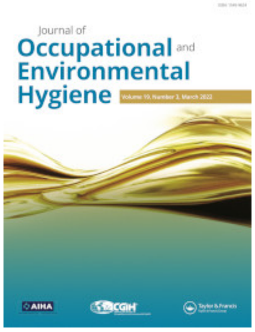

Taylor & Francis
Taylor & Francis Group

Journal of Occupational and Environmental Hygiene

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/uoeh20

Influence of face shields on exposures to respirable aerosol

Marion J. Woodfield, Rachael M. Jones & Darrah K. Sleeth

To cite this article: Marion J. Woodfield, Rachael M. Jones & Darrah K. Sleeth (2022) Influence of face shields on exposures to respirable aerosol, Journal of Occupational and Environmental Hygiene, 19:3, 139-144, DOI: 10.1080/15459624.2021.2023163

To link to this article: https://doi.org/10.1080/15459624.2021.2023163

Published online: 25 Feb 2022.

JOURNAL OF OCCUPATIONAL AND ENVIRONMENTAL HYGIENE
2022, VOL. 19, NO. 3, 139–144
https://doi.org/10.1080/15459624.2021.2023163

Taylor & Francis
Taylor & Francis Group

Check for updates

SHORT REPORT

Influence of face shields on exposures to respirable aerosol

Marion J. Woodfield, Rachael M. Jones, and Darrah K. Sleeth

Department of Family and Preventive Medicine, Spencer Fox Eccles School of Medicine, University of Utah, Salt Lake City, Utah

ABSTRACT

The objective of this study was to determine the influence of face shields on the concentration of respirable aerosols in the breathing zone of the wearer. The experimental approach involved the generation of poly-dispersed respirable test dust aerosol in a low-speed wind tunnel over 15 min, with a downstream breathing mannequin. Aerosol concentrations were measured in the breathing zone of the mannequin and at an upstream location using two laser spectrophotometers that measured particle number concentration over the range 0.25–31 µm. Three face shield designs were tested (A, B, and C) and were positioned on the mannequin operated at a high and low breathing rate. Efficiency—the reduction in aerosol concentration in the breathing zone—was calculated as a function of particle size and overall, for each face shield. Face shield A, a bucket hat with flexible shield, had the highest efficiency, approximately 95%, while more traditional face shield designs had efficiency 53–78%, depending on face shield and breathing rate. Efficiency varied by particle size, but the pattern differed among face shield designs. Face shields decreased the concentration of respirable aerosols in the breathing zone when aerosols were carried perpendicular to the face. Additional research is needed to understand the impact of face shield position relative to the source.

KEYWORDS

Infectious diseases; personal protective equipment; wind tunnel

Introduction

In response to the pandemic of Coronavirus Infectious Diseases 2019 (COVID-19), there has been an increased interest in the use of face shields, face coverings, and respirators to prevent the acquisition of infection among workers and the general public. Face shields exist in a variety of designs, but the basic element is a clear, plastic barrier that covers the facial area (Roberge 2016). Face shields are typically used to protect the face from splashes and sprays, and performance can vary with design (Roberge 2016). During the COVID-19 pandemic, face shield use increased among healthcare workers to reduce droplet contamination and prolong use of surgical masks and filtering facepiece respirators in the face of equipment shortages (Perencevich et al. 2020). Face shields, however, may also influence the concentration of inhalable aerosols in the breathing zone of the wearer, such as generated by coughs. Lindsley et al. (2014) found that a face shield worn by a breathing mannequin reduced inhalation of aerosolized influenza virus by 96% immediately after a simulated cough with volume median diameter 8.5 µm, but the effect diminished to 23% over 30 min owing to the ability of small particles to by-pass the face shield; the face shield reduced surface contamination of the respirator worn under the face shield by 97%. Lindsley et al. (2021) and Pan et al. (2021) both found that face shields were poor source controls due to the ability of the exhaled air to easily escape the wearer's breathing zone. Pan et al. (2021) also found that face shields did not provide much protection for the wearer, with essentially no blockage of aerosols $<0.7\,\mu m$; for particles $>5\,\mu m$ only 25% of particles were blocked from entering the wearer breathing zone. In none of these studies have face shields been tested as a receptor control with the inclusion of simulated exhalation by the wearer, which could conceivably influence the dispersion of particles in the breathing zone.

