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Quentin Brosseau

University of Pennsylvania

Ranjiangshang Ran

University of Pennsylvania <https://orcid.org/0000-0001-5810-1312>

Ian Graham

University of Pennsylvania

Douglas Jerolmack

University of Pennsylvania <https://orcid.org/0000-0003-4358-6999>

Paulo Arratia (✉ parratia@seas.upenn.edu)

parratia@seas.upenn.edu <https://orcid.org/0000-0002-2566-2663>

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Flow and aerosol dispersion from wind musical instruments

Quentin Brosseau,¹ Ranjiangshang Ran,¹ Ian Graham,² Douglas J. Jerolmack,^{1,3} and Paulo E. Arratia¹

¹*Department of Mechanical Engineering & Applied Mechanics, University of Pennsylvania, Philadelphia, PA 19104, USA*

²*Department of Physics & Astronomy, University of Pennsylvania, Philadelphia, PA 19104, USA*

³*Department of Earth & Environmental Science, University of Pennsylvania, Philadelphia, PA 19104, USA*

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In the midst of the SARS-COVID-19 pandemic, many live musical activities had to be postponed and even cancelled to protect musicians and audience. Orchestral ensembles face a particular challenge of contamination because they are personnel heavy and instrumentally diverse. A chief concern is whether wind instruments are vectors of contamination through aerosol dispersion. This study, made possible by the participation of members of the Philadelphia Orchestra, brings insight on the modes of production and early life of aerosols of human origin emitted by wind instruments. We find that these instruments produce aerosol levels that are comparable to normal speech in quantity and size distribution. However, the exit jet flow speeds are lower than violent expiratory events (coughing, sneezing). For most wind instruments, the flow decays to background indoor-air levels approx 2 m away from the instrument's opening. Long range aerosol dispersion is thus via ambient air currents.

The SARS-COVID-19 pandemic has disrupted many aspects of our daily lives. Live entertainment, for example, has experienced severe restrictions resulting (in some cases) in the temporary disbanding of large bands, orchestras, and choirs. Numerous live performances and festivals have been postponed and even canceled to avoid the spreading of the disease [1–4]. To date, orchestras are experimenting with new ways of maintaining a high level of artistic production while keeping their audience and personnel safe. Mainly, they have resorted to performing with remote audiences, adapting their repertoire to promote pieces featuring strings, and have made significant changes in the number of musicians and their position in the auditorium [5, 6].

Among professionals, musicians playing string instruments and percussion can maintain an activity fully compliant with the recommendations of the World Health Organization (WHO) regarding social distancing and the use of personal protections equipment (face masks, screens, etc.) [7–9]. The case of wind instruments, however, poses a unique challenge since they are actuated by the human respiratory system. The constant air stream forced in and out of the body, required to maintain basic tone quality while playing a wind instrument, results in the creation and expulsion of small aerosols from the body. In addition, mouth and tongue movement required for the interpretative aspect of the sound imposes mechanical constraints that further contribute to the production of aerosol particles [10]. Combined, these two process can lead to an enhancement of aerosol flux exiting the instrument.

Even in the absence of an audience, the use of wind musical instruments may pose risks to other musicians as they are likely to release airborne particles (~ 100 persons in modern orchestra and standard choirs). Airborne particle transport is usually defined as the spreading of pathogens by aerosol of size $< 5 \mu\text{m}$, which allows them to travel over a long distance (carried by air-flow) [11]. This transport process is regarded as the main

contamination pathway of the COVID-19 virus [12–16]. Studies have established that the vast majority of the aerosol generated during normal speech is under $1 \mu\text{m}$ [17–19]. But even coughing and sneezing – where larger size ($> 100 \mu\text{m}$) particles move ballistically [20] at speeds reaching 5 – 10 m/s [21, 22] – can be a factor in contamination, especially over shorter distances [14, 15, 23, 24]. For wind musical instruments, studies have found distributions similar to speech ($< 5 \mu\text{m}$) [25], indicating the potential for long-range transport. Furthermore, recent experiments have shown the the flow created by some wind instruments can extend to approximately 30 cm away from the instrument [26]; ambient flow remains undisturbed at a distance > 1.5 m away from the instrument [27]. Despite these advancements, there is still a dearth of relevant experimental work from which to draw conclusions about the safety of wind instruments.

