of 35 sensors from one repetition.

4.2 Effect of Different Procedures and Parameters

Surface drilling and full crown preparation are the two processes included in restoration therapy, as explained in section 3.2. One minute of occlusal preparation was completed, followed by two minutes of MOD preparation, all using a 557 carbide bur. The base case was done for 2-minute using a carbide bur as well. The results are shown in Figure 4-3. Here again, we noticed an unusually high particle concentration for a single repetition in the UA sextant. The anterior regions appear to be more susceptible to excess aerosolization of particles if special care is not given to the positioning of the HVS and the dental practitioner's positioning of the high-speed handpiece.

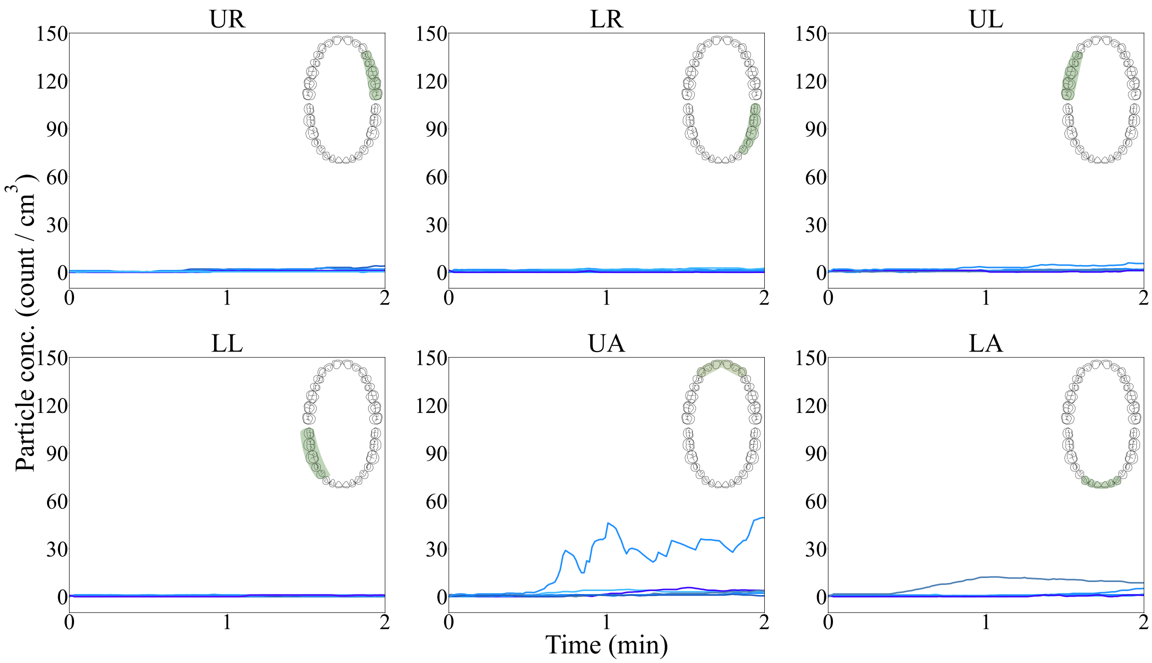


Figure 4-3: Particle concentration plots for six sextants during a 2-minute dental procedure. Each blue line represents median of 35 sensors from one repetition.

4.2.1 Effect of Dry Drilling

During the COVID-19 pandemic, it was recommended that dental practitioners perform dental procedures without spraying water. As such, we turned off the water line of the high-speed handpiece and performed the procedure for 2-minute. Due to the high-speed of the handpiece, the temperature on the surface of the tooth will increase if water not spray on the working area. Thus, to be realistic, we did not perform this procedure for 5-minute. Results of this procedure are provided in Figure 4-4. It becomes immediately clear, that even without spraying cooling water, a significant number of aerosols are still generated. To compound this, the elevated temperature of teeth being worked on can easily damage dental nerves irreparably and cause tooth discoloration.

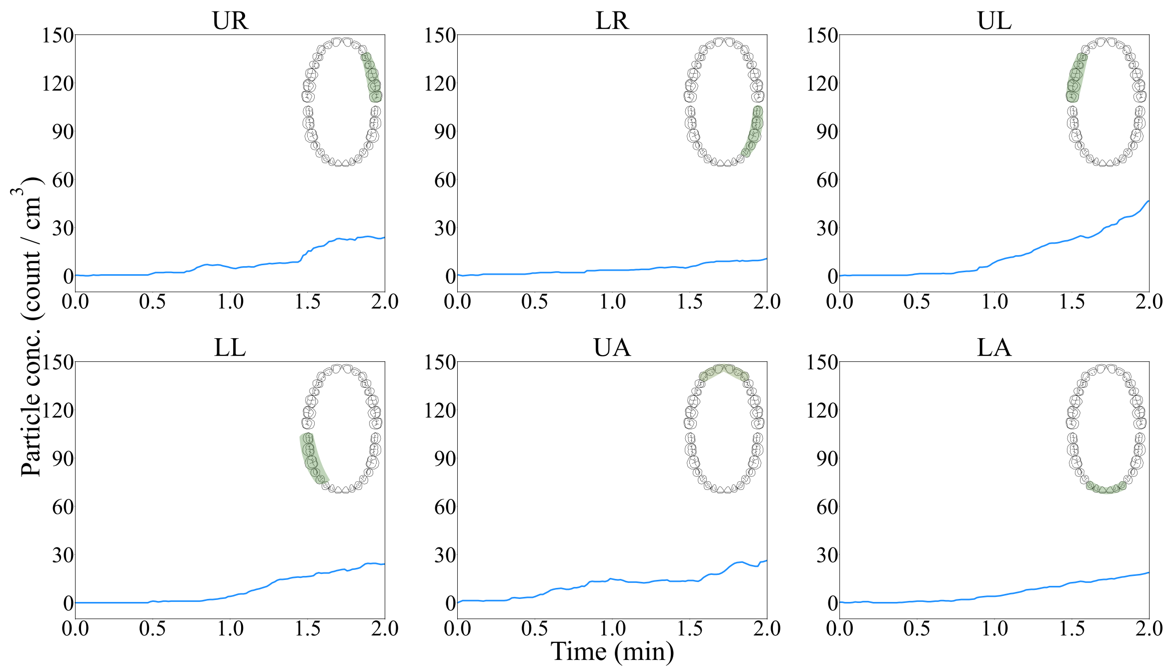


Figure 4-4: Particle concentration during 2-minute dry drilling.

4.2.2 Effect of Closed Door

Current guidelines suggest that practitioners keep the operatory room door close during dental procedures. Hence, we performed a 5-minute crown preparation on all posterior sextants in a closed door operatory. The results are shown in Figure 4-5.As compared to the open door scenario, the aerosol concentration is markedly higher during closed door procedures. The CDC recommends using negative pressure facilities could potentially mitigate this rise, however, such facilities are rare in dental practices.

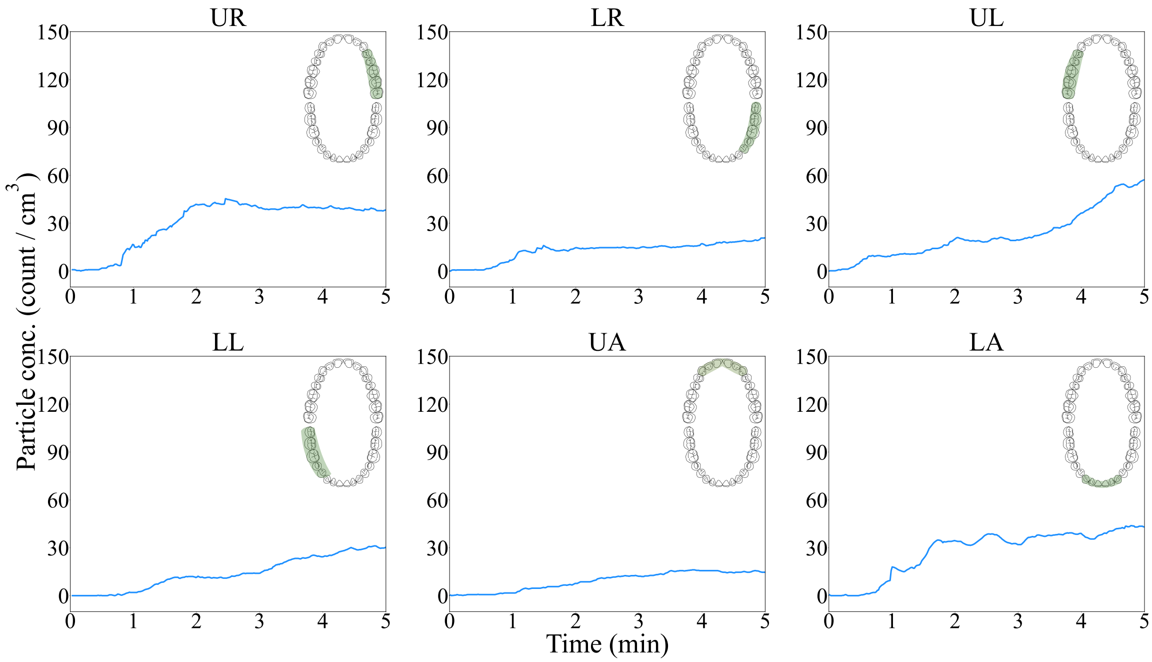


Figure 4-5: Particle concentration during 5-minute procedure in a closed door dental operatory.

4.2.3 Effect HEPA Filtered Air Purifier

It has been further recommended by several studies to use a HEPA filter air purifier in high risk areas as it helps to improve air quality. Therefore, we placed a HEPA filtered portable air purifier in the operatory with the suction side facing the practitioner and the blowing side facing the door. We performed the 5-minute procedure 3 times for all posterior sextants and the results are shown in Figure 4-6. Each blue line shows the median of 35 sensors during the experiment for each repetition. Surprisingly, it was noticed that there was quite a bit more variation in the results between different repetitions. The reason for this is not clear, however one cannot rule out variability due to the practitioner's and assistant's inputs. It should also be noted that the effect of using a portable HEPA filtered air purifier was only examined here during the dental procedure and with the door open. How beneficial this would be at reducing particle concentrations after the procedure, particularly with the door closed, is not examined in this study.

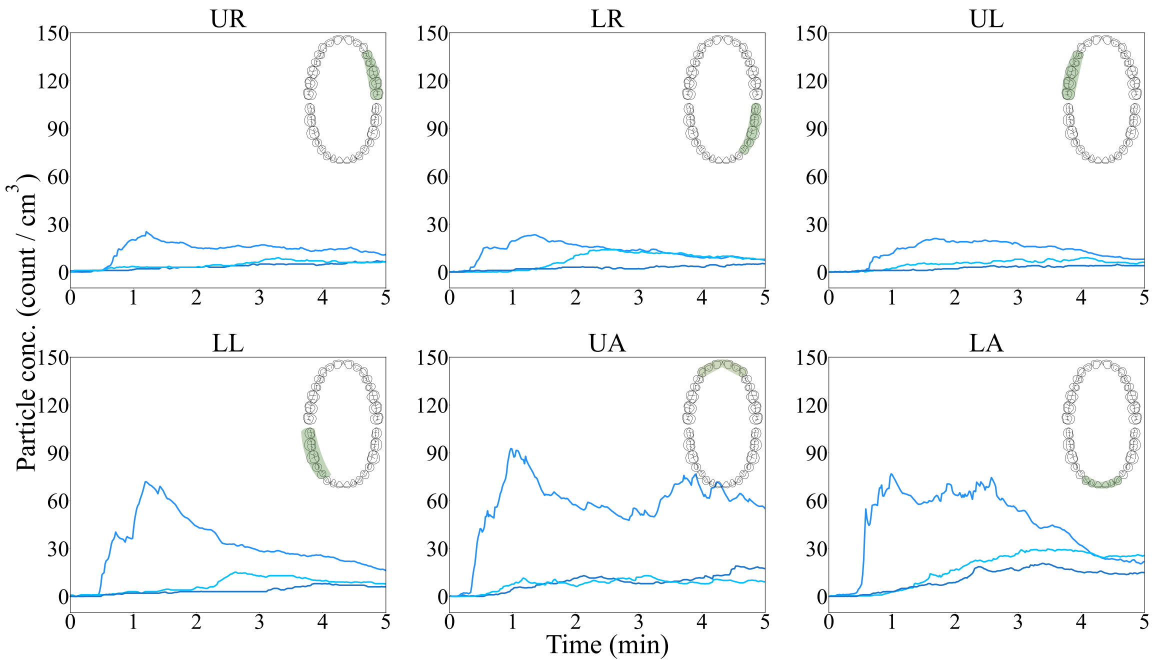


Figure 4-6: Particle concentration during 5-minute procedure in the presence of a HEPA filter air purifier.

4.2.4 Effect of Extraoral Suction

Since modern dental tools, by their nature, generate aerosols, several studies have recommended using extraoral suction (EOS) as an effective and low-cost method to mitigate their spread. In this study, we employed an EOS and set its nozzle on top of the mannequin's mouth. The results are provided in Figure 4-7 for three repetitions of a 5-minute procedure for all sextants. Again, we notice an unusually elevated particle concentration for one of the repetitions in the UA sextant, however in all other cases, the particle concentration appeared to be significantly reduced.

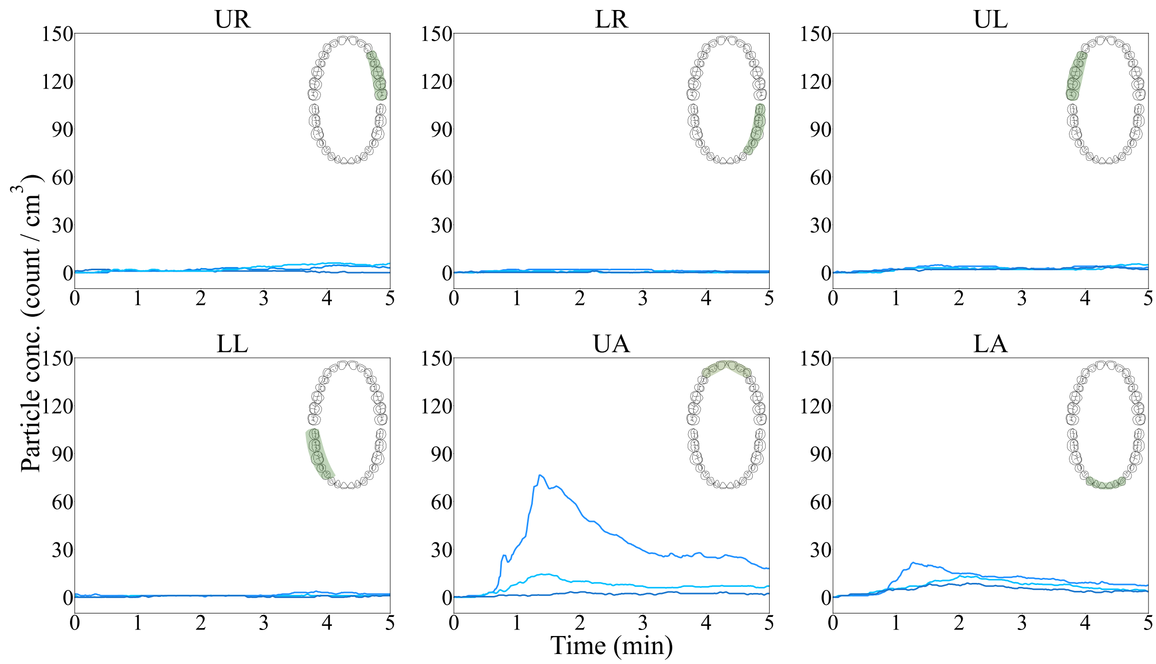


Figure 4-7: Particle concentration during 5-minute procedure in the presence of an extraoral suction.

A combination of EOS and HEPA filter air purifiers was utilized in this study to see their joint impact on particle concentration in a closed door operatory. The results for a 5-minute procedure in closed door room while the EOS and air purifier were running, are presented in Figure 4-8. With the door closed, the combined effect of these two aerosol mitigating tools appears to be quite effective.

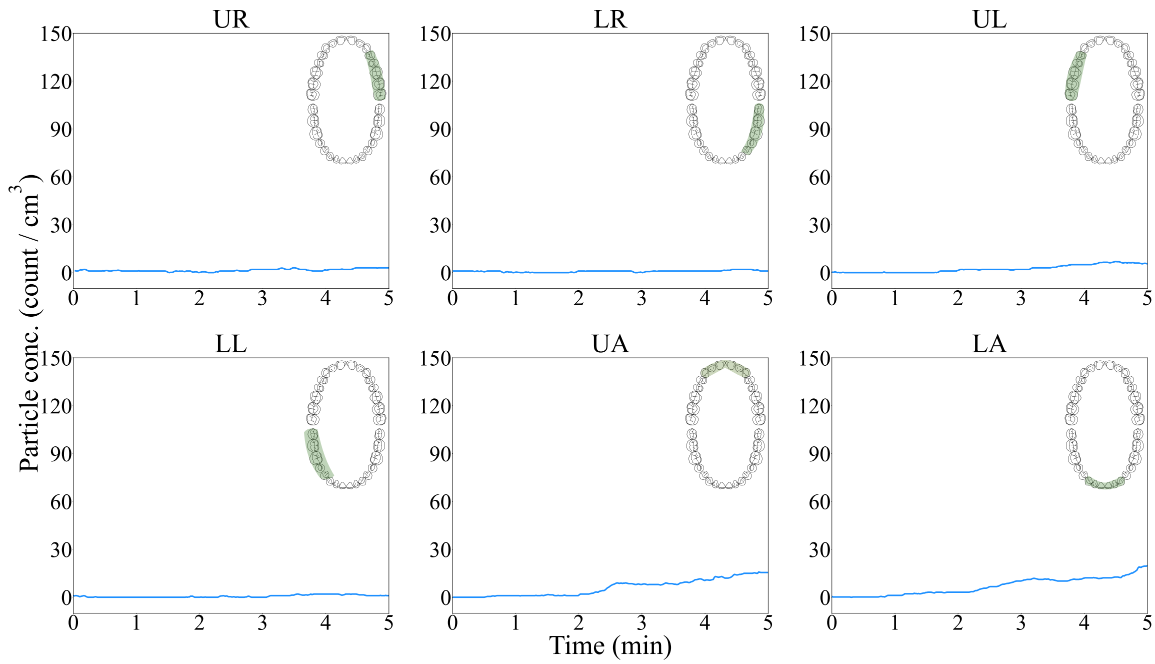


Figure 4-8: Particle concentration during 5-minute procedure in a closed door room in the presence of EOS and HEPA filter air purifier.

4.2.5 Effect of Alternative Handpiece (four-sprayer)

In this study, we used a single sprayer high-speed handpiece for the majority of the experiments. However, a four-sprayer high-speed handpiece has been advertised to decrease particle generation and transmission during a dental treatment. Therefore, we utilized a four-sprayer high-speed handpiece for a 5-minute crown preparation for all sextants and repeated this experiment three times. Here the results are somewhat mixed, with some cases showing a significant reduction of aerosols, while others appear to be less affected. Figure 4-9 shows the results for this set of experiments.

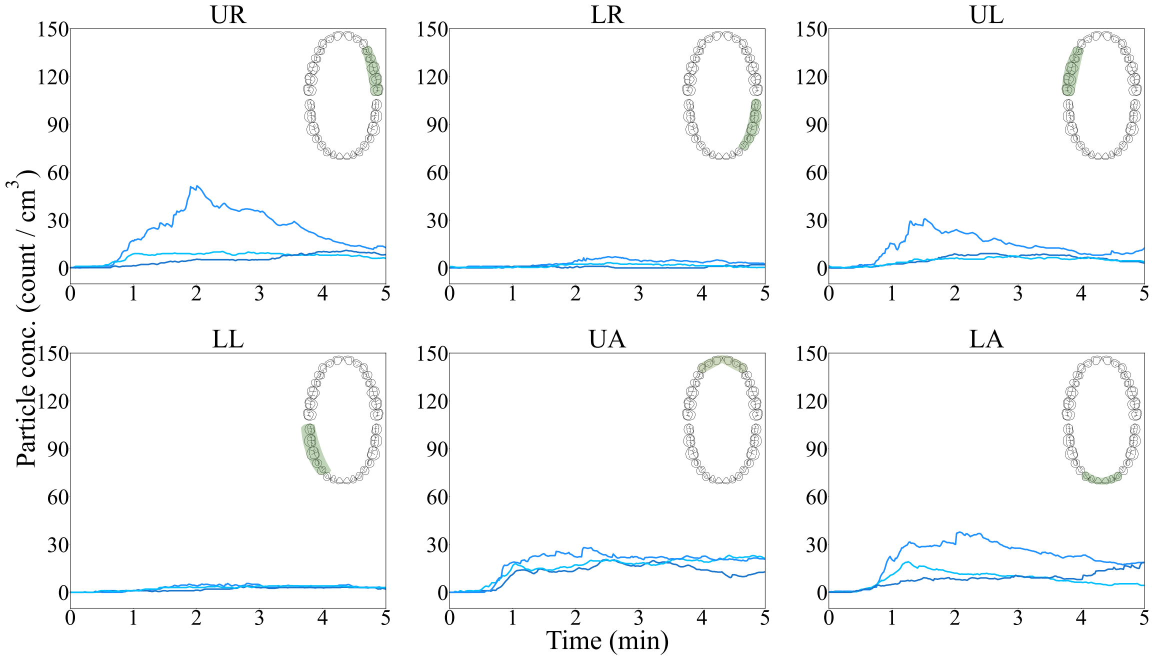


Figure 4-9: Particle concentration during 5-minute procedure using a four-sprayer high-speed handpiece.

