Science Bulletin 67 (2022) 565–568

Contents lists available at ScienceDirect

Science Bulletin

journal homepage: www.elsevier.com/locate/scib

News & Views

Filtration efficiency of face masks against aerosolized surrogate SARS-CoV-2 at different social distances

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The coronavirus disease 2019 (COVID-19) pandemic is an unpreedented global event. It has become clear that COVID-19 is transmitted by virus-containing droplets (>5 μm) and aerosols (<5 μm), and that all human exhalatory activities (e.g., breathing, speaking, singing, shouting, coughing, and sneezing) result in the emission of suspended droplets/aerosols of various sizes. As an example, COVID-19 patients exhale millions of severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) RNA copies into the air per hour [1]. SARS-CoV-2-laden aerosols play a profound role in disease transmission, as they can linger and remain viable in the air for a long duration (∼16 h) [2] and travel a long distance (∼4.8 m) due to their smaller size [3].

Although global vaccination campaigns against the COVID-19 pandemic are underway, vaccinating the entire global population to achieve herd immunity requires a prolonged time period. SARS-CoV-2 has mutated constantly, leading to multiple new variants, which are highly infectious with greater viral loads, and lowering the effectiveness of vaccination. As a mainstay non-pharmaceutical intervention (NPI), wearing face masks can effectively interrupt the transmission of COVID-19 in hospital and community settings with minimal cost and without dramatically disrupting social practices [4]. Therefore, the public is urged to continue to wear face masks even in the post-vaccination era to reduce infections either (1) by trapping exhaled virus-laden droplets/aerosols from a spreader or (2) by directly filtering virus-laden droplets/aerosols as the receiver inhales.

In part due to the global shortage of personal protection equipment (PPE), the use of cloth masks, mostly home-made with two or more layers, has become prevalent globally and is recommended by the World Health Organization (WHO) and the United States Centers for Disease Control and Prevention (U.S. CDC) outside of healthcare settings during the current pandemic [5,6]. However, unlike N95 respirators and surgical masks, there is a lack of standards and regulations for cloth masks, which vary largely in design, material, construction, and fit. Previous studies using mathematical modeling or simulated body fluids (e.g., sodium chloride) or viruses (e.g., bacteriophage MS2) have explored the filtering performance of various types of facial masks (e.g., N95 respirator, surgical mask, and cloth mask), but there remain considerable uncertainties and disagreements about their effectiveness and need to wear masks for protection leading to significantly different mask-wearing guidelines across countries.

Besides face masks, social distancing (>1 m) has been widely adopted globally as a basic and efficient NPI measure against COVID-19. However, high jet velocities from violent respiratory events (e.g., coughing or sneezing) are prone to reduce the effectiveness of face masks in preventing emission [7]. Viral-laden aerosols passing through the face mask may travel a considerable distance, reaching susceptible people who have maintained social distancing. Given this risk, it is crucial to assess the outward and inward filtration efficiencies (FEs) of different types of commonly available masks for turbulent cloud-generated droplets/aerosols containing SARS-CoV-2, and the potential for exposure among receivers at different social distances to the infectious source. To the best of our knowledge, to date, there are no experimental studies simultaneously examining the combination of facial masks and physical distancing in mitigating droplet/aerosol transmission of SARS-CoV-2. This information is crucial to understanding how universal masking and social distancing might flatten the current pandemic curve.

To this end, we quantified and compared the FEs of four types of masks (medical N95 respirator, medical-grade surgical mask, single-use disposable mask, and homemade cloth mask with three layers of cotton fabric) with respect to outward filtration (mask

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https://doi.org/10.1016/j.scib.2021.12.017

worn by source) and inward filtration (mask worn by receiver) of typical sneeze-generated droplets/aerosols containing SARS-CoV-2 pseudo-virions (Figs. S1, S2 online). The filtering performance of the masks was assessed by measuring pseudo-virion concentrations at different social distances (0, 0.5, 1.0, 1.5, or 2.0 m) away from a sneezing source in a quiescent indoor environment after sample collection, viral RNA purification, and digital PCR measurement. Sneezing was selected as the emission process because it is the most violent spasmodic expiration. Masks were completely sealed to the mannequin head using adhesive tape during testing, ensuring that the experiment tested only the FEs of the mask material. The experimental materials and methods are provided in detail in the Supplementary materials (online).