In this manuscript, we investigate the flow and flux of aerosols produced by wind musical instruments using flow visualization techniques and particle counting instruments. By combining flow with particle concentration measurements, we aim to gain insights into aerosols' early life (generated in the vicinity of a musician), and to formulate predictions regarding their spreading. Remarkably, we find that the flow produced by wind instruments is, in general, relatively gentle and that the aerosol fluxes produced are similar to those generated by normal speech. Flow visualization reveals that intermittent jets are produced at the instrument bells or tone holes. Using a simple model, we show that jet velocity decays to the indoor background flow within a few meters.

RESULTS

We begin by defining a few terms specific to musical instruments of the wind class (see Fig. 1a and b). The air column (or bore) of a wind instrument is the resonating space contained within the bore of the instruments. It is

FIG. 1. **Experimental setup, flow structure, & aerosol concentration data.** (a) Sketch of experimental setup. Two main experiments are performed: flow visualization and particle counting. These experiments are performed separately to avoid contamination. Particle/aerosol production is measured at the bell of wind instruments. Flow structures are visualized with artificial fog at different openings (bell for brass instruments, and tone holes and labium for woodwinds) using a laser sheet and a high-speed camera. (b) Flow structures produced by the tuba using green laser. (c) Time-dependent measurement of the particle/aerosol emission at the bell of a trumpet (inverted triangles) and a clarinet (hollow circle) compared with background (solid line) in discrete size channel $0.3\ \mu\text{m}$, $0.5\ \mu\text{m}$, $1\ \mu\text{m}$, $3\ \mu\text{m}$, $5\ \mu\text{m}$, $10\ \mu\text{m}$. Acquisition time 250 s; sampling rate 6 s. (d) Average number of aerosols N normalized by background signal N_0 and the corresponding concentration of aerosols (inset).

bounded by the physical walls made of metallic alloys or wood essences; these walls are designed to be impermeable to air under playing conditions [28]. The air column starts at the embouchure (at player's mouth) and ends at the bell, which is the opening (usually with a flared geometry) at the instrument's bottom/exit. In modern instruments, bore walls are usually pierced with tone holes or pistons that allow changes in the length of the air column.

For all experiments discussed here, musicians from the Philadelphia Orchestra were asked to play their instrument continuously (repeating the same cycle of notes) for approximately 2 minutes. The musical scale notes are shown in Supplementary Fig. 1; see also Methods for more information. We measure aerosol (particles or droplets) concentration and size distribution, as well as flow velocity in the vicinity of a given instrument using particle counting and flow velocimetry (see Methods). All measurements are recorded in a large amphitheater to mimic conditions of live performance.

Aerosol Production

Aerosol concentration and size distribution produced by wind musical instruments are characterized using a

particle counter (see Methods). Figure 1c shows aerosol counts, N , as a function of time ($\Delta t = 250\ \text{s}$) for one representative instrument of the brass family (trumpet) and one of the woodwinds family (clarinet). Results are shown for 6 discrete particle diameters ($d = 0.3\ \mu\text{m}$, $0.5\ \mu\text{m}$, $1\ \mu\text{m}$, $3\ \mu\text{m}$, $5\ \mu\text{m}$, $10\ \mu\text{m}$); also shown is the background count for control. For both instruments, the particle count time signals show significant deviation from background signal for sizes $\leq 1\ \mu\text{m}$; the signals become indistinguishable from background for larger sizes. We find that the aerosol production range (number of aerosol per unit time) decreases as aerosol size increases by several orders of magnitude. The data indicate that most of the aerosol is produced in the range of $0.3\ \mu\text{m}$ to $1\ \mu\text{m}$.