Furthermore, we performed a 5-minute crown preparation using a four-sprayer handpiece while the EOS and air purifier were running during the procedure. Results of this experiment are shown in Figure 4-10. With the exception of the UA sextant, the particle concentrations in all cases appear to be markedly reduced.

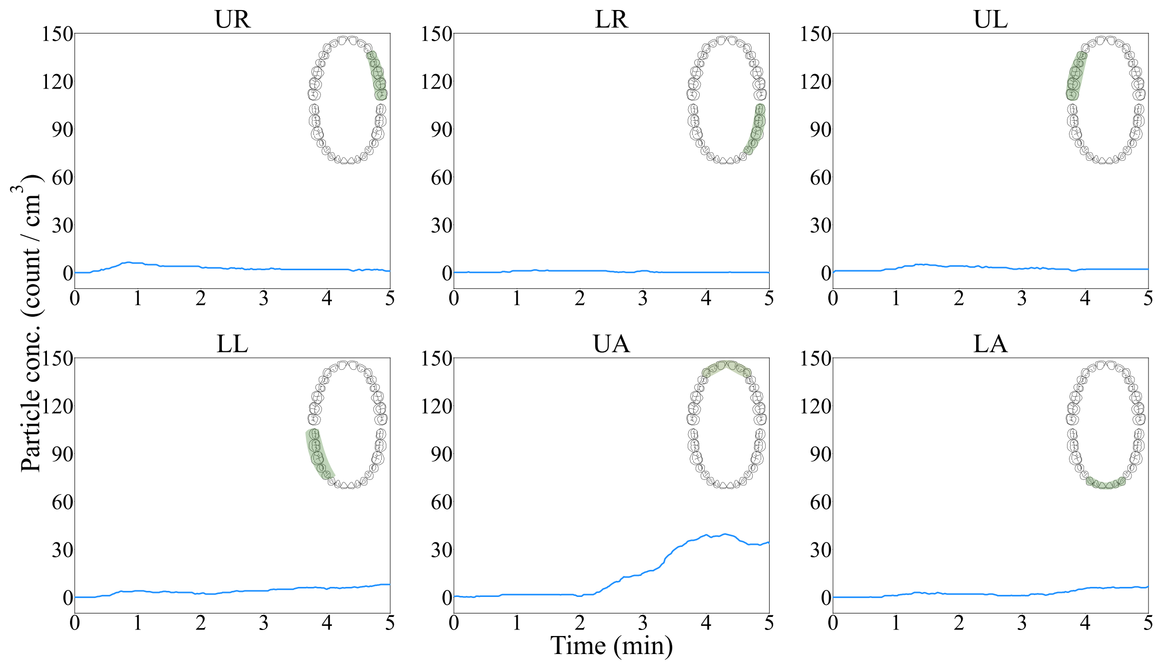


Figure 4-10: Particle concentration during 5-minute procedure using a four-sprayer high-speed handpiece and utilizing the EOS and air purifier.

4.2.6 Effect of Seating Position

In this study, we assessed the effect of dental chair position on the generation and transmission of dental aerosols. Most of the experiments were done while the dental chair was set in a supine position however in this particular experiment, we set the position of the mannequin on the dental chair in a semi-supine position as shown in Figure 3-9. Figure 4-11 represents the concentration of generated particles for the semi-supine dental chair position.

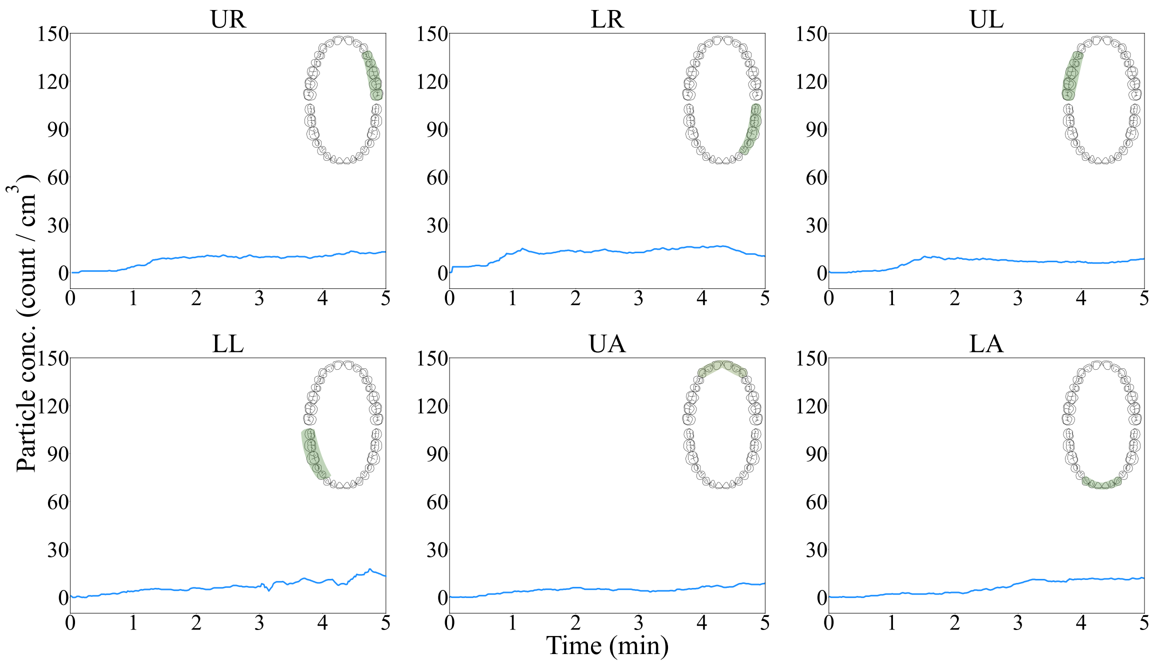


Figure 4-11: Particle concentration during 5-minute procedure while the mannequin was placed in a semi-supine position on the dental chair.

We also evaluated the effect of EOS on particle concentration when the mannequin was placed in a semi-supine position on the dental chair. Results for these experiments are shown in Figure 4-12. It may be inferred from these results that EOS is an effective strategy for reducing aerosols irrespective of seating position.

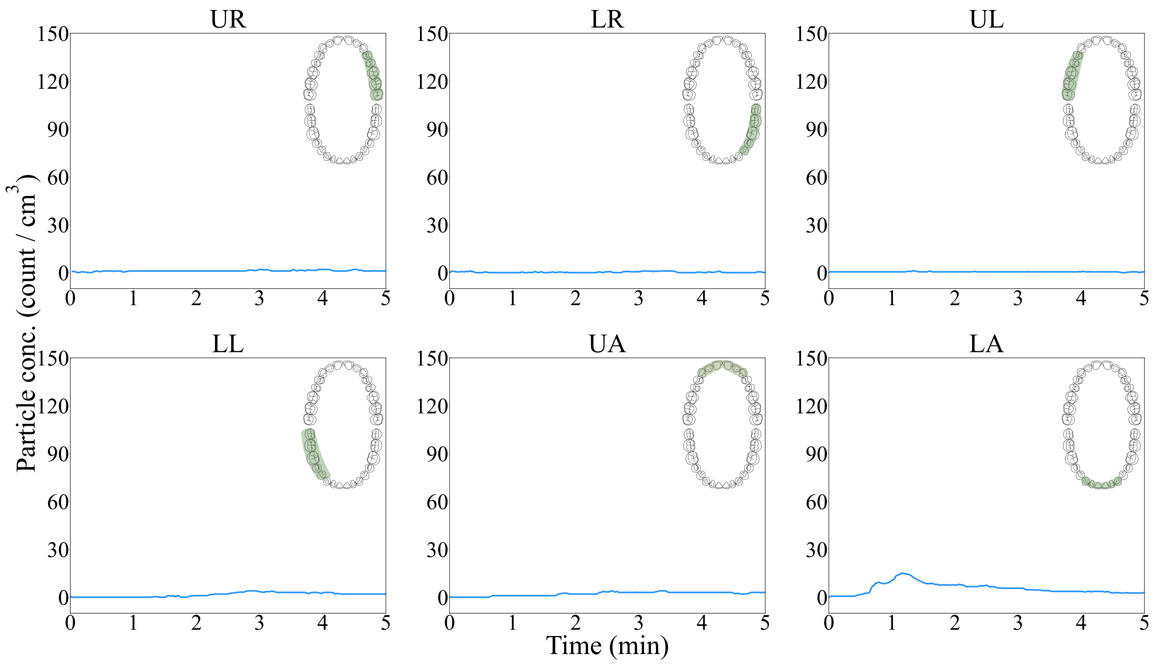


Figure 4-12: Particle concentration during 5-minute procedure in the presence of EOS, while the mannequin was placed in a semi-supine position on the dental chair.

4.2.7 Effect of Rubber Dams and Dental Isolation

Several studies and guidelines suggested using a rubber dam and performing the dental procedures. Therefore, in this study, we performed a 2-minute dental procedure for all sextants, while a rubber dam was set on the mannequin's mouth. Figure 4-13 represents this set of experiments. The rubber dam appears to significantly reduce aerosols, however it is unclear how larger particles, which result from splatter, are affected since our sensors only measure aerosols that are smaller than $10\mu m$.

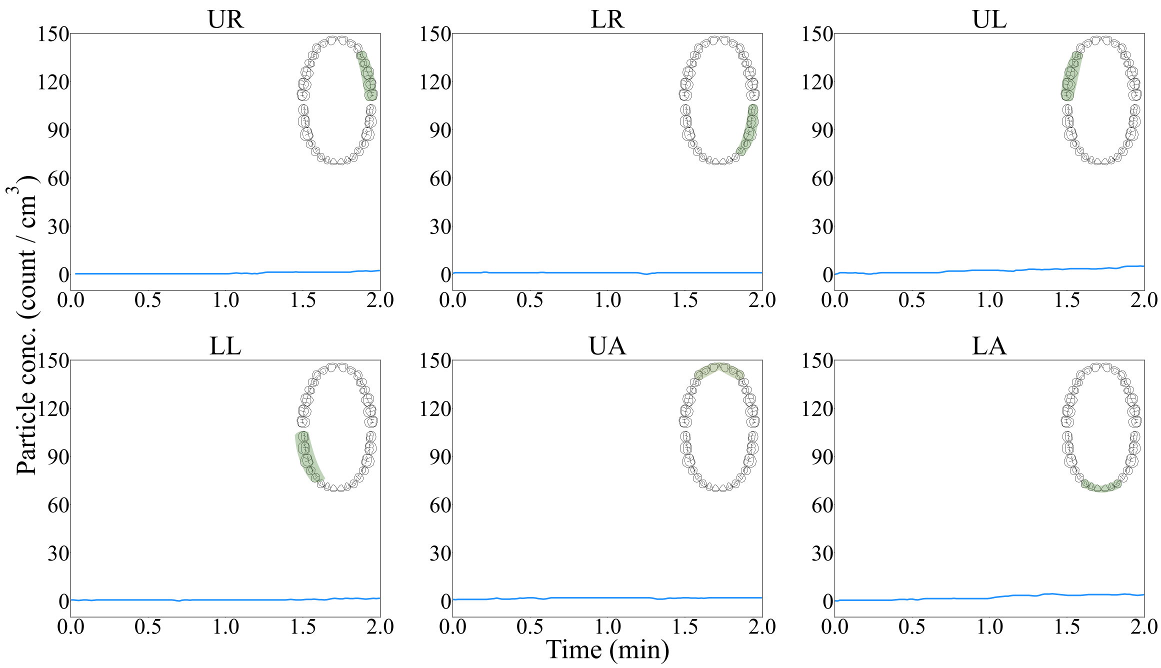


Figure 4-13: Particle concentration during a 2-minute procedure and using a rubber dam.

In addition to a rubber dam, several practitioners utilize a dental isolator while performing dental treatments. Hence, we used a dental isolator for one set of the experiments to investigate if this was effective at reducing particle concentrations. In this experiment, we did not use the HVS as the dental isolator connects to the HVS port of the dental unit. The results for these experiments are shown in Figure 4-14. Surprisingly, this strategy did not appear to be very effective at reducing aerosols, possibly due to the fact that the dental assistant not being able to use the HVS unit during the procedure.

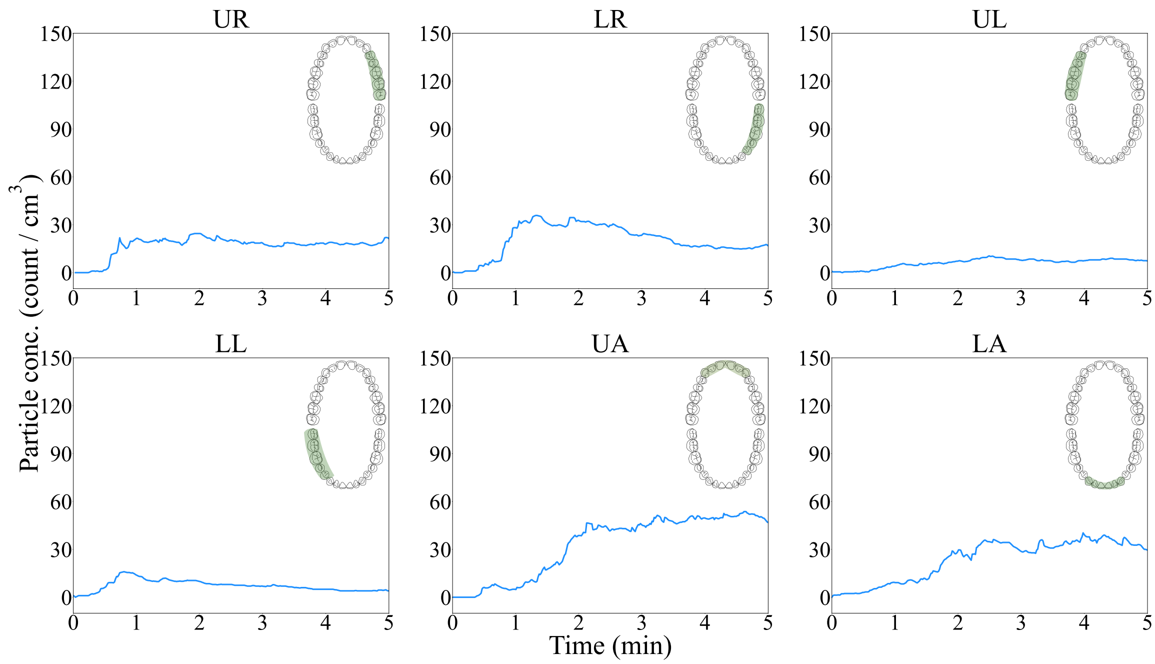


Figure 4-14: Particle concentration during a 5-minute procedure and using a dental isolator.

4.2.8 Effect of High-Volume Suction

Using a high-speed camera, we visualized the critical role of HVS in reducing particles. As shown in Figure 4-2, the lower left sextant produced fewer particles than other sextants, which is the result of positioning HVS in a more effective way by a right-handed assistant. This emphasizes the significance of the assistant's work in helping to remove aerosols and particle clouds utilizing the HVS. To see the effect of HVS visually, we did an experiment with and without the HVS on the third upper right molar tooth and the fourth upper anterior tooth as imaged by the high-speed camera. As shown in Figures 4-15 (a) and (c) particle transition is higher in the absence of the HVS. However, a significant number of particles were sucked into the HVS when it was used. Another study was done on the effect of the HVS [44] and they concluded that although holding the HVS by the practitioner reduces a large amount of the particles, they will reduce further if an assistant holds it.

Furthermore, we found that the quantity of particles created during an upper anterior (UA) tooth treatment is normally larger and somewhat with a higher variation when compared to the posterior placements (4-2), which may be associated with a less effective positioning of the HVS by the assistant. This can also be seen by comparing Figure 4-15 (a) with (c) and (b) with (d). Finally, since anterior teeth treatment is less prevalent than molar teeth [82, 83], we will be only providing the posterior teeth results for the following discussion and analysis chapter.

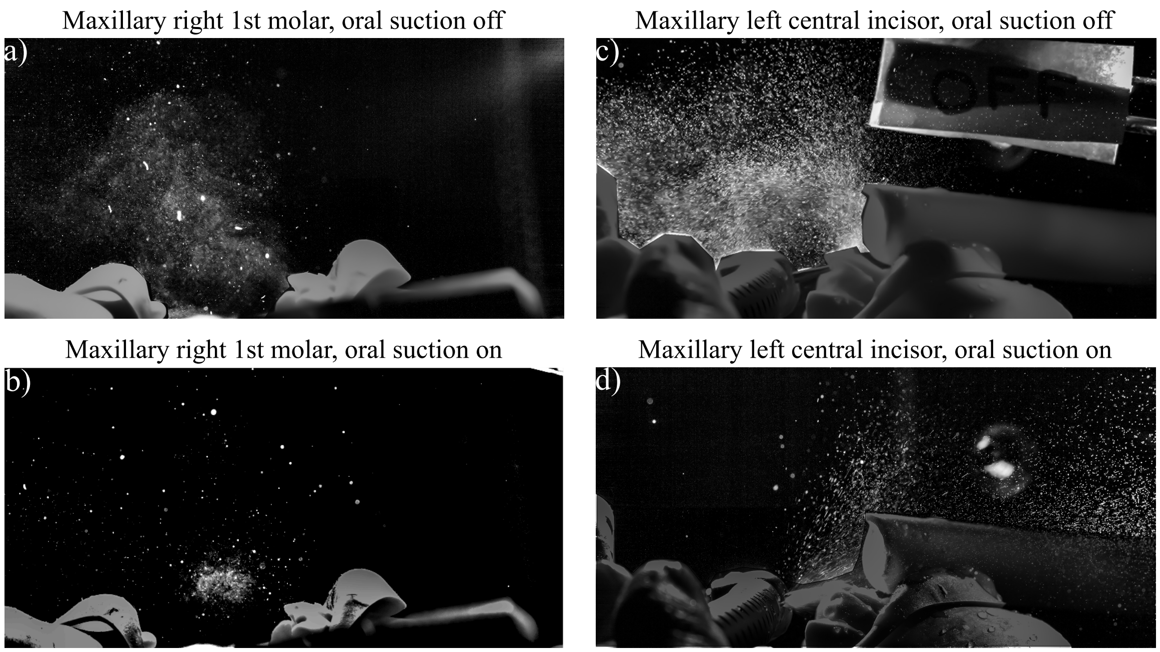


Figure 4-15: Concentration of generated particles visualized by a high-speed camera. Panels (a) and (b) show the concentration of particles during a procedure on an upper right posterior tooth and panels (c) and (d) represent generated particles during a dental treatment on an upper left anterior tooth. Distribution of particles is less when the HVS was utilized in panels (b) and (d).

Chapter 5

Discussion and Analysis

This chapter's objective is to provide a comprehensive discussion and analysis of the results and outcomes of this study. In the first section, we validate the grounds for comparing non-repeated experiments. In the second section, an analysis of the "base case" is provided. This type of analysis is also employed for analyzing the results of other experiments. After that, a comparison between the base case and other experiments is presented. Then, a statistical comparison of the experiments is performed, and finally, a set of conclusions as well as certain recommendations for future studies and dental services are provided.