The objective of this study was to measure the efficiency with which face shields prevent respirable aerosols from entering the breathing zone of the wearer. Three face shield designs were tested in a low-speed wind tunnel, using a computer controlled breathing mannequin and a standardized test dust. Efficiency was defined as the percent reduction in particle

CONTACT Darrah K. Sleeth Darrah.sleeth@hsc.utah.edu Department of Family and Preventive Medicine, Spencer Fox Eccles School of Medicine, University of Utah, 375 Chipeta Way, Suite A, Salt Lake City, UT 84018, USA.

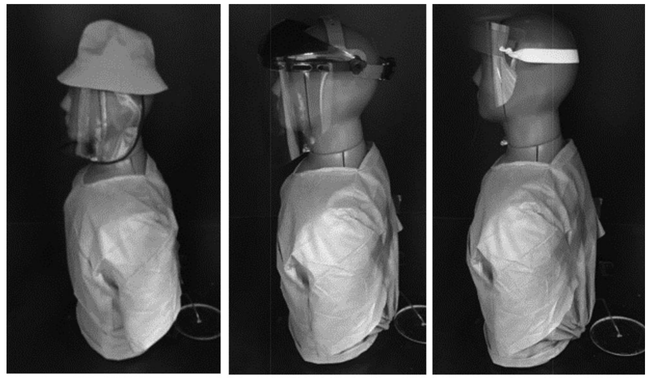

Figure 1. Face shield models tested, shown on the breathing mannequin in the wind tunnel.

concentration measured at a reference location outside the face shield, 81 cm upstream, to that in the breathing zone of a breathing mannequin wearing the face shield.

Methods

Face shields were tested in a low-speed wind tunnel with dust aerosol, a system that has been well described by Schmees et al. (2008). Briefly, laminar air flows were generated at a velocity of 0.1 m/s, representing typical indoor air conditions, through an area 1.2 m wide by 1.2 m tall and 3 m long. Dust was aerosolized by a Topas Solid Aerosol Generator (SAG 410, Topas GmbH, Dresden, Germany), connected to an aerosol injector wand and nozzle that moved vertically and horizontally behind a grated section of the wind tunnel to generate a uniform aerosol concentration. The dust that was used was ISO A1 Ultrafine Test Dust (Powder Technology Inc, Arden Hills, MN), which had a count median diameter of 4.1 µm (GSD = 2.6) and density of approximately 2.6 g/cm^3. A life-sized, breathing mannequin system (Thermetrics, Seattle, WA) was used to simulate a person wearing a face shield. The mannequin included a head, torso, and shoulders attached to a breathing machine set to mouth breathing minute volumes of 6 lpm and 20 lpm to generate typical mixing conditions in the breathing zone. The exhaled air was presumed to be particle free, which assumes that the wearer of the face shield is not a source of exposure.

Tests were performed with the mannequin stationary and facing upwind. A sampling inlet tube, threaded through the mannequin and out of a nostril, was attached to a GRIMM 1.109 Portable Laser Aerosol Spectrometer (Aerosol Technik, Germany), which measured particle number concentration (#/0.1 L) and physical diameter (31 size bins from 0.25–32 µm) every 6 sec. This instrument measured the concentration "inside" the face shield, i.e., in the breathing zone. A second GRIMM was located 81 cm upstream of the mannequin, at the same height as the mannequin breathing zone, and reflected the background concentrations "outside" the face shield.

