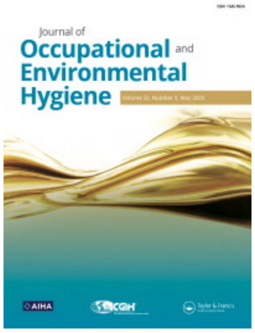

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REPORT

Aerosol emission, transmission, and mitigation from performing singing and wind instruments

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ABSTRACT
During the COVID-19 pandemic, concerns about potential airborne virus transmission and exposure during musical performances were raised. Past studies suggest that aerosols are emitted from exhaling and talking with varying magnitudes. Meanwhile, little was known about aerosol emissions from singing and playing wind instruments. The objective of this study was to examine the spatial and temporal build-up of aerosol concentration in a typical studio room where singing, talking, and playing wind instruments are involved, to represent musical practicing and teaching scenarios at the University of Cincinnati College-Conservatory of Music (CCM). Four condensation particle counters were strategically placed throughout a room at various distances from the performer. Besides singing, musical professionals played seven instruments (clarinet, flute, French horn, saxophone, trombone, trumpet, and tuba). Two types of tests were conducted for each instrument: 10 min of playing and 10 min of combined playing and talking to mimic the teaching session. The results show that singing increased aerosol concentration to $3.9 \times 10^3\ cm^{-3}$ at the performing point, more than double the background ($1.2 \times 10^3\ cm^{-3}$). Most wind instruments had minimal but detectable emission of aerosols over time, suggesting instruments could provide wall deposition for aerosols compared to singing. Particle concentrations decreased further from the performing point; however, they were still detectable over the background level at 10 feet away. Use of a portable high-efficiency particulate air (HEPA) filtration reduced aerosol concentrations developed during musical performances to below background level. These findings suggest that there are risks associated with aerosolized transmission of infectious agents such as SARS-CoV-2 from musical performance if the performer is infected. Distancing beyond the 6 ft distancing recommendation and proper room and local ventilation combined with disinfecting procedures are needed to minimize the risk of exposure to infectious aerosols.

KEYWORDS
COVID-19; droplet; music; musical performance; SARS-CoV-2; singing

Introduction

Human activities involving air movements and exhaling, such as breathing, talking, and singing, are known to produce aerosols above background levels of indoor air (Alsved et al. 2020; Archer et al. 2022; Echternach et al. 2020; Gregson et al. 2021; Johnson et al. 2011; Johnson and Morawska 2009; Mürbe et al. 2020). The emission of aerosols during these activities is typically attributed to the vibrations of vocal folds and adjustments of articulation (Johnson and Morawska 2009; Mahjoub Mohammed Merghani et al. 2021), turbulent air flows due to inhalation and exhalation, while production of moist saliva and mucus facilitate the formation of droplets (Good et al. 2021). Several studies suggested that the emission rates of aerosols from talking and singing are positively correlated to the vocal range, notes, frequencies, and volumes (Asadi et al. 2019; Westphalen et al. 2021; Zhang 2016). Particle concentration and size distribution in exhaled aerosols have also been shown to vary by age and gender, with emission rates ranging between hundreds to thousands of particles per second (Firle et al. 2021; Mürbe, Kriegel et al. 2021; Mürbe et al. 2021; Volckens et al. 2022). Besides talking and vocal performance, wind instruments were also suspected as potential aerosol emission sources. In general, wind instruments made of either brass or wood contain a mouthpiece that is directly in contact with the musician's mouth, while the musician blows into a pipe-like resonator to produce various notes. Each type of

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wind instrument is designed differently on how the airstream travels through the complex pipes and exit bells (McCarthy et al. 2021; Stockman et al. 2021). In the past, most studies of infectious risk were on microbial (virus and bacteria) contamination of wind instruments, with speculations of microbial survival on instrument surfaces. However, before the COVID-19 pandemic, very few studies have been conducted on the emission of infectious aerosols from playing wind instruments. Even though the COVID-19 Pandemic has ended, it is critical to understand the airborne transmission route of similar infectious agents and the implications for musical performances in indoor space settings.