5.1 Analysis of the Repeated Cases

As mentioned in section 3.1.7, 35 sensors was placed in the room to detect aerosols. The median of these 35 sensors were calculated at each time-step and reported. In order to minimize the effects of the human operators on the results, we repeated the base case experiment six times for all sextants (i.e. 36 measurements combined). Experiments in which we utilized an air purifier, a four-sprayer handpiece, and extraoral suction were repeated three times each. However, we could not repeat all other experiments multiple times for practical reasons. Hence, in order to have a valid comparison, we normalized the standard deviation of the particle concentration of the repeated cases by their mean over the time. Figure 5.1 left column shows the normalized standard deviation of each repeated case as compared to the base case for four posterior sextants. Black lines show normalized standard deviation of the base case and blue lines represent normalized standard deviation of extraoral suction, air purifier, and four-sprayer high-speed handpiece in Figures 5.1 (a), (c), and (e), respectively. The Probability Density Function (PDF) plot of these normalized standard deviation is shown in the right column of Figure 5.1. As the plots show, the standard deviation for different cases is well within each others' range, which indicates the same level of variation is expected for the cases that were repeated less than six times; and thus a valid ground for comparison of different cases with the base case.

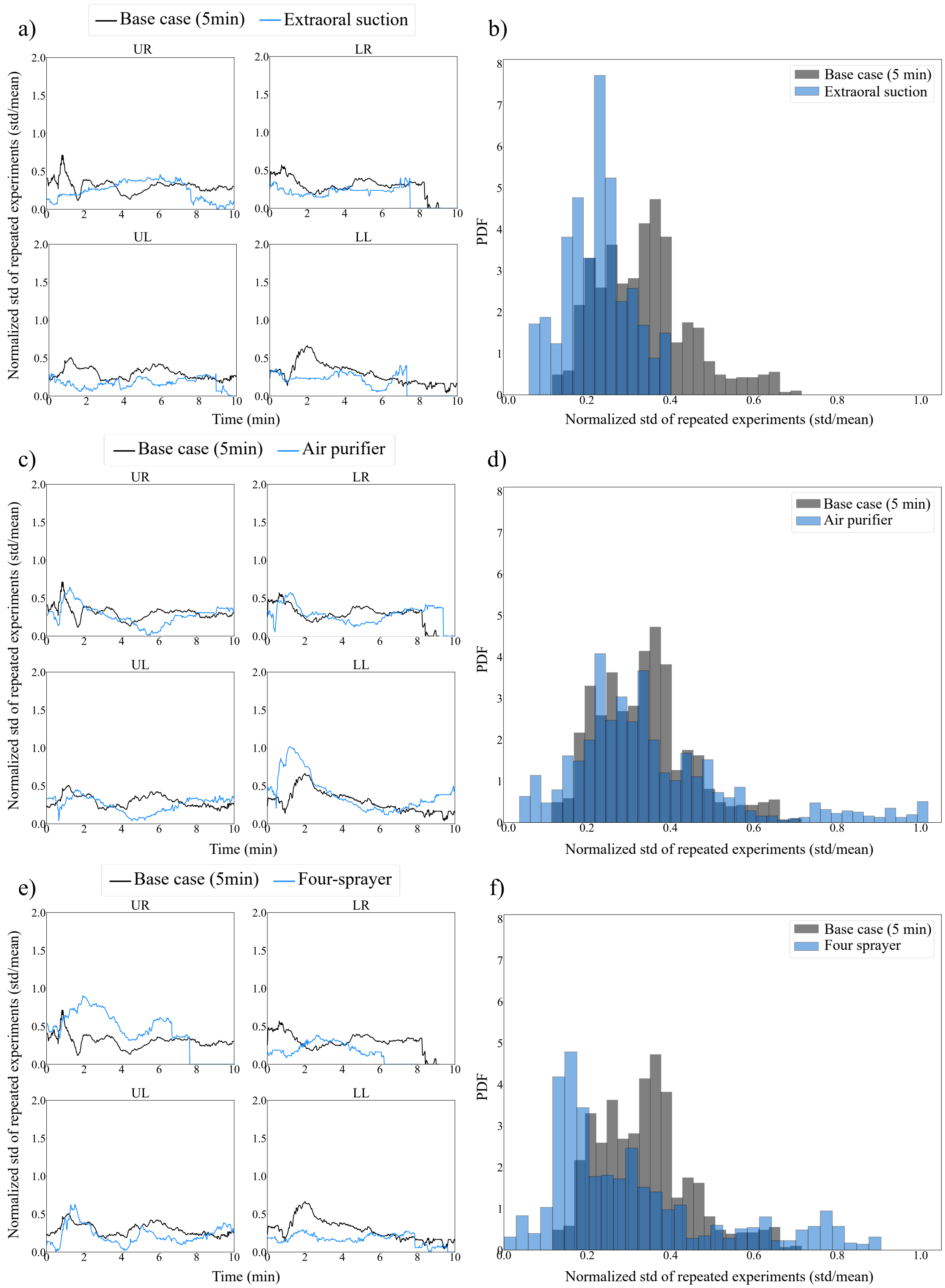


Figure 5-1: Left column: normalized standard deviation of the particle count over time, right column: probability density function (PDF) of the normalized particle standard deviation.

5.2 Base case

After calculating the median of the measured particle concentration from all sensors, the minimum particle concentration of each procedure was subtracted from it in order to remove the effect of the background particles which were present in the room prior to performing the experiments. Following that, the weighted average and weighted standard deviation of the repeated processes were computed throughout the experiment. The weight of each data point is calculated based on its distance from other repetitions. In equation 5.1, $\overline{W}$ is the weighted average, and w_i is the way that we calculated the weight of each data point. Equation 5.2 was used to calculate the weighted standard deviation. For instance, a 5-minute crown preparation procedure was conducted on a tooth in the upper right sextant six times. Throughout, the median of each repetition was calculated, and the global minimum of the median data set was subtracted from each data point. The next step was to figure out the weighted average and the weighted standard deviation. This calculation was also done for "air purifier", "extraoral suction", and "four-sprayer high-speed handpiece", which were repeated three times for each sextant.

$$\overline{W} = \frac{\sum_{i=1}^{6} w_i x_i}{\sum_{i=1}^{6} w_i} \qquad w_i = \frac{1}{\sum_{j=1}^{6} \mid x_i - x_j \mid}. \tag{5.1}$$

$$\overline{S} = \sqrt{\frac{\sum_{i=1}^{6} w_i (x_i - \overline{W})^2}{\sum_{i=1}^{6} w_i - 1}}. \tag{5.2}$$

Figure 5-2 shows such a plot that is the resultant of the weighted average of six repeated base case measurements, which is shown by a black line accompanied by a gray shadow that represents the weighted standard deviation of the repetitions. From this figure, it is clear that for the UA sextant, there is a higher spread in the data as was anticipated from what we reported in the results section.

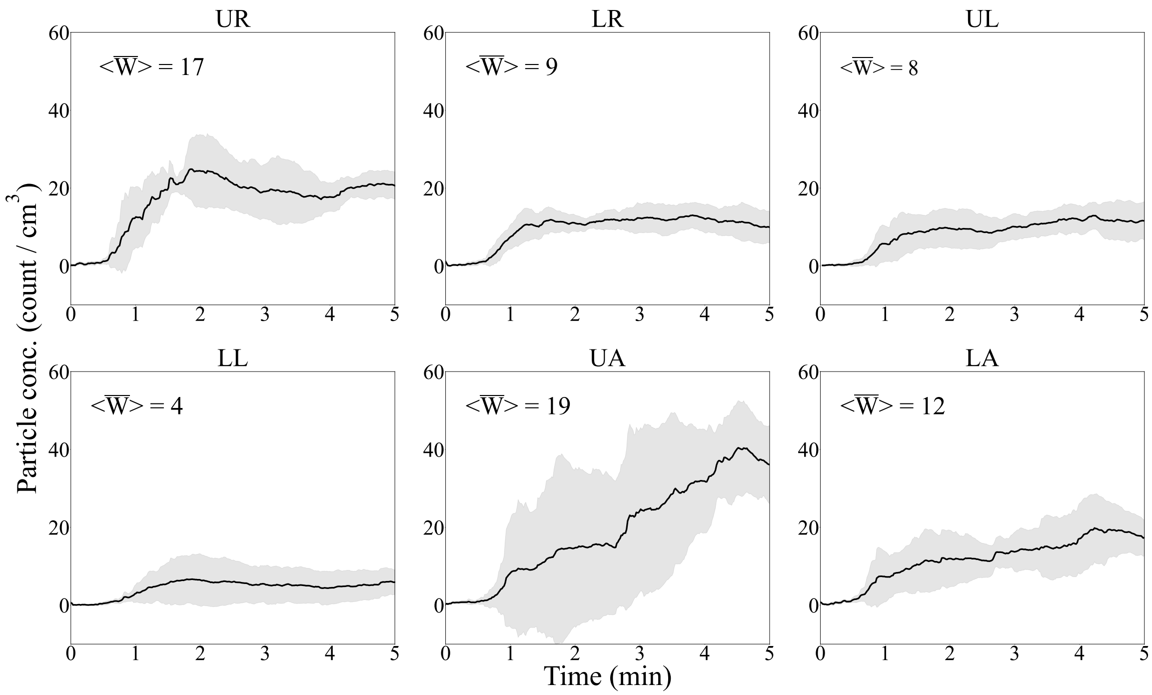


Figure 5-2: Particle concentration plots for six sextants during a 5-minute crown preparation. The black line shows the weighted average of the particle concentration from six repetitions, which are subtracted by the minimum of the experiment, and the gray shadow represents the corresponding weighted standard deviation. <Weighted avg.> refers to the ensemble average of the black line over the procedure period.

5.2.1 Effect of Different Procedures (MOD Preparation and Crown Preparation)

Here we compare the effects of MOD preparation procedures with the longer crown preparation procedures. Blue lines in Figure 5-3 shows 2-minute surface drilling and the small blue shadow around them indicate small standard deviation in repetitions of this procedure. The figure indicates that the concentration of particles did not measurably grow during the 2-minute procedure, however, in the first two minutes of a 5-minute crown preparation, the number of particles is at least 5 times larger than in the 2-minute procedure. As a matter of fact, we discovered that carbide burs, which were used for 2-minute procedures, generated far fewer particles than diamond burs, which were used for 5-minute procedures.

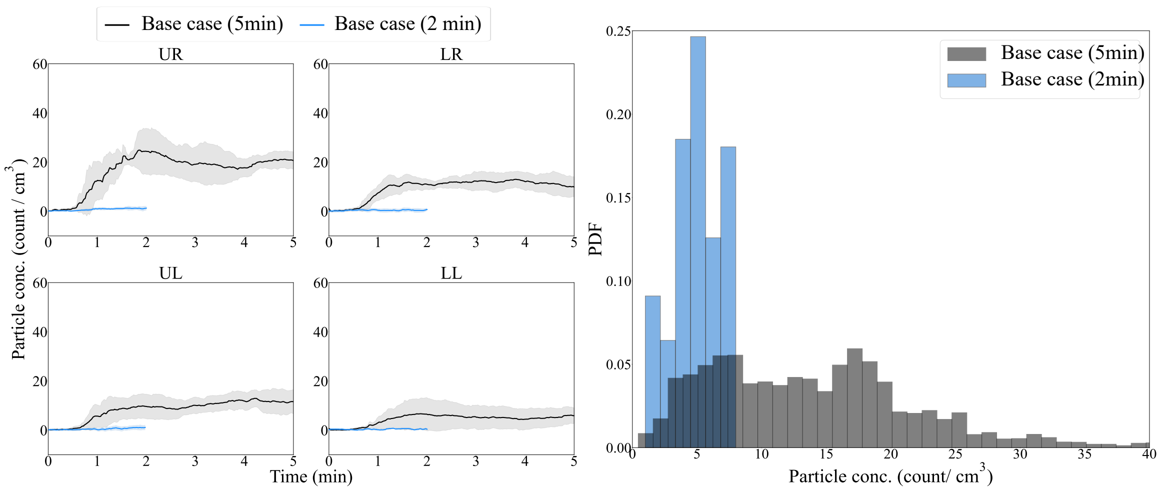


Figure 5-3: Effect of the procedures on aerosols and particle generation. The MOD procedure was done using a carbide bur for 2-minute, which generated less particles, and crown preparation was don using diamond burs for 5-minute, which generated higher particles and aerosols.

5.3 Different Parameters Group

By examining several parameters, we were able to assess parts of the current guidelines for safe dental practices. These include managing indoor air quality, dry drilling, and dental treatments in a closed door operatory. An extraoral suction unit and an air purifier were utilized to see their influence on particle management, as well as the position of the dental chair, utilizing a four-sprayer high-speed handpiece, utilizing particle control accessories such as rubber dam and dental isolator. Figures presented in each section here show the comparison of particle concentration of each experiment with the base case (i.e results in Figure 5-2). Blue lines show the median of particle concentration from 35 sensors for the experiments, which are compared with the base case. For extraoral suction, air purifier, and four-sprayer high-speed handpiece, the blue shadow represents the standard deviation of the particle concentration from three repetitions. To compare procedures statistically, the level of significant difference was set to a P-value < 0.05.

5.3.1 Dry Drilling

Of importance, and in contrast to the initial recommendations, we noticed that 2-minute dry drilling generates much more particles than a standard wet drilling during a 2-minute MOD preparation, as shown in Figure 5-4. The average of particle concentration during a 2-minute drilling is 7 times more than the base case with a P-value< 0.001, which indicates a significant statistical difference between these two experiments. It is possible that the high temperatures generated by dry drilling result in aerosols which are inert, and thus less likely to carry pathogens, however solely on the basis of aerosol concentration, it appears that the dry drilling suggestion should be re-examined.

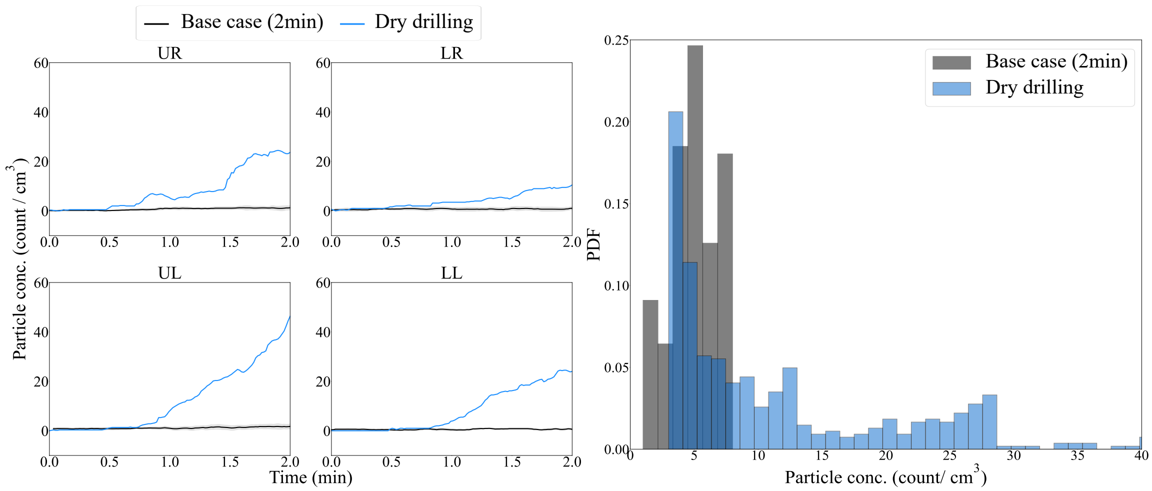


Figure 5-4: Effect of drilling without water on concentration of the generated particles in comparison with wet drilling. Dry drilling generated much more particles.

5.3.2 Effect of Closed Door Operatory on Particle Concentration

Although the probability of aerosol transmission to other rooms will be reduced in a setting with a closed door, both the practitioner and the assistant will be exposed to a considerably greater quantity of particles, as it is shown in Figure 5-5. The average concentration of particles in a closed door setting is almost two times more than the base case with a P-value ≈ 0.016 indicating a significant statistical difference between the two cases. Ideally, one can use a closed door operatory with negative pressure and a high air changes per hour (ACPH) rate. However, such facilities are uncommon in dental settings and may be cost prohibitive to implement.

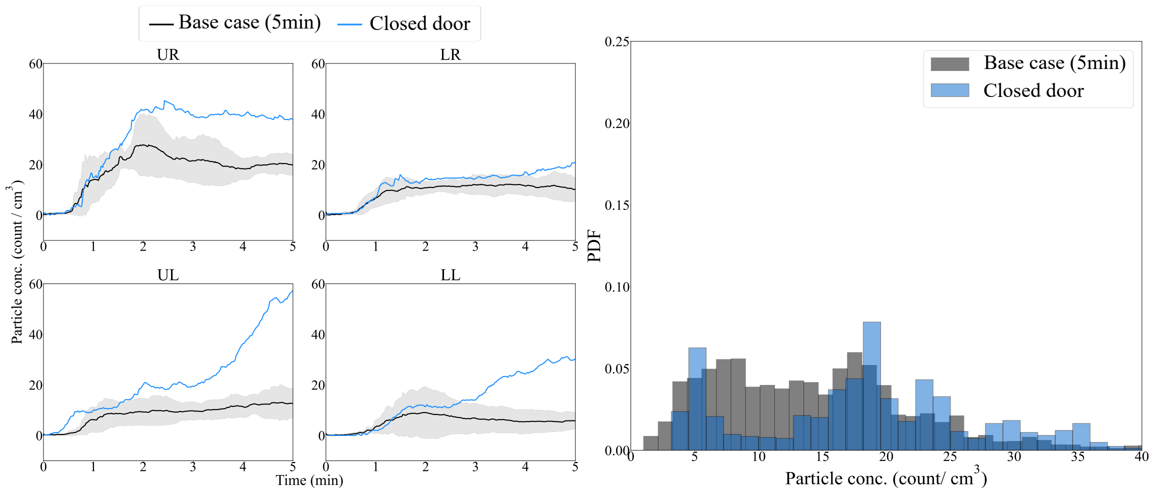


Figure 5-5: Concentration of the generated particles during a 5-minute dental procedure of the base case in comparison with a closed door setting. Particle concentration increases during the procedures in a closed door room.

5.3.3 Effect of Air Purifier on Particle Concentration

In contrast to the recommendations, we noticed that a HEPA filtered air purifier does not have a significant effect on particle concentrations during a dental procedure. Qualitatively it appears that in some cases the air purifier provides some improvement (Figure 5-6: UR), while in others, it has the opposite effect (Figure 5-6: LL). Therefore we base our conclusion on the quantitative assessment of P-value $= 0.526$ which is larger than 0.05 for this experiment; it demonstrates that the air purifier produced no statistically significant difference in terms of aerosol concentrations. Of note, this conclusion does not extend to how HEPA filtered air purifiers affect air quality after the 5-minute procedure.

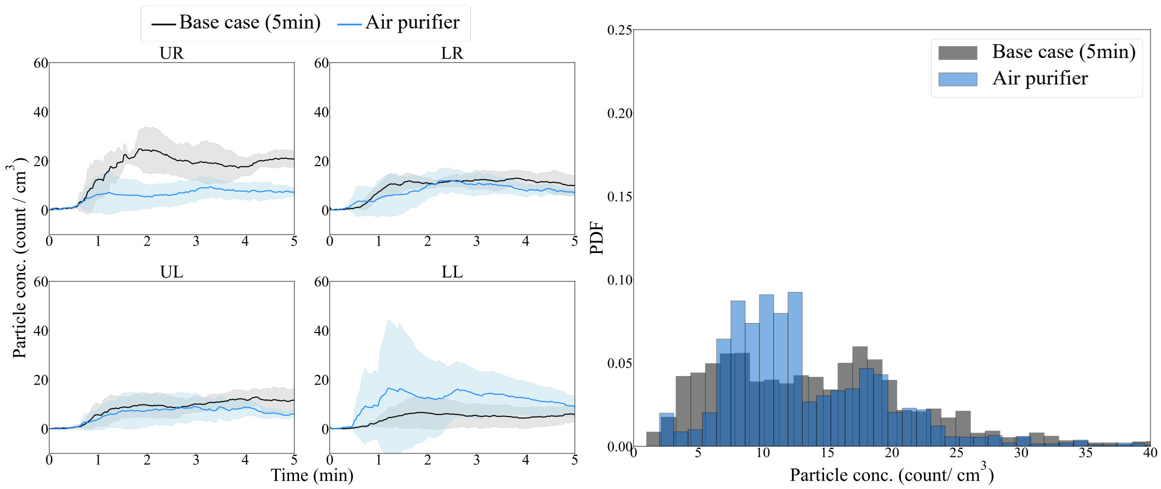


Figure 5-6: Concentration of the generated particles during a 5-minute dental procedure of the base case in comparison with utilizing a HEPA filter air purifier during the experiment. Air purifier has a margin effect on reducing particle concentration and this effect is consistent for all sextants.

