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Research Article

Investigation of the Emission Rate of Particles when Musicians Play Wind, Woodwind, and Brass Instruments

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In the context of the high risk of airborne transmission of COVID-19, the question of the production of particles while playing wind instruments is highly relevant. Therefore, in this study, 23 professional musicians played their instruments in a cleanroom in cleanroom-grade clothing. The most common orchestral wind instruments flute, oboe, clarinet, and trumpet were therefore chosen. Aerosol measurements using a laser particle counter were conducted to quantify the emission rate of respiratory particles. Orchestral excerpts as well as sustained tones in two dynamic levels were played. The emitted particles were mostly in a submicron size range. For all instruments besides the clarinet, an influence of the loudness of playing on the emission rate could be observed. The emission rates for all musical instruments were independent of the passages played. Flute and oboe showed similar emission rates but lower than the values for clarinet and trumpet. While playing a note with a small volume, the flute, oboe, and trumpet have a similar emission rate as found for speaking.

1. Introduction

Since the outbreak of the COVID-19 pandemic, there have been extensive restrictions on musical performances especially with regard to singing and playing wind instruments. Viruses, like SARS-CoV-2 causing COVID-19, are often transmitted on the respiratory route [1]. In inappropriately ventilated rooms with sufficient distance, with droplet transmission being less dominant, aerosol transmission is the main transmission route for the virus [2].The number of particles produced in the respiratory and vocal tract varies according to individuals and their activities. The viral load of these particles depends on the pathogen and can only be measured in infected persons. Former investigations indicated that respiratory activities like breathing and speaking lead to the emission of respiratory particles [3, 4]. Recent studies showed an increase in the emission rate of respiratory particles during singing compared to breathing and speaking and a strong correlation with the volume used for adult [5] and adolescent [6] singers during measurements in a cleanroom environment with a particle counter as well as for adults in a similar protected environment using an aerodynamic particle sizer (APS) [7, 8]. It stands to reason that particles can also be produced when playing wind instruments, due to the physical processes, such as the vibration of the moistened reed in the clarinet, which occurs when sound is produced [9].

An important factor in the production of particles when playing wind and brass instruments might be the way of the tone production. In the case of the oboe and clarinet, this is done by the vibrating reed. A reed is a flexible element, a valve, which vibrates through flow-induced oscillations. This modulates the flow and produces sound. In the clarinet, a single reed moistened with saliva is attached with a string, while in the oboe, a double reed consisting of two reed wedges attached to a metal tube segment (staple) influences the production of sound. When the wet reeds vibrate, a production of aerosol particles is to be expected. On the other hand, flute instruments are wind instruments in which the sound is produced by flow instability without significant wall vibrations, not even by a reed [9]. In case of the transverse flute, a fine jet of air is formed by blowing through a slit formed by the musician's lips. There, typical air velocities of 40 m s^{-1} occur [10]. This can lead to suspension of saliva into the air. The jet flows through an opening in the sound box called the blowhole. Particles are expected to be produced only when flowing through the lips. The lips of brass instrument players vibrate when the instrument is played [9]. This can lead to the generation of respiratory particles on the lips moistened with saliva.

For wind and brass instruments, previous studies have already shown that the emission rates of particles are in some cases significantly higher than would be expected from normal breathing. In the study by Abraham et al. [11], it was shown that a larger flow rate was important for the trumpet to increase the amplitude, while it was not required for woodwind instruments. McCarthy et al. [12] did find out that the size distributions of emitted particles by various instruments when playing in different volumes were similar to activities without vocalization, but not comparable to singing and speaking due to the bimodal distribution originating from the additional particles produced in the mouth and larynx. They also found out that a dependence between aerosol generation and increase of dynamic level exists. No large droplets $> 20\,\mu$m could be found while using water-sensitive paper at the outlet of the instruments in contrast to singing and coughing. Only sustained tones were investigated in this study. In the study by Firle et al. [13], the aerosol emissions of 19 flutists, 11 oboists, 1 clarinetist, and 1 trumpeter were measured in an operating theatre. In this study, typical orchestral excerpts (o.e.) were played. A size distribution with 70-80% of emitted particles $\leq 0.4\,\mu$m could be observed. In contrast to McCarthy et al.'s study [12], the size distributions from breathing and speaking appeared to be similar. While sampling respiratory aerosol, it is important to have the lowest possible background concentration of particles to gather reliable results [14]. Depending on the type of virus, the size distribution with those viruses present or absent could be different [15].

When playing most wind instruments, the air flows out with low momentum, and the emerging free jet only covers a short distance. That has already been shown in other investigations using the Schlieren technique. Whereas Abraham et al. [11] claimed that the distance travelled by escaping air is limited to 30 cm, Becher et al. [16], however, showed that free jets from instruments can cover a distance of up to 90 cm and the secondary air even 120 cm. Spahn et al. [17] found only in exceptional cases flow velocities of >0.1 m s^{-1} at the outlet of various wind instruments.

Therefore, the intention of this study was to determine the particle emission rates of different wind and brass instruments by including the entire instrument in the experimental setup in order to capture all potential sources of emissions (secondary air at the mouthpiece, flaps, and outlet). For this purpose, particle measurements on professional musicians were conducted under cleanroom conditions with unidirectional airflow and particle-free supply air. Apart from differences between instruments, the influence of dynamic level was investigated, and the emission rates were compared to other respiratory activities that are known for particle generation such as breathing, speaking, and singing available from recently published studies [5]. Similar studies mostly had low subject numbers and did not take place in cleanroom environments. This study stands out because a low background concentration as well as a large cohort are needed due to the small number concentration and intersubject variability in respiratory aerosols to derive reliable results [14]. Also, protective clothing is needed to reduce the emission of misleading abrasive particles that do not originate from the respiratory tract.

This study provides information on the emission rate of respiratory particles and their properties and can therefore be used to calculate infectious doses. That can be assessed for varying airborne-transmitted infections and does not solely focus on the transmission of SARS-CoV-2.