Three face shields—labeled A, B, and C—were tested (Figure 1). Face shield A was a bucket hat design with a flexible plastic face shield that wrapped around the face and covered past the ears toward the back of the head. Face shield B was worn around the head with a plastic cross bar system. The headpiece was adjustable and the hard plastic face shield wrapped around the face ending approximately at the ear. Face shield C was a thin, plastic face shield attached to a foam pad for forehead comfort and an elastic band that wrapped around the head. All three face shields had shields that went past the chin, covering a portion of the neck.

The experimental design involved the two design factors—face shield design (A–C) and breathing rate (6 or 20 lpm). Triplicates for each experimental condition were performed sequentially, with additional sets of triplicate sequential experiments performed on different days. Each condition was tested six or nine times. Experiments involved 15 min of aerosol generation, followed by 10 min of wind tunnel operation to remove all aerosols from the airflow. Both GRIMM instruments were sampling for the entire 15 min of aerosol generation, and it was assumed that approximately steady state conditions were present.

Quality control included: (1) a daily zero-check on the GRIMM instruments before sampling began; (2) the face shield was cleaned with a clean, damp cloth and allowed to dry between tests; and (3) cleaning of the wind tunnel at the end of each day with a vacuum attached to a HEPA filter to prevent particle re-entrainment. In addition, 16 control "location" tests

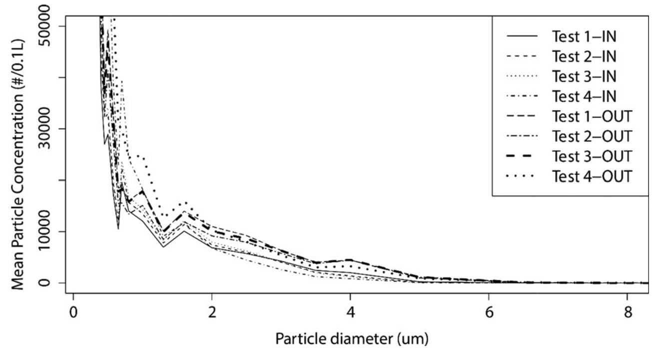

Figure 2. Particle concentrations by particle diameter sampled in four randomly selected control location tests show that concentrations are higher at the "outside" location than at the "inside" location (e.g., nostril of the breathing mannequin). Note, axes are truncated for visibility.

were performed across 8 days to quantify the loss of aerosol owing to physical transport process between the two GRIMM locations, if any occurred. In these tests, the experiment was performed without a face shield and the breathing mannequin turned off. Using the location test data, a correction factor was calculated for each of the $i = \{1, 2, \ldots, 32\}$ particle size bins in each replicate, and then averaged over the $j = \{1, 2, \ldots, 16\}$ replicates:

$$f_i = \frac{1}{n}\sum\nolimits_{j=1}^{n} \frac{\bar{c}_{in,ij}}{\bar{c}_{out,ij}} \quad (1)$$

where $\bar{c}_{in,ij}$ and $\bar{c}_{out,ij}$ are the average particle concentrations measured in the mannequin breathing zone (in this case without a face shield) and at the outside location upstream of the mannequin, for each size bin, respectively.

Efficiency of each face shield was defined as the percent reduction in the breathing zone achieved by the face shield. Efficiency denoted ε_{ij} (%), was first calculated for each of the j experimental replicates for each of the i particle size bin as:

$$\varepsilon_{ij} = 1 - \left(\frac{\bar{c}_{in,ij}}{\bar{c}_{out,ij}} \times \frac{1}{f_i}\right) \times 100\% \quad (2)$$

where variables are as previously defined. The overall efficiency of a face shield in experimental replicate j was calculated:

$$\varepsilon_j = \frac{1}{n}\sum\nolimits_{i=1}^{n} \varepsilon_{ij} \quad (3)$$

Note that ε_j is not weighted by the relative number of particles in each size bin as the size distribution used in this study is not directly relevant to the size distribution of infectious aerosols, such as those generated by cough.