Among all recent infectious agents, SARS-CoV-2 is a highly infectious and somewhat deadly virus that emerged in late 2019. It poses unique health risks to musicians and audiences (Karimzadeh et al. 2021). Although the exact transmission and primary infection route of COVID-19 has been debated to be via droplet particles ($> 5\,\mu m$ in diameter) *vs.* aerosols (p$\leq$ µm in diameter), there is strong evidence suggesting airborne transmission from several superspreading events of musical nature (Jayaweera et al. 2020; Sills et al. 2020; Tang et al. 2020). Choir practices early on during the COVID-19 pandemic in Europe and the US were reported to have nearly 80% of participants infected. Participants in the Washington State Choir reported having used facemasks and observing 6 ft distancing, while still having 52 out of 60 participants infected. Protective measures such as 6 ft distancing and use of loose-fitting facemasks work relatively well with droplet transmission, since larger particles tend to stay airborne for less time and settle due to gravity (Prather et al. 2020). However, these measures are less effective with smaller particles, as these particles can stay airborne longer and penetrate cloth facemasks (Howard et al. 2021). Other characteristics of COVID-19, including asymptomatic infection and high viral load in the upper respiratory tract, also facilitated the transmission during these events (Baghizadeh Fini 2020; Eiche and Kuster 2020).

Because of the nature of singing and playing wind instruments, it is rather difficult to implement the use of face masks and other source reduction measures (Graf et al. 2021; Kniesburges et al. 2022). Most musical events, including practices and performances, are held in crowded indoor environments with inadequate ventilation, increasing the risk of musician and audience exposure to SARS-CoV-2 virus-laden aerosols when someone in the group is infected (Kähler and Hain 2020). One study showed that COVID-19-positive patients can emit a significant amount of virus-laden fine aerosol from singing (Coleman et al. 2021). Other studies showed generation of large amounts of particles from playing instruments (Quentin et al. 2022; Stockman et al. 2021; Volckens et al. 2022; Wang et al. 2022). Exposure to elevated aerosol concentrations containing infectious virus particles indoors could lead to spreading events (Abraham et al. 2021). The aerosol concentration in the room can also be affected by several factors such as temperature, humidity, room size and layout, ventilation, and air exchange rates (Morawska et al. 2017; Narayanan and Yang 2021).

Musical performance is an integral part of human society that begins with musical education (Austin 2021; Shaw and Mayo 2021). Many organizations, such as K-12 musical education programs, colleges, and orchestras, resumed practice, teaching, and performing during the pandemic while the risks associated with COVID-19 infection still existed (de Bruin 2021; Firle et al. 2021; Goursaud 2021; Naunheim et al. 2021; Vance et al. 2021). In late 2020, the College-Conservatory of Music (CCM) at the University of Cincinnati was planning to bring instructors and students back to campus. CCM hosts various music education programs that utilize 1-on-1 teaching and practicing in small studio settings. Unlike larger rooms, such as a rehearsal hall, smaller rooms, or studios with people near one another present a higher risk of occupant infection. Due to the potential risks of COVID-19 transmission, these activities only resumed after an examination of aerosol emissions from singing and playing wind instruments, potential exposures, and efficacy of mitigation measures beyond facemasks and/or 6 ft social distancing recommendations (Hedworth et al. 2021; Joshi and Battaglia 2021).

This study aimed to characterize spatial and temporal changes in aerosol concentrations during musical practice and education in the small studio setting at CCM. High-pitched vocal singing and playing of wind instruments were conducted in a studio, with several direct-reading aerosol instruments placed strategically to collect time-series data on particle count concentrations. Different scenarios, such as practicing and teaching, were reflected in the experimental plan with the combination of musical performance and talking. Use of a portable air filtration unit as a potential mitigation measure was evaluated.

