Aerosols and Particulates Emitted by Speech and Breath

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Human-to-human transmission of upper respiratory diseases such as COVID-19 is primarily driven by the dispersion of virus-laden droplets that are expelled from the nose and mouth. Aerosolized droplets can concentrate in the air for hours and pose a significant threat to human activities in the aerospace and aeronautics industry, which frequently occur in confined environments. Tracking data has shown that the virus spread quickly in confined spaces, such as airplanes and ships. Updated guidelines for human interaction in confined spaces (i.e., less than 6ft in distance between individuals) is critical as the world tries to return to normal operations. A lack of data exists concerning the extent of exposure to aerosolized particles in ecologically relevant, non-intrusive scenarios. Studies involving exhalation into small boxes or funnels do little to advance the fundamental understanding of exposure risk associated with many activities. This research aims to meet the need by investigating the quantity, concentration, and distribution of particles exhaled while speaking and breathing. This data can be used to verify computational models of the same. To accomplish this, specific vocal exercises and activities will be performed in a clean, room-sized environment to generate the airborne droplets associated with each activity. Images of these particles will be captured using a 1200 frame-per-second optical camera and a high-power laser, then analyzed numerically using computer software. The resulting data sets will be compared and used to draw conclusions about the volume and behavior of aerosolized particles associated with various vocal activities. Initial tests suggest very different results than those which implement intrusive data collection. Future studies using this experimental setup will investigate patterns that are discovered and the effectiveness of risk mitigation.

I. Introduction

Airborne transmission of diseases has become an obstacle for many activities in which face-to-face contact is unavoidable. Many aerospace pursuits involve situations in which people are confined in small spaces together. Some examples include small cockpits with multiple operators or the passengers on a commercial flight. Non-aerospace situations of interest include dentistry, speech pathology, and music education/performance. Since wearing a mask is impractical or impossible for such activities, new safe practices must be implemented based on a better understanding of exposure to exhaled particles. Specific vocal activities will be selected for the research that are relevant to these scenarios to better understand how the particles behave after exhalation.

Some of the best and most well-known investigations in this topic are focused on investigating the airflow that originates at the oral and nasal cavity. Techniques used to observe the airflow usually include shadow-graphing or schlieren imaging to collect optical data; this type of data is shown in Fig. 1. This kind of imaging is non-intrusive to the expiration event, and the data is therefore ecologically relevant for everyday scenarios. However, many studies

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focus exclusively on abrupt events like coughing and sneezing, such as a 2008 study which documented airspeed during a cough [1]. Other studies that apply this technique to speaking and regular breathing still do not provide data about the particles expelled by the airflows they investigate.

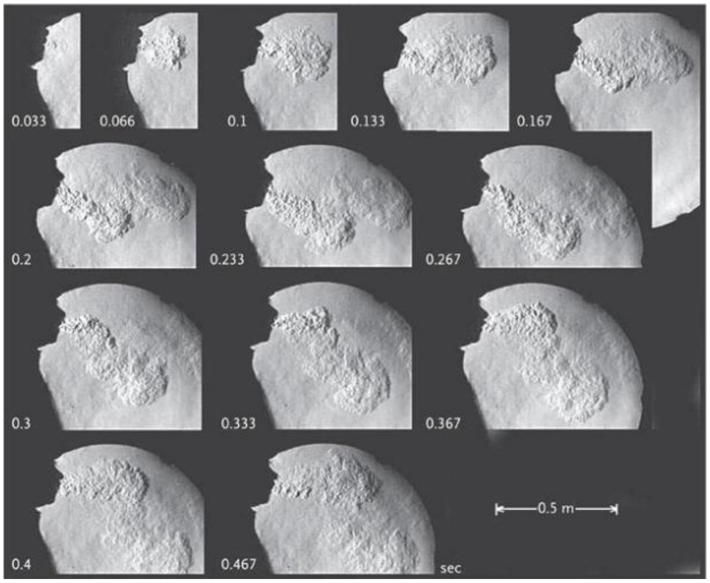

Fig. 1 Schlieren Images of Airflow during a Cough [1]