Particle concentrations measured by the GRIMM were downloaded to Microsoft Excel (Microsoft Inc., Redmond, WA), and this software was used to calculate average particle concentrations during each experimental trial. Statistical analyses were performed using the R Project for Statistical Computing (R. Core Team, Vienna, Austria). As the particle diameters could not considered independent and the data exhibited heterogenous variance, the method of nonparametric analysis of longitudinal data in factorial experiments with ANOVA statistics—an F2-LD-F1 design—was used to test effect of face shield design and breathing rate on face shield efficiency for particles of different sizes (Brunner et al. 2002; Noguchi et al. 2012). Overall efficiency was summarized by mean and standard deviation.

Results

The particle concentrations by particle diameter sampled in selected control location tests are shown in Figure 2. The overlap of the experimental replicates indicate that the test system yielded reproducible conditions. Particle concentrations were higher at the reference sampling location "outside" the face shield than at the location "inside" the face shield, indicating that there is some particle loss between the two sampling locations. Few particles with physical diameters $>5\,\mu m$ were measured at either location (Figure 2). As a result, analysis for face shield performance was limited to particles with physical diameters $\leq 5\,\mu m$ (equivalent aerodynamic diameter of $\sim 8\,\mu m$).

Figure 3 shows the correction factors calculated for each particle size bin based on 16 location tests. The horizontal red line in Figure 3 denotes $f_i = 1$, where values below this line mean that the particle concentration was smaller at the breathing mannequin than at the reference location (81 cm upwind). Particle loss over this distance was more significant for particles with diameter $>3\,\mu m$ than for smaller particles.

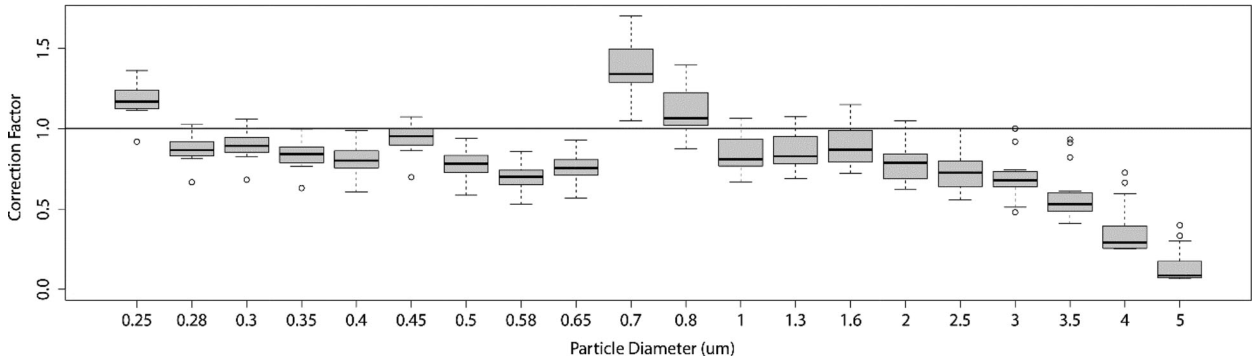

Figure 3. Correction factors from location control tests (n = 16) by particle size bin, f_i. Red horizontal line shows $f_i = 1$.

Table 1. Summary of overall face shield efficiency, ε, for high and low breathing rates considering particles with diameter 0.25–5.0 μm.

Face shield	Breathing Rate (lpm)	No. Replicates	Efficiency, ε (%) Mean	Std. Dev
A	6	6	95.1	3.25
	20	6	94.8	1.10
B	6	9	60.5	11.5
	20	6	53.1	10.4
C	6	6	78.0	9.79
	20	6	65.1	16.4

Table 2. ANOVA result for the face shield efficiency.