2. Material and Methods

23 professional musicians from the "Konzerthausorchester Berlin" and the "Staatskapelle Berlin" participated in the study and included 5 transverse flutists, 6 clarinetists, 6 trumpeters, and 6 oboists.

The tests were carried out in an ISO class 2 cleanroom of the Hermann-Rietschel-Institute of the Technische Universität Berlin with particle-free supply air. The room temperature was 295.15 ± 0.5 K, and the relative humidity was 35 ± 5%.

The test persons wore cleanroom-grade overalls and bonnets type ION-NOSTAT VI.2 (Dastex, Muggensturm, Germany) and also wore hairnets, shoe covers, and nitrile gloves to prevent abrasion of particles when pressing the keys or valves, which might have a great influence on the measurement results.

Since the overall setup of the measurements was mostly similar to the methods described previously (see [5]), only the most important information and differences to the other studies are named. The subjects sat in front of the apparatus, consisting of a FFU (Filter-Fan-Unit), a glass tube, and a turbulence generating baffle, while breathing and speaking. All examinations with instruments held in playing positions were carried out in a standing position. For this purpose, a duct made of a DN 300 aluminum flex pipe was used, which was formed into a funnel of 0.35 m × 0.40 m at the air inlet, in which the instruments could be positioned. The overall measurement setup is displayed in Figure 1. For the

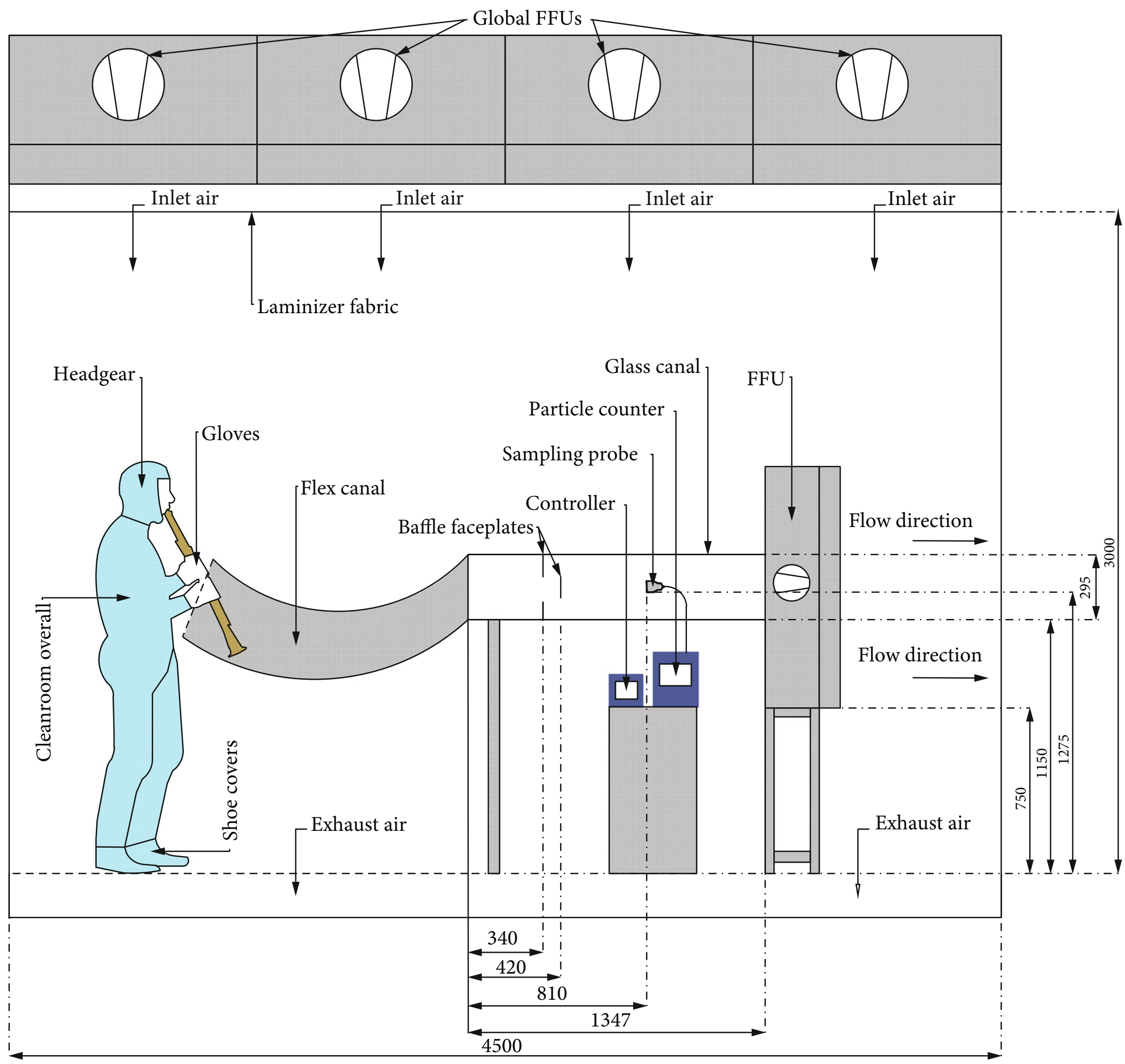


Figure 1: Measurement setup. The subjects wore protective gear and stood in front of the equipment and inserted the instrument as far as possible into the channel. The suction of the FFU generated a volume flow of 400 $m^3 h^{-1}$. The overall air flow in the cleanroom was 0.3 $m s^{-1}$. The sampling probe had a diameter of 37 mm.

transverse flute, the air outlet positions deviate. Therefore, and because of length of the instrument of about 0.7 m, an individual solution had to be used for this. An oval attachment with a width of 0.75 m and a height of 0.25 m was used to insert the transverse flutes into the duct and to enable the collection of all respiratory particles without loss.

