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Technical note: Impact of face covering on aerosol transport patterns during coughing and sneezing

Sergey A. Grinshpun *, Michael Yermakov

Center for Health-Related Aerosol Studies, College of Medicine, University of Cincinnati, Cincinnati, OH, USA

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ABSTRACT

COVID-19 is spread via different routes, including virus-laden airborne particles generated by human respiratory activities. In addition to large droplets, coughing and sneezing produce a lot of small aerosol particles. While face coverings are believed to reduce the aerosol transmission, information about their outward effectiveness is limited. Here, we determined the aerosol concentration patterns around a coughing and sneezing manikin and established spatial zones representing specific elevations of the aerosol concentration relative to the background. Real-time measurements of sub-micrometer aerosol particles were performed in the vicinity of the manikin. The tests were carried out without any face covering and with three different types of face covers: a safety faceshield, low-efficiency facemask and high-efficiency surgical mask. With no face covering, the simulated coughing and sneezing created a powerful forward-propagating fine aerosol flow. At 6 ft forward from the manikin head, the aerosol concentration was still 20-fold above the background. Adding a face covering reconfigured the forward-directed aerosol transmission pattern. The tested face coverings were found capable of mitigating the risk of coronavirus transmission; their effectiveness is dependent on the protective device. The outward leakage associated with a specific face covering was shown to be a major determinant of the exposure level for a person standing or seating next to or behind the coughing or sneezing "spreader" in a bus/train/aircraft/auditorium setting. Along with reports recently published in the literature, the study findings help assess the infectious dose and ultimately health risk for persons located within a 6-ft radius around the "spreader."

1. Introduction

COVID-19 can be transmitted via different routes, including virus-laden particles aerosolized due to human activities such as breathing, speaking, singing, coughing, sneezing, etc. (Bahlet al., 2021; CDC, 2021; Ma et al., 2021; Morawska & Cao, 2020; Morawska & Milton, 2020; Schijven et al., 2021). Better recognized for producing larger droplets, coughing and sneezing also aerosolize tremendous amounts of small aerosol particles (Lindsley et al., 2012; Han et al., 2013), primarily in the sub-micrometer size range. In addition, large human-generated liquid droplets rapidly evaporate in a typical indoor environment, shrinking by a factor of 10 or 100 and contributing to the sub-micrometer aerosol fraction.

Face coverings are believed to inhibit transmission of infectious aerosols in the vicinity of a "spreader" (Asadi et al., 2020; Brooks &

* Corresponding author. Center for Health-Related Aerosol Studies, College of Medicine, University of Cincinnati, 160 Panzeca Way, POB 670056, 45267-0056, Cincinnati, OH, USA.

E-mail address: sergey.grinshpun@uc.edu (S.A. Grinshpun).

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Butler, 2021; Howard et al., 2021; Leung et al., 2020; Lindsley et al, 2021a, 2021b; Pan et al., 2021; Patel et al., 2016). However, information about the outward effectiveness of commercial and homemade/improvised protective devices is limited, especially for small particles. It is important to understand the dynamics of propagation of fine aerosol particles generated during human expiratory activities in indoor air – with no protective device being worn and when the "spreader" is equipped with any kind of face covering. To our knowledge, no data has been obtained under controlled experimental conditions that would allow visualizing the aerosol propagation and assessing the impact of different face coverings on the transport of fine particles generated by exhalation.

In the present study, we determined the aerosol concentration patterns around a coughing and sneezing manikin through direct real-time measurements and established spatial zones representing specific elevations of the aerosol concentration relative to the background. The tests were performed without face covering as well as with three different types of face covers. The effectiveness of face covering for mitigating the aerosol transmission was characterized by these patterns.

2. Methods

The study was conducted in a 24-m^3 aerosol chamber with a human manikin positioned in the center. The manikin set-up was equipped with coughing and sneezing generators specially designed for this study.