Other studies focus exclusively on the particulate matter that is expelled during a cough, a sneeze, or regular breathing. The number and size of particles have been investigated and documented in various studies, as well as some identifying the presence of pathogens and viral material [2]. However, as shown in Fig. 2, the techniques used for these studies are usually intrusive and involve collection of the particles in a funnel or box as soon as they leave the subject's oral or nasal cavity, interrupting the airflows that occur naturally. There is also no visualization of the behavior of particles as they disperse in the air.

Fig. 2 Collection Mask used in Viral Aerosol Study [2]

The current study aims to give a visual representation of the particles emitted from the nose and mouth, while also providing quantitative conclusions about particle count, size, distribution, and dispersion at three different close-range distances from the source. A careful process of image collection and algorithmic analysis for data collection allows both objectives to be accomplished. The unique experimental setup of this study allows participants to be safely positioned near a light source powerful enough to illuminate the particles in question and capture images of them with a high-speed camera for analysis. The images and image sequences can provide a better understanding of the behavior of the particles, while the numerical and statistical data can be used to verify computational models which attempt to predict the motion of the particles.

II. Background

The particles this research aims to study, aerosols and droplets, range from one to about one-hundred micrometers in diameter and are not visible to the naked eye in most cases. Recent studies have found two of the three primary routes of human-to-human transmission of COVID-19 are the droplet and airborne routes. The droplet route involves those larger particles that are ejected at a close enough range to contact another person's mouth or nose directly, while the airborne route involves the inhalation of aerosolized droplet nuclei which are carried through the air some time after their initial expulsion [2].

Aerosols, usually defined as particles less than 10 micrometers in diameter, are a subject of particular interest because virus-carrying aerosols can stay airborne and travel through a space, posing a risk of infection for hours. A study published in 2009 demonstrates that exhaled particles carry multiple pathogens, even influenza [3]. Other studies can estimate how many aerosolized particles are likely to be viral. Combining that data with an estimate of how many particles a person is likely to be exposed to allows the exposure risk of an activity to be determined quantitatively. Thus, a meaningful investigation of viral exposure risk for an activity needs to take into account the number of particles a person can expect to encounter.

III. Experiment Design and Setup

To meet the aims of the research study, an experiment was designed with the goal of quantifying particle count, size, distribution, and dispersion at three different close-range distances while a participant is performing predefined vocal activities. These activities were designed to capture a range of speech characteristics (sounds with frication and plosive emissions and with voicing). Physiological measurements were also included to better understand individual differences in particle emission, which included respiratory (chest wall excursion, vital capacity, oral and nasal airflow), vocal (frequency/ intensity, glottal contact area), and cardiovascular (heart rate, oxygen saturation) measures. The study which is approved by the Institutional Research Board (PRO-FY2021-26) will include approximately 25 participants to assess whether the results obtained are statistically significant.

Figure 3 illustrates the original conceptual design for the setup of the proposed experiment which includes the laser, camera, and participant head enclosure mounted on an optical table. The concept involves a participant performing vocal activities while seated with their head placed in a small enclosure that consists of a frame with a solid front panel with an opening for the nose and mouth. Laser sheet imaging is the technique that will be used for data collection. The laser in the lab is a neodymium yttrium-aluminum garnet pulsed laser that operates at 532 nanometers, a wavelength in the green visible-light spectrum. The beam passes through a beam-spreader lens to transform the shape of the laser into a vertical sheet which is two to three millimeters in thickness. This laser sheet will pass in front of an opening in a vertical board which the participant will be seated behind as illustrated in Fig. 3.