To exclude sedimentation inside the duct, a defined particle source with the aerosol generator type ATM 226 (Topas, Dresden, Germany) was used. The test aerosol was DEHS with a polydisperse size distribution with 0.19 μm as a mean diameter and a density of 912 $kg m^{-3}$. The particles were emitted with the flex tube and without. The particle concentration did not vary noticeably, and as a conclusion, the deposition of small particles < 3.0 μm in the duct and at the baffles was classified as of minor importance. However, care was taken not to let the instruments touch the walls to avoid reaerosolization. The results of the preliminary study are displayed in figure S4-S7.

The particles were recorded with a laser particle counter (LPC) type Lighthouse Solair 3100 E (Lighthouse Worldwide Solutions, Fremont, CA) in the size of 0.3 up to 25.0 μm and graded into six size classes (0.3-0.5, 0.5-1.0, 1.0-3.0, 3.0-5.0, 5.0-10.0, and 10.0-25.0 μm). The zero-count rate of the LPC is <1 in 5 min and the counting rate 50% for 0.3 μm and 100% for 0.5 μm. By the assumption of an ideal mixed flow, the volume flow of the FFU of 400 $m^3 h^{-1}$, and the volume flow of the sampling probe being 28.3 l min^{-1}, the emission rates P_N for all size classes were calculated. Considering the low relative humidity of about 35 ± 5% in the room and the average time to transport of the respiratory particles to the measuring probe, it can be assumed that particles that are emitted with a size < 10 μm have reached a state of equilibrium [18] due to the average time of transport between emission and counting. More precisely, the evaporation time is by about a factor of ten lower than the average transport time.

To record the maximum sound pressure level during each task, a calibrated sound level meter of type Center 322_ Datalogger Sound Level Meter (Center Technologies, Houston, TX) was placed in a distance of 30 cm from the sound source.

Aerosol emissions for five different test conditions were investigated, which were each repeated five times in a row with intervals of at least 10 s in between to wait for the background aerosol number concentration to return to 0 cf^{-1}. It should be noted that the instruments were played for 10 s longer than the respective measuring period. The first 10 s was not evaluated, in order to consider any lags and establishing stationary particle concentrations at the sampling probe due to the long inlet length of the duct. Notes and text were handed out as plastic-laminated sheets to avoid unexpected particle contaminations.

The conditions were defined as follows:

Breathing. Sitting directly in front of the funnel entry, participants breathed calmly for 30 s.

Speaking. Participants read a German text ("Der Nordwind und die Sonne" by Aesop) at medium vocal loudness for 40 s. They were seated facing the funnel entry.

Playing a Comparable, Instrument-Independent Piece (Ode to the Joy). Standing in front of the funnel entry, all participants played the melody of "Ode to the Joy" from Beethoven's symphony no. 9 for 40 s (further referenced as "Ode"). The instrument was protruding into the funnel without direct contact. In a first run, this was conducted silently, by just moving the keys or valves, to detect the number of particles produced by abrasion. For this condition, finger movements were permitted, the mouth was closed, and the instrument was not blown on. The subjects did not explicitly exhale into the measuring duct during this task. This particle abrasion, independent of the generation of respiratory particles, was considered as a correction factor for the measurements when playing the instrument. Finally, the measured values of the pieces of music played are subtracted for each measurement channel by the amount of nonrespiratory particles counted with these reference measurements. For a few repetitions, the number of aerosol particles provoked by abrasive effects was higher than for trials where the instrument was played audibly. For these cases, P_N was set to zero. Subsequently, participants played with sound as usual.

Playing an Instrument-Specific Orchestral Excerpt. For 40 s, participants played a characteristic orchestral excerpts specific for their instrument from the following:

(i) Flute: J. Brahms, Symphony No. IV, Mvt. IV

(ii) Oboe: J. Brahms, Violin Concerto, Mvt. II

(iii) Clarinet: L. v. Beethoven, Symphony No. 6, Mvt. II

(iv) Trumpet: M. Mussorgsky, Pictures at an Exhibition, Promenade

Likewise, a soundless measurement run was performed before actually playing.

Playing a Sustained Single Note. Participants played tuning note A3 440 Hz (transverse flutes A4 880 Hz) for 20s initially with low volume (*piano*) and subsequently with high volume (*forte*).

Analyzing the data was conducted using the linear mixed-effect modeling (LMER) in R (v4.2.0, https://www.r-project.org/) using the lmerTest package (v3.1-3).

Considering the different mechanisms and conditions of tone production, the analysis was divided in two models. In model I, the volume conditions piano and forte, and the instrument types were considered as fixed effects and participant ID as random effect. In model II, the conditions playing "Ode to the Joy" and the individual played piece as well as the instrument type were considered as fixed effects and participant ID as random effect [5]. For both models, the particle emission rate was chosen as the dependent variable. p values were calculated using the degrees of freedom method of Satterthwaite. The significance level was set to 95%.

3. Results

Figure 2 shows the mean particle emission rate referring to particle diameter with P_N on the ordinate and the particle diameter on the abscissa for all instruments and conditions.

Every instrument is displayed in its own plot, with the condition of activity shown in different colors. It can be seen that almost no particles in the highest size class were counted. >99% of all particles detected were ≤5.0 μm, and more than 90% of all particles detected were ≤1.0 μm. Therefore, the distribution appears to be right-skewed with the highest count of particles in the particle size class >0.3–0.5 μm.

In Figure 3, the boxplots for the cumulative emission rate P_N (the sum of all size classes) of respiratory particles for all instruments and conditions are displayed. The conditions are shown on the abscissa while the instruments are separated by different colors. The boxes for the results of breathing and speaking are combined for all participants, independent of the instruments they play. It can be seen that the medians for the instruments played are always higher than for speaking, except for the condition piano. In this case, only the clarinet has higher values for P_N. For all instruments, P_N is increased by a factor of about 7.3 from forte to piano ($p < 0.001$).