5.3.4 Effect of Extraoral Suction on Particle Concentration

As Figure 5-7 shows, EOS is an effective device in removing aerosols during dental procedures, and it can create a safe environment for both the dental health care workers and patients. The average particle concentration was found to be 11 times less than the base case. The calculated P-value was less than 0.001 which indicates a statistically significant effect of the EOS on reducing aerosols.

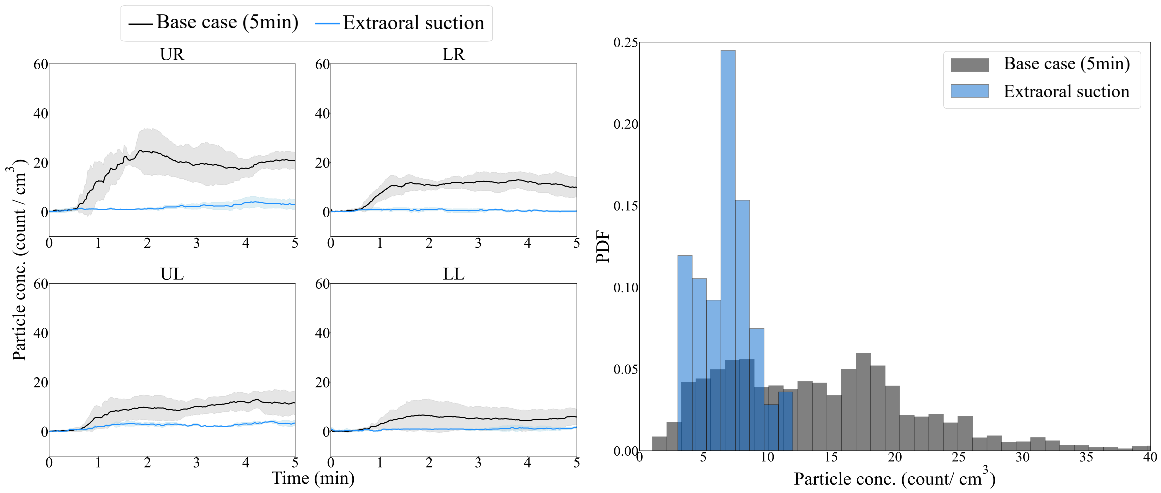


Figure 5-7: Concentration of the generated particles during a 5-minute dental procedure of the base case in comparison with utilizing an extraoral suction during the experiment. The EOS reduces a huge amount of particles during the procedures.

5.3.5 Effect of High-speed Handpieces on Particle Concentration

In this work, we primarily used a single-sprayer high-speed handpiece, but a four-sprayer handpiece was also used to examine how different types of handpieces affected aerosol generation. The concentration of aerosols produced by a four-sprayer handpiece is shown in Figure 5-8 relative to that produced by the single-sprayer handpiece (the base case). The four-sprayer appears to lower particle concentrations by a small amount; however, this impact is not conclusive and does not remain consistent across all sextants. The average particle concentration during this experiment was almost half of that of the base case, but the calculated P-value was 0.041, which is not much smaller than the significant level which indicates a statistically significant difference (0.05). In this case, we suggest that the results show a marginal positive effect of the four-sprayer handpiece in reducing aerosol concentrations.

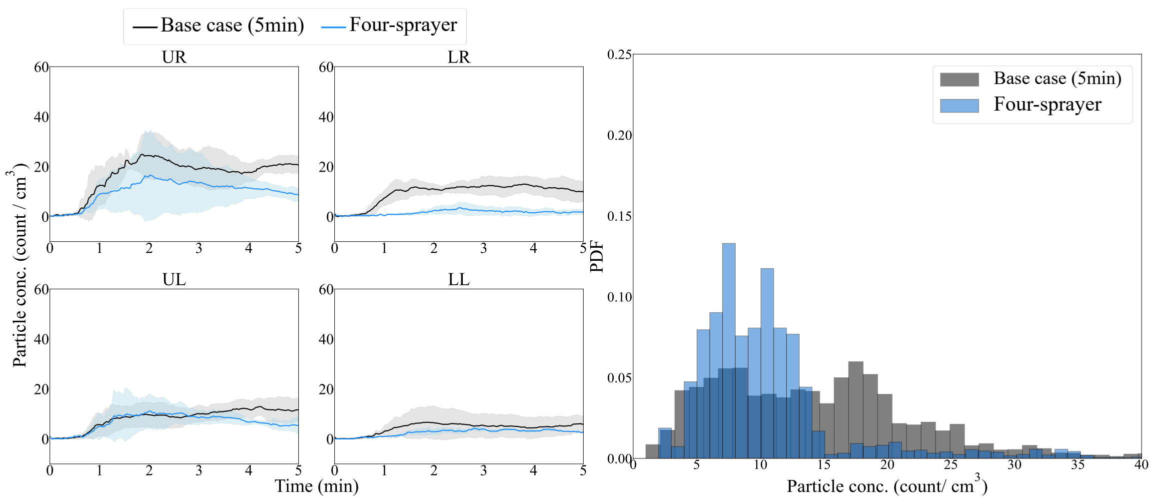


Figure 5-8: Concentration of the generated particles during a 5-minute dental procedure of the base case in comparison with using a four-sprayer high-speed handpiece instead of a single sprayer, which was used for the base case. Four-sprayer high-speed handpiece has a marginal effect on reducing particle concentration and this effect is not consistent for all sextants.

5.3.6 Effect of Extraoral Suction and Air Purifier on Particle Concentration in a Closed Door Operatory

In the closed door setting, we noticed that the concentration of particles increases during dental procedures (Figure 5-5). However, the use of an extraoral suction unit in combination with an air purifier is effective in reducing the particle concentration of a closed door operatory during a procedure, as demonstrated in Figure 5-9. Generated particles were 11 times smaller than the base case with a P-value< 0.001 showing a markable difference between the base case and the usage of the EOS and a HEPA filtered air-purifier in a closed door operatory. This configuration also has the added benefit of reducing the spread of aerosols into other rooms of the dental practice as the operatory room door is closed.

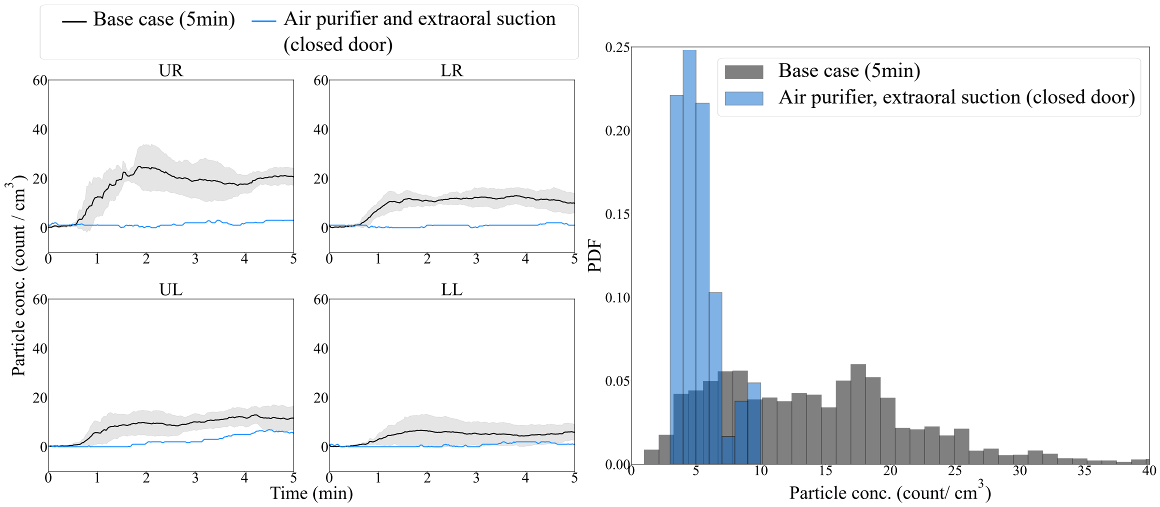


Figure 5-9: Effect of the air purifier and extraoral suction on generated particle concentration in a closed door operatory in comparison with the base case.

5.3.7 Effect of Air Purifier, Extraoral Suction, and Four-sprayer Handpiece on Particle Concentration

Although the results in sections 5.3.5 and 5.3.3 showed that the four-sprayer handpiece and air purifier have insignificant effects on particle concentrations, their combination with extraoral suction does show a significant difference, as shown in Figure 5-10. The concentration of generated particles was almost 11 times less than the base case with a P-value < 0.001. These results are comparable to those in the previous subsection, so the cumulative benefit of adding the 4-sprayer is not immediately obvious.

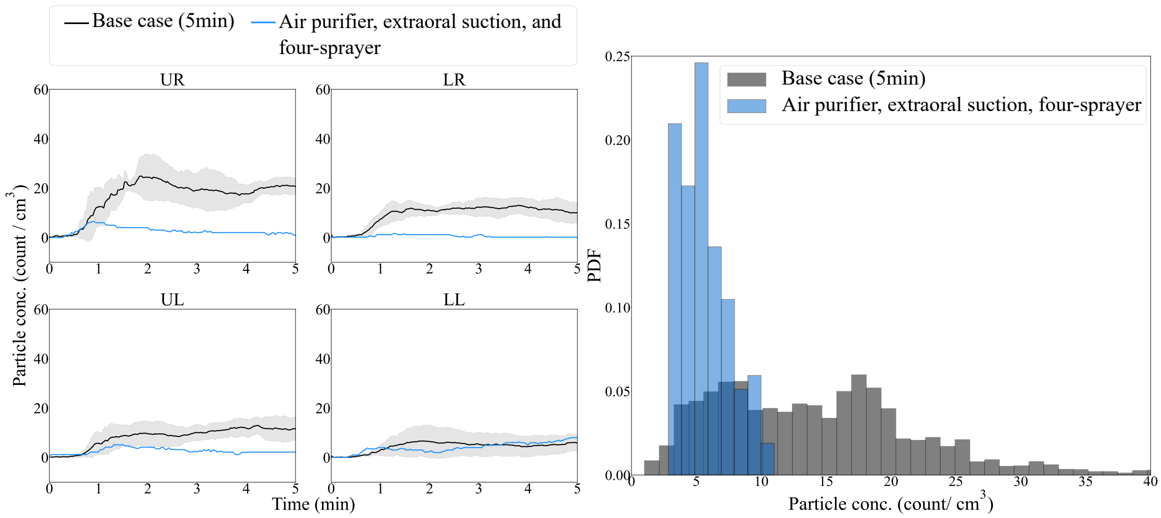


Figure 5-10: Utilizing an extraoral suction with air purifier and four-sprayer handpiece reduces a huge amount of aerosols in comparison with the base case.

5.3.8 Effect of Dental Chair Position on Particle Concentration

Figure 5-11 displays our analysis of the effects of the dental chair position on particle concentration. The results demonstrate that the position of a patient on the dental chair does not have an effect on the concentration of the generated aerosols. The average number of particles is almost equal and there is not a significant difference between the concentration of the generated particles during these two experiments as the P-value ≈ 0.62 is far larger than 0.05.

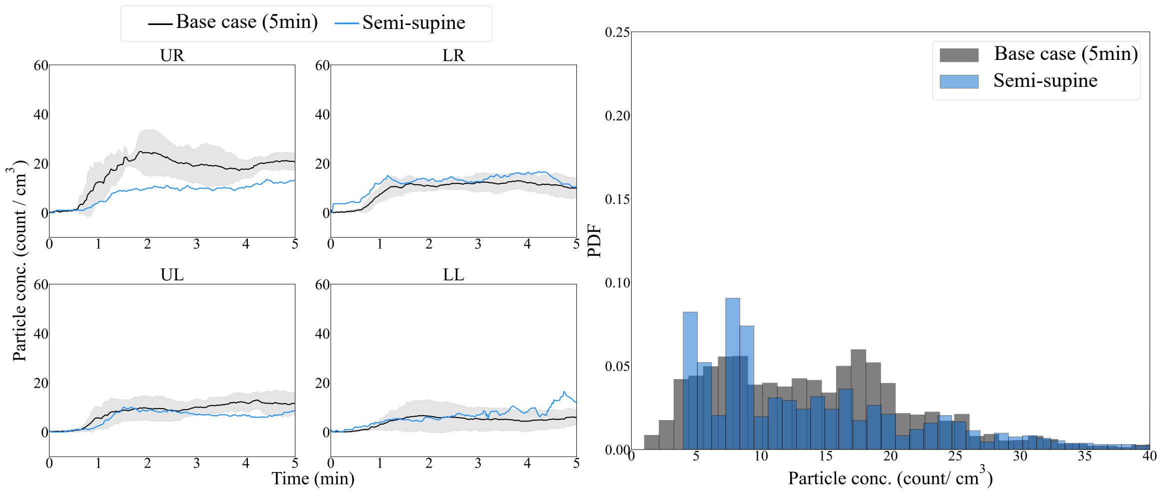


Figure 5-11: Concentration of the generated particles during a 5-minute dental procedure of the base case in comparison with changing the dental chair position from supine to semi-supine. Patient position does not have any effect on particle concentration during the procedures.

5.3.9 Effect of Extraoral Suction and Dental Chair Position on Particle Concentration

Figure 5-12 demonstrates that although the semi-supine position cannot reduce the concentration of the particles on its own, utilizing the EOS is still effective at reducing aerosols in this position as well. The EOS reduced the average concentration of particles during this experiment to 1 particle/cm^3 with a statistically significant difference from the base case calculated as P-value< 0.001.

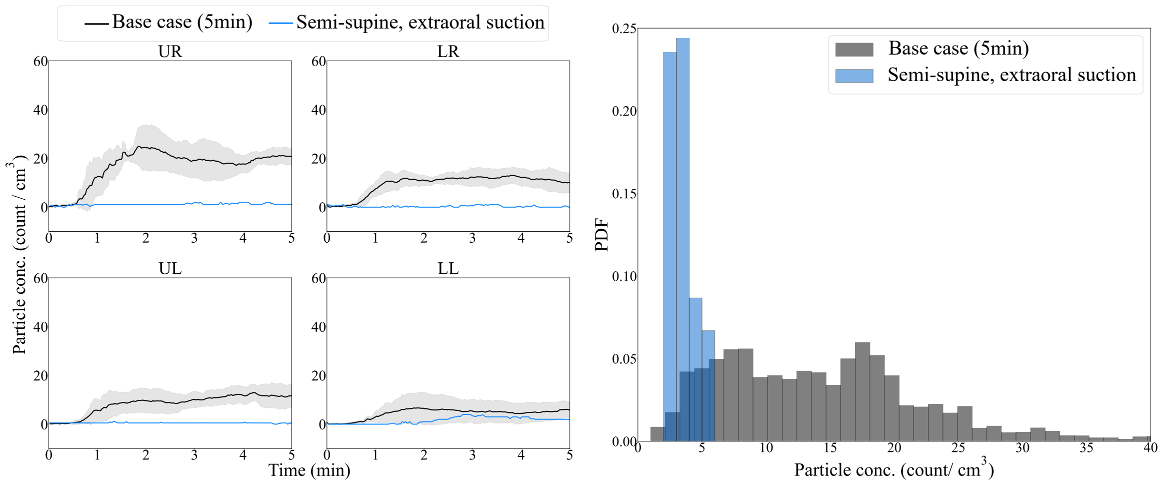


Figure 5-12: Concentration of the generated particles during a 5-minute dental procedure of the base case in comparison with changing the dental chair position from supine to semi-supine and utilizing an EOS. EOS reduces lots of particles.

5.3.10 Effect of Rubber Dam on Particle Concentration

A rubber dam was utilized during one set of a 2-minute MOD preparation, which is explained in detail in section 3.2. As clearly shown in Figure 5-13, a rubber dam does not have any effect on particle concentration during a 2-minute procedure since the P-value $= 0.432$. However, our mannequin did not simulate saliva in the mouth, which could be one rational for using the rubber dam.

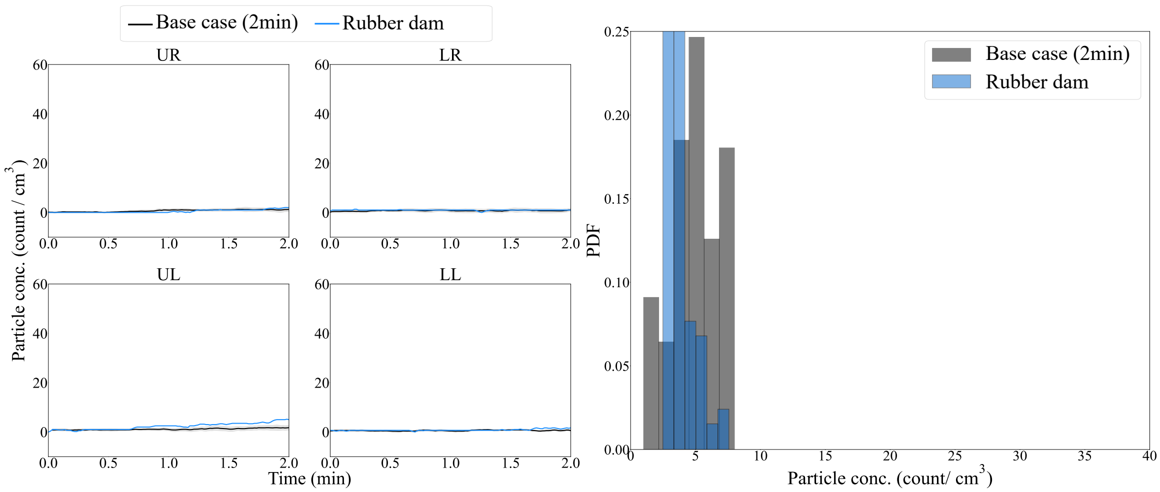


Figure 5-13: Concentration of the generated particles during a 2-minute dental procedure of the base case in comparison with utilizing a rubber dam during the experiment. Rubber dam does not have any effect on particle concentration during the procedures.

5.3.11 Effect of Dental Isolator on Particle Concentration

A dental isolator was utilized during one set of experiments. The procedure was the same as the base case; however, the HVS could not be used by the dental assistant as the dental isolator was connected to the HVS port of the dental unit (more details in section 3.1.1). The results in Figure 5-14 shows that the dental isolator may increase the particle concentrations during procedures. The average concentration of generated particle while utilizing a dental isolator was similar to the base case and the P-value ≈ 0.475 shows that on average, there was no significant effect on particle concentrations while a dental isolator was used.

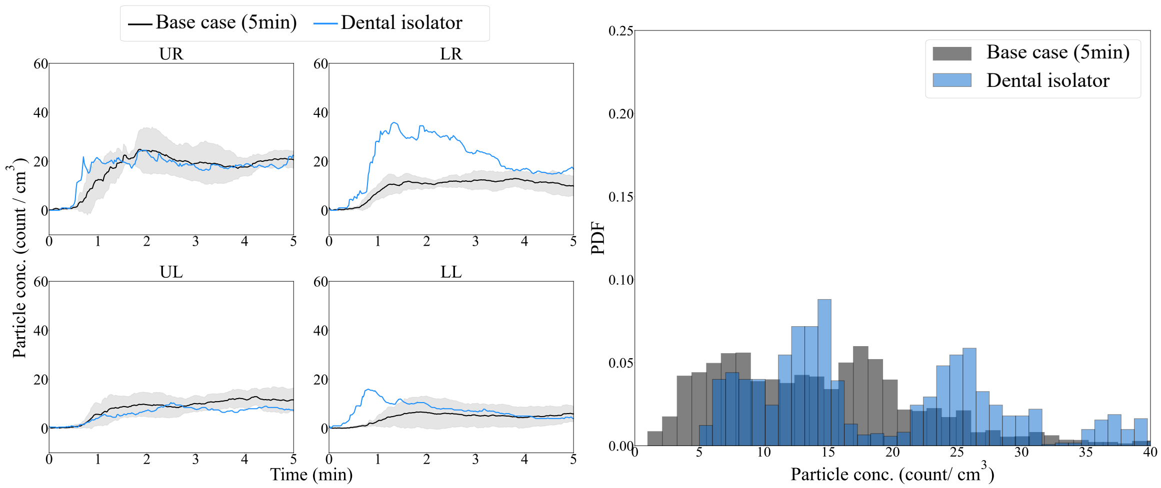


Figure 5-14: Concentration of the generated particles during a 5-minute dental procedure of the base case in comparison with utilizing a dental isolator during the experiment. Dental isolator may increase particle concentration during the procedures.

5.4 Summary of Statistical Analysis

Table 5.1 summarizes the average of the particle concentration for the studied parameter space and their corresponding P-values compared to the "base case". The calculation was performed over the entire procedure duration (e.g. 5-minute crown preparation). We also checked, and verified that the results are robust by comparing results at different time intervals. For example, we excluded results from the first 1-minute of the procedure where particle concentrations were transitional and dramatically increasing; we also compared the results at the very end of the procedure where one would assume the concentrations approach their asymptotic levels.