Variable	*df*	Statistic	*p*-Value
Face Shield Design	2	55.85	<0.001
Breathing Rate	1	4.52	0.003
Particle Size Bin	1.5	25.07	<0.001
Rate:Design	1.7	1.05	0.340
Design:Bin	2.50	3.48	0.022
Rate:Bin	1.50	3.54	0.042
Rate:Design:Bin	2.48	1.64	0.187

The mean efficiency for each face shield and breathing rate is shown in Table 1. Overall efficiency was highest for face shield A, followed by face shields C and B, respectively. The ANOVA results are shown in Table 2. The three-way interaction term was not statistically significant ($p = 0.187$). Two of the two-way interaction terms were statistically significant ($p < 0.05$) indicating that efficiency varied between particle sizes among the face shield designs and with breathing rate. These patterns are graphically displayed in Figure 4, which shows corrected efficiency. The efficiency varied somewhat with particle size for each face shield and breathing rate, but this effect was small compared to other experimental factors. The effect of breathing rate was larger for face shields B and C than for face shield A.

Discussion

The objective of this study was to evaluate the efficiency of face shields at preventing respirable aerosol from entering the breathing zone of the wearer. Three face shield designs were tested, with face shield A having consistently better performance than B and C (Figure 4, Table 1). An efficiency of 95%, such as achieved by face shield A, means that 95% of particles moving toward the face shield at a low wind speed do not enter the breathing zone of the wearer. Some of the performance of face shield A is likely due to the close fit of the shield to the mannequin face, not due to the design that integrated the face shield into the bucket hat, as the hat was child-sized but on an adult-sized mannequin head.

In this study, overall efficiency varied between face shield design and breathing rate over the range of approximately 53–95% (Table 1). The overall efficiency observed in this study is not inconsistent with the findings of others. Wendling et al. (2021) found that a face shield (similar in coverage to face shield B) reduced the concentration of respirable water particles emitted at approximately 5 m/sec in the breathing zone of a mannequin by 55%, where the effect increased with increasing particle diameters over the range of 0.5–10 µm. Ronen et al. (2021) found a face shield reduced the concentration of respirable sodium chloride particles emitted in a jet toward a breathing mannequin (21 lpm) by more than 90%. Lindsley et al. (2014) found that a face shield reduced the inhalation exposure to influenza viruses by 96% immediately after a simulated cough, but over 30 min the exposure reduction was only 26%. To our knowledge, other published studies have not explored the influence of breathing rate, and the high breathing rate used in this study was similar to that used by Ronen et al. (2021), but lower than that used by Lindsley et al. (2014) (20 lpm in this study versus 21 lpm and 32 lpm, respectively).

A limitation of this study was that the face shields were challenged with respirable aerosols delivered from the front, in a laminar airflow, and performance