Comparing both Ode and the orchestral excerpts, no major differences regarding the emission rate were obtained (factor of about 0.91, $p = 0.279$). For the conditions Beethoven and the orchestral excerpts, the emission rate for playing the clarinet and trumpet is higher than for flute and oboe.

For breathing at rest, a median value of 16 P s^{-1} was obtained. For speaking, the value for P_N was about 86 P s^{-1}. Furthermore, the particle emission rates while playing the piece "Ode to the joy" for all instruments regarded are named. The emission rates for the flutists were 259 P s^{-1}, for the oboists 494 P s^{-1}, for the trumpeters 1938P s^{-1}, and for the clarinetists 2052 P s^{-1}. The emission rates for playing orchestral excerpts for the flutists were 487P s^{-1}, for the oboists 432 P s^{-1}, for the trumpeters 2649 P s^{-1}, and for the clarinetists 1640 P s^{-1}. It should be noted that the given numbers for the medians of emission rates are based on the medians of all repetitions (group medians) for each participant and

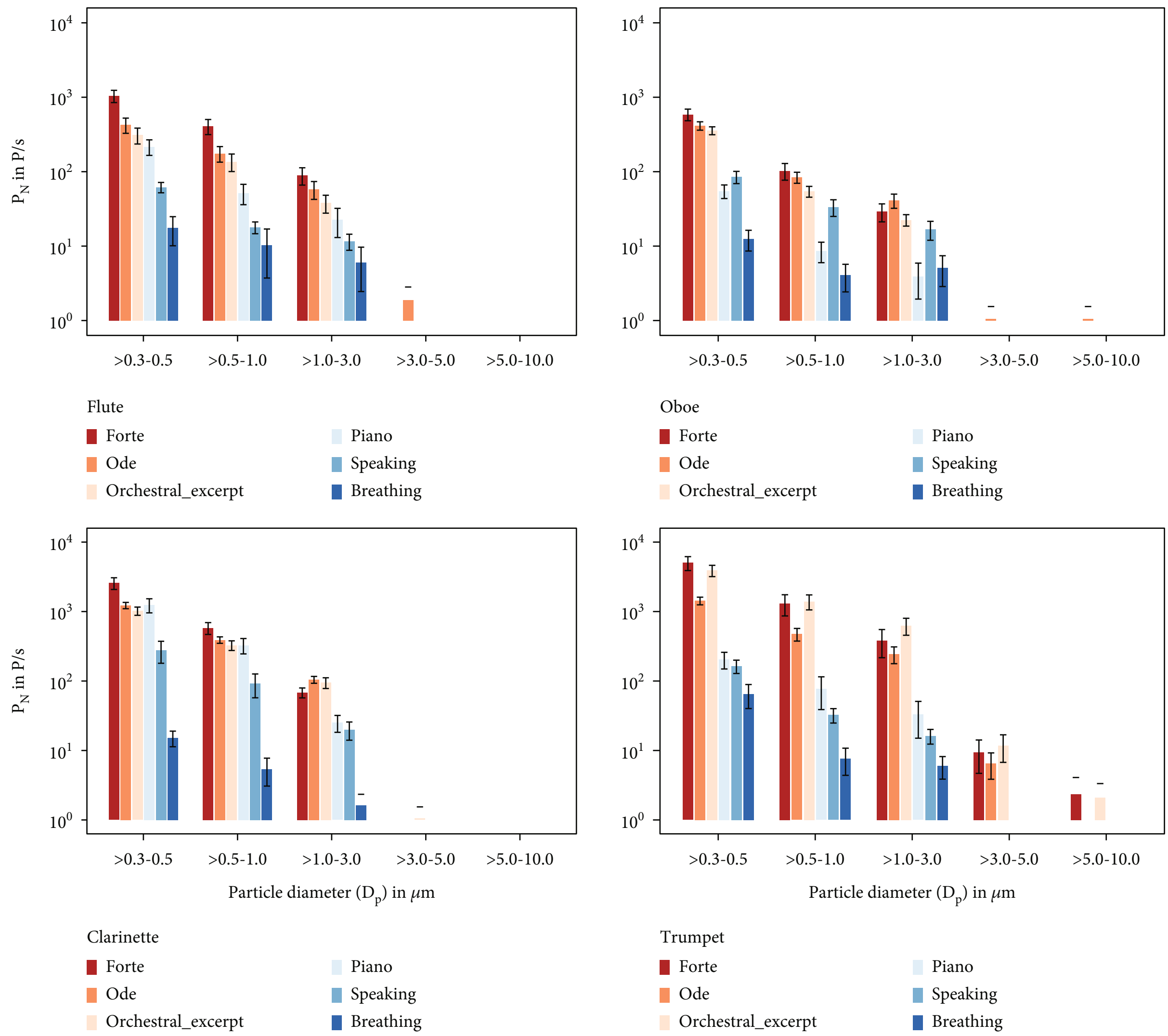


FIGURE 2: Particle emission rates for all instruments and conditions as denoted in the legends. The bars represent the mean values for all participants and repetitions. Error bars represent the standard error. For visual purposes, all mean values < 1 P/s have been ignored in the diagram.

condition. Considering results of model I, oboe emitted 2.04-fold ($p = 0.316$), clarinets about 5.92-fold ($p = 0.018$), and trumpets about 13.34-fold ($p = 0.001$) more than flutes (standard error was 2.00).

Figure 4 shows on the left-hand side the sound pressure levels on the ordinate and the dynamic level on the abscissa. The different instruments are displayed in the same colors as before. It can be clearly seen that all instruments were substantially louder when played in forte. As expected, the trumpet was the loudest in forte. For both dynamic levels, the clarinet has the lowest group medians. The diagram on the right hand of Figure 4 shows the particle emission rate related to the sound pressure $P_N\,p^{-1}$ for both dynamic levels regarded. For all instruments—except the clarinet—the group median of $P_N\,p^{-1}$ is lower while playing piano. In contrast, the $P_N\,p^{-1}$ for the clarinet does not change remarkably between both dynamic levels.