Methods

Testing locations and musical performance sessions

Real-world practicing and teaching scenarios at CCM were replicated as part of this study. A typical studio

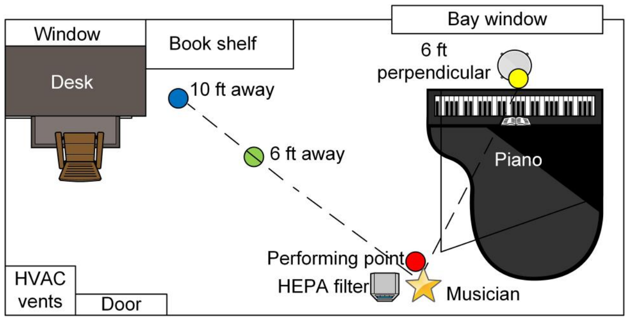

Figure 1. The layout of the studio room, points of interest, and sampling locations. The CPC was located at the performing point (red dot) next to the musician (star) who was facing desk/book shelf at the far end. The P-Traks were placed at 6 ft (green dot) and 10 ft (blue dot) along the direction that the performer was facing and 6 ft perpendicular at the pianist's location (yellow dot).

(Room 274 in Memorial Hall) was chosen as the study site. There are many near identically sized teaching and practicing rooms throughout Memorial Hall. The room is rectangular-shaped with a dimension of 10.5 feet by 22 feet, with an 11-foot ceiling height. The room layout is depicted in Figure 1. There was a grand piano on one side of the room, separating singers/wind instrument players and pianists. Some furniture was placed on the other side of the room (i.e., desk, chair, and bookshelves). Locations of heating, ventilation, and air conditioning (HVAC) air vent grilles and doors are shown in Figure 1. The relatively small size of the studio allowed a higher air exchange rate than larger rooms, and was also equipped with an isolated HVAC unit primarily to prevent sound transmission in different studio rooms, with the side benefits of isolating rooms from exchanging air through the HVAC system. The HVAC air handling unit setting was fixed at medium throughout the study. Ventilation rates at the HVAC vents were measured with a thermoanemometer (TSI VelociCheck, Minneapolis, MN) using 5×5 grid traverses to measure air velocity (ft/s) at the grille faces. The air exchange rates (ACH) were then calculated by dividing flow rates (CFM) by the room volume. Room temperatures and relative humidity were recorded by a probe connected to a multifunction indoor air meter (TSI Q-Trak, Minneapolis, MN). During the study, average temperature and humidity were relatively consistent at $76 \pm 2.1\,°F$ and $49 \pm 4\%$, respectively.

A total of ten musical performers with different instrument specialties participated in the study. The performers' ages ranged between 24 and 58 years old, with four males and six females. Musical performers were asked to stand or sit at the "musician spot" by themselves while singing/playing wind instruments in the room, while researchers conducted the time logging and gave out directions (singing, playing, talking, taking breaks) through a two-way radio in the adjacent room. Each experiment session lasted 10 min, with two types of activities:

1. Practicing scenario: 10 min of singing or playing wind instruments
2. Teaching scenario: 3 min of singing or playing wind instruments, followed by 2 min of talking, mimicking teaching, and then repeating the cycle.

For the singing sessions, singers performed mezzo-soprano voice since it represents the typical middle to high range for female singers volunteering for this study. Besides singing, seven wind instruments were played in the study: clarinet, flute, French horn, saxophone, trombone, trumpet, and tuba. Table 1 summarizes the characteristics relevant to airflow and aerosol transportation of these instruments. The combination of each type of activity (practicing *vs.* teaching) with every instrument was repeated three times ($n = 48$). Singers and wind instrument players were asked to perform the same notes consistently during all the 10-min sessions. There was at least a 30-min break between each session, with the room being empty and purged to reduce aerosol concentration back to near the original background level as measured before the experiment session. The purging process involved increasing airflow by increasing the air handler fan speed and opening windows and the door to facilitate fresh air exchange. This "purging" process ensured the minimal impact from residual particles generated during the previous experiment session.

Particle counting

Four points of interest were strategically identified and shown in Figure 1. A portable condensational particle counter (CPC, TSI 3007, Shoreview, MN) and three portable ultrafine particle counters (P-Trak, TSI 8525, Shoreview, MN) were put on stands sitting at a 43-inch height throughout the room. The height of the stand was determined based on the average breathing height of seated individuals. The layout of placements ensured the examination of potential exposure at various distances.

Detection limits of CPC and P-Trak used in this study were nearly identical, with a maximum concentration of 10^5 # cm^{-3}, except the CPC has a lower size cutoff of 10 nm, compared to 20 nm in the P-Trak. This slight difference is negligible since the size of interest in this study was much higher than 10–

Table 1. Characteristics of wind instruments related to airflow and aerosol transportation.