Table 5.1: The ensemble average of the particle concentration for different procedures and their corresponding P-values when compared with the base case obtained from two-sample t-test. The purple colorbar shows the particle concentration from bright (low) to dark (high). P-values smaller than 0.05 are shown with green and larger than 0.05 are shown with red.

Statistics	5-minute procedure										2-minute procedure		
	Closed door	Dental isolation	Basecase (5 min)	Semi-supine	Air purifier	Four-sprayer	Extraoral suction	Four-spr., extra. suc., air puri.	Air puri., extra. suc., closed door	Semi-supine, extraoral suction	Dry drilling	Rubber dam	Basecase (2 min)
avg. of particle conc. during procedure	21	14	11	9	9	6	1	2	1	1	7	2	1
P-value	0.016	0.475	_	0.620	0.526	0.041	<0.001	<0.001	<0.001	<0.001	<0.001	0.432	_
avg. of particle conc. during procedure (first 1-minute excluded)	22	14	12	10	10	7	2	2	1	1	15	2	1
P-value	0.018	0.581	_	0.482	0.372	0.045	<0.001	<0.001	<0.001	<0.001	<0.001	0.386	_
avg. of particle conc. at the end of procedure	36	13	12	14	8	4	2	3	3	1	24	2	1
P-value	<0.001	0.888	_	0.654	0.048	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	0.416	_

Colorbar: 36 – 0, Partcile concentration (count/ cm^3)

This statistical analysis shows that the extraoral suction significantly reduces aerosols in all periods of the procedure, and the four-sprayer high-speed handpiece slightly reduces the particle concentration. On the other hand, implementing procedures in a closed door setting increases the generated particle concentration. The increase was found to be significant with a P-value<0.05 when data over the entire procedure period was used; the difference was even more significant when one examined only concentrations at the end of the procedure (P-value<0.001). Also, it shows that the air purifier did not affect particles during the procedure however it reduced particles slightly at the end of the procedure. During a 2-minute procedure, dry drilling significantly increases particle concentration and rubber dam does not have any effect on concentration of generated particles.

5.5 Conclusions

In this study, we mapped aerosol concentrations from 462 well-controlled dental procedures in a dental operatory under a variety of conditions. We began by establishing a "base case" for aerosol concentrations during common dental procedures. Next, we compared this data with the alterations made to the standard of care practices using a variety of statistical methods. First and foremost, our data implied that the dental assistant's placement of the high-volume suction is a crucial component in decreasing particle concentration. In addition, when dental procedures are performed without the use of a water spray, a much higher concentration of aerosols is produced. Another major finding from this research is that an extraoral suction has a strong positive influence on minimizing the spread of aerosols. Furthermore, performing dental procedures in a closed-door operatory raises the risk of being exposed to excessive particle concentrations. As such, the air quality in the operatory might be improved by using an extraoral suction unit in conjunction with a HEPA filtered air purifier.

To the best of the author's knowledge, no studies have systematically examined the statistical significance of a broad range of dental operations and the influence of proposed recommendations at the time of this work. The findings reported here highlight the importance of developing evidence-based guidelines to avoid intuitive-based recommendations. Several distinct approaches were used in order to validate and examine the findings of this research. However, the physical operatory geometry and HVAC ventilation specifications may impact these results. For example, the use of a negative pressure room with high air changes per hour can present different outcomes to what we concluded here. In addition, our results may have been influenced by the fact that we employed a patient simulator rather than real patients. As the presence of patient breathing, saliva and blood, are real factors which complicate this issue, follow-up studies should be conducted to overcome these limitations. Also, increasing the power of the HEPA filter air purifier, and changing the temperature and humidity in the large scales may affect particle concentrations which we could not perform in this study.

As a recommendation to dental services, we suggest continuing to use water sprays during the routine dental treatments as this reduces the concentration of aerosols. Also, we highly recommend the use of extraoral suction. Furthermore, although keeping the operatory door closed reduces the transmission of aerosols to other rooms, the practitioner and their assistant are exposed to a higher risk of aerosol inhalation in a closed room. In case of keeping the door closed, using an air purifier and an extraoral suction unit will help to enhance the air quality of the room, and also to maintain a safe space for both the patients and dental staff.

References

[1] Wikibooks. Student's t-distribution. (accessed: 2022-07-06). https://en.wikibooks.org/wiki/Engineering_Tables/Student%27s_T-Distribution.

[2] Darya Dabiri, Samuel Richard Conti, Niloufar Sadoughi Pour, Andrew Chong, Shaahin Dadjoo, Donya Dabiri, Carol Wiese, Joyce Badal, Margaret Raquel Hoogland, Heather Raquel Conti, et al. A multi-disciplinary review on aerobiology of covid-19 in the dental setting. *Frontiers in Dental Medicine*, page 66, 2021.

[3] Ann-Charlotte Almstrand, Evert Ljungstrom, Jukka Lausmaa, Björn Bake, Peter Sjovall, and Anna-Carin Olin. Airway monitoring by collection and mass spectrometric analysis of exhaled particles. *Analytical chemistry*, 81(2):662–668, 2009.

[4] Robert L Miller, Rudolph E Micik, Cabot Abel, and Gunnar Ryge. Studies on dental aerobiology: Ii. microbial splatter discharged from the oral cavity of dental patients. *Journal of dental research*, 50(3):621–625, 1971.

[5] Stephen K Harrel. Airborne spread of disease–the implications for dentistry. *Journal of the California Dental Association*, 32(11):901–906, 2004.

[6] Mirela Cesar Barros, Victor Feliz Pedrinha, Evelyn Giuliana Velásquez-Espedilla, Maricel Rosario Cardenas Cuellar, and Flaviana Bombarda de Andrade. Aerosols generated by high-speed handpiece and ultrasonic unit during endodontic coronal access alluding to the covid-19 pandemic. *Scientific Reports*, 12(1):1–8, 2022.

[7] James R Allison, David C Edwards, Charlotte Bowes, Kimberley Pickering, Christopher Dowson, Simon J Stone, Joanna Lumb, Justin Durham, Nicholas Jakubovics, and Richard Holliday. The effect of high-speed dental handpiece coolant delivery and design on aerosol and droplet production. *Journal of Dentistry*, 112:103746, 2021.

[8] World Health Organization et al. Considerations for the provision of essential oral health services in the context of covid-19: interim guidance, 3 august 2020. Technical report, World Health Organization, 2020.

[9] Center for Disease Control and Prevention (CDC). Recommended infection-control practices for dentistry. (accessed: 2022-06-17), 1993. `https://www.cdc.gov/mmwr/PDF/rr/rr4208.pdf`.

[10] American Dental Association. Covid-19 economic impact on dental practices. (accessed: 2021-11-29). `https://www.ada.org/en/science-research/health-policy-institute/covid-19-dentists-economic-impact`.

[11] SDCEP. 2021a. Mitigation of aerosol generating procedures in dentistry: a rapid review (version 1.2). (accessed: 2020-09-25). `https://alliancefororalhealthacrossborders.com/wp-content/uploads/2020/11/SDCEP-Mitigation-of-AGPS-in-Dentistry-Rapid-Review.pdf`.

[12] Yada Chestsuttayangkul, Wannee Lertsooksawat, and Sivaporn Horsophonphong. Efficacy of dental barriers in aerosols and splatters reduction during an ultrasonic scaling: An in-vitro study. *Journal of International Society of Preventive & Community Dentistry*, 12(1):71, 2022.

[13] Yan-Fang Ren, Qirong Huang, Tamer Marzouk, Ray Richard, Karen Pembroke, Pat Martone, Tom Venner, Hans Malmstrom, and Eli Eliav. Effects of mechanical

ventilation and portable air cleaner on aerosol removal from dental treatment rooms. *Journal of dentistry*, 105:103576, 2021.

[14] Mehael Fennelly, Catherine Gallagher, Mairead Harding, Stig Hellebust, John Wenger, Niall O'Sullivan, David O'Connor, and Michael Prentice. Real-time monitoring of aerosol generating dental procedures. *Journal of Dentistry*, 120:104092, 2022.

[15] Purnima S Kumar and Kumar Subramanian. Demystifying the mist: Sources of microbial bioload in dental aerosols. *Journal of periodontology*, 91(9):1113–1122, 2020.

[16] Sima Asadi, Nicole Bouvier, Anthony S Wexler, and William D Ristenpart. The coronavirus pandemic and aerosols: Does covid-19 transmit via expiratory particles?, 2020.

[17] Center for Disease Control and Prevention (CDC). How covid-19 spreads. (accessed: 2021-07-14), 2020. `https://www.cdc.gov/coronavirus/2019-ncov/prevent-getting-sick/how-covid-spreads.html`.

[18] Lydia Bourouiba. Turbulent gas clouds and respiratory pathogen emissions: Potential implications for reducing transmission of covid-19. *Jama*, 323(18):1837–1838, 2020.

[19] GR Johnson, Lidia Morawska, ZD Ristovski, Megan Hargreaves, Kerrie Mengersen, CY Hang Chao, MP Wan, Y Li, Xaiojan Xie, David Katoshevski, et al. Modality of human expired aerosol size distributions. *Journal of Aerosol Science*, 42(12):839–851, 2011.

[20] Ann-Charlotte Almstrand, Björn Bake, Evert Ljungström, Per Larsson, Anna Bredberg, Ekaterina Mirgorodskaya, and Anna-Carin Olin. Effect of airway open-

ing on production of exhaled particles. *Journal of applied physiology*, 108(3):584–588, 2010.

[21] Jianjian Wei and Yuguo Li. Airborne spread of infectious agents in the indoor environment. *American journal of infection control*, 44(9):S102–S108, 2016.

[22] Graham Richard Johnson and Lidia Morawska. The mechanism of breath aerosol formation. *Journal of aerosol medicine and pulmonary drug delivery*, 22(3):229–237, 2009.

[23] John A Moriarty and James B Grotberg. Flow-induced instabilities of a mucus–serous bilayer. *Journal of Fluid Mechanics*, 397:1–22, 1999.

[24] Katharina Schwarz, Heike Biller, Horst Windt, Wolfgang Koch, and Jens M Hohlfeld. Characterization of exhaled particles from the healthy human lung—a systematic analysis in relation to pulmonary function variables. *Journal of aerosol medicine and pulmonary drug delivery*, 23(6):371–379, 2010.

[25] LJGR Morawska, GR Johnson, ZD Ristovski, Megan Hargreaves, Kerrie Mengersen, Shay Corbett, Christopher Yu Hang Chao, Yuguo Li, and David Katoshevski. Size distribution and sites of origin of droplets expelled from the human respiratory tract during expiratory activities. *Journal of aerosol science*, 40(3):256–269, 2009.

[26] Christopher Yu Hang Chao, Man Pun Wan, Lidia Morawska, Graham R Johnson, ZD Ristovski, Megan Hargreaves, Kerrie Mengersen, Stephen Corbett, Yuguo Li, Xiaojian Xie, et al. Characterization of expiration air jets and droplet size distributions immediately at the mouth opening. *Journal of aerosol science*, 40(2):122–133, 2009.

[27] Central for Diseases Control. Interim infection prevention and control recommendations for healthcare personnel during the coronavirus disease 2019 (covid-19)

pandemic. (accessed: 2021-11-29). https://www.cdc.gov/coronavirus/2019-ncov/hcp/infection-control-recommendations.html.

[28] World Health Organization. Modes of transmission of virus causing covid-19: implications for ipc precaution recommendations. (accessed: 2020-03-29). https://www.who.int/news-room/commentaries/detail/modes-of-transmission-of-virus-causing-covid-19-implications-for-ipc-precaution-recommendations.

[29] Stephen K Harrel and John Molinari. Aerosols and splatter in dentistry: a brief review of the literature and infection control implications. *The Journal of the American Dental Association*, 135(4):429–437, 2004.

[30] Amber Ather, Biraj Patel, Nikita B Ruparel, Anibal Diogenes, and Kenneth M Hargreaves. Coronavirus disease 19 (covid-19): implications for clinical dental care. *Journal of endodontics*, 46(5):584–595, 2020.

[31] Mason Bahador, Rayyan A Alfirdous, Theeb A Alquria, Ina L Griffin, Patricia A Tordik, and Frederico C Martinho. Aerosols generated during endodontic treatment: a special concern during the coronavirus disease 2019 pandemic. *Journal of Endodontics*, 47(5):732–739, 2021.

[32] Pingping Han, Honghui Li, Laurence J Walsh, and Sašo Ivanovski. Splatters and aerosols contamination in dental aerosol generating procedures. *Applied Sciences*, 11(4):1914, 2021.

[33] Chi-Yu Chuang, Hsin-Chung Cheng, Shinhao Yang, Wei Fang, Po-Chen Hung, and Sheng-Yen Chuang. Investigation of the spreading characteristics of bacterial aerosol contamination during dental scaling treatment. *Journal of Dental Sciences*, 9(3):294–296, 2014.

[34] Rajat Mittal, Rui Ni, and Jung-Hee Seo. The flow physics of covid-19. *Journal of fluid Mechanics*, 894, 2020.

[35] X Xie, Y Li, AT Chwang, PL Ho, and WH Seto. How far droplets can move in indoor environments–revisiting the wells evaporation-falling curve. *Indoor air*, 17(3):211–225, 2007.

[36] C Zemouri, CMC Volgenant, MJ Buijs, W Crielaard, NAM Rosema, BW Brandt, AMGA Laheij, and JJ De Soet. Dental aerosols: microbial composition and spatial distribution. *Journal of Oral Microbiology*, 12(1):1762040, 2020.

[37] Jennifer Fiegel, Robert Clarke, and David A Edwards. Airborne infectious disease and the suppression of pulmonary bioaerosols. *Drug discovery today*, 11(1-2):51–57, 2006.

[38] Michael P Atkinson and Lawrence M Wein. Quantifying the routes of transmission for pandemic influenza. *Bulletin of mathematical biology*, 70(3):820–867, 2008.

[39] Mark Nicas, William Nazaroff, and Alan Hubbard. Toward understanding the risk of secondary airborne infection: Emission of respirable pathogens. *Journal of occupational and environmental hygiene*, 2:143–54, 04 2005.

[40] Joachim Heyder. Deposition of inhaled particles in the human respiratory tract and consequences for regional targeting in respiratory drug delivery. *Proceedings of the American Thoracic Society*, 1(4):315–320, 2004.

[41] LJGR Morawska, GR Johnson, ZD Ristovski, Megan Hargreaves, Kerrie Mengersen, Shay Corbett, Christopher Yu Hang Chao, Yuguo Li, and David Katoshevski. Size distribution and sites of origin of droplets expelled from the human respiratory tract during expiratory activities. *Journal of aerosol science*, 40(3):256–269, 2009.

[42] John Hunt. Exhaled breath condensate: an evolving tool for noninvasive evaluation of lung disease. *Journal of Allergy and Clinical Immunology*, 110(1):28–34, 2002.

[43] Ariel A Andersen. New sampler for the collection, sizing, and enumeration of viable airborne particles. *Journal of Bacteriology*, 76(5):471–484, 1958.

[44] James R Allison, Charlotte C Currie, David C Edwards, Charlotte Bowes, Jamie Coulter, Kimberley Pickering, Ekaterina Kozhevnikova, Justin Durham, Christopher J Nile, Nicholas Jakubovics, et al. Evaluating aerosol and splatter following dental procedures: Addressing new challenges for oral health care and rehabilitation. *Journal of oral rehabilitation*, 48(1):61–72, 2021.

[45] Trijani Suwandi, Vidya Nursolihati, Mikha Sundjojo, and Armelia Sari Widyarman. The efficacy of high-volume evacuators and extraoral vacuum aspirators in reducing aerosol and droplet in ultrasonic scaling procedures during the covid-19 pandemic. *European Journal of Dentistry*, 2022.

[46] Sivaporn Horsophonphong, Yada Chestsuttayangkul, Rudee Surarit, and Wannee Lertsooksawat. Efficacy of extraoral suction devices in aerosol and splatter reduction during ultrasonic scaling: A laboratory investigation. *Journal of Dental Research, Dental Clinics, Dental Prospects*, 15(3):197, 2021.

[47] Min Zhu, Mario Medina, Romesh Nalliah, Viyan Kadhium, Eric Bell, Taehoon Han, André Boehman, Jesse Capecelatro, and Margaret Wooldridge. Experimental evaluation of aerosol mitigation strategies in large open-plan dental clinics. *The Journal of the American Dental Association*, 153(3):208–220, 2022.

[48] Raffaele Ragucci, Antonio Cavaliere, and Patrizio Massoli. Drop sizing by laser light scattring exploiting intensity angular oscillation in the mie regime. *Particle & Particle Systems Characterization*, 7(1-4):221–225, 1990.

[49] Shengwei Zhu, Shinsuke Kato, and Jeong-Hoon Yang. Study on transport characteristics of saliva droplets produced by coughing in a calm indoor environment. *Building and environment*, 41(12):1691–1702, 2006.

[50] Meg VanSciver, Shelly Miller, and Jean Hertzberg. Particle image velocimetry of human cough. *Aerosol Science and Technology*, 45(3):415–422, 2011.

[51] Gustavo Zayas, Ming C Chiang, Eric Wong, Fred MacDonald, Carlos F Lange, Ambikaipakan Senthilselvan, and Malcolm King. Cough aerosol in healthy participants: fundamental knowledge to optimize droplet-spread infectious respiratory disease management. *BMC pulmonary medicine*, 12(1):1–12, 2012.

[52] Sepehr Makhsous, Joelle M Segovia, Jiayang He, Daniel Chan, Larry Lee, Igor V Novosselov, and Alexander V Mamishev. Methodology for addressing infectious aerosol persistence in real-time using sensor network. *Sensors*, 21(11):3928, 2021.

[53] Maobin Yang, Asad Chaghtai, Marc Melendez, Hana Hasson, Eugene Whitaker, Mustafa Badi, Leona Sperrazza, Jeffrey Godel, Cemil Yesilsoy, Marisol Tellez, et al. Mitigating saliva aerosol contamination in a dental school clinic. *BMC Oral Health*, 21(1):1–8, 2021.

[54] Qisheng Ou, Rafael Grazzini Placucci, Judy Danielson, Gary Anderson, Paul Olin, Paul Jardine, John Madden, Qinghui Yuan, Timothy H Grafe, Siyao Shao, et al. Characterization and mitigation of aerosols and spatters from ultrasonic scalers. *The Journal of the American Dental Association*, 152(12):981–990, 2021.

[55] Franz Durst, Günter Brenn, and TH Xu. A review of the development and characteristics of planar phase-doppler anemometry. *Measurement Science and Technology*, 8(11):1203, 1997.

[56] Stephen K. Harrel, James B Barnes, and Francisco Rivera-Hidalgo. Aerosol and

splatter contamination from the operative site during ultrasonic scaling. *Journal of the American Dental Association*, 129 9:1241–9, 1998.

[57] STEVE K. HARREL, JAMES B. BARNES, and FRANCISCO RIVERA-HIDALGO. Aerosol and splatter contamination from the operative site during ultrasonic scaling. *The Journal of the American Dental Association*, 129(9):1241–1249, 1998.

[58] H. R. Veena, S. R. Vijaya Mahantesha, Preethi A Joseph, Sudhir R. Patil, and Suvarna H Patil. Dissemination of aerosol and splatter during ultrasonic scaling: a pilot study. *Journal of infection and public health*, 8 3:260–5, 2015.

[59] Giuseppe Alessio Messano, Aisha A. A. Sofan, Stefano Petti, and Acta Stomatologica Naissi. Quality of air and water in dental healthcare settings during professional toothcleaning. *Acta Stomatologica Naissi*, 29:1230–1235, 2013.

[60] Stefano Petti and Antonella Polimeni. The rationale of guidelines for infection control in dentistry: Precautionary principle or acceptable risk? *Infection Control & Hospital Epidemiology*, 31:1308 – 1310, 2010.

[61] Center for Disease Control and Prevention (CDC). Ventilation in buildings. (accessed: 2022-06-17), 2021. `https://www.cdc.gov/coronavirus/2019-ncov/community/ventilation.html#refphf`.

[62] Enzo Maria Giuseppe Cumbo, Giuseppe Gallina, Pietro Messina, and Giuseppe Alessandro Scardina. Alternative methods of sterilization in dental practices against covid-19. *International Journal of Environmental Research and Public Health*, 17, 2020.

[63] Paolo Capparé, Raffaele D'Ambrosio, Renato De Cunto, Atanaz Darvizeh, Matteo Nagni, and Enrico Felice Gherlone. The usage of an air purifier device with

hepa 14 filter during dental procedures in covid-19 pandemic: A randomized clinical trial. *International Journal of Environmental Research and Public Health*, 19, 2022.