Comparing P_N in forte and piano, there was no significant difference between the instruments (see Figure 3). Oboe emitted slightly lower values than flute (factor of 1.84, standard error of 1.99, $p = 0.386$), whereas trumpet and clarinet emitted more particles (factor of about 1.93 and 3.08, standard error of 1.99, $p = 0.350$ and 0.118, respectively) according to the results of model I. But for forte, we found a significant increase to piano by a factor of 7.28 (standard error 1.11, $p < 0.001$).

4. Discussion

In this study particle emission while playing various wind instruments under cleanroom conditions was investigated. In the following, the principles of sound production of each musical instrument will be explained, and a comparison of the emission rates and size distribution of particles with

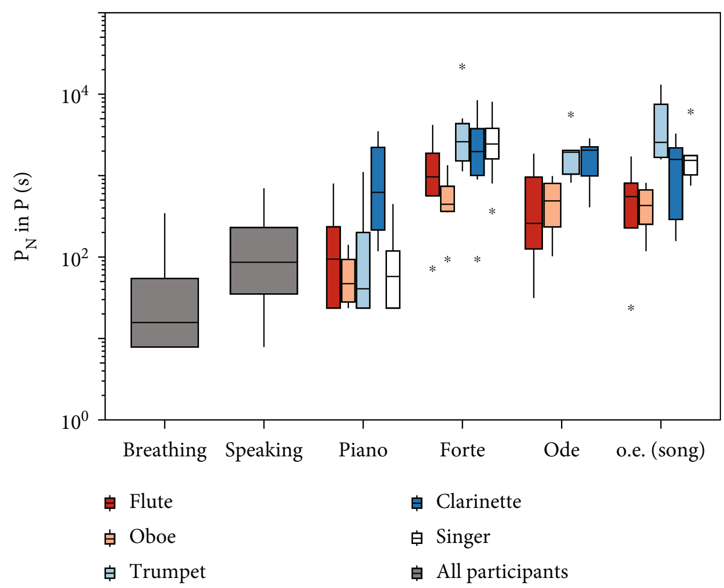
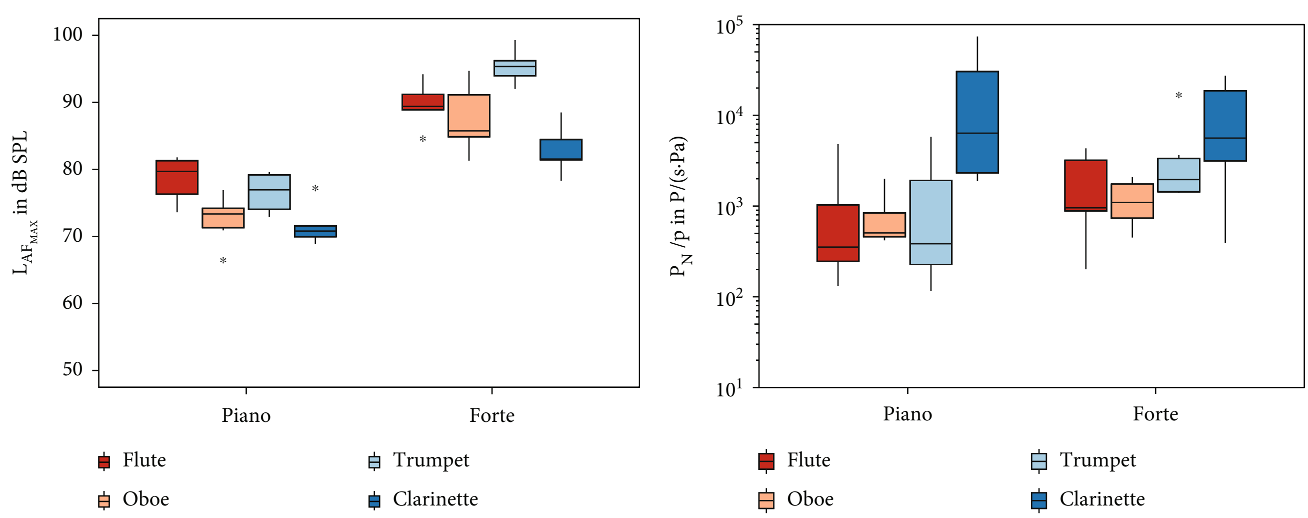


FIGURE 3: Emission rate P_N of respiratory particles as a boxplot for all instruments and conditions. Flute data is marked red, oboe in orange, trumpet in salmon, and clarinet in light blue according to the legend. For comparison, singers' data are taken from Mürbe et al. [5].



(a) (b)

FIGURE 4: (a) Display of the sound pressure level LAF_{MAX} for all instruments regarding sustained notes. (b) Emission rate of respiratory particles in relation to the sound pressure $P_N\,p^{-1}$.

similar studies will be conducted. Because different measurement principles for the determination of emitted particles have been used in previous studies (e.g. [12, 13, 19–21]), these measures cannot be directly compared to our values. Therefore, a direct comparison of our measured emission rate with the findings from other studies is not possible. But, within this study, the given numbers can be compared qualitatively with the values of breathing or speaking. Regarding dispersion in indoor air, the impulse with which the aerosol flows out of the instrument plays a role. Therefore, for the instruments, also the outlet flow is briefly characterized in the following. Consequently, the discussion is separated by instruments to maintain clarity. At the end of the discussion, overall limitations and a comparison with the aerosol emissions of singers can be found.