Instrument	Material	Mouthpiece design	Tube design	Tube length	Bell design	Bell facing when performing
Clarinet	Wood	Single reed	Straight cylindrical	2 ft	Flared	Downward at 45 degrees
Flute	Metal	Reedless	Straight	2 ft	Straight	Side
French horn	Brass	Brass mouthpiece	Conical many turns	12-13 ft	Flared	Backward
Saxophone	brass	Single reed	Conical 2 turns	4 ft	Flared	Forward
Trombone	Brass	Brass mouthpiece	Mainly cylindrical until the bell	9 ft	Flared	Forward
Trumpet	Silver-plated brass	Brass mouthpiece	Mainly cylindrical until the bell	6.5 feet	Flared	Forward
Tuba	Silver-plated brass	Brass mouthpiece	Conical many turns	16 feet	Flared	Upward

20 nm, with SARS-CoV-2 being over 100 nm and droplets over 5 µm. All the particle counters used in this study have a nominal inlet airflow rate of 0.7 liters per minute (Lpm). The measurement intervals for CPC and P-Traks were synchronized at 5 s.

Mitigation of aerosol concentrations

Most building HVAC systems are ineffective against fine and ultrafine aerosols due to air circulated with low minimum efficiency reporting value (MERV) rated filters. One potential method to control elevated aerosol concentration at the performing point is to have localized ventilation with HEPA filtration capacity close to the performer to capture aerosols as close to the source as practicable. After the initial experiment of studying aerosol emission from singing and playing wind instruments, a follow-up study was conducted with the singer with a portable HEPA air filtration unit (Germ Guardian 22-inch Tower unit, West Chester, PA). The air filtration unit had a nominal filtration efficiency of at least 99.97% for particulate matter greater than 0.3 µm in size. However, virus particles can be smaller than 0.3 µm and may not be fully captured by the filter alone. Clean air delivery rates (CADR) are standardized measures that indicate the volume of clean air produced by an air purifier (AHAM 2022). This unit provided a CADR of 96/98/102 against smoke/pollen/dust with an air exchange rate of 3.7 air changes per hour (ACH) in the room studied. The air filtration unit was placed next to the performer, as noted in Figure 1. The air filtration unit came with an ultraviolet (UV) lamp for disinfection, but the UV lamp was not activated during the study to avoid potential confounding factors.

Quality control and statistical analysis

All CPC and P-Traks were calibrated before the study, and zero tested with a HEPA-filtered inlet. A blank test with a zero filter was periodically conducted during the experiment. Background aerosol concentrations in the room were acquired before any session. The criterion for background level was to have a stable aerosol concentration over 1 min with a fluctuation of less than 5%. There was at least 30-min break period between switching singers/players. During the break period, room airflow was increased through the opening of windows and doors, and the HVAC setting was turned to high, to clear residual particle concentrations contributed by prior experiments.

Triplicate experiments were conducted for each combination of singing/instruments and practicing/teaching. Time-series data of particle concentrations were fitted to the time log, and elevated particle concentrations contributed by singing/instruments were plotted over each 10-min session. Average time series data could reduce the autocorrelation effect commonly seen with time-series data from a direct reading instrument. Results were expressed as mean ± standard deviation (SD). Normality and homogeneity of data variances were validated using a normality test and Levene's test before any statistical test was conducted. To assess the significance of differences in background concentrations with and without people present, a Student *t*-test was utilized. The effects of instrument types, sampling locations, and practicing *vs.* teaching were evaluated using a three-way analysis of variance (ANOVA) followed by the Holm-Šídák paired comparison test, with a significance level of $p = 0.05$.