The central element of each of the two generators is the cylindrical flowthrough chamber (length = 100 mm, diameter = 25 mm) operating at a flow rate of 10 L min^{-1}. Concentrically, a shorter and narrower cylindrical tube (length = 36 mm, diameter = 7 mm) is installed, and a compressed air is supplied through this tube at a pressure of 50 psi during specific time intervals. The air supply is controlled by an electromagnetic valve equipped with an electronic relay. The challenge aerosol is generated by a 0.75 W, 127 kHz ultrasonic aerosol nebulizer (MN-01 A, 127 kHz, Mayluck Inc., China) from the protein suspension and delivered to the flowthrough chamber downstream of the exit from the compressed air tube (a mixing zone). The initial suspension was made of 50% (by volume) of distilled water and 50% (by volume) of fresh egg whites' protein. It was mixed and filtered through a 1-mm mesh to remove large aggregates. The generated aerosol particles were not charge-neutralized, and no conditioning was introduced in the system. The resulting particles were expelled forward from the emission point between the manikin's lips.

The time of a single simulated cough was set at 0.27 ± 0.03 s, and a single simulated sneeze was set at a longer duration of 1.05 ± 0.15 s. These intervals are consistent with those indicated in the literature (e.g., Gupta et al., 2009; Tang et al., 2013). The cough air flow was approximately 7.0 L s^{-1} while the sneeze air flow was approximately 4.5 L s^{-1}. Based on these flow rates and the respective time intervals, the volumes were approximately 1.9 L and 4.7 L, respectively. The above numbers are consistent with those reported by Gupta et al. (2009) and Lindsley et al. (2020b) for a human cough or recalculated from Tang et al.'s (2013) findings for a human sneeze.

The challenge aerosol was, first, characterized with respect to the particle size distribution during the coughing and sneezing activities using an Electric Low-Pressure Impactor (ELPI, Dekati, Finland). The ELPI-measured aerosol contained the protein droplets generated by the nebulizer as well as the background particles. The background aerosol was mostly represented by the sub-micrometer particle size fraction. The overall aerosol concentration measured at 30 cm from the source was approximately 80,000 cm^{-3} in the size range of 0.1–0.5 μm, 20,000 cm^{-3} in the size range of 0.5–1.0 μm, and 5000 cm^{-3} in the size range of 1.0–5.0 μm.

The manikin's head was 22 cm high and had an oval cross-section with a width of 20 cm (ear-to-ear) and a depth of 24 cm. A distance from the back of the head to the lips was 22 cm.

The total aerosol concentration was measured in real time with a condensation particle counter (CPC, P-Trak, TSI Inc., USA) operating at 0.7 L min^{-1} for 1 min, within the sub-micrometer (<1 μm) particle size range covering a single aerosolized SARS-CoV-2 virus (≈0.1 μm), virus agglomerates and virus-carrying particles. The measurements were conducted in the nods of a horizontally-oriented 2D polar coordinate system with the aerosol emission point designated as zero. One CPC instrument was used at a time. Each location point on the plane was determined by the distance from the emission point (30, 60, 90, 120, 150, and 180 cm) and the angle from the front-forward direction (0°, 30°, 60°, 90°, 120°, 150°, 180°, 210°, 240°, 270°, 300°, and 330°). Altogether, the aerosol concentration was obtained at 72 points. At each location, the concentration value was calculated as an average of 10 CPC readings in a single measurement. Then it was normalized to the background concentration measured in the same test to determine a non-dimensional concentration. Three replicate tests were conducted; the arithmetic mean and standard deviation of the non-dimensional concentration were calculated for each location. A new protective device as donned for every replicate test.

The above experiments were performed without face covering as well as with a faceshield (Model MZ-SLTP, Delta Plus Corp., USA), low-efficiency facemask (Model GED, Heypex Global Inc., China) and high-efficiency surgical mask (Model 1818, 3M Corp., USA).

