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Short Communication

Viral aerosol transmission of SARS-CoV-2 from simulated human emission in a concert hall

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ABSTRACT

The dispersion of aerosols was studied experimentally in several concert halls to evaluate their airborne route and thus the risk of severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) spreading. For this, a dummy was used that emits simulated human breath containing aerosols (mean diameter of 0.3 μm) and CO_2, with a horizontal exhalation velocity of v = 2.4 m/s, measured 10 cm in front of the mouth. Aerosol and CO_2 concentration profiles were mapped using sensors placed around the dummy. No substantial enrichment of aerosols and CO_2 was found at adjacent seats, provided that (1) there were floor displacement outlets under each seat enabling a minimum local fresh air vertical flow of v_v = 0.05 m/s, (2) the air exchange rate (ACH) was more than 3, and (3) the dummy wore a surgical face mask. Knowledge of dispersion of viral droplets by airborne routes in real environments will help in risk assessment when re-opening concert halls and theatres after a pandemic lockdown.

Very recently, the role of aerosols in the transmission of severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) by airborne route has been highlighted in several papers (Morawska and Milton, 2020; Prather et al., 2020). However, to date no experimental data are available for the spatial distribution of aerosols in public spaces such as concert halls, theatres, and event facilities. Humans typically emit respiratory droplets ranging from 0.1 μm to several tens of micrometres in diameter (Bar-on et al., 2020; Mittal et al., 2020; Riediker and Tsai, 2020), depending on the respiratory activity. For just breathing, the average diameter of the most prominent mode is about 0.3 μm (Pöhlker et al., 2021). While large particles either fall down due to gravity within a few metres or are held back by surgical face masks, small ones (aerosols) can stay airborne for quite a long time (Chen et al., 2020). Without ventilation, small virus-laden particles (diameter <5 μm) can reach a distance of up to d = 10 m at a nearly constant height after exhalation (Asadi et al., 2019; Bourouiba, 2020). Considering this, special attention should be paid to small particle sizes (diameter <1 μm) when indoor viral dispersion by aerosols is evaluated.

Measurements were performed at different concert halls and theatres to derive data for aerosol dispersion under real conditions. For this, a dummy continuously exhaled aerosols (di-2-ethylhexyl sebacate aerosol (DEHS)) and CO_2 with a horizontal velocity of v = 2.4 m/s measured 10 cm in front of the mouth. The aerosol concentration was adjusted to be 35 000 p/cm^3 and the CO_2 concentration to 7500 ppm. Experiments were performed with and without a surgical mask (3-ply, MACSEIS, MCG01). Aerosol droplets were generated by an aerosol generator (AGF 2.0ip; Palas GmbH, Germany) delivering a size distribution of 0.2–0.7 μm in diameter, with a mean particle diameter of 0.3 μm. The particles were monitored by two measuring devices (Palas Promo 2000 with Welas 2300 Sensor and Fidas Frog; Palas GmbH, Germany). Simultaneously, CO_2 concentrations were mapped by non-dispersive infrared (NDIR) CO_2 sensors (LP8, SenseAir).

There is low-level displacement ventilation in all of the investigated concert halls, i.e., fresh air is introduced under each seat with low momentum and is exhausted at the ceiling zone, providing a vertical air flow with a velocity of approximately v_v = 0.05 m/s. This flow is eventually augmented by body heat plumes of spectators. Horizontally, only minor temporally and spatially

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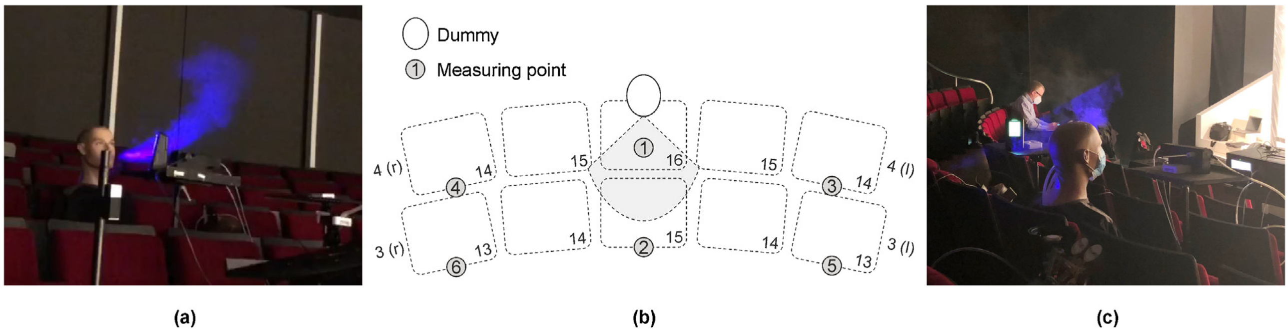

Figure 1. Experimental set-up: (a) dummy without a face mask (emitted aerosols were visualized by blue light illumination); (b) seat layout and measurement points; (c) dummy wearing a surgical mask.

Table 1
Aerosol and CO_2 concentrations measured at the positions given in Figure 1 for the dummy not wearing a mask and the dummy wearing a surgical face mask.