Results

Background particle concentration

At the beginning of each session, a background level of particle concentration was recorded without human presence. Then the musician entered the room, and another 10 min of particle concentration with human presence was recorded. These sessions were used to determine if the "true" background of the room was affected by merely human breathing without talking or any musical activity. As shown in Figure 2, the average aerosol concentration at the performing point with and without human presence was 1.8×10^3 # cm^{-3}, without any significant difference ($p = 0.40$). Sampling locations did not affect background aerosol concentration ($p = 0.08$). The average room background level between 1.7 and 1.9×10^3 # cm^{-3} was considerably lower than

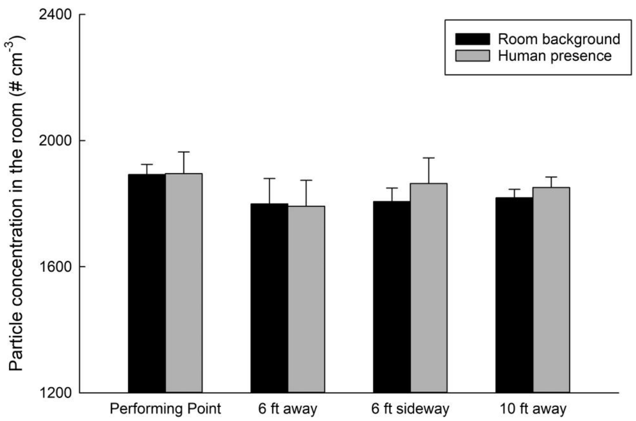

Figure 2. Average aerosol concentration (±standard deviation) in the room with and without human presence.

reported values in similar studies. (Buonanno et al. 2013) This was attributed to the average air exchange rate of 6.8 ACH in a small room setting.

Discrepancy of sampling locations and practice vs. teaching

The statistical analysis showed a significant difference ($p < 0.01$) between practicing and teaching for two instruments, namely the trumpet and saxophone. There was no statistical difference between practicing and teaching singing and other instruments.

Regarding sampling locations, concentrations at the performing point were consistently higher than all the other locations ($p < 0.01$), while 10 ft away was always lower ($p = 0.03$). In general, there was no statistically significant difference between 6 ft away and 6 ft perpendicular ($p = 0.11$) for all instruments, indicating distance was the dominating factor for the spatial distribution of aerosol concentration, not direction.

Particle concentrations of singing and instruments

Figure 3 depicts the average aerosol concentrations during singing and playing seven instruments at different distances, with a direct comparison to the average background level. The results showed there was a significant increase in aerosol concentration during singing and trumpet, and saxophone performances compared to the background level ($p < 0.01$). Between singing and instruments, singing produced the highest average particle concentration of 3.5×10^3 # cm^{-3} at the performing point with a peak level of 3.9×10^3 # cm^{-3}, which was over a 100% increase from the background level. Trumpet and saxophone playing had average concentrations of 2.3×10^3 # cm^{-3} and 2.1×10^3 # cm^{-3} at the performing point, respectively, which were higher than the background concentration. The other five instruments, with an average aerosol concentration range of 1.8 to 1.9×10^3 # cm^{-3}, had no significant difference between the background or each instrument in the paired comparison test (all p-values > 0.05), respectively.

Figure 4 illustrates average aerosol concentrations at different sampling locations as a function of time in the 10-min experiment sessions. The corresponding background levels were already deducted in this graph to single out the contribution of musical performance to elevate aerosol concentration. During singing, the room concentration increased an average of 1.7×10^3 # cm^{-3} with a peak of 2.0×10^3 # cm^{-3} at the performing point, with the 6 ft perpendicular location being the lowest of 1.0×10^3 # cm^{-3}. Trumpet and saxophone performances resulted in an average increase of 0.4×10^3 # cm^{-3} and 0.2×10^3 # cm^{-3} at the performing point, respectively. However, there was no significant difference across sampling locations for trumpet and saxophone performances. For the rest of the instruments, the average elevated aerosol concentration was less than 0.1×10^3 # cm^{-3}.

Particle concentrations with the HEPA filtration unit

Since the result indicated that singing had the highest production of aerosols compared to the background level and performing wind instruments, we only used singing to examine the efficiency of the portable HEPA filtration unit placed next to a performer. The singer was asked to perform the same 10-min session identical to the prior experiment, following a 10-min break, and repeat this three times for a total of 60 min. The HEPA filtration unit was turned on once the singer started to perform and continuously ran during the whole 60-min period. Figure 5 is the aggregated time-series data with a clear reduction trend observed. The HEPA filtration unit reduced the room concentration below the background level at the beginning of the session to between 0.3 and 0.4×10^3 # cm^{-3} across four different sampling locations. After using the HEPA filtration unit, the background level was about 17% of the original background level of 1.8×10^3 # cm^{-3} at the performing point.