The participant head frame was subsequently modified after some trial and error to increase participant comfort and to reduce reflective light from the laser sheet. As shown in Fig. 4, the top and sides in the enclosure are covered by a dark cloth capable of preventing ambient light from entering the enclosure. The front of the enclosure is constructed of a solid wood frame, and its main purpose is to ensure the source of particulates, namely, the subject's oral and nasal cavity, stays at a consistent distance from the laser. The frame can be set such that the participant is seated at three distances from the laser. The set distances are roughly one, six, and twelve inches. The laser is fixed in place with little ability to move in a planar direction, so this frame solution allows data to be collected for three different cross-sections of the airflow that is being expired.

As the participant performs the vocal exercises, particulate matter scatters the laser light when it passes through the illuminated plane, and the light is scattered into the lens of the camera. The camera captures images in sequence of all the aerosols and droplets that pass through the plane of the laser.

All proper PPE (personal protective equipment), including laser safety goggles, are provided for the participant and the technical operator in the lab. The laser and camera are positioned on a table, and the entire setup is enclosed in a 10ft x 10ft x 12ft sealed canopy tent as shown in Fig. 5. A HEPA filtration unit is used to reduce the number of stray particulate matter in the air before each data collection scenario. This allows for an ecologically relevant simulation of speech in a small room or enclosed space, while also isolating the particles of interest as they are carried along by expired airflow.

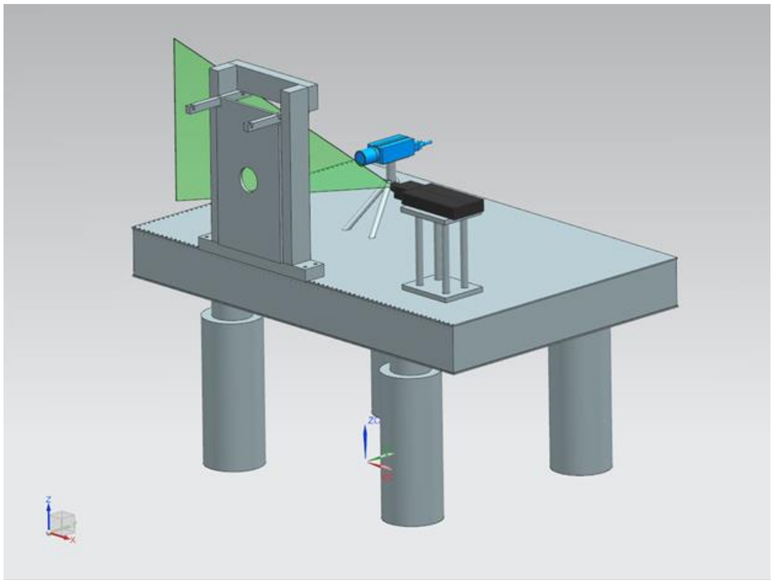

Fig. 3 Model of Camera, Laser, and Enclosure Frame Setup

Fig. 4 Participant Enclosure Position in Laboratory

Fig. 5 Enclosed Space with Laboratory Setup

IV. Experiment Procedures

A. Speech Pathology

Before a participant enters the laser laboratory, a speech pathologist will conduct a short, voluntary survey of the subject's vocal physiology and characteristics. This de-identified data may be used in future investigations on factors that affect levels of aerosol expiration from person to person. Then, they will introduce the subject to the vocal tasks they will perform while in the data collection portion of the study.

The vocal tasks include repetitions of vowels, mid-fricative, front-plosive, and back-plosive consonants, as well as oral breathing, nasal breathing, coughing, and sneezing. For some of these tests, a loud version and a soft version will be performed, and a high-pitched and low-pitched version. Exercises covering all these categories will be done three times – one each at one, six and twelve inches from the laser sheet.

B. Laser and Camera Data Collection

Once in the laboratory, participants are positioned on an adjustable seat such that their mouth and nose line up with the opening in the enclosure. As they perform the vocal tasks, the laser will illuminate the particles and the camera will capture images. An audio recording and a decibel level reading will also be collected and synchronized.