Measurement point	Without mask		With surgical mask	
	Aerosol (p/cm^3)	CO_2 (ppm)	Aerosol (p/cm^3)	CO_2 (ppm)
1	6000	4703	120	440
2	180	481	91	477
3	157	440	90	440
4	230	456	170	453
5	103	455	98	453
6	200	426	65	425

fluctuating flows with $v_H < 0.01$ m/s could be measured. The air change rate per hour (ACH) was ACH = 3 for all concert halls investigated in this study. After a traveling distance of d = 150 cm, the initial particle velocity was reduced to v = 0.04 m/s by interaction with the surrounding air. This corresponds to the vertical flow speed of the fresh air ventilation. Accordingly, the emitted aerosols were discharged by the vertical upward airflow.

Experiments were performed at four different concert halls with similar low-level displacement ventilation systems (ACH = 3) and with capacity ranging from 400 to 1650 seats. Figure 1a shows

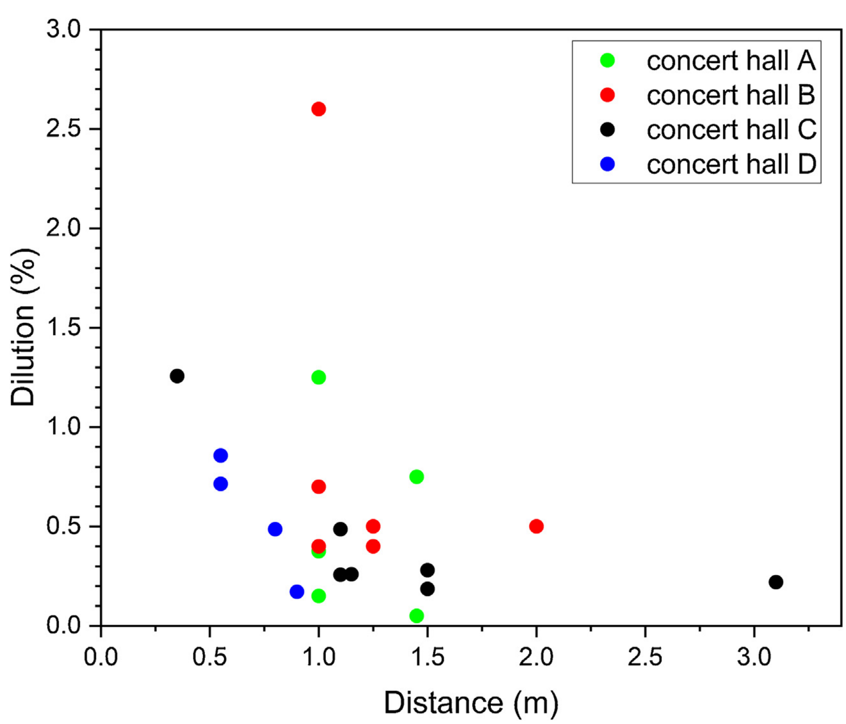

Figure 2. Association of the dilution of the initial aerosol concentration and the distance to the source for four different concert halls with similar low-level displacement ventilation systems, for the source wearing a surgical face mask.

a representative exhaled plume visualized by blue light. It can be seen that the initial horizontal flow is diverted upwards. Figure 1b shows the seat layout close to the dummy and the measurement points; Figure 1c shows the exhaled plume when the dummy was wearing a surgical face mask. Representative results for these points are summarized in Table 1.

The data show that both the aerosol and CO_2 concentrations were diluted down rapidly with increasing distance from the emitter. At measurement point 4, a slightly increased value was obtained. This was due to the presence of a temporally fluctuating horizontal air flow with v_H = 0.01 m/s. These results show the importance of even slight and temporally changing air flow conditions on aerosol dispersion, which will be very difficult to consider in models when calculating infection risks by airborne routes of viral droplets (Jones et al., 2021).

The effect of wearing a face mask is twofold: (1) large particles are blocked, with the threshold size depending on the filter class, and (2) small droplets that penetrate the mask lose their specific horizontal velocity component; having a flow speed of less than 0.05 m/s, they will be dispersed directly towards the ceiling by the ventilation system (Figure 1c). Consequently, even seats directly neighbouring the dummy did not show significantly increased aerosol and CO_2 concentrations over a long period of time. Experiments with about 50 real persons located around the dummy did not show measurable effects due to body thermal plumes.

Measurements taken within different concert halls using similar displacement ventilation systems were compared. Concentration data for the source wearing a surgical mask are shown in Figure 2; these were further analysed statistically. A *t*-test confirmed the hypothesis that for concert halls with low-level displacement ventilation, the initial aerosol concentration is diluted down to less than 0.85% when the distance to the source is $\geq$1 m.

This study demonstrates the importance of local vertical upward fresh air flow around the seat with at least v_v = 0.05 m/s for the ventilation system to protect the audience from viral droplet dispersion. Such experimental data are needed to improve models for calculating SARS-CoV-2 infection risks (Bourouiba, 2020) and developing risk assessment when re-opening public indoor spaces after a pandemic lockdown.

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Ethical approval

No ethical approval was required.

Conflict of interest

The authors have no conflict of interest to declare.

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