To quantify the above observations, we compute a normalized mean aerosol count N/N_0 , where N_0 is the background count averaged over many runs for both instruments (Fig. 1d). We find that N/N_0 is non-monotonic in aerosol size, d , with a peak at $0.5\ \mu\text{m}$ for both instruments. We note that non-monotonic size distribution in aerosol production has also been observed in activities based on mouth vocalization [18, 19, 21, 29]. We find that the averaged number of aerosols produced by the trumpet (at the peak) is nearly twice as much as the clarinet. Aerosol emission data, ϕ (particles/ m^3), also

FIG. 2. **Aerosol production by wind instruments.** Time-averaged number of aerosols N produced by different woodwinds and brass instruments (separated by the dashed line) for diameters 0.3 and 0.5 μm . Data are normalized with the background signal N_0 . Brass instruments produce larger amounts of aerosols than woodwinds.

show that the trumpet produces more aerosols than the clarinet (1d, inset), in agreement with recent results [25]. This may be due to instrument construction material; the wood of the clarinet is able to retain more moisture than the metal alloy of the trumpet [28]. The clarinet, similar to other woodwinds, possesses a large number of tone holes through which part of the flow is expelled [26], thus reducing the concentration of aerosol at the bell.

For both wind instruments, however, we find that $\phi \sim d^{-1.5}$. These results show that most of the aerosols emitted by these instruments are in the sub-micrometer ($\leq 1 \mu\text{m}$) range, similar to normal respiration (10^4 m^{-3}) and vocalization (10^5 m^{-3}) [19]. That is, our data are more consistent with values obtained by the processes involving vocal cords rather than mouth movements (lips of tongue) such as reading or normal breathing. These results suggest that the aerosol production during vocalization and the practice of wind instruments may originate from a similar mechanism. Interestingly, the modification of the air flux during play and the changes in the mouth opening geometry – constrained by the shape of the mouthpiece – do not seem to affect the aerosolization mechanisms (in the body) as well as aerosol transport through upper air ducts. Our data also indicate that aerosol distribution and concentration values are not affected by the transit inside the instrument bore for particle sizes $\leq 10 \mu\text{m}$. It seems that moisture deposition inside bores is a process involving larger aerosol sizes.

Next, we compare aerosol emission by a broader set of wind instruments. Figure 2 shows the normalized mean aerosol count (or emission), N/N_0 , for an extended sample of instruments; only the 0.3 μm and 0.5 μm channels are presented here since they are the most abundant. Data are shown for woodwinds (oboe, clarinet, bassoon) characterized by small tube length, wooden walls and tone holes; and brass (trumpet and tuba), with piston and large tube length. Similar to our previous results, we find that aerosol size distributions for all instruments peak at approximately $d = 0.5 \mu\text{m}$ – except the clar-

inet, which peaks at $d = 0.3 \mu\text{m}$. The emission reported here is roughly 1.5 to 2 times that of the background of the room. Surprisingly, for the selected size range (0.3 - 0.5 μm), the amount of aerosol emitted is independent of the instrument’s tube length. For example, the tuba, with its large cross section and tube (length $\sim 5.5 \text{ m}$), has a comparable emission rate to the trumpet tube (length $\sim 1.5 \text{ m}$) which itself is twice as long as the clarinet (length $\sim 70 \text{ cm}$). This is further evidence that condensation is minimal for this size range.

Overall, our results show wind instruments emit aerosols mostly in the sub-micrometer range ($\leq 1 \mu\text{m}$) at concentrations comparable to normal respiration and vocalization. Particle counting data show that woodwind instruments are lower emitters relative to brass instruments. However, the flute stands apart; it has particle concentrations similar to brass instruments, albeit lower. Note that the flute’s aerosol measurements are performed next to the instrumentalist’s mouth above the mouthpiece, since this is the most significant stream exiting the instrument [30, 31]. Thus, the flute data are not affected by possible losses through the tone holes. But how far do these aerosols travel? To answer this question, we characterize the flow emanating from the musical instruments.

Flow Characterization

FIG. 3. **Flow characterization & exit flow speeds.** (a) Laser-induced flow visualisation (left) and velocity vector field (right) obtained from PIV for the trombone during play. Also shown is the region of interest (ROI) at the instrument’s opening. The mean flow speed is defined as the average over the velocity field in the ROI. (b) Mean flow speed records were measured above the woodwind tone holes (clarinet, flute, oboe) and at the bell of brass instruments (trombone, trumpet and tuba) as a function of time. Flow speeds are much lower compared to sneezing and coughing events (see text).