In this study, the sizes of droplets/aerosols that were generated by the sneezing aerosol simulator ranged from 0.3 to 10 μm using a laser particle counter (Y09-301, AC-DC, Jiangsu Sujing Group Co., Ltd., Suzhou, China), and numerous aerosols (<5 μm) travelled >2 m (Table S1 online), indicating that the simulator successfully produced both droplets and aerosols. The concentrations of pseudovirus aerosol were inversely and significantly proportional to the distance between the sneeze simulator outlet and the mannequin receiver (Fig. 1 and Table S2 online), confirming that the aerosol concentration decreases as it moves outward from the emission source. Pseudovirus concentrations at a 2 m distance from the source were below the limit of detection (LoD) when no mask was worn, indicating the importance of commonly accepted social distancing (>1.8 m) as a low-cost and low-tech tool for curbing the spread of SARS-CoV-2. This finding is consistent with that of a large prospective U.S. cohort study of 198,077 participants, wherein individuals living in communities with the greatest social distancing were predicted to have a 31% lower risk of predicted COVID-19 than those living in communities with poor social distancing [8]. Hence, it is strongly recommended to use social distancing in all situations during the pandemic.

All masks tested had a protective effect in reducing pseudovirus concentrations (Fig. 1 and Table S3 online). Pseudovirus, however, was still detectable at one distance or more with all masks. Specifically, pseudovirus was detectable at 1.0 m for the single-use and cloth masks but only at 0.5 m for the surgical mask and N95 respirator. As the distance traveled by droplets in a quiescent indoor environment mostly relies on the initial air jet velocity, the observed movement of sneezed droplets within relatively stagnant surrounding air may underestimate the travel distance. However, the data indicate that the N95 respirators and surgical masks are superior to the single-use masks or cotton cloth masks in reducing the viral spread.

For each mask type, the outward and inward FEs were almost the same (Fig. 1 and Table S3 online). The N95 respirator and surgical mask had the highest and nearly equivalent FEs for both inward and outward aerosol penetration, reducing pseudovirus concentrations by >96.67% at 0–1.5 m distances from the sneeze source (Fig. 1 and Table S3 online). This level of filtration performance is consistent with the testing criteria for the filtration materials used in N95 respirators and surgical masks and previous experimental studies of surgical mask performance [9]. For example, surgical masks reduced the release of seasonal coronaviruses in coarse and fine aerosols to undetectable levels, and N95 (and equivalent) respirators efficiently blocked SARS-CoV-2 particles released from coughing patients [10,11]. The single-use mask showed moderate FEs (80.33% outward and 88% inward) when assessed at 0 m from the source but has improved FEs at 0.5 m (97.33% outward and 98.67% inward) and 1 m (97.67% outward and 97.67% inward) from the source (Fig. 1 and Table S3 online). The cloth mask had the poorest FE (e.g., 55% outward and 69.33% inward at 0 m from the source, Fig. 1 and Table S3 online), affirming that surgical masks provided approximately twice as much protection as homemade masks [12]. The reasons for the improved performance of the single-use and cloth mask with distance from the source are unclear. It is possible that in the outward system, the single-use and cotton cloth masks disrupt the turbulent jet of the sneeze, which limits the transport of aerosols. As for the inward system, the FE generally increases as the air velocity decreases, and the velocity of the sneeze's turbulent jet likely decreases with distance. The FEs of the cloth mask and single-use mask observed here were somewhat different from those found in other research, with FEs ranging from 10% to 86% [13]. The differences may be due to variations in fabric materials, fiber density (thread count), number of fabric layers, and different experimental conditions, e.g., aerosol composition, aerosol size distribution, particle electrical charge, and challenge velocity.

A strength of this study is the use of pseudovirus in artificial saliva aerosolized in a process that mimics sneezing, characteristics which are consistent with how people are actually exposed to respiratory viruses. This study used the most common variation of cloth masks, a cotton mask with three layers, and confirmed that cotton is not a suitable fabric for the outer layer of a mask [14], with a water-resistant fabric being a better choice. As this study was conducted in a laboratory with simulated sneeze aerosols, there is an inherent limitation arising from the fact that it is extremely difficult to reproduce real scenarios in the laboratory. For example, the aerosol size distribution, fluid volume, and turbulent jet generated by a human sneeze is highly variable between people and depends on time and environmental factors (e.g., humidity, temperature, air exchange rate, and airflow). In addition, the distance and orientation between people are highly variable, and people wear different types of masks in different ways that influence their effectiveness. Importantly, this study did not consider any leakage of aerosol through the mask edges. Surgical, single-use, and cloth masks, unlike N95 respirators, are not designed to fit tightly to the face and allow aerosols to leak around the mask edges, decreasing mask effectiveness [15]. Therefore, the FEs reported here cannot be generalized to actual use conditions, where mask fit may be poor. Opportunities for future studies include evaluating the impact of leakage due to poor fit on mask performance, the role of environmental factors such as humidity (arising from exhalation), and the role of mask-wearing duration and repeated mask use. Future work should also consider involving human subjects.