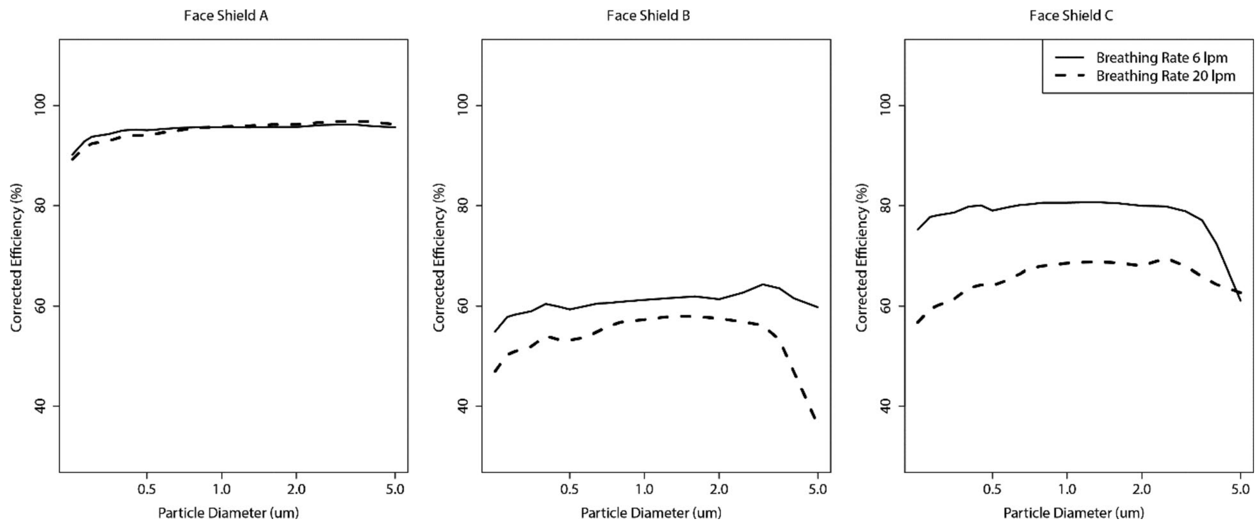

Figure 4. Corrected efficiency of face shields by face shield design (A, B, and C), breathing rate (6 and 20 lpm) and particle physical diameter (0.25–5.0 µm).

may vary with orientation of the face shield and head relative to the source. Ronen et al. (2021) found that the blocking efficacy of face shields challenged with a jet (5 m/sec) of water droplets (>3 µm) from the side, or shifted up or down 30 cm relative to the face shield was lower than when challenged from the front, 30–95% compared to nearly 100%. In a slightly different test system, Ronen et al. (2021) also found that the particle concentration behind the face shield was lower with an "extended" face shield design than with a standard design when challenged from the side. The wind tunnel system used herein, however, distributes the aerosols across the cross-section of the wind tunnel, and not as a "jet", such that aerosol passing by the sides of the face shield over the 15-min duration of the experiment could be entrained by the breathing mannequin.

The effect of breathing rate on the efficiency of face shields (Figure 4; Table 1) suggests that this may be an important factor to consider in future work. Several recent studies (Lindsley et al. 2021; Pan et al. 2021) have found that face shields were a very poor source control, with simulated coughs easily escaping out of the face shield of the wearer. The results here show that higher breathing rates typically resulted in lower efficiency for some face shield designs. On one hand, the exhalation jet (i.e., a directed bolus of air that pushes contamination away from the breathing zone) may be a primary means by which a face shield might provide some protection for the wearer, but high exhalation rates could be associated with more turbulent air around the face shield that could also entrain particles into the wearer breathing zone. This dynamic environment suggests that face shields may be inconsistent in their ability to protect the wearer.

The overall efficiency of face shields measured in this study may not equate to their real-world performance. First, given that the efficiency of the face shields varied to some extent by particle size (Figure 3), face shield performance may be higher or lower in the real-world, depending upon the characteristics of the infectious aerosol encountered relative to those of the test dust. Second, the face shield and breathing mannequin was oriented forward into the airflow, and may underestimate the efficiency of the face shield when it is not parallel to the emitted infectious aerosol. The long duration of the experiments in this study and the inclusion of an exhalation jet enables this study to capture the ability of face shields to block respirable aerosols that may be entrained to the face shield over time, an effect that meaningfully reduced the efficiency of face shields in the experiments of Lindsley et al. (2014).

The designs of face shields evaluated herein, and in other studies (Lindsley et al. 2014; Ronen et al. 2021; Wendling et al. 2021) are relatively similar, but design variations may improve performance. For example, using computational fluid dynamics, Akagi et al. (2021) demonstrated that changing the shapes at the edge of the face shield (e.g., addition of a bridge or deflector) can limit airflow into the breathing zone behind the face shield. And, extended face shield designs that have increased coverage of the size of the face can reduce droplet penetration (Ronen et al. 2021).

Face shields are known to prevent droplet spray onto the face (Roberge 2016), and this study contributes to the knowledge base as to their impact on inhalation exposures. Though face shields may reduce the concentration of respirable particles in the breathing zone of the wearer by as much as 95%, depending upon design (Table 1), they are not a replacement for respiratory protection when there is concern about airborne or aerosol transmission of infectious diseases, or exposure to other inhalable airborne contaminants. While this study was one of few to compare multiple face shield designs in the same test system, knowledge gaps persist about the impact of face shield design, orientation, and aerosol size on performance. While these dimensions can be explored through experimental work, human subjects should begin to be incorporated into this research so as to increase realism.