4.1. Particle Size Distribution. The particle size for playing wind instruments was in comparable order of magnitude as in similar studies, with 0.25-0.8 μm [13], most particles $< 1.0\,\mu$m [20]. In the findings of Volckens et al. [22], the mode of the fractional number concentration was below 1.0 μm for flute, oboe, clarinet, and trumpet as well as the human voice while singing. However, also other particle sizes were measured. He et al. found a log-normal distribution within a range of 1.9-3.1 μm for instruments played [19]. The size distribution can influence the number of pathogens in the respiratory aerosol emitted. We expect that larger particles contain more viruses. Therefore, the size distribution and the emission rate of particles P_N could link to pathogen concentration. However, since the particles in this study might originate from different places in the respiratory tract, the concentration of virions might differ [23].

4.2. Flute. In the flute, air flows across the mouthpiece and creates a resonant frequency in the instrument. Apart from possible aerosol generation within the respiratory system, there are no obvious existing structures within the instrument for particle generation. Since no sound is formed in the larynx, particles generated by vibrating vocal folds are unlikely to be produced for playing the flute. Due to the high flow velocity at the lips, the suspension of saliva droplets into the air occurs. The flute was identified as an instrument with one of the highest outlet velocities by Abraham et al. [11]. Furthermore, significant air movements close to the mouthpiece with a directed movement into the room were found [17]. He et al. [19] found an increase in aerosol concentration by using special blowing techniques. By using the tongue ram, where the exhaled air is led over the tongue, the aerosol production increased by a factor of 50. It is unlikely that respiratory particles are deposited or suspended within the flute to any great extent, since most of the respiratory air flows over the flute and is not entering the instrument while playing. However, particles from the aerosol entering the flute may be deposited within the long and narrow channel of the flute. A visual explanation of the airflow while playing the flute is given in figure S1.

The particle emission rate for playing the flute quietly is of a similar order of magnitude to that for speaking, but at a higher volume, the particle emission rate rises above the level for speaking. This can probably be attributed to the higher flow velocity as well as the increasing pressure in the lungs. In the findings of He et al. [19], the emission rates for the flute were in a similar range to breathing. Quantitative values were not compared due to different measurement principles. Volckens et al. [22] categorized the median aerosol emission rate at $9.9\,P\,s^{-1}$. A reason for the large difference to their results could be the comparably low volume flow of the sampling apparatus with $0.06\,m^3\,h^{-1}$ ($400\,m^3\,h^{-1}$ in the present study). Further, it seems plausible that not all the aerosol emitted flows into the sampling apparatus. That can be achieved by considering the airflow while playing the flute.

4.3. Clarinet and Oboe. While playing the clarinet, sound is produced by the vibrating reed attached to the mouthpiece. Being also a woodwind instrument, the oboe's principle of sound production is similar to that of the clarinet. For this reason, the discussion on clarinets and oboes is combined.

However, the oboe has two reeds between which the air passes. Therefore, a very high pressure is needed [9]. For both instruments, the lungs and the vibrating reeds could be decisive for the production of particles. Since the mouthpiece is moistened with saliva, aerosol generation may also occur here due to vibration. Due to the straight, wide construction of the instruments, sedimentation of respiratory particles within the clarinet and oboe is rather unlikely. However, the oboe is considerably narrower, which favors the sedimentation of small particles in particular, for example, by the effects of turbophoresis or Brownian motion [24]. Large particles would probably be deposited on the reed(s) while flowing through the small gap. A visual explanation of the airflow while playing the clarinet and oboe is given in figure S2 and S3.

Regarding measurements with emphasis on the dynamic level, the emission rate did not increase a lot while playing the clarinet in forte. The emission rate might not be connected as much to the sound level as at the other instruments investigated. In contrast, for the oboe, an increase in the emission rate was observed. The particle emission rate while playing the clarinet is very high, at the same level as the particle emission rate while singing. The oboe emitted particles in the same order of magnitude as the flute. A striking characteristic is the significantly reduced release of particles during quieter playing of the oboe, which was not observed with the clarinet. The emission rates each for the oboe and clarinet were in a similar range to speaking in the study be He et al. [19]. Wang et al. [20] found a similar number of emitted particles while singing and playing clarinet and oboe which is in accordance to the findings of our study. The mean aerosol emission rate was $408\,P\,s^{-1}$ while singing and $480\,P\,s^{-1}$ for playing woodwind instruments. Volckens et al. [22] found a median particle emission rate for clarinet at $13.0\,P\,s^{-1}$ and for oboe $14.3\,P\,s^{-1}$.

Secondary air while playing these woodwind instruments can occur to a great extent in unpracticed players [11]. However, the subjects in this study were asked to reduce secondary air to full extent.

Furthermore, playing the oboe led to slightly lower outlet velocities than playing the clarinet. Spahn et al. [17] measured velocities with less than $0.1\,m\,s^{-1}$ in 1 m distance from the bell at the clarinet. They stated that for double-reed instruments, the results should be in a similar order of magnitude.

4.4. Trumpet. As a brass instrument, the trumpet has a different principle for sound production than flute, oboe, and clarinet: the vibration of the lips excites a resonance in the instrument, which is significantly amplified by the funnel-shaped outlet. Within the trumpet, very high flow velocities occur [25], which could allow, for example, the resuspension of condensation. Conversely, due to the curved shape and the large barrel length with a narrow diameter, it is conceivable that respiratory particles are separated to a large extent within the instrument, similar to a droplet separator. Particularly large particles may be affected by increased separation due to inertial forces. The outlet velocities are very low due to the large diameter of the opening. A visual explanation of the airflow while playing the trumpet is given in figure S4.

The amount of released particles at playing piano is in a low range for the trumpet and can be ranked between the ranges of breathing and speaking. However, if played loudly, a considerable change occurs, with a median particle emission rate of $2649\,P\,s^{-1}$ while playing an orchestral excerpt. Especially with players who played very loudly, the emission rate increased significantly. However, within our study, it is not possible to determine to what extent the released particles are resuspended condensate from inside the instrument. Parker and Crookston [21] found a lower emission of aerosols while playing brass instruments compared to the activities speaking and singing. In the findings of He et al. [19], the concentration of particles in the aerosol was approx. 5-fold higher than while speaking for the trumpet. Since the particle emissions for two trumpeters in this study were also excessive, this value could be linked to the small subject count. The aerosol emission rate was 383P s^{-1} for brass instruments in the study by Wang et al. [20]. In the findings of Volckens et al. [22], the median emission rate of particles was 125.4 P s^{-1}.