[64] Hollie Hawrot. What are the effects of portable air cleaners with a high-efficiency particulate air filter on aerosol removal in dental surgeries? *Evidence-based dentistry*, 22 2:56–57, 2021.

[65] Chun Chen, Bin Zhao, Weilin Cui, Lei Dong, Na An, and Xiangying Ouyang. The effectiveness of an air cleaner in controlling droplet/aerosol particle dispersion emitted from a patient's mouth in the indoor environment of dental clinics. *Journal of the Royal Society Interface*, 7(48):1105–1118, 2010.

[66] Jon J Vernon, Emma VI Black, Thomas Dennis, Deirdre A Devine, Louise Fletcher, David J Wood, and Brian R Nattress. Dental mitigation strategies to reduce aerosolization of sars-cov-2. *Journal of dental research*, 100(13):1461–1467, 2021.

[67] Amber Ather, Biraj Patel, Nikita B Ruparel, Anibal R Diogenes, and Kenneth M. Hargreaves. Coronavirus disease 19 (covid-19): Implications for clinical dental care. *Journal of Endodontics*, 46:584 – 595, 2020.

[68] Xian Peng, Xin Xu, Yuqing Li, Lei Cheng, Xuedong Zhou, and Biao Ren. Transmission routes of 2019-ncov and controls in dental practice. *International Journal of Oral Science*, 12, 2020.

[69] Julián Balanta-Melo, Albio D. Gutierrez, Gustavo Sinisterra, María del Mar Díaz-Posso, David Gallego, Judy Villavicencio, and Adolfo Contreras. Rubber dam isolation and high-volume suction reduce ultrafine dental aerosol particles: An experiment in a simulated patient. *Applied Sciences*, 10:6345, 2020.

[70] Safco dental supply. Beavers operative carbide burs. (accessed: 2022-07-05). https://www.safcodental.com/catalog/burs-and-diamonds/carbide-burs-operative/beavers-operative-carbide-burs.

[71] Safco dental supply. Beavers operative carbide burs. (accessed: 2022-07-05). https://www.safcodental.com/catalog/burs-and-diamonds/diamond-instruments-multi-use/bluwhite-diamonds.

[72] Wan Jiao, Gayle Hagler, Ronald Williams, Robert Sharpe, Ryan Brown, Daniel Garver, Robert Judge, Motria Caudill, Joshua Rickard, Michael Davis, et al. Community air sensor network (cairsense) project: evaluation of low-cost sensor performance in a suburban environment in the southeastern united states. *Atmospheric Measurement Techniques*, 9(11):5281–5292, 2016.

[73] Shruti Hegde, Kyeong T Min, James Moore, Philip Lundrigan, Neal Patwari, Scott Collingwood, Alfred Balch, Kerry E Kelly, et al. Indoor household particulate matter measurements using a network of low-cost sensors. *Aerosol and Air Quality Research*, 20(2):381–394, 2020.

[74] Xiaoting Liu, Rohan Jayaratne, Phong Thai, Tara Kuhn, Isak Zing, Bryce Christensen, Riki Lamont, Matthew Dunbabin, Sicong Zhu, Jian Gao, et al. Low-cost sensors as an alternative for long-term air quality monitoring. *Environmental research*, 185:109438, 2020.

[75] Yuanyuan Shi, Yanfeng Ji, Hui Sun, Fei Hui, Jianchen Hu, Yaxi Wu, Jianlong Fang, Hao Lin, Jianxiang Wang, Huiling Duan, et al. Nanoscale characterization of pm 2.5 airborne pollutants reveals high adhesiveness and aggregation capability of soot particles. *Scientific reports*, 5(1):1–10, 2015.

[76] California Dental Association. Dental aerosol management. (accessed: 2020-05-

26). https://www.cda.org/Home/Resource-Library/Resources/category/guidance/dental-aerosol-management.

[77] Public Health Ontario. Open operatory dental setting infection control practices and risk of transmission during aerosol-generating dental procedures. (accessed: 2020-11-26). https://www.publichealthontario.ca/-/media/documents/ncov/ipac/2020/11/open-operatory-dental-ipac-aerosol-procedures.pdf?la=en.

[78] American Academy of Pediatric Dentistry. Practice checklist. (accessed: 2020-04-28). https://www.aapd.org/globalassets/media/covid-19/aapd-practicechecklist.pdf.

[79] Jens-Dominik Mueller Noha Seoudi Claire Morgan Shakeel Shahdad, Annika Hindocha and Ahmed Din. The efficacy of an extraoral scavenging device on reduction of splatter contamination during dental aerosol generating procedures: an exploratory study. *British Dental Journal*, pages 1–10, 2020.

[80] Hulin Jin, Vahid Andalib, Ghulam Yasin, Dmitry Olegovich Bokov, Mehnaz Kamal, May Alashwal, Sami Ghazali, Mohammed Algarni, and Amr Mamdouh. Computational simulation using machine learning models in prediction of co2 absorption in environmental applications. *Journal of Molecular Liquids*, 358:119159, 2022.

[81] Vahid Andalib and Jyotirmoy Sarkar. A system with two spare units, two repair facilities, and two types of repairers. *Mathematics*, 10(6):852, 2022.

[82] Cameron G Estrich, Ruth D Lipman, and Marcelo WB Araujo. Dental amalgam restorations in nationally representative sample of us population aged 15 years: Nhanes 2011–2016. *Journal of Public Health Dentistry*, 2021.

[83] American Dental Association. ADA study finds about half of restored teeth in us contain amalgam. (accessed: 2021-06-22). https://www.ada.org/publications/ada-news/2021/june/ada-study-finds-about-half-of-restored-teeth-in-us-contain-amalgam.

Appendix A

Arduino Code

A.1 Sender Teensy

```
int led = 13;
HardwareSerial * pSer[8] = {&Serial1, &Serial2, &Serial3, &Serial4, &Serial5, &Serial6, &Serial7, &Serial8};

int isSensor[8];
int i;

//Sensirion
byte sens_startmeasurment[] = {0x7E,0x00,0x00,0x02,0x01,0x03,0xF9,0x7E};
byte sens_pulse[] =           {0xFF};
byte sens_wakeup[] =          {0x7E,0x00,0x11,0x00,0xEE,0x7E};
byte sens_startfanclean[] =   {0x7E,0x00,0x56,0x00,0xA9,0x7E};
byte sens_readmeasurment[] =  {0x7E,0x00,0x03,0x00,0xFC,0x7E};
byte sens_response[][47] = {{0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00},
                           {0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00},
                           {0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00},
                           {0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00},
```

```
                                        {0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
    ,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
    ,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
    ,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
    },
                                        {0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
    ,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
    ,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
    ,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
    },
                                        {0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
    ,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
    ,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
    ,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
    },
                                        {0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
    ,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
    ,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
    ,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
    }
                                        };

byte send_sens_response[376] = {0x00,0x00,0x00,0x00,0x00,0x00,0x00,0
    x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0
    x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0
    x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0
    x00,
                                        0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
    ,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
    ,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
    ,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
    ,
                                        0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
    ,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
    ,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
    ,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
    ,
                                        0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
    ,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
    ,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
    ,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
    ,
                                        0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
    ,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
    ,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
    ,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
    ,
                                        0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
    ,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
    ,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
    ,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
    ,
                                        0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
```

```
,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
,
                            0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
};

//////////////////////////////////////////////
void setup() {
 pinMode(led, OUTPUT);
 digitalWrite(led, HIGH);   // turn the LED on (HIGH is the voltage
   level)
   digitalWrite(led, LOW);    // turn the LED off by making the
   voltage LOW
  delay(1000);                // wait for a second
 digitalWrite(led, HIGH);   // turn the LED on (HIGH is the voltage
   level)
   delay(1000);
     for (int j = 0; j < 8; j++) {
 sensirion_begin(j);
     }
}
////////////////////////////////////////////////
void loop() {
  digitalWrite(led, HIGH);   // turn the LED on (HIGH is the voltage
    level)
  delay(500);               // wait for a second
  for (int j = 0; j < 8; j++) {   //Niloufar - Increase to number
    if (isSensor[j] < 2){
// DUST SENSOR WRITE
            pSer[j]->write(sens_readmeasurment,6);
// DUST SENSOR READ
            ReadSensData(j);
    }else{
      //
    }
}
           WriteSensData();
  digitalWrite(led, LOW);    // turn the LED off by making the
   voltage LOW
  delay(500);               // wait for a second
}

//////////////////////////////////////////////////
void ReadSensData(int cj){
  //Sensirion
          while(!pSer[cj]->available()){
            delay (100);
          }
            i = 0;
```

```
          while(pSer[cj]->available()){
          sens_response[cj][i] = pSer[cj]->read();
          if (sens_response[cj][i] == 125){
            sens_response[cj][i] = pSer[cj]->read();
            if (sens_response[cj][i] == 94){
              sens_response[cj][i] = 126;
            }else if(sens_response[cj][i] == 93){
              sens_response[cj][i] = 125;
            }else if(sens_response[cj][i] == 49){
              sens_response[cj][i] = 17;
            }else if(sens_response[cj][i] == 51){
              sens_response[cj][i] =19;
            }
          }
          i++;
          }
}

////////////////////////////////////////////////


////////////////////////////////////////////////
void sensirion_begin(int sj){
        i = 0;
     //Sensirion
    pSer[sj]->begin(115200);
    while(!pSer[sj]){
    }
    pSer[sj]->write(sens_startmeasurment,8);
          i = 0;
      while(!pSer[sj]->available() and isSensor[sj] < 1){
            delay (100);
            i++;
            if (i > 10){
                 isSensor[sj] = 2;
            }
      }

   if(isSensor[sj] < 1){
    pSer[sj]->write(sens_pulse,1);
    pSer[sj]->write(sens_wakeup,6);
   }
      i = 0;
      while(!pSer[sj]->available() and isSensor[sj] < 1){
            delay (100);
            i++;
            if (i > 10){
              isSensor[sj] = 2;
            }
      }
   if (isSensor[sj] < 1){
        while(pSer[sj]->available() and isSensor[sj] < 1){
          pSer[sj]->read();
```

```
        }
        pSer[sj]->write(sens_startfanclean,6);
        //delay(10000);
          while(!pSer[sj]->available() and isSensor[sj] < 1){
           delay (100);
            i++;
            if (i > 10){
              isSensor[sj] = 2;
            }
          }

        while(pSer[sj]->available() and isSensor[sj] < 1){
         pSer[sj]->read();
        }
        if (isSensor[sj] < 1){
       isSensor[sj] = 1;
        }
       }
}
//////////////////////////////////////////////////
void WriteSensData(){
  //Sensirion
  int k = 0;
for (int x = 0; x < 8; x++){
   for (int y = 0; y < 47; y++)
   {
            send_sens_response[k] = sens_response[x][y];
            k++;
   }
}
            Serial1.write(send_sens_response, 376);
}
```

A.2 Receiver Teensy

```
int led = 13;
int isSensor[8];
int i;
HardwareSerial * pSer[8] = {&Serial1, &Serial2, &Serial3, &Serial4,
   &Serial5, &Serial6, &Serial7, &Serial8};

unsigned long PM01[3];
unsigned long PM25[3];
unsigned long PM04[3];
unsigned long PM10[3];
unsigned int C005[3];
unsigned int C01[3];
unsigned int C25[3];
unsigned int C04[3];
unsigned int C05[3];
unsigned int C10[3];

```

```
union TEMP
{
  float f;
  byte b[4];
};

              TEMP temp;

byte sens_response[][47] = {{0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
    ,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
    ,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
    ,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
    },
                            {0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
    ,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
    ,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
    ,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
    },
                            {0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
    ,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
    ,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
    ,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
    },
                            {0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
    ,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
    ,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
    ,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
    },
                            {0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
    ,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
    ,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
    ,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
    },
                            {0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
    ,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
    ,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
    ,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
    },
                            {0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
    ,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
    ,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
    ,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
    },
                            {0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
    ,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
    ,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
    ,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
    }
                            };

byte send_sens_response[][376] = {{0x00,0x00,0x00,0x00,0x00,0x00,0
    x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0
    x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0
```

```
x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0
x00,0x00,
                            0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
,
                            0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
,
                            0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
,
                            0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
,
                            0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
,
                            0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
,
                            0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
},
                            {0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
,
                            0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
,
                            0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
,
                            0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
```

```
,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
,
                                0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
,
                                0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
,
                                0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
,
                                0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
},
                                {0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
,
                                0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
,
                                0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
,
                                0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
,
                                0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
,
                                0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
```

```
,
                                   0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
,
                                   0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
},
                                   {0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
,
                                   0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
,
                                   0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
,
                                   0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
,
                                   0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
,
                                   0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
,
                                   0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
,
                                   0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00
}
                                   };
```

```
void setup() {
  // put your setup code here, to run once:
 pinMode(led, OUTPUT);
 digitalWrite(led, HIGH);   // turn the LED on (HIGH is the voltage level)
  Serial.begin(115200);
  while (!Serial) {
    // wait for serial port to connect. Needed for native USB
  }
     digitalWrite(led, LOW);    // turn the LED off by making the voltage LOW
  delay(1000);                // wait for a second
 digitalWrite(led, HIGH);   // turn the LED on (HIGH is the voltage level)
   delay(1000);
     for (int j = 0; j < 8; j++) {
 sensirion_begin(j);
     }
}

void loop() {
  delay(10);
  // put your main code here, to run repeatedly:
     for (int j = 0; j < 6; j++) {
              digitalWrite(led, HIGH);    // turn the LED off by making the voltage LOW
            i = 0;
  while(pSer[j]->available() < 375 and isSensor[j] < 2){
            delay(10);
            i++;
            if (i > 10){
              isSensor[j] = 2;
            }
  }

  if(pSer[j]->available() > 375 and isSensor[j] < 2){
          Serial.print(j);
              i = 0;
               while(pSer[j]->available()){
                 send_sens_response[j][i] = pSer[j]->read();
                 i++;
               }
               i = 0;
for (int x = 0; x < 8; x++){
   for (int y = 0; y < 47; y++){
                 sens_response[x][y] =  send_sens_response[j][i];
                 i++;
   }
   ParseSensirion(x);
}
               Serial.println("");
        }else{
                 if (isSensor[j] < 1){
```

```
                  isSensor[j] = 1;
               }
             digitalWrite(led, LOW);    // turn the LED off by
    making the voltage LOW
          }

    }
}

void sensirion_begin(int sj){
    pSer[sj]->begin(115200);
    while(!pSer[sj]){
      Serial.print("hi");
    }
}

////////////////////////////////////////////////
void ParseSensirion(int cj){
             //Sensirion
            if ((sens_response[cj][0] == 126) &&(sens_response[cj
    ][46] == 126) ) {
            temp.b[3] = sens_response[cj][5]; temp.b[2] =
    sens_response[cj][6]; temp.b[1] = sens_response[cj][7]; temp.b[0]
     = sens_response[cj][8];
                  PM01[cj] = temp.f;
            temp.b[3] = sens_response[cj][9]; temp.b[2] =
    sens_response[cj][10]; temp.b[1] = sens_response[cj][11]; temp.b
    [0] = sens_response[cj][12];
                  PM25[cj] = temp.f;
            temp.b[3] = sens_response[cj][13]; temp.b[2] =
    sens_response[cj][14]; temp.b[1] = sens_response[cj][15]; temp.b
    [0] = sens_response[cj][16];
                  PM04[cj] = temp.f;
            temp.b[3] = sens_response[cj][17]; temp.b[2] =
    sens_response[cj][18]; temp.b[1] = sens_response[cj][19]; temp.b
    [0] = sens_response[cj][20];
                  PM10[cj] = temp.f;
            temp.b[3] = sens_response[cj][21]; temp.b[2] =
    sens_response[cj][22]; temp.b[1] = sens_response[cj][23]; temp.b
    [0] = sens_response[cj][24];
                  C005[cj] = temp.f;
            temp.b[3] = sens_response[cj][25]; temp.b[2] =
    sens_response[cj][26]; temp.b[1] = sens_response[cj][27]; temp.b
    [0] = sens_response[cj][28];
                  C01[cj] = temp.f;
            temp.b[3] = sens_response[cj][29]; temp.b[2] =
    sens_response[cj][30]; temp.b[1] = sens_response[cj][31]; temp.b
    [0] = sens_response[cj][32];
                  C25[cj] = temp.f;
            temp.b[3] = sens_response[cj][33]; temp.b[2] =
    sens_response[cj][34]; temp.b[1] = sens_response[cj][35]; temp.b
    [0] = sens_response[cj][36];
                  C04[cj] = temp.f;
```

```
            temp.b[3] = sens_response[cj][37]; temp.b[2] = sens_response[cj][38]; temp.b[1] = sens_response[cj][39]; temp.b[0] = sens_response[cj][40];
                  C10[cj] = temp.f;

                  Serial.print(";");
                  Serial.print(PM01[cj]);
                  Serial.print(";");
                  Serial.print(PM25[cj]);
                  Serial.print(";");
                  Serial.print(PM04[cj]);
                  Serial.print(";");
                  Serial.print(PM10[cj]);
                  Serial.print(";");
                  Serial.print(C005[cj]);
                  Serial.print(";");
                  Serial.print(C01[cj]);
                  Serial.print(";");
                  Serial.print(C25[cj]);
                  Serial.print(";");
                  Serial.print(C04[cj]);
                  Serial.print(";");
                  Serial.print(C10[cj]);
                              } else {
                  Serial.print(";");
                  Serial.print("-1");
                  Serial.print(";");
                  Serial.print("-1");
                  Serial.print(";");
                  Serial.print("-1");
                  Serial.print(";");
                  Serial.print("-1");
                  Serial.print(";");
                  Serial.print("-1");
                  Serial.print(";");
                  Serial.print("-1");
                  Serial.print(";");
                  Serial.print("-1");
                  Serial.print(";");
                  Serial.print("-1");
            }
}
```