3. Results

The total background aerosol concentration in the chamber measured in the absence of any manikin breathing activity was found to range from 500 to 1500 cm^{-3} (averaging at 1000 cm^{-3}). The sub-micrometer fraction accounted for at least 95% of particles by

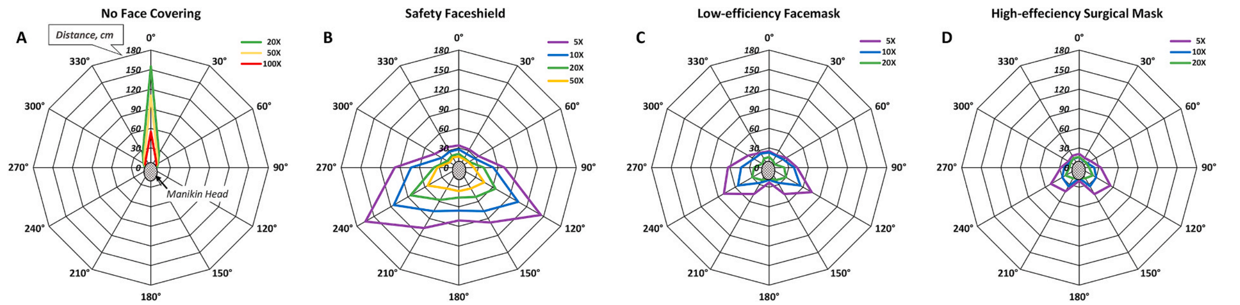

Fig. 1. Isoline patterns for aerosol concentration measured during coughing. Each color represents a specific concentration Excess Factor (compared to the background): 5, 10, 20, 50, and 100.

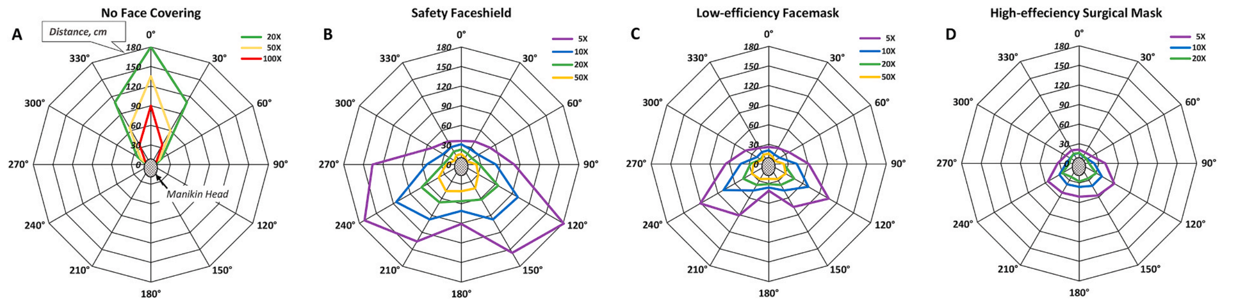

Fig. 2. Isoline patterns for aerosol concentration measured during sneezing. Each color represents a specific concentration Excess Factor (compared to the background): 5, 10, 20, 50, and 100.

number. The two-dimensional spatial patterns were established for specific concentrations levels of coughing- and sneezing-generated aerosols. The concentration isolines shown in Figs. 1 and 2 were drawn for the aerosol concentration values that represented the background level multiplied by 5, 10, 20, 50, and 100 (defined as Excess Factor, EF). The isolines help visualize the concentration patterns for the CPC-measured sub-micrometer particles around the "spreader" (each color corresponds to a specific EF). It is noted that the cross-section of the manikin head is shown in the figures slightly off-center to reflect the location of the aerosol emission point.

A powerful forward-propagating aerosol transmission was observed when no face covering was implemented (Fig. 1A and Fig. 2A). For instance, an individual located at 150 cm downstream (0°) of a coughing "spreader" with no face covering is exposed to the aerosol concentration level as much as 20-fold greater than the background (a green isoline in Fig. 1A). As much as a 100-fold elevation of the aerosol concentration compared to the background was found at 60 cm from a coughing "spreader" and 90 cm from a sneezing one in the forward direction.