4.5. Influence of Dynamic. Regarding the sound pressure level, Volckens et al. [22] did find a statistically significant correlation between sound pressure level and particle emissions for brass instruments, but not for woodwind instruments. In the findings by McCarthy et al. [12], the particle emission rate while playing forte was comparable to the emission of particles while singing at a sound pressure level of 70-80 dBA. A differentiation between the single instruments was not conducted due to the small count of subjects. Moreover, comparing the aerosol mass flow, playing instruments in forte was comparable to the mass flow while breathing and speaking and below the aerosol mass flow while singing. A trend of oboe and trumpet could not be shown. In the study by Firle et al. [13], the aerosol emission rates while playing instruments appeared to be higher than during the activities breathing and speaking.

4.6. Aerosol Emissions of Playing Wind Instruments Compared to Singing. In Figure 5, the particle volume rate $\dot{V}$ in ml s^{-1} for all instruments and conditions is displayed. For the professional singers, the particle volume rate, according to the methods of Netz [26], was calculated based on the results of Mürbe et al. [5]. Here, it can be seen that for the activities breathing and speaking, the plots are in the same range, but still, an intersubject difference appears and leads, e.g., to a low particle volume rate for the clarinetists while breathing. While playing "forte," singing seems to lead to the highest particle volume rate. The particle volume rate is higher for all instruments compared to speaking. Furthermore, playing the orchestral excerpt and "Ode to the Joy" leads to similar results. But the particle volume rate appears to be lower for flute and oboe than trumpet, clarinet, and singing.

4.7. Limitations. The articulation while playing instruments was not part of this study, as it was found in preliminary studies that the differences in particle emission rate were small compared to other factors such as loudness [11].

As there are varying instruments in this study with different shapes, blowing directions, and keyholes, a large funnel is needed to eliminate any potential sources of abrasion by unwanted touching it during playing. Furthermore, with varying volume flows emitted by the subjects connected to the differing conditions, a high sampling volume flow is needed to guarantee the sampling of all the emitted particles. As shown in Figure 1, flow obstacles (i.e., baffle plates) were used, where due to inertial effects, large particles deposit. Additionally, a long, flexible inlet section was used where large particles that are not ideally airborne can undergo sedimentation.

During sampling, efficiency for transport becomes significantly worse for particles > 3 μm. Deposition can occur in the canal and at the baffle plates. At the sampling probe, the aspiration coefficient gives information about the sampling efficiency of particles. Due to the under-isokinetic sampling, the aspiration coefficient is 1.002 for 0.5 μm, 1.005 for 3.0 μm, and 1.26 for 10 μm. Due to a steady narrowing, sedimentation within the probe is negligible. The hose of the probe was as short as possible. Here, a short hose of 30 cm in length with a diameter of 6 mm and bent by an angle of about 90° was used, to connect the particle counter and the sampling probe. Therefore, deposition of particles > 3 μm could occur inside the hose [27].

Larger particles could be emitted, but they would only play a predominant role in the spread of pathogens in the near field because of the fast deposition due to gravitational forces. Due to this measurement setup with a long duct and the turbulence generating baffle, the particles measured already are in a steady state [28]. Especially small particles with low influence of gravitational force can be carried over large distances.

We did not measure particles < 0.3 μm at a steady state, i.e., after shrinking. For these particles < 0.3 μm, the number concentration could be very high, extrapolating the skewness of the distributions. However, even when considering a high shrinkage factor of 3-5, they are not expected to be larger than 0.5 μm at the facial area of the subjects during the emission. That leads to the assumption that they can only carry few or no viruses. That was the reason why we did not consider this particle size. Notably, for viruses, mainly transmitted in particles < 0.3 μm, the technical limitations of the setup in our study limits risk assessments.

4.8. Outlook. The suspended particles can remain in the air for a long time, and, especially in the vicinity of infected persons, the concentration in the room air can be very high as stated by [1] and explained and analyzed in detail by [29]. Due to its small size, SARS-CoV-2 can occur even in submicron particles [30].

Regarding the particle volume rate, it is difficult to determine the corresponding viral load. For example, there is evidence that influenza virus RNA was detected more often in breathable particles < 5 μm than in particles > 5 μm as shown in the metastudy by Nikitin et al. [31]. Moreover, Yan et al. found a similar trend in their case study for size ranges of aerosols of persons infected with seasonal influenza [32]. Regarding SARS-CoV-2, virus RNA was found in particles in the size range of 1-4 and >4 μm in hospital rooms [33] as well as in the size range of <1, 1-4, and >4 μm with the most dominant size being 1-4 μm in household transmission [34]. Furthermore, Lai et al. [35] found out that smaller particles (<5 μm) accounted for most of the total exhaled viral RNA load.