Appendix B

Python Code

B.1 Making SQLite Database

```
import sqlite3
import pandas as pd
import numpy as np

def read_database(filename, row, win, exp_day):
    conn = sqlite3.connect(filename)
    temp = pd.read_sql_query("SELECT Temperature from DataTeensy",
   conn)
    humidity = pd.read_sql_query("SELECT Humidity from DataTeensy",
   conn)
    data = pd.read_sql_query(
        "SELECT T0S1numPM10, T0S2numPM10, T0S3numPM10, T0S4numPM10,
   T0S5numPM10, T0S6numPM10, T0S7numPM10, \\\
        T1S1numPM10, T1S2numPM10, T1S3numPM10, T1S4numPM10,
   T1S5numPM10, T1S6numPM10, T1S7numPM10, T2S1numPM10, \\\
        T2S2numPM10, T2S3numPM10, T2S4numPM10, T2S5numPM10,
   T2S6numPM10, T2S7numPM10, T3S1numPM10, T3S2numPM10,\\\
        T3S3numPM10, T3S4numPM10, T3S5numPM10, T3S7numPM10,
   T4S2numPM10, T4S3numPM10, T4S4numPM10, T4S5numPM10, \\\
        T4S6numPM10, T4S7numPM10 from DataTeensy",conn)
    conn.close()

    if exp_day==1:
        sorted_columns = data.loc[row, data.max().sort_values(
   ascending=False).index]
        first_n_columns = sorted_columns.iloc[:, :Nsensor]
    elif exp_day==2:
        first_n_columns = data = data.loc[row,:]
    else:
        print('wrong input')

    time = np.double(list(range(0, int(first_n_columns.shape[0]))))
   / 60
    temp_rows = temp.loc[row, :]
    humidity_rows = humidity.loc[row, :]
    temp_moving_ave = moving_ave(temp_rows, win)
    humidity_moving_ave = moving_ave(humidity_rows, win)
    pm10_moving_ave = moving_ave(data.loc[row,:], win)
```

```

    return (time, temp_moving_ave, humidity_moving_ave, pm10_moving_ave, data)

def read_processed_data(filename):
    conn = sqlite3.connect(filename)
    exp = pd.read_sql_query("SELECT * from PM10_ave", conn)
    time = pd.read_sql_query("SELECT time from fluid_prop", conn)
    temp = pd.read_sql_query("SELECT temperature from fluid_prop", conn)
    humi = pd.read_sql_query("SELECT humidity from fluid_prop", conn)
    conn.close()
    return (exp,time,temp,humi)

def moving_ave(var, win):
    var_moving_ave = var.rolling(window=win).mean()
    return (var_moving_ave)

def export_pm(savefilename, sensor_matrix, time, temp_moving_ave, humidity_moving_ave, Nsensor, Nsextant):
    conn = sqlite3.connect(savefilename)
    c = conn.cursor()
    create_table_pm(conn,c,Nsextant,Nsensor)
    sensors = np.full([max([len(x) for x in indexes]),Nsextant*Nsensor],np.nan)
     shift = [0, len(indexes[0]), len(indexes[0])+len(indexes[1]),

        len(indexes[0])+len(indexes[1])+ len(indexes[2]),

     len(indexes[0])+len(indexes[1])+len(indexes[2])+len(indexes[3]),

     len(indexes[0])+len(indexes[1])+len(indexes[2])+ len(indexes[3])+len(indexes[4])]

     for i in range(0, max([len(x) for x in indexes])):
        for j in range(0, Nsensor):
            for k in range(0, Nsextant):
                if i < len(indexes[k]):
                    sensors[i,k+j*Nsextant] = np.double(sensor_matrix.values[i+shift[k],j] )
                else:
                    sensors[i,k] = np.nan
        write_variables_pm(conn,c,sensors[i,:],Nsextant,Nsensor)
     c.close()
    conn.close()
    conn = sqlite3.connect(savefilename)
    c = conn.cursor()
    create_table_fluid(conn,c)
    for i in range(0, max([len(x) for x in indexes])):
        write_variables_fluid(conn,c,time[i],
        np.double(temp_moving_ave.values[i]), np.double(
```

```
    humidity_moving_ave.values[i]))
    c.close()
    conn.close()
    return ()

def create_table_pm(conn,c,Nsextant,Nsensor):
    query = ''
    for jdx in range(Nsensor):
        for idx in range(Nsextant):
            query += f'S{idx + 1}S{jdx + 1} real, '
    c.execute('DROP TABLE IF EXISTS PM10_ave')
    c.execute(f'''CREATE TABLE IF NOT EXISTS PM10_ave ({query[:-2]})''')
    return(c)

def create_table_fluid(conn,c):
    c.execute('DROP TABLE IF EXISTS fluid_prop')
    c.execute('''CREATE TABLE IF NOT EXISTS fluid_prop (time real, temperature real, humidity real)''')
    return(c)

def write_variables_pm(conn,c,sensors,Nsextant,Nsensor):
    squery = ''
    for jdx in range(Nsensor):
        for idx in range(Nsextant):
            squery += f'S{idx + 1}S{jdx + 1}, '
    c.execute(f"INSERT INTO PM10_ave ({squery[:-2]}) VALUES
    "f"({','.join(['?' for _ in range(Nsextant*Nsensor)])})", tuple(sensors) )
    conn.commit()
    return(c)

def write_variables_fluid(conn,c,Var1,Var2,Var3):
    c.execute("INSERT INTO fluid_prop (time, temperature, humidity) VALUES (?,?,?)", (Var1, Var2, Var3))
    conn.commit()
    return(c)
```

B.2 Making SQLite Database for Analysis

```
import sqlite3
import pandas as pd
import numpy as np

def read_processed_data(filename):
    conn = sqlite3.connect(filename)
    exp = pd.read_sql_query("SELECT * from PM10_ave", conn)
    time = pd.read_sql_query("SELECT time from fluid_prop", conn)
    temp = pd.read_sql_query("SELECT temperature from fluid_prop", conn)
    humi = pd.read_sql_query("SELECT humidity from fluid_prop", conn)
```

```
    conn.close()
    return (exp,time,temp,humi)

def min_max_median_mean_std(exp,time,Nsensor, sextant_no):
    pm10min = np.full([len(time)],np.nan)
    pm10max = np.full([len(time)],np.nan)
    pm10median = np.full([len(time)],np.nan)
    pm10mean = np.full([len(time)],np.nan)
    pm10std = np.full([len(time)],np.nan)
    tmp=np.full(Nsensor,np.nan)

    for t in range(0,len(time)):
        for sensor_no in range (1,Nsensor):
            tmp[sensor_no-1] = exp.values[t,sextant_no+6*(sensor_no-1)]
            # tmp[sensor_no-1] = exp.values[t,sextant_no+(sensor_no-1)]
        #pm10minfull[t] = np.sort(tmp)[0]
        pm10min[t] = np.nanmin(tmp[:])
        pm10max[t] = np.nanmax(tmp[:])
        pm10median[t] = np.nanmedian(tmp[:])
        pm10mean[t] = np.nanmean(tmp[:])
        pm10std[t] = np.nanstd(tmp[:])
    return(pm10min,pm10max,pm10median,pm10mean,pm10std)

def create_table_parameters(conn,c,sextant_name):
    c.execute('DROP TABLE IF EXISTS ' + sextant_name)
    c.execute('''CREATE TABLE IF NOT EXISTS '''+sextant_name+''' (time real,\
    temperature real, humidity real, median real, average real, max real, min real, std real)''')
    return(c)

def write_variables_parameters(conn,c,sextant_name,Var1,Var2,Var3,Var4,Var5,Var6,Var7,Var8):
    c.execute("INSERT INTO "+sextant_name+" (time, temperature, humidity, median, average,\
    max, min, std) VALUES (?,?,?,?,?,?,?,?)", (Var1,Var2,Var3,Var4,Var5,Var6,Var7,Var8))
    conn.commit()
    return(c)

Nsextant = 6
Nsensor= 33
filename= ''
savefilename = 'data_analysis_'+filename+'.db'
if Nsextant == 6:
    for sextant_no in range(0,Nsextant):
        if sextant_no == 0:
            sextant_name= 'UR'
        if sextant_no ==1:
            sextant_name ='LR'
        if sextant_no ==2:
```

```
            sextant_name='UL'
        if sextant_no ==3:
            sextant_name='LL'
        if sextant_no ==4:
           sextant_name ='UA'
        if sextant_no ==5:
           sextant_name ='LA'

        exp,time,temp,humi=read_processed_data(pathname+filename)
        pm10min,pm10max,pm10median,pm10mean,pm10std =\
        min_max_median_mean_std(exp,time,Nsensor,sextant_no)
        export(pathname+savefilename, sextant_name, time, temp,\
        humi, pm10median, pm10mean, pm10max, pm10min,pm10std )
```

B.3 To Plot Results and Analysis

```

import sqlite3
import pandas as pd
import numpy as np
from numpy import matlib
import matplotlib.pyplot as plt
from IPython.display import set_matplotlib_formats
import seaborn as sns
from scipy import stats
import statistics
from matplotlib.ticker import PercentFormatter
import math

def read_processed_stats(filename):
    conn = sqlite3.connect(filename)
    UR = pd.read_sql_query("SELECT * from UR", conn)
    LR = pd.read_sql_query("SELECT * from LR", conn)
    UL = pd.read_sql_query("SELECT * from UL", conn)
    LL = pd.read_sql_query("SELECT * from LL", conn)
    UA = pd.read_sql_query("SELECT * from UA", conn)
    LA = pd.read_sql_query("SELECT * from LA", conn)
    conn.close()
    return (UR, LR, UL, LL, UA, LA)

lightblue=  np.double([30,144,255])/255
blue = np.double([0,0,255])/255
gray = np.double([204,204,204])/255

pathname = ''
pathnameplot = ''
experiment_name = ''
method='distance_weighted_avg'  #weighted_average

offset=10
duration=300
procedure = '5min'
```

```
index = 'minIndex' #'threshIndex'
func_of ='mean'
func = 'median' #'median'
thresh = 10 #baseline particle count as threshold
Nsextant = 4  #6
Nsensor = 33
Nexp_base = 6
Nexp = 3

if func== 'median':
    column = 3
elif func== 'mean':
    column = 4
elif func=='max':
    column = 5
elif func=='min':
    column = 6
elif func=='std':
    column = 7
else:
    print('wrong func name')

if procedure == '5min':
#read data stats of base cases 5min
    UR1,LR1,UL1,LL1,UA1,LA1 = read_processed_stats(pathname+'
   data_analysis_F0S0R0W1D0L1P1H1C1T5exp1.db')
    UR2,LR2,UL2,LL2,UA2,LA2 = read_processed_stats(pathname+'
   data_analysis_F0S0R0W1D0L1P1H1C1T5exp2.db')
    UR3,LR3,UL3,LL3,UA3,LA3 = read_processed_stats(pathname+'
   data_analysis_F0S0R0W1D0L1P1H1C1T5exp3.db')
    UR4,LR4,UL4,LL4,UA4,LA4 = read_processed_stats(pathname+'
   data_analysis_F0S0R0W1D0L1P1H1C1T5exp4.db')
    UR5,LR5,UL5,LL5,UA5,LA5 = read_processed_stats(pathname+'
   data_analysis_F0S0R0W1D0L1P1H1C1T5exp5.db')
    UR6,LR6,UL6,LL6,UA6,LA6 = read_processed_stats(pathname+'
   data_analysis_F0S0R0W1D0L1P1H1C1T5(05_14_2021).db')

    index1_UR=303
    index1_LR=303
    index1_UL=303
    index1_LL=303
    index1_UA=303
    index1_LA=303

    index2_UR=303
    index2_LR=303
    index2_UL=303
    index2_LL=303
    index2_UA=303
    index2_LA=303

    index3_UR=303
    index3_LR=303
```

```python
    index3_UL=292
    index3_LL=303
    index3_UA=303
    index3_LA=303

    index4_UR=303
    index4_LR=248
    index4_UL=303
    index4_LL=303
    index4_UA=303
    index4_LA=303

    index5_UR=303
    index5_LR=303
    index5_UL=303
    index5_LL=303
    index5_UA=303
    index5_LA=303

    index6_UR=303
    index6_LR=303
    index6_UL=303
    index6_LL=303
    index6_UA=303
    index6_LA=303

    if Nexp == 1:
        if experiment_name == 'fanNsuction_opendoor_MaximaPro':
            filename = 'data_analysis_F1S1R0W1D0L1P1H0C1T5(05_25_2021).db'
            index_UR=303
            index_LR=303
            index_UL=303
            index_LL=303
            index_UA=303
            index_LA=303

        elif experiment_name == 'fanNsuction_closeDoor':
            filename = 'data_analysis_F1S1R0W1D1L1P1H1C1T5(05_18_2021).db'
            index_UR=303
            index_LR=303
            index_UL=303
            index_LL=303
            index_UA=303
            index_LA=303

        elif experiment_name == 'dryshield':
            filename = 'data_analysis_F0S0R0W0D0L1P1H1C1T5_dryshield.db'
            index_UR=303
            index_LR=303
            index_UL=303
```

```python
            index_LL=303
            index_UA=303
            index_LA=303

        elif experiment_name == 'close_door':
            filename = 'data_analysis_F0S0R0W1D1L1P1H1C1T5(05_15_2021).db'
            index_UR=303
            index_LR=303
            index_UL=295
            index_LL=303
            index_UA=303
            index_LA=303

        elif experiment_name == 'semisupine_base':
            filename = 'data_analysis_F0S0R0W1D0L1P1H1C0T5_(07_06_2021).db'
            index_UR=303
            index_LR=303
            index_UL=303
            index_LL=303
            index_UA=303
            index_LA=303

        elif experiment_name == 'semisupine_suction':
            filename = 'data_analysis_F0S1R0W1D0L1P1H1C0T5_(07_10_2021).db'
            index_UR=303
            index_LR=303
            index_UL=303
            index_LL=303
            index_UA=303
            index_LA=303

        UR,LR,UL,LL,UA,LA = read_processed_stats(pathname+filename)

    else:
        if experiment_name == 'MaximaPro_Handpiece':
            UR,LR,UL,LL,UA,LA = read_processed_stats(pathname+'data_analysis_F0S0R0W1D0L1P1H0C1T5(05_16_2021).db')
            UR_2,LR_2,UL_2,LL_2,UA_2,LA_2 = read_processed_stats(pathname+'data_analysis_F0S0R0W1D0L1P1H0C1T5\
            _(11_07_2021).db')
            UR_3,LR_3,UL_3,LL_3,UA_3,LA_3 = read_processed_stats(pathname+'data_analysis_Repeat_F0S0R0W1D0L1P1H0C1T5\
            _(11_07_2021).db')

            index_UR=323
            index_LR=320
            index_UL=273
            index_LL=303
            index_UA=303
            index_LA=307
```

```

            index_UR_2=302
            index_LR_2=304
            index_UL_2=304
            index_LL_2=304
            index_UA_2=304
            index_LA_2=304

            index_UR_3=304
            index_LR_3=304
            index_UL_3=304
            index_LL_3=304
            index_UA_3=304
            index_LA_3=304

        elif experiment_name == 'air_purifier':
            #filename = 'data_analysis_F1S0R0W1D0L1P1H1C1T5(05
    _16_2021).db'
            UR,LR,UL,LL,UA,LA = read_processed_stats(pathname+'
    data_analysis_F1S0R0W1D0L1P1H1C1T5(05_16_2021).db')
            UR_2,LR_2,UL_2,LL_2,UA_2,LA_2 = read_processed_stats(
    pathname+'data_analysis_F1S0R0W1D0L1P1H1C1T5\
            _(11_07_2021).db')
            UR_3,LR_3,UL_3,LL_3,UA_3,LA_3 = read_processed_stats(
    pathname+'data_analysis_Repeat_F1S0R0W1D0L1P1H1C1T5\
            _(11_07_2021).db')

            index_UR=303
            index_LR=307
            index_UL=303
            index_LL=303
            index_UA=303
            index_LA=303

            index_UR_2=304
            index_LR_2=304
            index_UL_2=304
            index_LL_2=304
            index_UA_2=304
            index_LA_2=304

            index_UR_3=304
            index_LR_3=304
            index_UL_3=304
            index_LL_3=304
            index_UA_3=304
            index_LA_3=304

        elif experiment_name == 'extraoral_suction':
            #filename = 'data_analysis_F0S1R0W1D0L1P1H1C1T5(05
    _16_2021).db'
            UR,LR,UL,LL,UA,LA = read_processed_stats(pathname+'
    data_analysis_F0S1R0W1D0L1P1H1C1T5(05_16_2021).db')
```

```
            UR_2,LR_2,UL_2,LL_2,UA_2,LA_2 = read_processed_stats(pathname+'data_analysis_F0S1R0W1D0L1P1H1C1T5\
            _(11_07_2021).db')
            UR_3,LR_3,UL_3,LL_3,UA_3,LA_3 = read_processed_stats(pathname+'data_analysis_Repeat_F0S1R0W1D0L1P1H1C1T5\
            _(11_07_2021).db')

            index_UR=303
            index_LR=303
            index_UL=302
            index_LL=303
            index_UA=303
            index_LA=303

            index_UR_2=304
            index_LR_2=304
            index_UL_2=304
            index_LL_2=304
            index_UA_2=304
            index_LA_2=304

            index_UR_3=304
            index_LR_3=304
            index_UL_3=304
            index_LL_3=300
            index_UA_3=304
            index_LA_3=300

elif procedure == '2min':
    UR1,LR1,UL1,LL1,UA1,LA1=read_processed_stats(pathname+'data_analysis_F0S0R0W1D0L1P1H1C1T2exp1.db')
    UR2,LR2,UL2,LL2,UA2,LA2=read_processed_stats(pathname+'data_analysis_F0S0R0W1D0L1P1H1C1T2exp2.db')
    UR3,LR3,UL3,LL3,UA3,LA3=read_processed_stats(pathname+'data_analysis_F0S0R0W1D0L1P1H1C1T2exp3.db')
    UR4,LR4,UL4,LL4,UA4,LA4=read_processed_stats(pathname+'data_analysis_F0S0R0W1D0L1P1H1C1T2exp4.db')
    UR5,LR5,UL5,LL5,UA5,LA5=read_processed_stats(pathname+'data_analysis_F0S0R0W1D0L1P1H1C1T2exp5.db')
    UR6,LR6,UL6,LL6,UA6,LA6=read_processed_stats(pathname+'data_analysis_F0S0R0W1D0L1P1H1C1T2(05_14_2021).db')

    index1_UR=122
    index1_LR=122
    index1_UL=123
    index1_LL=122
    index1_UA=122
    index1_LA=122

    index2_UR=122
    index2_LR=122
    index2_UL=122
    index2_LL=122
```

```
    index2_UA=122
    index2_LA=122

    index3_UR=122
    index3_LR=122
    index3_UL=122
    index3_LL=122
    index3_UA=121
    index3_LA=123

    index4_UR=122
    index4_LR=123
    index4_UL=122
    index4_LL=122
    index4_UA=124
    index4_LA=123

    index5_UR=122
    index5_LR=122
    index5_UL=122
    index5_LL=122
    index5_UA=122
    index5_LA=122

    index6_UR=122
    index6_LR=122
    index6_UL=122
    index6_LL=122
    index6_UA=122
    index6_LA=122

    if experiment_name == 'dry_drilling':
        filename = 'data_analysis_F0S0R0W0D1L1P1H1C1T2(04_30_2021).
    db'
        index_UR=122
        index_LR=123
        index_UL=122
        index_LL=122
        index_UA=123
        index_LA=123
    elif experiment_name == 'rubberdam':
        filename = 'data_analysis_F0S0R1W1D0L1P1H1C1T2_(06_26_2021).
    db'
        index_UR=122
        index_LR=122
        index_UL=122
        index_LL=122
        index_UA=122
        index_LA=122
    UR,LR,UL,LL,UA,LA=read_processed_stats(pathname+filename)

def base_case_stat(func,column):
    tmp = np.full([Nexp_base,Nsextant],np.nan)   #columns in order
```

```
    from left to right: UR, LR, UL, LL, UA, LA (rows are different experiments)
     if index == 'threshIndex':
        tmp[:,0] = eval('[np.nan'+func+'(UR1.values[0:min_index1_UR,column]),\
        np.nan'+func+'(UR2.values[0:min_index2_UR,column]),np.nan'+func+'(UR3.values[0:min_index3_UR,column]),\
        np.nan'+func+'(UR4.values[0:min_index4_UR,column]),np.nan'+func+'(UR5.values[0:min_index5_UR,column]),\
        np.nan'+func+'(UR6.values[0:min_index6_UR,column])]')
        tmp[:,1] = eval('[np.nan'+func+'(LR1.values[0:min_index1_LR,column]),\
        np.nan'+func+'(LR2.values[0:min_index2_LR,column]),np.nan'+func+'(LR3.values[0:min_index3_LR,column]),\
        np.nan'+func+'(LR4.values[0:min_index4_LR,column]),np.nan'+func+'(LR5.values[0:min_index5_LR,column]),\
        np.nan'+func+'(LR6.values[0:min_index6_LR,column])]')
        tmp[:,2] = eval('[np.nan'+func+'(UL1.values[0:min_index1_UL,column]),\
        np.nan'+func+'(UL2.values[0:min_index2_UL,column]),np.nan'+func+'(UL3.values[0:min_index3_UL,column]),\
        np.nan'+func+'(UL4.values[0:min_index4_UL,column]),np.nan'+func+'(UL5.values[0:min_index5_UL,column]),\
        np.nan'+func+'(UL6.values[0:min_index6_UL,column])]')
        tmp[:,3] = eval('[np.nan'+func+'(LL1.values[0:min_index1_LL,column]),\
        np.nan'+func+'(LL2.values[0:min_index2_LL,column]),np.nan'+func+'(LL3.values[0:min_index3_LL,column]),\
        np.nan'+func+'(LL4.values[0:min_index4_LL,column]),np.nan'+func+'(LL5.values[0:min_index5_LL,column]),\
        np.nan'+func+'(LL6.values[0:min_index6_LL,column])]')
        tmp[:,4] = eval('[np.nan'+func+'(UA1.values[0:min_index1_UA,column]),\
        np.nan'+func+'(UA2.values[0:min_index2_UA,column]),np.nan'+func+'(UA3.values[0:min_index3_UA,column]),\
        np.nan'+func+'(UA4.values[0:min_index4_UA,column]),np.nan'+func+'(UA5.values[0:min_index5_UA,column]),\
        np.nan'+func+'(UA6.values[0:min_index6_UA,column])]')
        tmp[:,5] = eval('[np.nan'+func+'(LA1.values[0:min_index1_LA,column]),\
        np.nan'+func+'(LA2.values[0:min_index2_LA,column]),np.nan'+func+'(LA3.values[0:min_index3_LA,column]),\
        np.nan'+func+'(LA4.values[0:min_index4_LA,column]),np.nan'+func+'(LA5.values[0:min_index5_LA,column]),\
        np.nan'+func+'(LA6.values[0:min_index6_LA,column])]')

elif index == 'minIndex':
        tmp[:,0] = eval('[np.nan'+func+'(UR1.values[0:index1_UR,column]),\
        np.nan'+func+'(UR2.values[0:index2_UR,column]),np.nan'+func+'(UR3.values[0:index3_UR,column]),\
        np.nan'+func+'(UR4.values[0:index4_UR,column]),np.nan'+func+'(UR5.values[0:index5_UR,column]),\
```

```
        np.nan'+func+'(UR6.values[0:index6_UR,column])]')
        tmp[:,1] = eval('[np.nan'+func+'(LR1.values[0:index1_LR,
    column]),\
        np.nan'+func+'(LR2.values[0:index2_LR,column]),np.nan'+func+
    '(LR3.values[0:index3_LR,column]),\
        np.nan'+func+'(LR4.values[0:index4_LR,column]),np.nan'+func+
    '(LR5.values[0:index5_LR,column]),\
        np.nan'+func+'(LR6.values[0:index6_LR,column])]')
        tmp[:,2] = eval('[np.nan'+func+'(UL1.values[0:index1_UL,
    column]),\
        np.nan'+func+'(UL2.values[0:index2_UL,column]),np.nan'+func+
    '(UL3.values[0:index3_UL,column]),\
        np.nan'+func+'(UL4.values[0:index4_UL,column]),np.nan'+func+
    '(UL5.values[0:index5_UL,column]),\
        np.nan'+func+'(UL6.values[0:index6_UL,column])]')
        tmp[:,3] = eval('[np.nan'+func+'(LL1.values[0:index1_LL,
    column]),\
        np.nan'+func+'(LL2.values[0:index2_LL,column]),np.nan'+func+
    '(LL3.values[0:index3_LL,column]),\
        np.nan'+func+'(LL4.values[0:index4_LL,column]),np.nan'+func+
    '(LL5.values[0:index5_LL,column]),\
        np.nan'+func+'(LL6.values[0:index6_LL,column])]')
        tmp[:,4] = eval('[np.nan'+func+'(UA1.values[0:index1_UA,
    column]),\
        np.nan'+func+'(UA2.values[0:index2_UA,column]),np.nan'+func+
    '(UA3.values[0:index3_UA,column]),\
        np.nan'+func+'(UA4.values[0:index4_UA,column]),np.nan'+func+
    '(UA5.values[0:index5_UA,column]),\
        np.nan'+func+'(UA6.values[0:index6_UA,column])]')
        tmp[:,5] = eval('[np.nan'+func+'(LA1.values[0:index1_LA,
    column]),\
        np.nan'+func+'(LA2.values[0:index2_LA,column]),np.nan'+func+
    '(LA3.values[0:index3_LA,column]),\
        np.nan'+func+'(LA4.values[0:index4_LA,column]),np.nan'+func+
    '(LA5.values[0:index5_LA,column]),\
        np.nan'+func+'(LA6.values[0:index6_LA,column])]')

    return(tmp)

base_stats = np.full([5,Nsextant],np.nan)   #rows in order from top
    to bottom: median, mean, max, min, std
tmp = base_case_stat(func,column)
base_stats[0,:] = np.round(np.median(tmp,0))
base_stats[1,:] = np.round(np.mean(tmp,0))
base_stats[2,:] = np.round(np.max(tmp,0))
base_stats[3,:] = np.round(np.min(tmp,0))
base_stats[4,:] = np.round(np.std(tmp,0))

if Nexp == 1:
    def compared_exp_stat(func,column):
        tmp_exp = np.full([Nexp,Nsextant],np.nan)
        if index == 'threshIndex':
            tmp_exp[:,0] = eval('(np.nan'+func+'(UR.values[0:
```

```
min_index_UR,column]))')
            tmp_exp[:,1] = eval('(np.nan'+func+'(LR.values[0:min_index_LR,column]))')
            tmp_exp[:,2] = eval('(np.nan'+func+'(UL.values[0:min_index_UL,column]))')
            tmp_exp[:,3] = eval('(np.nan'+func+'(LL.values[0:min_index_LL,column]))')
        elif index == 'minIndex':
            tmp_exp[:,0] = eval('(np.nan'+func+'(UR.values[0:index_UR,column]))')
            tmp_exp[:,1] = eval('(np.nan'+func+'(LR.values[0:index_LR,column]))')
            tmp_exp[:,2] = eval('(np.nan'+func+'(UL.values[0:index_UL,column]))')
            tmp_exp[:,3] = eval('(np.nan'+func+'(LL.values[0:index_LL,column]))')

else:
    def compared_exp_stat(func,column):
        tmp_exp = np.full([Nexp,Nsextant],np.nan)
        if index == 'threshIndex':
            tmp_exp[:,0] = eval('(np.nan'+func+'(UR.values[0:min_index_UR,column]),\
            np.nan'+func+'(UR_2.values[0:min_index_UR2,column]),\
            np.nan'+func+'(UR_3.values[0:min_index_UR3,column]))')
            tmp_exp[:,1] = eval('(np.nan'+func+'(LR.values[0:min_index_LR,column]),\
            np.nan'+func+'(LR_2.values[0:min_index_LR2,column]),\
            np.nan'+func+'(LR_3.values[0:min_index_LR3,column]))')
            tmp_exp[:,2] = eval('(np.nan'+func+'(UL.values[0:min_index_UL,column]),\
            np.nan'+func+'(UL_2.values[0:min_index_UL2,column]),\
            np.nan'+func+'(UL_3.values[0:min_index_UL3,column]))')
            tmp_exp[:,3] = eval('(np.nan'+func+'(LL.values[0:min_index_LL,column]),\
            np.nan'+func+'(LL_2.values[0:min_index_LL2,column]),\
            np.nan'+func+'(LL_3.values[0:min_index_LL3,column]))')

        elif index == 'minIndex':
            tmp_exp[:,0] = eval('(np.nan'+func+'(UR.values[0:index_UR,column]),\
            np.nan'+func+'(UR_2.values[0:index_UR_2,column]),\
            np.nan'+func+'(UR_3.values[0:index_UR_3,column]))')
            tmp_exp[:,1] = eval('(np.nan'+func+'(LR.values[0:index_LR,column]),\
            np.nan'+func+'(LR_2.values[0:index_LR_2,column]),\
            np.nan'+func+'(LR_3.values[0:index_LR_3,column]))')
            tmp_exp[:,2] = eval('(np.nan'+func+'(UL.values[0:index_UL,column]),\
            np.nan'+func+'(UL_2.values[0:index_UL_2,column]),\
            np.nan'+func+'(UL_3.values[0:index_UL_3,column]))')
            tmp_exp[:,3] = eval('(np.nan'+func+'(LL.values[0:index_LL,column]),\
```

```
            np.nan'+func+'(LL_2.values[0:index_LL_2,column]),\
            np.nan'+func+'(LL_3.values[0:index_LL_3,column]))')

        return(tmp_exp)

exp_stats = np.full([5,Nsextant],np.nan)   #rows in order from top
    to bottom: median, mean, max, min, std
tmp_exp = compared_exp_stat(func,column)
exp_stats[0,:] = np.round(np.median(tmp_exp,0))
exp_stats[1,:] = np.round(np.mean(tmp_exp,0))
exp_stats[2,:] = np.round(np.max(tmp_exp,0))
exp_stats[3,:] = np.round(np.min(tmp_exp,0))
exp_stats[4,:] = np.round(np.std(tmp_exp,0))

Nbin=3
exp_Nbins=3
percent=75
### to calculate 75% & 25% of the data and calculate weightwd
    average and std average

t_upper=np.full((duration,Nsextant),np.nan)
t_lower=np.full((duration,Nsextant),np.nan)
weighted_average = np.full((duration,Nsextant),np.nan)
conct = np.full((duration,Nexp_base,Nsextant),np.nan)
weights = np.full((duration,Nexp_base,Nsextant),np.nan)
weighted_std = np.full((duration,Nsextant),np.nan)
weighted_average_mean=np.full((Nsextant),np.nan)
for k in range(0,Nsextant):
    if k == 0:
        sextant = 'UR'
    elif k == 1:
        sextant = 'LR'
    elif k == 2:
        sextant= 'UL'
    elif k == 3:
        sextant= 'LL'
    elif k == 4:
        sextant= 'UA'
    elif k == 5:
        sextant= 'LA'
    for t in range(0,duration):
        t_upper[t,k]=np.percentile(eval('(all_basecase_'+sextant+'
    _func'+'[t,:])'), percent)
        t_lower[t,k]=np.percentile(eval('(all_basecase_'+sextant+'
    _func'+'[t,:])'), 100-percent)

        hist = plt.hist(eval('(all_basecase_'+sextant+'_func'+'[t
    ,:])'),Nbin)
        plt.close()
        weight = np.full(Nexp_base,np.nan)

        for i in range(0,6):  #6 or 4 experiment
            tmp = np.sort(eval('(all_basecase_'+sextant+'_func'+'[t
```

```
,:])'))
            if method=='weighted_avg':
                for j in range(0,Nbin):   # 3 bins
                    if hist[1][j+0] <= tmp[i] <= hist[1][j+1]:
                    ###print(hist[0][j])
                        weight[i] = hist[0][j]
            elif method=='distance_weighted_avg':
                weight[i]=1/(np.sum(abs(tmp[i]-tmp)))   ### to calculate distance-weighted average

        conct[t,:,k] = tmp
        weights[t,:,k] = weight

        weighted_average[t,k] = np.sum(weight*tmp)/np.sum(weight)

        if method=='weighted_avg':
            weighted_std[t,k] = np.sqrt( np.sum(weight*((tmp-weighted_average[t,k])**2))/(np.sum(weight)-1))
        elif method=='distance_weighted_avg':
            weighted_std[t,k] = np.sqrt( np.sum(weight*((tmp-weighted_average[t,k])**2))/(np.sum(weight)))

    weighted_average_mean[k]=np.nanmean(weighted_average[:,k])
    average_base=np.round(np.nanmean(weighted_average))

if Nexp==3:
    exp_t_upper=np.full((duration,Nsextant),np.nan)
    exp_t_lower=np.full((duration,Nsextant),np.nan)
    exp_weighted_average = np.full((duration,Nsextant),np.nan)
    exp_weighted_std = np.full((duration,Nsextant),np.nan)
    number_of_bins = np.full((duration,Nsextant),np.nan)
    exp_weighted_average_mean=np.full((Nsextant),np.nan)
    for k in range(0,Nsextant):
        if k == 0:
            sextant = 'UR'
        elif k == 1:
            sextant = 'LR'
        elif k == 2:
            sextant= 'UL'
        elif k == 3:
            sextant= 'LL'
        elif k == 4:
            sextant= 'UA'
        elif k == 5:
            sextant= 'LA'
        for exp_t in range(0,duration):
            exp_t_upper[exp_t,k]=np.percentile(eval('(all_exp_'+sextant+'_func'+'[exp_t,:])'), percent)
            exp_t_lower[exp_t,k]=np.percentile(eval('(all_exp_'+sextant+'_func'+'[exp_t,:])'), 100-percent)

            number_of_bins[exp_t,k] = np.round((np.nanmax(eval('(all_exp_'+sextant+'_func'+'[exp_t,:])'))
```

```
            -np.nanmin(eval('(all_exp_'+sextant+'_func'+'[exp_t,:])')))
            /np.std(eval('(all_exp_'+sextant+'_func'+'[exp_t,:])')))

            exp_hist = plt.hist(eval('(all_exp_'+sextant+'_func'+'[exp_t,:])'),exp_Nbins)
            plt.close()
            exp_weight = np.full(Nexp,np.nan)

            for i in range(0,Nexp):  #3 experiment
                exp_tmp = np.sort(eval('(all_exp_'+sextant+'_func'+'[exp_t,:])'))
                if method=='weighted_avg':
                    for j in range(0,exp_Nbins):   # 2 or 3 bins
                        if exp_hist[1][j+0] <= exp_tmp[i] <= exp_hist[1][j+1]:
                            exp_weight[i] = exp_hist[0][j]
                elif method=='distance_weighted_avg':
                    if np.sum(abs(exp_tmp[i]-exp_tmp))==0:
                        exp_weight[i]=1
                    else:
                        exp_weight[i]= 1/(np.sum(abs(exp_tmp[i]-exp_tmp)))

            exp_weighted_average[exp_t,k] = np.sum(exp_weight*exp_tmp)/np.sum(exp_weight)

            if method=='weighted_avg':
                exp_weighted_std[exp_t,k] = np.sqrt( np.sum(exp_weight*((exp_tmp-exp_weighted_average[exp_t,k])**2))
                /(np.sum(exp_weight)-1))
            elif method=='distance_weighted_avg':
                exp_weighted_std[exp_t,k] = np.sqrt( np.sum(exp_weight*((exp_tmp-exp_weighted_average[exp_t,k])**2))
                /(np.sum(exp_weight)))

        exp_weighted_average_mean[k]=np.nanmean(exp_weighted_average[:,k])
        average_exp=np.round(np.nanmean(exp_weighted_average))

weighted_average=np.concatenate(weighted_average)
exp_weighted_average=np.concatenate(exp_weighted_average)

stats.shapiro(weighted_average_mean)
stats.shapiro(exp_weighted_average_mean)

[np.var(x, ddof=1) for x in [weighted_average_mean, exp_weighted_average_mean]]
stats.ttest_ind(np.concatenate(weighted_average_mean), np.concatenate(exp_weighted_average_mean), equal_var=True)
```