The camera captures black and white images very rapidly. These images are not in color which requires the setup to be calibrated for high-contrast images such that any particles that pass through the plane of illumination stand out in stark contrast to the background. For this reason, a dark color was chosen to cover the board with the opening for the mouth and nose, a dark cloth covers the top and sides of the enclosure to keep ambient light from bouncing off any interior surfaces, and the participants will wear a dark face covering so none of their features are visible in the data. The resulting images isolate the particulate matter in the plane of the laser. Then, an image processor can prepare the image to be numerically analyzed. For each vocal task performed, between four hundred and six hundred images are taken, which are analyzed in batches by the software. The number of particles present as well as their size are recorded for each image in the sequence. Examples of a raw image and processed image are shown in Fig. 6a and Fig 6b, respectively. Many of the particles are only a few pixels in diameter, but they are large enough to be counted by the software accurately.

(a)

(b)

Fig. 6 Vocal Aerosols Illuminated in the Laser Plane Before (a) and After (b) Processing

C. Data Processing and Analysis

The numerical data can be synchronized with the audio recording and decibel level data to show how many particles are being emitted at each moment during a vocal activity. This data is available for cross-sections of the flow one, six, and twelve inches from the mouth and nose. Since the data can be plotted against time, it can be inferred how quickly particles have propagated away from the source. The decrease in concentration of these particles over this short distance from the source can also be investigated.

An early obstacle to isolation of the data is air quality. With no filtration system in place, the particulate matter and dust that is already present in the air appears in the captured image. This creates a steady average of background particles in the data, even when no vocal activity is taking place. To reduce the number of unwanted particles, we introduced the 10ft x 10ft x 12ft canopy which was large enough to cover the entire setup and can be sealed at all openings to the outside, creating a smaller isolated space. A 400 CFM (cubic feet per minute) 4-layer HEPA filter is placed inside the canopy and is run continuously in the lab to keep the number of unwanted particles very low. The filter is turned off during testing so the air movement it causes will not interfere with the behavior of the particles expelled by the participant.

A small number of background particles, 2 to 3 particles per frame on average, is likely to remain present in each trial. These levels can be estimated for each case so the additional data can be factored out of the results numerically. Any data points that are statistically significant above that background particle level can safely be used to analyze the behavior of aerosols expelled by the vocal task being performed in the test.

V. Results

The study is in early stages of testing and data collection. The only tests performed have been those using student researchers as the subjects. However, the early data shows a very clear ability to see the particles that have been expelled and how quickly they disperse over time. The graph shown in Fig. 7 is the result of a researcher performing an exercise called a lip trill at a distance of one inch from the laser sheet. A lip trill is a sharp exhalation through the mouth while tightening the lips, which is expected to produce a large number of aerosols and droplets. A clear spike in particle count occurs as soon as the exercise begins, and the decrease over time shows how quickly the number returns to a background level, even in a cross-section this close to the mouth and nose. A similar result can be seen in Fig. 8 from a front-plosive consonant, “Pa,” which occurs three times in the data shown below where three spikes in the particle count are clearly visible. For the test in Fig. 8, the participant was six inches from the laser sheet.