Most of the particles counted in this study can be considered ideally airborne. Regarding the range the emitted air

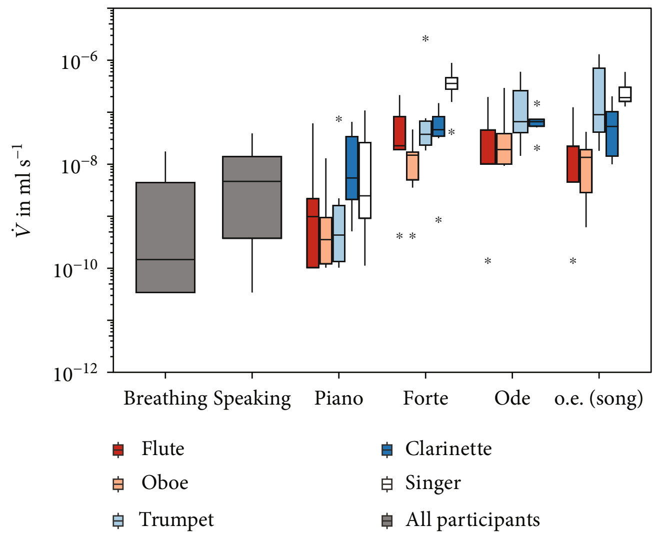


Figure 5: Particle volume rate $\dot{V}$ in ml s^{-1} for all instruments and conditions.

can exceed in a free jet, the volume flow and the air velocity play the main roles. Due to the angle of exhaled air and the low volume flow, the thermal plume is the driving force in the spread of exhaled air while breathing. The free jets in all cases are strongly influenced by the flow regime in the room.

According to the remarks in the introduction considering the free jet leaving the instrument, as soon as the free jet dissipates, other driving forces, such as the thermal buoyancy of the person playing the instrument or mechanical ventilation, might be more decisive for the dispersion of small particles.

However, regarding the infection risk, not only the emission rate of the respiratory particles is important. There are many factors that influence the risk of infection: the air exchange rate in the room, the distance between individual persons, the number of persons, the duration of stay, and virus-dependent parameters, e.g., the contagious dose and the viability of the virus. For the exemplary case of SARS-CoV-2, the measured half-life in air is approximately 1.1–1.2 h [36].

Increasing the emission rate increases the particle concentration while keeping the parameters constant and thus ensures that a contagious dose is reached more quickly [2]. Therefore, knowing the emission rate of such virus-laden aerosols is of crucial importance for the risk assessment of music rehearsals or concert situations.

Concerning the direct effect of emitted particles on the risk of infection when playing wind instruments, parameters dependent on the piece played, such as duration and individual volume, must also be considered. Brass players, for example, tend to play for a shorter time than woodwind players. Trumpets usually play very loudly, but only for short periods. An accurate assessment of the infection risk should therefore consider the score played.

Data Availability

The measurement data of the particle measurements as well as the sound pressure level measurements used to support the findings of this study are included within the supplementary information file(s). Additionally, previously reported particle emission data while singing were used to support this study and are available at doi:10.1038/s41598-021-93281-x. These prior studies (and datasets) are cited at relevant places within the text as reference [5].

Additional Points

Practical Implication. (i) The particle emission rate while playing the clarinet and trumpet is higher than it is while playing the flute and oboe. All emission rates while playing a musical instrument are higher than for speaking and breathing. (ii) Especially for trumpet, oboe, and flute, the particle emission rate was determined by volume. (iii) For low volume, the emission rates determined for flute, oboe, and trumpet are comparable to those for speaking. (iv) For high volume, the emission rates determined for trumpet and clarinet are in the same order of magnitude as previously observed for singing. (v) The findings support our understanding of sources of emissions of respiratory aerosols for infection risk calculations.

Ethical Approval

The study was conducted according to the ethical principles based on the WMA Declaration of Helsinki and was approved by the ethics committee of the Charité–Universitätsmedizin Berlin, Germany (EA2/172720).

Consent

Informed written consent was obtained from all subjects.

Conflicts of Interest

The authors declare no competing interests.

Authors' Contributions

L.S. carried out data curation, formal analysis, and methodology and wrote the original draft preparation. D.v.Z. contributed to data curation and wrote, reviewed, and edited the manuscript. A.S. assisted in the conceptualization and project administration. I.F. carried out the investigation. A.H. contributed to data curation and wrote, reviewed, and edited the manuscript. L.I. assisted in the data curation. M.K. contributed to the conceptualization, resources, and project administration and wrote, reviewed, and edited the manuscript. J.S. was responsible for the funding acquisition and project administration. D.M. assisted in the conceptualization, data curation, funding acquisition, and project administration; provided resources; and wrote, reviewed, and edited the manuscript. M.F. contributed to conceptualization, data curation, formal analysis, project administration, and software and wrote, reviewed, and edited the manuscript.

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Supplementary Materials

Supplementary 1. Figure S1: exemplary airflow while playing the flute; adapted from [16] (airflow) and [19] (blowing mechanism).

Supplementary 2. Figure S2: exemplary airflow while playing the clarinet; adapted from [16] (airflow) and [19] (blowing mechanism).

Supplementary 3. Figure S3: exemplary airflow while playing the oboe; adapted from [16] (airflow) and [19] (blowing mechanism).

Supplementary 4. Figure S4: exemplary airflow while playing the trumpet; adapted from [16] (airflow) and [19] (blowing mechanism).

Supplementary 5. Figure S5: preliminary study; effect of adding the additional canal to the measurement setup on the particle concentration at the sampling probe; particle size 0.3 μm. Case 1: measurement in central position without additional duct. Case 2: measurement 10 cm below central position without additional duct. Case 3: measurement in central position with additional duct. Case 4: measurement 10 cm below central position with additional duct.

Supplementary 6. Figure S6: preliminary study; effect of adding the additional canal to the measurement setup on the particle concentration at the sampling probe; particle size 0.5 μm. Case 1: measurement in central position without additional duct. Case 2: measurement 10 cm below central position without additional duct. Case 3: measurement in central position with additional duct. Case 4: measurement 10 cm below central position with additional duct.

Supplementary 7. Figure S7: preliminary study; effect of adding the additional canal to the measurement setup on the particle concentration at the sampling probe; particle size 1.0 μm. Case 1: measurement in central position without additional duct. Case 2: measurement 10 cm below central position without additional duct. Case 3: measurement in central position with additional duct. Case 4: measurement 10 cm below central position with additional duct.

Supplementary 8. Figure S8: dataset of the raw data of emitted aerosols and R-code (RMarkdown) for statistical analyses.

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