Discussion

Aerosol emissions from singing and instruments

The background levels in the studied studio room were between 1.7 and 1.9×10^3 # cm^{-3}, and breathing

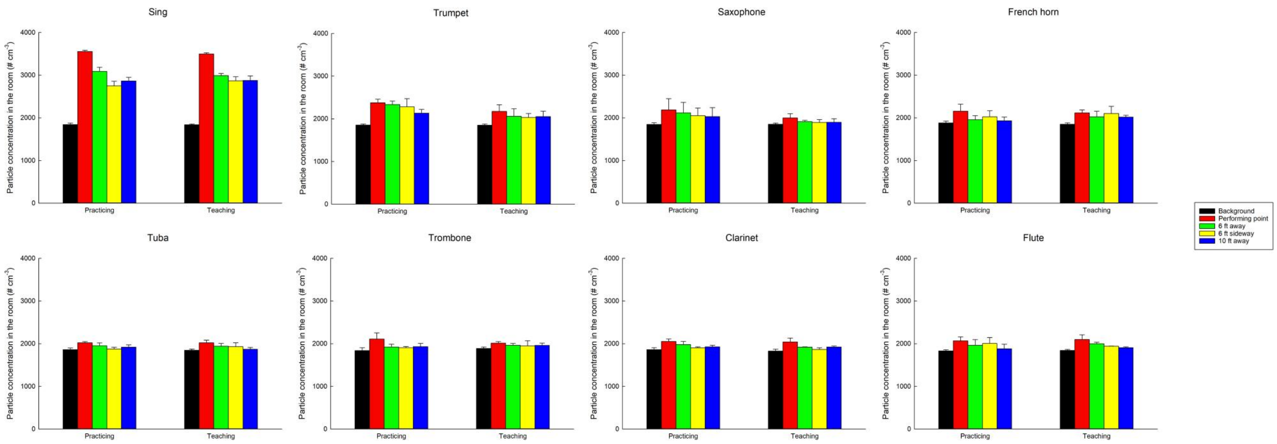

Figure 3. Average aerosol concentration (±standard deviation) in the room with different instruments, locations, and practice/teaching sessions.

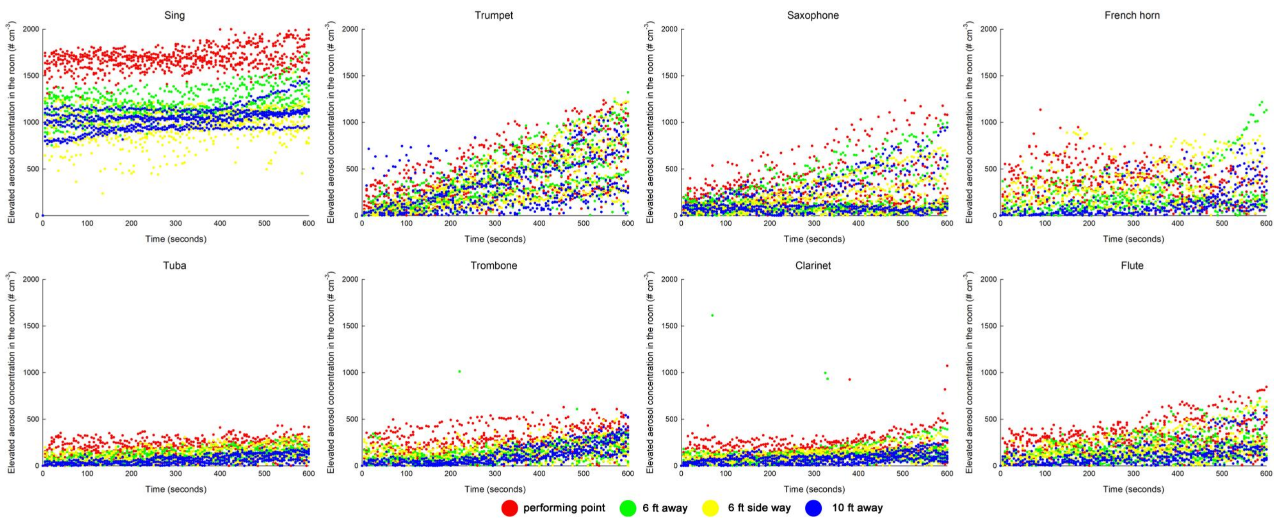

Figure 4. Elevated aerosol concentration over room background level with different instruments and at different distances.