We now characterize the flow at the openings (bells and tone holes) of wind musical instruments using a particle image velocimetry (PIV) technique with a high-speed camera (see Methods). In short, fog is used as seeding particles that are visualized using a laser sheet (see Fig. 1b and Supplementary Fig. 1). Flow velocities are obtained by the cross-correlation between two successive images taken by the camera. We define the reference frame so that the z -axis is oriented parallel to the ground in the direction away from the instrument opening and y -axis points upward (see Fig. 3a). The region of interest is roughly 20 cm by 20 cm. Figure 3a and b show an example of a flow field extracted at the bell of a trombone. Each time-dependent flow field is then averaged to obtain the instrument's mean flow speed U_{mean} .

Figure 3b shows U_{mean} as a function of time for all instruments analyzed here. In general, the values of U_{mean} are relatively similar for all instruments. In fact, our measurements do not show a distinct correlation between the pitch evolution (up or down a musical scale) and the value of the mean velocity; see the SI for more details pitch evolution. Importantly, these speeds (~ 0.1 m/s) are relatively low compared to coughs and sneezes (~ 5 – 10 m/s) [20]. Even for the flute, the highest instantaneous mean speed (~ 0.7 m/s) is an order of magnitude lower than the speeds for coughing and sneezing [22, 32].

In order to gain further insight into the flow generated by the instruments, we compute and analyze the distribution of U_z (obtained from PIV) over the duration of the recordings (Fig. 4a, b); note that our measurements interrogate a 20 cm x 20 cm area in the vicinity of the instrument's exit. For all the instruments, the mean of the

distribution is approximately 10^{-2} m/s, indicating that the flow is quite gentle in accordance to recent results [27]. The maximum velocity, defined as the upper 99-percentile of the distribution, reaches speeds as large as $\sim 10^{-1}$ m/s (Fig. 4c), which are comparable to normal respiration events ~ 1 m/s [33], but small in comparison to coughing and sneezing events [22, 32].

The skewness (Sk) of each distributions has a visible bias towards positive values (direction away from the instrument opening). We find that $Sk \sim 1$ for woodwinds and $Sk \sim 0.5$ at the bell of brass instruments, which indicates a stronger directional displacement above tone holes compared to the bell. Curiously, the tuba shows a negative skewness (Fig. 4d). Tuba is the only measurement in the upright direction, and it is likely that the negative skewness is due to (fog) droplet sedimentation (Fig. 4d). Overall, both the skewness and mean velocity data show that rather than a continuous stream, the flow displacement at the opening is better characterized by transient events that dominate the background ambient flow intermittently. The observed intermittency might originate from pressure variations necessary for the inception or "attack" of a pitch [34], as well as changes in fingering that release or block pistons and tone holes. This results in flow structures that contain puffs and jets [26]; see Fig. 1b as well as SI for time lapse images and videos).

It is worth noting that flutes (together with recorders and organ pipes) stand apart as the vibration of the air columns is set in motion by an air jet instability that originates at the mouth of the musician over the embouchure [30, 35]. In that case, our measurements are taken in a direction aligned with the mouth of the musician, instead of above the tone holes. Despite this peculiarity, the flute displays a skewed velocity distribution comparable to other woodwinds.

A simple model

In order to better understand the release of aerosols in the ambient, we analyse the characteristics of the jets emitted by the instruments during play. First, we compute the peak Reynolds number (Re) for each instrument. Here, we define $Re = U_m D / \nu$, where U_m is the maximum axial velocity (from PIV), D is the diameter of the instrument opening (bell or tone hole), and ν is the kinematic viscosity of the air. We use the maximum speed to provide a conservative analysis. The (peak) Reynolds numbers for all instruments are well below 300 (Fig. 5a), which indicates that the jet flow is still laminar. Therefore, we treat the flow produced by the instruments as steady axisymmetric laminar jets, for which an analytical solution ("Schlichting jet") exists [36] (see SI). The steady and axisymmetric assumptions are clearly simplifications, but they allow us to make a few important calculations without resorting to numerical simulations. For example, the solution to the lami-