The inward and outward FEs for SARS-CoV-2-laden aerosols reported in this study can inform policies on the usage of face masks by both healthcare providers and the general public. While the physical barrier provided by any mask provides some protection, the type of mask plays an important role in preventing patients from exhaling virus particles and reducing the chances that healthy individuals become infected. Based on our study, for healthcare workers and other individuals in hospital settings facing a high risk of airborne infection through sneezing or coughing by patients, N95 respirators and surgical masks are necessary. Considering the magnitude of SARS-CoV-2 concentrations and the frequency of SARS-CoV-2 detection in hospitals, single-use, and cloth masks are not recommended in these settings. For people at lower risk of SARS-CoV-2 infection, a homemade cloth mask may be an adequate alternative if there are shortages of medical masks and respirators. However, it should be noted that cloth masks are not standardized nor regulated by any government authorities and organizations so far. As such, the quality of homemade cloth masks varies greatly, and their FEs are greatly affected by factors such as material properties, thread count, number of fab-

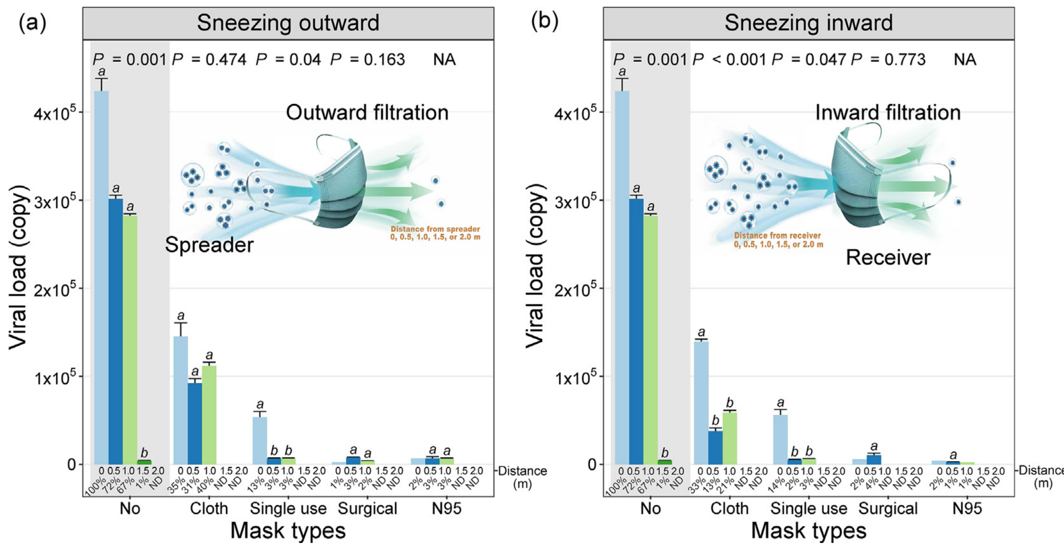

Fig. 1. SARS-CoV-2 pseudovirus gene copies (determined by digital PCR) as a function of distance (0, 0.5, 1.0, 1.5, or 2.0 m) from the sneeze source, given outward (a) and inward (b) penetration through four different masks. The numbers below the bars show the percentages (%) relative to the leftmost bar values without mask wear. The *x*-axis shows the type of mask and distance from the source. The bars are the means of three experimental replicates, and the whiskers denote the standard errors of the means. Analysis of variance (ANOVA) was used to test the overall differences between distances from the source (*P* values are given on the top). Different letters indicate significant differences from values for the no-mask-group (the leftmost column), based on the least significant difference (LSD) test. ND, none detected (below LoD); NA, not available.

ric layers, particle electrostatic charge, face velocity, and leaks. Therefore, the homemade cloth mask used in the present study cannot represent other cloth masks. In any case, a lower FE can be significantly compensated by using a mask in combination with physical distancing. This study demonstrated that aerosol concentrations decrease with distance from a source, affirming that social distances of >1.8 m along with protective measures such as universal mask-wearing can significantly reduce exposures to SARS-CoV-2 and other respiratory pathogens. More research is needed to properly improve the filtration provided by cloth masks, given the role that these masks play in COVID-19 prevention.

Conflict of interest

The authors declare that they have no conflicts of interest.

Acknowledgments

This work was supported by the National Institute of Environmental Health (NIEH), the Chinese Center for Disease Control and Prevention (GWTX05 and SWJC05), and the Capital Health Development Scientific Research Project (2021-1G-2172). We acknowledge Sino Biological Inc. and Bio-Rad in Beijing for the provision of digital PCR measurements.

Appendix A. Supplementary materials

Supplementary materials to this article can be found online at https://doi.org/10.1016/j.scib.2021.12.017.

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