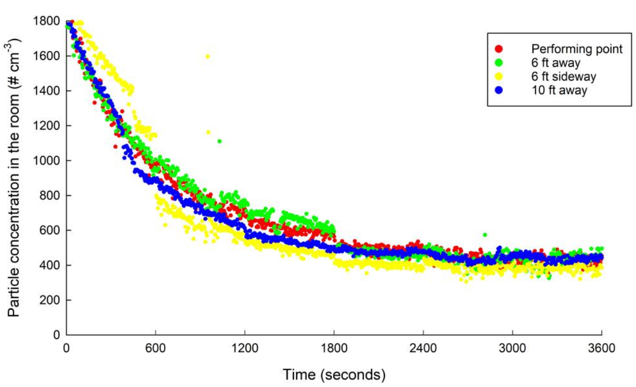

Figure 5. Aerosol concentration in the room as a function of time, during the 60 min of the singing session with HEPA filtration unit.

activity did not create detectable differences in room concentration. Other studies also suggest that breathing only produces a minuscule number of aerosols compared to talking and singing. Breathing aerosols might be detectable in a clean chamber with a near-zero background level, but not in the realistic room setting as in this study.

The average aerosol concentrations at different locations, as well as the time-series data, clearly indicate that singing emitted much more aerosols than playing wind instruments, in most cases, more than double the background levels. This finding is in line with results documented in other studies where singing generated higher numbers and mass concentrations of aerosols (Alsved et al. 2020; Archer et al. 2022; Stockman et al. 2021). Singing can emit aerosols directly from the openings of airways (mouth and nose), and mezzo-soprano singing employed in this study involved high pitch, high frequency, and presumably more vibration of vocal cords. Other styles of singing with lower pitch and frequency could have less drastic aerosol emissions (Gregson et al. 2021; Mürbe et al. 2020; Mürbe, Kriegel, Lange, Schumann, et al. 2021).

Despite statistical analysis showing that aerosol emissions from the trumpet and saxophone were statistically different from the rest of the instrument group, the differences were minimal. Compared to singing with studio concentrations reaching 3.9×10^3 # cm^{-3}, which doubled the background concentration, the use of wind instruments elevated room concentrations to 2.3×10^3 # cm^{-3}. On average, wind instruments contributed to about 0.2×10^3 # cm^{-3} above background concentrations. Attempts were made to link the results of wind instruments to the design of each instrument; however, no significant linkage was established. As speculated, the complex design of most wind instruments acted as long and curved tubing, which likely induced significant particle-wall deposition. If virus-laden aerosols were deposited on the sidewall of the wind tube, they would not be released into the room initially but could be resuspended during future use.

Time-series data showed that singing and playing wind instruments consistently increased aerosol concentrations in this studio room during the 10-min session. The increase could multiply with more performers and/or over a longer period (more than 10 min). The contributions over time from singing were much higher than those of other instruments, indicating a higher emission factor per unit time for singing.

Distances and practice vs. teaching

In this study, two types of sessions were designed based on the feedback from CCM faculty: the practice session mimicked 100% performing, while the teaching session simulated a mix of 60% performing and 40% talking. Practicing singing and teaching singing did not have a significant difference in aerosol emission and build-up, as singing and talking could be similar. Practicing trumpet and saxophone produced marginally more aerosol concentrations than teaching. Overall, intermittent talking did not affect the emission of aerosols in this study.

The 6 ft social distancing recommendation was based on the recommendation from the Centers for Disease Control and Prevention (CDC) and other agencies. In this study, the 6 ft distance from the performer exhibited higher concentrations than 10 ft away, although both were lower than the concentration at the performing point. For singing, there was a discrepancy between 6 ft away in the facing direction and 6 ft in the perpendicular direction. This discrepancy was not observed during performance with most wind instruments, regardless of bell opening directions or bell shapes. The reason could be that more droplets were produced during singing, and droplets traveled farther in the ejecting trajectory. This result suggests that the risk of sitting in front of singers within proximity is higher than sitting to the side of singers. The 6-ft social distancing recommendation may not be sufficient to reduce exposure to fine aerosols emitted from musical performances, as shown by the results measured at 10 ft away.