FIG. 4. **Flow statistics** (a, b) Probability distribution functions (PDF) of axial velocity U_x for brass in a and woodwinds in b. (c) The maximum axial velocity, defined by the 99-percentile of the velocity distribution, shows the maximum speed at which the exit jet travels. (d) The skewness, Sk , of the velocity distribution shows velocity bias away from the instrument opening. The flute shows the strongest directional flow of all the wind instruments.

nar jet leads to an instrument's exit jet center-line velocity $U_c = 3\nu Re^2/4(z + z_0)$ where z is the distance away from the exit of the bell, and $z_0 = U_m D^2/32\nu$ is a parameter varying for different instruments (See Methods). This calculation predicts that jet velocity far away from the bell exit is inversely proportional to the propagation distance z , and proportional to the square of Reynolds number: $U_c \sim Re^2/z$. Figure 5b and c show the computed jet velocity decay as a function of the distance from the opening, for woodwinds and brass instruments. The data show that the flute and the trombone have significantly higher velocity than other instruments, due to either small opening and/or higher flow speeds. In both cases the distance needed for the flow jet to decay to the indoor air draft (0.1 to 0.2 m/s) is of the order of a few meters.

But would the particles generated by the instruments follow the flow? In order to address this question, we compute the Stokes number (Stk), which characterizes

the “attachment” of a suspended particle to the surrounding flow. For the range of flow speeds and aerosol diameters found in this study, the Stokes number $Stk \sim 10^{-4}$ (see Supplementary Fig. 5). In this regime, the particles act as ideal tracers that follow the jet streamlines. As the jet speed decays to room air draft level, the ambient air flow will dissipate the particles away. Thus, we can define a length scale, L_d , that represents the farthest distance that (aerosol) particles can be carried by the jet flow (until jet speeds decay to indoor air draft level). Figure 5a show the values of L_d for all instruments as an average between low (0.1 m/s) and high (0.2 m/s) indoor air draft speeds. The analysis shows that aerosols emanating from the flute and trombone can propagate over a distance of 2 m to 6 m before reaching the room air draft level. For other instruments, the propagation distance (L_d) is much shorter, ranging from 1 m to 2 m, correlating well with the WHO guideline. For aerosols of a size $\leq 10 \mu\text{m}$, the settling time due to gravity in the absence of flow varies from an hour to a month (see Supplementary Fig. 6), which is much larger than the time scale considered here. This means that settling plays a negligible role in the process of aerosol dispersion. Note that these calculations are performed using the instrument's peak speeds, and thus they represent the most conservative estimate. Estimates using average speeds would lead to significantly lower distances ($L_d \approx 1 \text{ m}$).

FIG. 5. **Jet velocity decay.** (a) Images of the expulsion of the jet from clarinet tone hole in time sequence. The coordinates shown are the axial and radial direction of the jet, r and z , respectively. (b) Maximum Reynolds number Re and jet velocity decay length L_d for different wind instruments. Here, L_d is the distance for the jet centerline velocity to decay to indoor air draft level (0.1 to 0.2 m/s), as shown by the grey area in c and d. (c, d) Axial velocity decay of the jet as a function of distance from the instrument's bell exit, for woodwind in c and brass in d. The lines are computed estimates of the centerline velocity of a Schlichting jet based on the Re values in a. Only flute and trombone instruments can reach beyond 2 m, based on a conservative estimate using the maximum speed and the lowest air draft level.

DISCUSSION

Our flow and particle concentration measurements allow us to draw insight on the early life of aerosols, from production to release in the ambient. Overall, we find that aerosols emitted by wind instruments share similar concentration and size distributions to normal speech and respiration events. We show that in the range of diameter $< 10 \mu\text{m}$, aerosol particles travel down the instrument bore with little trapping and are either ejected through tone holes or the instrument bell. Flow measurements show that exit jet speeds are much lower ($\sim 0.1 \text{ m/s}$) than coughing and sneezing ($\sim 10 \text{ m/s}$) events. We use an analytical solution for an axisymmetric laminar jet to estimate each instrument's exit jet speed decay. We find that, for most instruments, the maximum decay length is less than 2 meters away from the instrument's opening. The aerosol particles in the size range explored here ($\leq 10 \mu\text{m}$) follow the (jet) flow closely until this decay length is reached. Beyond that, we expect aerosols to be dispersed by the ambient flow.

