Tracking the Air Exhaled by an Opera Singer

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Opera singers are known for their ability to control their respiration and exhalations during a musical performance. However, air flows exhaled by singers were questioned during the COVID-19 pandemic as clusters of infections were identified within choirs due to the release of pathogenic droplets during rehearsals \square . Indeed, singing leads to an increased number of aerosol droplets released by a person \square . The expiratory air flows from a singer are of interest as there is a possibility of contaminated droplets to be transported by the exhaled air \square .

We observed the air exhaled by a mezzo-soprano singer during her performance of an Armenian lullaby 'Oror'. We use a high-speed infrared camera (FLIR X6900SC) operating in the mid-wave range of the infrared spectrum (1.5 - 5 μ m). The use of a filter in the absorption range of CO₂ (4.2 μ m) enables tracking the warm exhaled CO₂. The opera singer sat beside a dark non-reflective curtain that provided a uniform background at the ambient temperature. As seen in the image sequence of Fig. 11 the infrared imaging captures the warm face of the singer and the warm exhaled CO₂. The spatial extent of the exhaled CO₂ can thus be estimated. In Fig. 11 the exhaled air is detected at around one meter from the singer within a few seconds after the beginning of the song (t = 0 s).

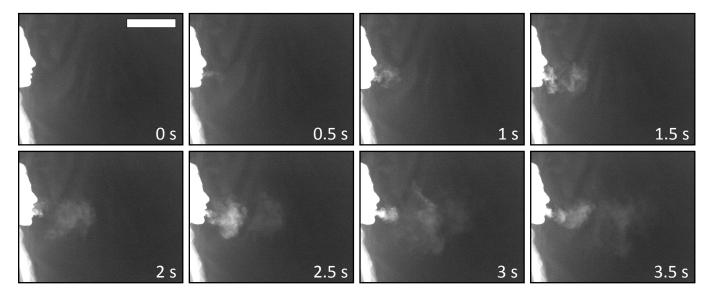


FIG. 1. Tracking the exhaled CO_2 from an opera singer. Sequence of infrared images (time-step of 500 ms) of a mezzo-soprano singing the Armenian lullaby 'Oror'. The warm exhaled CO_2 emanating from the singer traveled distances close to one meter within a few seconds. The scale bar represents 30 cm.

During the performance, three distinct air flows can be identified, as reported in the close-up views in Fig. 2. First, breathing generates rapid air jets emanating from the nose as seen in the sequence of images in Fig. 2(a). The initial velocity of the breathing jet is about 1 m/s and leads to a straight downward trajectory driven by the inertia of the air flows. Then, the singer performs most of the song with an open mouth, singing vowel-based sounds of frequent occurrence in the opera. As she maintains tonalities during 10-20 s without any inhalation, her performance requires a low value of expiratory flow-rate ($Q \approx 10 \text{ L/min}$) due to the intrinsic limit of her lung capacity. The remarkable control of the expiratory flow-rate by the opera singer during her performance and her wide-open mouth lead to air flows slower than breathing, with initial velocity around 0.3 m/s. The warm CO₂ cloud exhaled during the performance

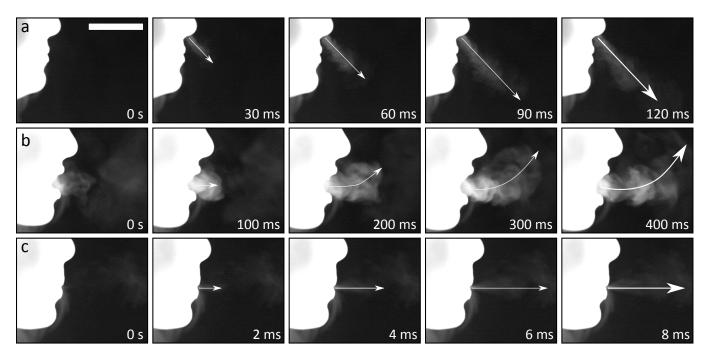


FIG. 2. Different air flows during the performance. (a) Sequence of infrared images (time-step of 100 ms) tracking the exhaled CO₂ as the singer breathes from the nose prior to the performance. The warm air is exhaled at an initial velocity around 1 m/s. The front of the exhaled air has a straight downward trajectory as shown by the white arrow depicting the trajectory of the front of the exhaled air jet. The scale bar represents 10 cm. (b) Sequence of infrared images (time-step of 100 ms) tracking the exhaled CO₂ as the singer sings with a wide-open mouth. The warm air is exhaled at an initial velocity around 0.3 m/s. The curved trajectory of the air front (white arrow) demonstrates the redirection of the warm exhaled air due to the buoyancy. (c) Sequence of infrared images (time-step of 100 ms) tracking the exhaled CO₂ as the singer starts singing with a closed mouth. The warm air is exhaled at an initial velocity above 10 m/s. The front of the air jet has a horizontal straight trajectory (white arrow).

rises, as shown by the curved trajectory (white arrow) in Fig. 2(b), as buoyancy dominates the reduced inertia of the exhaled air jet. However, a third kind of air flow can be identified when the singer closes her mouth during the performance. The pronunciation of consonant sounds, such as plosives, requires closing the lips, which leads to a significant reduction of the mouth opening and thus to the generation of a rapid air jet, with velocities around 10 m/s, as seen in Fig. 2(c) where the air jet reaches distances of 10 cm within 10 ms. When singing consonant sounds, the opera singer generates rapid air jets reaching velocities similar to the ones observed during the pronunciation of spoken plosives 4. This observation suggests that singing consonant sounds and plosives might enhance the transport of possible pathogenic droplets emanating from a singer.

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^[1] S. L. Miller, W. W. Nazaroff, J. L. Jimenez, A. Boerstra, G. Buonanno, S. J. Dancer, J. Kurnitski, L. C. Marr, L. Morawska, and C. Noakes, Transmission of SARS-CoV-2 by inhalation of respiratory aerosol in the Skagit Valley Chorale superspreading event, Indoor Air (2020).

^[2] M. Alsved, A. Matamis, R. Bohlin, M. Richter, P.-E. Bengtsson, C.-J. Fraenkel, P. Medstrand, and J. Löndahl, Exhaled respiratory particles during singing and talking, Aerosol Sci Technol 54, 1245 (2020).

^[3] W. F. Wells, On air-borne infection. Study II. Droplets and droplet nuclei., Am. J. Hyg. 20, 611 (1934).

[4] M. Abkarian, S. Mendez, N. Xue, F. Yang, and H. A. Stone, Speech can produce jet-like transport relevant to asymptomatic spreading of virus, Proc Natl Acad Sci USA, 202012156 (2020).