Mitigation of aerosol emission and exposure

In general, it is hard to wear a facemask while singing, and covering the bells of wind instruments could alter the performance of instruments. Musicians did not favor these interventions at the source. Purging the room with natural ventilation (open window/door), room ventilation (HVAC), and local ventilation (HEPA) may be more practical to mitigate aerosol exposure during an indoor musical performance.

The purging process after each session to return the concentration to the original background level can be used during real-world scenarios to reduce aerosol concentrations in any room. During the study, it was observed that at least 30 min of elevated airflow and exchange can effectively reduce the aerosol concentration to the level before musical performance. However, this may only apply to small to medium-sized rooms like the studio setting in this study.

The HEPA filtration unit proved to be an effective way to reduce aerosol concentration close to the performer. Due to the short timeframe, only the highest aerosol emission activity, i.e., singing, was tested with the HEPA filtration unit. It was assumed that if the HEPA filtration unit could reduce aerosol concentration by over 83% with singing, it would perform better with wind instruments, as they produced fewer aerosols. It is essential to follow the recommendation of a CADR for a certain size of room to ensure adequate filtration with continuous emission sources.

Although wind instrument performances produced fewer aerosols compared to singing, there is an additional risk that virus-laden aerosols can be deposited within the instrument. This is because most wind instruments have a water key or spit valve to clear out "condensation" build-up in the tube. Disinfecting the internal tube is rather difficult for most wind instruments due to the design. Sharing wind instruments between different performers is strongly discouraged.

Conclusion

This study attempted to characterize the spatial and temporal distribution of aerosols in a small practicing/teaching studio room. Compared to other studies done in either an aerosol chamber or a much larger room, (Quentin et al. 2022; Stockman et al. 2021; Volckens et al. 2022; Wang et al. 2022) this studio room setting is more realistic for musical education scenarios. The studio background aerosol concentration was around $1.8 \times 10^3\,cm^{-3}$, with and without human presence. Singing increased the aerosol concentration to 3.9×10^3 # cm^{-3}, while performing with wind instruments resulted in much less but detectable contributions. Practicing and teaching did not show significant differences in aerosol concentrations, except for trumpet and saxophone. Time-series data also illustrated the general trend of aerosol build-up in the room throughout the whole musical performance. The distances between the performer and other persons were critical, and elevated aerosol concentration was detected even at 10 ft away, further than the 6 ft social distancing recommendation.

The use of the HEPA filtration unit effectively diminished the aerosol emission of singing and presumably wind instruments, and it also reduced the background level of the room to about 1/5 of the original concentration. The result suggests that using a HEPA filtration unit could be beneficial in reducing particle concentrations indoors, provided the size of the filtration unit is adequate for the room and placed next to the performer. In general, ventilation is the most effective way to mitigate aerosol exposure risk in indoor musical performances.

The results of the study are generally in line with other studies published since the COVID-19 pandemic (Firle et al. 2021; Gregson et al. 2021; McCarthy et al. 2021; Mürbe, Kriegel, Lange, Rotheudt, et al. 2021; Mürbe, Kriegel, Lange, Schumann, et al. 2021; Stockman et al. 2021; Volckens et al. 2022; Wang et al. 2022), with singing producing the highest aerosol concentrations, highlighting the importance of cautiously reopening choir practices and performances. More studies are needed to identify the mechanism of aerosol emission and transportation within wind instruments. Future studies should also include various sizes of room settings, such as a large musical hall, where performing is more complex, with the involvement of group singing, wind instruments, and non-wind instruments. These types of studies on aerosol emission and transmission could be critical not only to ending the COVID-19 pandemic but also to prepare the public for preventing future airborne respiratory diseases from spreading.

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Disclaimer

The content is solely the responsibility of the authors and does not necessarily represent the official position of NIOSH or the Centers for Disease Control and Prevention.

Disclosure statement

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Data availability statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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