Conclusions

Face shields were 53–95% efficient at reducing the concentration of respirable particles in the breathing zone of a breathing mannequin receptor in the test system, with efficiency varying by face shield design, particle size, and mannequin breathing rate. Despite the high efficiency of face shield A, face shields are not a substitute for respiratory protection. Future research should explore the impact of face shield design—particularly with modifications at the edges to reduce air entrainment—and orientation on face shield efficiency, including evaluations on actual human subjects.

Funding

This research was supported by the University of Utah Office of the Vice President for Research in partnership with the Immunology, Inflammation and Infectious Disease (3i) Initiative. MW received additional financial support from the Rocky Mountain Center for Occupational and Environmental Health, CDC/NIOSH T42/OH008414.

ORCID

Rachael M. Jones http://orcid.org/0000-0003-1611-7900
Darrah K. Sleeth http://orcid.org/0000-0002-8519-9092

Data availability statement

The data that support the findings of this study are openly available in The Hive: University of Utah Research Data Repository at https://doi.org/10.7278/S50d-be9d-yp2c

References

Akagi F, Haraga I, Inage S, Akiyoshi K. 2021. Effect of face shield design on the prevention of sneeze droplet inhalation. Phys Fluids. 33(3):037131. doi:10.1063/5.0044367

Brunner E, Domhof S, Langer F. 2002. Nonparametric analysis of longitudinal data in factorial experiments. New York (NY): Wiley-Interscience.

Lindsley WG, Blachere FM, Law BF, Beezhold DH, Noti JD. 2021. Efficacy of face masks, neck gaiters and face shields for reducing the expulsion of simulated cough-generated aerosols. Aerosol Sci Tech. 55(4):449–457. doi:10.1080/02786826.2020.1862409

Lindsley WG, Noti JD, Blachere FM, Szalajda JV, Beezhold DH. 2014. Efficacy of face shields against cough aerosol droplets from a cough simulator. J Occup Environ Hyg. 11(8):509–518. doi:10.1080/15459624.2013.877591

Noguchi K, Gel YUR, Burnner E, Konietschke F. 2012. nparLD: an R software package for the nonparametric analysis of longitudinal data in factorial statistics. J Stat Softw. 50(12):1–23.

Pan J, Harb C, Leng W, Marr L. 2021. Inward and outward effectiveness of cloth masks, a surgical mask, and a face shield. Aerosol Sci Tech. 55(6):718–733. doi:10.1080/02786826.2021.1890687

Perencevich EN, Diekema DJ, Edmond MB. 2020. Moving personal protective equipment into the community: face shields and containment of COVID-19. JAMA. 323(22): 2252–2253. doi:10.1001/jama.2020.7477

Roberge R. 2016. Face shields for infection control: a review. J Occup Environ Hyg. 13(4):235–242.

Ronen A, Rotter H, Elisha S, Sevilia S, Parizer B, Hafif N, Manor A. 2021. Investigation of the protection efficacy of face shields against aerosol cough droplets. J Occup Environ Hyg. 18(2):72–83. doi:10.1080/15459624.2020.1854459

Schmees DK, Wu Y-H, Vincent JH. 2008. Experimental methods to determine inhalability and personal sampler performance for aerosols in ultra-low windspeed environments. J Environ Monit. 10(12):1426–1436. doi:10.1039/b806431h

Wendling J-M, Fabacher T, Pébaÿ P-P, Cosperec I, Rochoy M. 2021. Experimental efficacy of the face shield and the mask against emitted and potentially received particles. Int J Environ Res Public Health. 18(4):1942. doi:10.3390/ijerph18041942