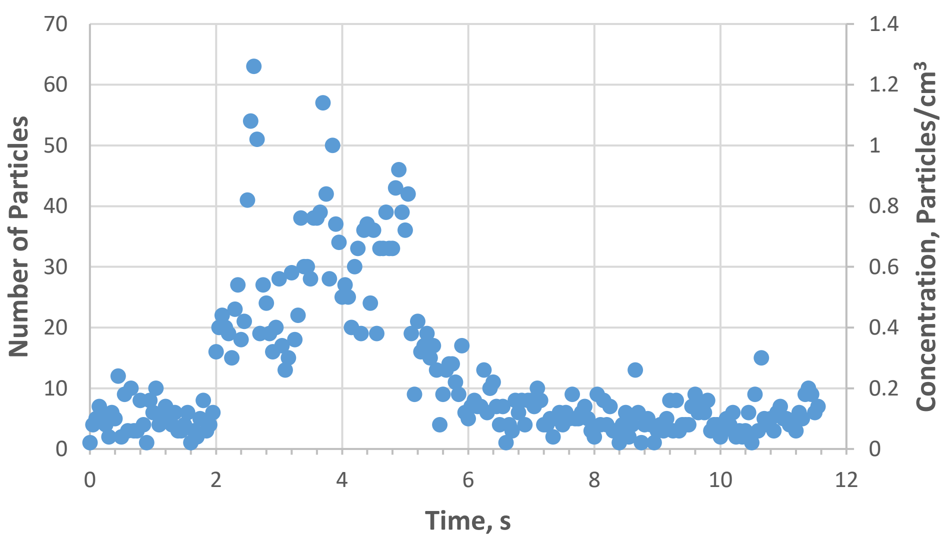

Fig. 7 Number and Concentration of Aerosols One Inch from the Source during a Lip Trill

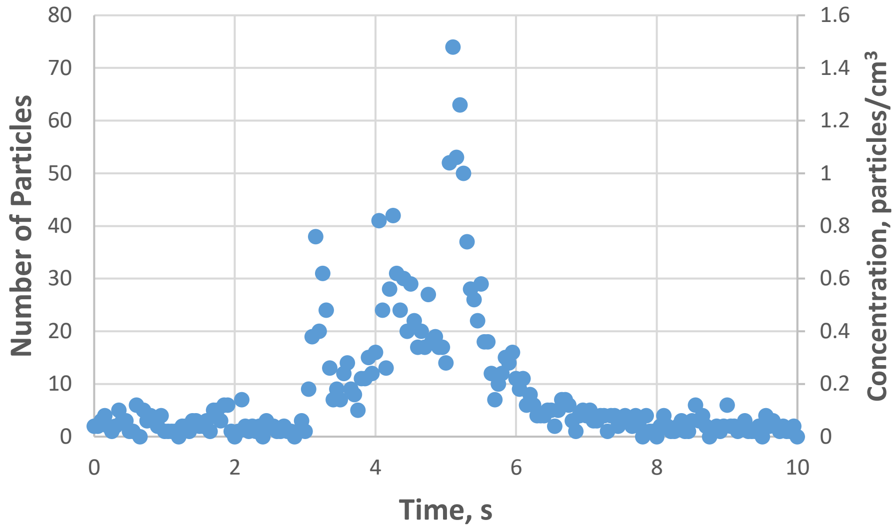

Fig. 8 Number and Concentration of Aerosols Six Inches from Source During Three Instances of a Front-Plosive Consonant

Data collection will involve collecting roughly sixty such data sets for each participant. The subsequent analysis is expected to produce qualitative visual results and quantitative statistical results.

VI. Conclusions and Future Investigation

The initial results of this study are expected to uncover relationships between ecologically relevant factors and aerosol emission. This can inform further investigation of the strongest observed relationships. Some of the factors considered in this phase of the study include speech, simple breathing (nasal and oral), decibel level and pitch for each, and participant lung capacity. These factors will be compared to the number, average size, and concentration of particles, as well as how far and fast they travel from the mouth.

Other factors can also be accounted for in future studies. In the current tests, the relative humidity will be held constant. Varying this could influence the number or size of particles, or how quickly they move away from the source. Vocal activities that appear to pose a higher risk of exposure may be studied further, and potential mitigation factors can also be tested for effectiveness using this method.

The study will meet the need for quantitative data supporting safe practices and risk mitigation needs for activities in which people interact in small, enclosed spaces. This is the first time to the researchers' knowledge that data sets ecologically relevant to everyday scenarios have been collected for analysis. Knowledge of the conclusions can help many aerospace activities to continue safely and with peace of mind.

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