Introducing a face covering inhibited the aerosol transmission. Most importantly, it entirely reconfigured the particle concentration patterns so that EF as high as 20 could not be reached anywhere along the forward direction, and even a lower EF of 5 was not observed directly upfront. While the forward propagation was considerably impeded by all three face coverings, a substantially elevated exposure was found to occur in the sideway and backward areas in the vicinity of the "spreader" wearing a faceshield or a low-efficiency facemask, which is visualized in Fig. 1 (B and C) and Fig. 2 (B and C). The elevated exposure zones notably shrunk as the face cover performance improved – from the faceshield to the low-efficiency facemask and then the high-efficiency surgical mask. The latter provided a relatively high source-control effectiveness. The coughing and sneezing data sets show similar trends with some differences partially attributed to different durations of the aerosol generation cycles between the two.

4. Discussion

This study was focused on small particles. Emission of larger particles are of a lesser interest because their high initial inertia combined with a very short travel time until they hit the faceshield/mask interior surface (which does not allow for significant evaporation) – all of this greatly hinders release of large particles.

In contrast, the sub-micrometer particles are much more likely to get released through the opening of the faceshield or the faceseal leakage of a poorly fit mask. The patterns of the released particles show a remarkable shift from the forward aerosol transmission observed for the uncovered "spreader" to the sideway and backward transmission observed for the "spreader" with a covered face. This important observation demonstrates how the outward leakage – associated with a specific face covering – affects the exposure of a person standing or seating next to or behind the coughing or sneezing "spreader" in a bus/train/aircraft/auditorium setting. A faceshield-wearing "spreader" can transmit particles to relatively large sideway and backward areas (Fig. 1B and Fig. 2B) while deploying a high-efficiency surgical mask notably localizes the aerosol cloud (Fig. 1D and Fig. 2D).

For example, a coughing or sneezing individual seating on seat 16E of an airplane and wearing a faceshield generates an aerosol cloud so that a person on seat 18E directly two rows behind experiences an about 10-fold increase in aerosol exposure. Passengers on seats 18D and 18G (a diagonal configuration) may be exposed to a level exceeding the background by a factor of 20. A “spreader” wearing a simple general-purpose facemask generates a smaller aerosol cloud as compared to the one with a faceshield, and he/she exposes the passengers seating two rows behind to a level of only about 5X background. The aerosol transmission from “spreaders” wearing a high-performance medical-grade mask covers a very concise area (Fig. 1D and Fig. 2D), which translates to a significantly reduced health risk for the surrounding passengers. This finding is more pronounced for coughing than for sneezing as seen in the figures.

5. Conclusions

The aerosol concentration patterns were determined through real-time measurements of sub-micrometer particles in the vicinity of coughing and sneezing manikin. Spatial zones representing specific ranges of the increased aerosol concentration relative to the background were established. Not surprisingly, a powerful forward-propagating aerosol transmission was observed for coughing and sneezing when no face covering was introduced. However, we identified a major shift from this aerosol transmission pattern to the sideway and backward transmissions that were observed for the “spreader” with a covered face. The outward leakage associated with a face covering determines characteristics of the aerosol cloud, which reaches the persons standing or seating next to or behind the coughing or sneezing “spreader.” The results obtained in this effort are applicable to various scenarios, including but not limited to the spread of coronavirus in public transport, school, and theater settings.

The study findings are important for assessing the infectious dose and ultimately health risk for individuals situated within a 180 cm radius around a coughing or sneezing “spreader” with and without face covering. Note that the study’s spatial boundary (the 180 cm radius) was chosen to acknowledge the 6-ft social distancing that has been globally recognized during the COVID-19 pandemic. The quantitative evidence produced in this study confirms that the face covering can mitigate the risk of coronavirus transmission and its effectiveness vastly depends on the type of the protective device worn by the “spreader.”

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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