METHODS

Experimental methods: For both aerosol measurements and flow characterization, professional musicians were isolated in a large amphitheater with the operators as to minimize the impact of human activities on the

background flow and lower spurious aerosol generation. For each measurement, each musician was asked to play the same musical pattern continuously for approximately 2 minutes. The musician was free to play a cycle of notes up and down along the whole range of the instrument, at a moderate tempo and at mezzo forte dynamical range. Supplementary material Fig. 1 shows the cycles followed by the flute for the flow detection experiment. More examples can be listened in the supplementary videos.

Aerosol detection: A particle counter (Lighthouse Handheld 3016) with 6 discrete size channels operating a 2.83 L/min suction and a refreshment rate of 6 seconds was used to measure particle (aerosol) concentration. The opening of the aerosol counter was set at a distance of 5 to 20 cm from the instrument bell and tone holes. For each counting the musician was asked to play up and down a scale, in the natural range of the instrument, at a comfortable tempo, and at a mezzo forte dynamic range. The experiments were purposefully performed in a large amphitheater to reproduce performance conditions, and to avoid the accumulation of released aerosols near the area of the musician.

Flow characterization: The characterization of the flow was performed at the bell for brass instruments and in the region above tone holes for woodwinds, with a custom Particle Image Velocimetry (PIV) setup similar to a previous study [37]. An artificial fog was produced by a commercial ultrasonic humidifier (AquaOasis) and directed towards the instrument (see Fig. 1). A slice of the fog parallel to the axis of the bell was illuminated by a green laser sheet (517 nm, 50 mW, BioRay), while a camera equipped with a lens (AF-D, 80-200 mm, Nikon) recorded images of the fog at a rate of 60 fps, while the musician performed continuous scales up and down in pitch at a comfortable tempo for a duration of $t \sim 2$ min.

Laminar jet model: We model the flow exiting the instruments as a “Schlichting jet”, the axial velocity of which can be expressed as:

$$U(z, r) = \frac{\nu}{z} \frac{3Re^2/4}{(1 + 3Re^2r^2/32z^2)^2}, \quad (1)$$

where z is the axial direction parallel to the jet flow, r is the radial direction normal to the flow, ν is the kinematic viscosity of the air, and Re is the Reynolds number of the jet. Here, to consider the furthest distance aerosol may travel, Re is defined by the maximum velocity of the instruments, U_m , measured from PIV experiments:

$$Re = \frac{U_mD}{\nu}, \quad (2)$$

where D is the size of the opening of the instruments. The volumetric flow rate of the jet, Q , increases with

axial distance z due to the entrainment of ambient air:

$$Q = 2\pi \int_0^\infty U r dr = 8\pi\nu z. \quad (3)$$

Eqn. (1) is valid for distances far away from the jet origin, i.e., for larger z values. We select a reference distance, z_0 , that matches the volumetric flow rate from the instruments:

$$z_0 = \frac{U_mA}{8\pi\nu} = \frac{U_m\pi D^2/4}{8\pi\nu} = \frac{U_mD^2}{32\nu}, \quad (4)$$

where $A = \pi D^2/4$ is the cross-sectional area of the opening of the instruments. We can replace the variable z by $(z + z_0)$, and the centerline velocity of the jet at $r = 0$ can be expressed as:

$$U_c = U(z + z_0, 0) = \frac{3Re^2\nu}{4(z + z_0)}. \quad (5)$$

The axial velocity decay as a function of axial distance predicted from eqn. (5) is plotted in Fig. 5b and c for different instruments.

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AUTHOR CONTRIBUTIONS

D.J.J. and P.E.A. conceived and designed the research, Q.B. and I.G. performed aerosol characterization, Q.B. and R.R. performed PIV measurements, R.R. and P.E.A. developed jet analytical models, Q.B., R.R., I.G., D.J.J. and P.E.A. wrote the manuscript. Q.B. and R.R. contributed equally to this work.

COMPETING INTERESTS

The authors declare no competing interests.

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