Appendix C

Critical Values for t Distribution

Table of Critical Values, $t_{\alpha,v}$, in a Student T-Distribution with v degrees of freedom and a confidence limit p where $\alpha=1-p$.

v	Confidence Limits (top) and α (bottom) for a One-Tailed Test.												
	60%	**75%**	**80%**	**85%**	**90%**	**95%**	**97.5%**	**98%**	**99%**	**99.5%**	**99.75%**	**99.9%**	**99.95%**
	0.4	**0.25**	**0.2**	**0.15**	**0.1**	**0.05**	**0.025**	**0.02**	**0.01**	**0.005**	**0.0025**	**0.001**	**0.0005**
1	0.32492	1.00000	1.37638	1.96261	3.07768	6.31375	12.70620	15.89454	31.82052	63.65674	127.32134	318.30884	636.61925
2	0.28868	0.81650	1.06066	1.38621	1.88562	2.91999	4.30265	4.84873	6.96456	9.92484	14.08905	22.32712	31.59905
3	0.27667	0.76489	0.97847	1.24978	1.63774	2.35336	3.18245	3.48191	4.54070	5.84091	7.45332	10.21453	12.92398
4	0.27072	0.74070	0.94096	1.18957	1.53321	2.13185	2.77645	2.99853	3.74695	4.60409	5.59757	7.17318	8.61030
5	0.26718	0.72669	0.91954	1.15577	1.47588	2.01505	2.57058	2.75651	3.36493	4.03214	4.77334	5.89343	6.86883
6	0.26483	0.71756	0.90570	1.13416	1.43976	1.94318	2.44691	2.61224	3.14267	3.70743	4.31683	5.20763	5.95882
7	0.26317	0.71114	0.89603	1.11916	1.41492	1.89458	2.36462	2.51675	2.99795	3.49948	4.02934	4.78529	5.40788
8	0.26192	0.70639	0.88889	1.10815	1.39682	1.85955	2.30600	2.44898	2.89646	3.35539	3.83252	4.50079	5.04131
9	0.26096	0.70272	0.88340	1.09972	1.38303	1.83311	2.26216	2.39844	2.82144	3.24984	3.68966	4.29681	4.78091
10	0.26018	0.69981	0.87906	1.09306	1.37218	1.81246	2.22814	2.35931	2.76377	3.16927	3.58141	4.14370	4.58689
11	0.25956	0.69745	0.87553	1.08767	1.36343	1.79588	2.20099	2.32814	2.71808	3.10581	3.49661	4.02470	4.43698
12	0.25903	0.69548	0.87261	1.08321	1.35622	1.78229	2.17881	2.30272	2.68100	3.05454	3.42844	3.92963	4.31779
13	0.25859	0.69383	0.87015	1.07947	1.35017	1.77093	2.16037	2.28160	2.65031	3.01228	3.37247	3.85198	4.22083
14	0.25821	0.69242	0.86805	1.07628	1.34503	1.76131	2.14479	2.26378	2.62449	2.97684	3.32570	3.78739	4.14045
15	0.25789	0.69120	0.86624	1.07353	1.34061	1.75305	2.13145	2.24854	2.60248	2.94671	3.28604	3.73283	4.07277
16	0.25760	0.69013	0.86467	1.07114	1.33676	1.74588	2.11991	2.23536	2.58349	2.92078	3.25199	3.68615	4.01500
17	0.25735	0.68920	0.86328	1.06903	1.33338	1.73961	2.10982	2.22385	2.56693	2.89823	3.22245	3.64577	3.96513
18	0.25712	0.68836	0.86205	1.06717	1.33039	1.73406	2.10092	2.21370	2.55238	2.87844	3.19657	3.61048	3.92165
19	0.25692	0.68762	0.86095	1.06551	1.32773	1.72913	2.09302	2.20470	2.53948	2.86093	3.17372	3.57940	3.88341
20	0.25674	0.68695	0.85996	1.06402	1.32534	1.72472	2.08596	2.19666	2.52798	2.84534	3.15340	3.55181	3.84952
21	0.25658	0.68635	0.85907	1.06267	1.32319	1.72074	2.07961	2.18943	2.51765	2.83136	3.13521	3.52715	3.81928
22	0.25643	0.68581	0.85827	1.06145	1.32124	1.71714	2.07387	2.18289	2.50832	2.81876	3.11882	3.50499	3.79213
23	0.25630	0.68531	0.85753	1.06034	1.31946	1.71387	2.06866	2.17696	2.49987	2.80734	3.10400	3.48496	3.76763
24	0.25617	0.68485	0.85686	1.05932	1.31784	1.71088	2.06390	2.17154	2.49216	2.79694	3.09051	3.46678	3.74540
25	0.25606	0.68443	0.85624	1.05838	1.31635	1.70814	2.05954	2.16659	2.48511	2.78744	3.07820	3.45019	3.72514
26	0.25595	0.68404	0.85567	1.05752	1.31497	1.70562	2.05553	2.16203	2.47863	2.77871	3.06691	3.43500	3.70661
27	0.25586	0.68368	0.85514	1.05673	1.31370	1.70329	2.05183	2.15782	2.47266	2.77068	3.05652	3.42103	3.68959
28	0.25577	0.68335	0.85465	1.05599	1.31253	1.70113	2.04841	2.15393	2.46714	2.76326	3.04693	3.40816	3.67391
29	0.25568	0.68304	0.85419	1.05530	1.31143	1.69913	2.04523	2.15033	2.46202	2.75639	3.03805	3.39624	3.65941
30	0.25561	0.68276	0.85377	1.05466	1.31042	1.69726	2.04227	2.14697	2.45726	2.75000	3.02980	3.38518	3.64596
40	0.25504	0.68067	0.85070	1.05005	1.30308	1.68385	2.02108	2.12291	2.42326	2.70446	2.97117	3.30688	3.55097
50	0.25470	0.67943	0.84887	1.04729	1.29871	1.67591	2.00856	2.10872	2.40327	2.67779	2.93696	3.26141	3.49601
60	0.25447	0.67860	0.84765	1.04547	1.29582	1.67065	2.00030	2.09936	2.39012	2.66028	2.91455	3.23171	3.46020
70	0.25431	0.67801	0.84679	1.04417	1.29376	1.66691	1.99444	2.09273	2.38081	2.64790	2.89873	3.21079	3.43501
80	0.25419	0.67757	0.84614	1.04320	1.29222	1.66412	1.99006	2.08778	2.37387	2.63869	2.88697	3.19526	3.41634
90	0.25410	0.67723	0.84563	1.04244	1.29103	1.66196	1.98667	2.08394	2.36850	2.63157	2.87788	3.18327	3.40194
100	0.25402	0.67695	0.84523	1.04184	1.29007	1.66023	1.98397	2.08088	2.36422	2.62589	2.87065	3.17374	3.39049
500	0.25348	0.67498	0.84234	1.03751	1.28325	1.64791	1.96472	2.05912	2.33383	2.58570	2.81955	3.10661	3.31009
1000	0.25341	0.67474	0.84198	1.03697	1.28240	1.64638	1.96234	2.05643	2.33008	2.58075	2.81328	3.09840	3.30028
∞	0.25335	0.67449	0.84162	1.03643	1.28155	1.64485	1.95996	2.05375	2.32635	2.57583	2.80703	3.09023	3.29053

Explanatory Notes

- For a **Two-Tailed Test**, use the α here that corresponds to *half* the two-tailed α.
  - For example if a two-tailed confidence limit of 90% is desired (α=0.1), use a one-tailed α from this table of 0.05
- In the limit $v=\infty$, this distribution is equivalent to a normal distribution X~N(0,1)

Figure C-1: Critical value table of the t distribution [1].