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Human Research Study of Particulate Propagation Distance From Human Respiratory Function

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Background. Airborne viral pathogens like severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) can be encapsulated and transmitted through liquid droplets/aerosols formed during human respiratory events.

Methods. The number and extent of droplets/aerosols at distances between 1 and 6 ft (0.305–1.829 m) for a participant wearing no face covering, a cotton single-layer cloth face covering, and a 3-layer disposable face covering were measured for defined speech and cough events. The data include planar particle imagery to illuminate emissions by a light-sheet and local aerosol/droplet probes taken with phase Doppler interferometry and an aerodynamic particle sizer.

Results. Without face coverings, droplets/aerosols were detected up to a maximum of 1.25 m (4.1ft ± 0.22–0.28 ft) during speech and up to 1.37 m (4.5ft ± 0.19–0.33 ft) while coughing. The cloth face covering reduced maximum axial distances to 0.61 m (2.0 ft ± 0.11–0.15 ft) for speech and to 0.67 m (2.2 ft ± 0.02–0.20 ft) while coughing. Using the disposable face covering, safe distance was reduced further to 0.15 m (0.50 ft ± 0.01–0.03 ft) measured for both emission scenarios. In addition, the use of face coverings was highly effective in reducing the count of expelled aerosols.

Conclusions. The experimental study indicates that 0.914 m (3 ft) physical distancing with face coverings is equally as effective at reducing aerosol/droplet exposure as 1.829 m (6 ft) with no face covering.

Keywords. aerosols and droplets; COVID-19; face coverings; human respiratory function; social distance study.

Pandemics like that of coronavirus disease 2019 (COVID-19) can be driven by airborne-transmitted pathogens. Airborne transmission paths associated with natural human respiratory functions (speaking and coughing) are driven by pathogen-carrying droplets and aerosols [1, 2] ejected from the host and leading to various transmission paths [3, 4]. The impact of the pandemic has resulted in global-scale infection and deaths, health system overloads, and severe economic damage [5–9]. Originating from biofilms, the liquid includes multiple scales of droplets, including large-scale droplets (that settle), mid-scale droplets that evaporate, and small-scale droplets (described as aerosols). The World Health Organization and the Centers for Disease Control and Prevention (CDC) recommend physical distancing of 1 m (3.28 ft) and 6 ft (1.829 m), respectively, with face coverings to reduce droplet-related pathogen transmission.

Studies with high-speed stroboscopic light photography [10] found a majority of respiratory droplets to lie within the 7–10 μm diameter range and expelled no more than 2–3 ft (0.610–0.914 m). The study also qualitatively measured the effectiveness of face covering, identifying 3 main parameters that influence filtering: material/mesh size, air permeability, and droplet permeability [10]. The tested face coverings heavily reduced droplet counts due to large droplets being either filtered/absorbed by the face covering or divided by the mesh in the fabric and slowed down. The quantity and travel distance of particles after passing through the face covering was based on the pressure drop. As such, the face covering showed effectivity at reducing droplet/aerosol quantity and propagation distance for coughing and speaking, while being less effective against sneezes. Studies by Weaver [11] recommended the use of 3-layer face coverings with a mesh of 40 threads or more to remove the majority of bacteria-carrying droplets. In addition, the sensitivity to ambient variables was considered to drive the virus transmission. Studies by Ratnesar-Shumate et al [12] found a rapid inactivation of severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) while drying in suspension under simulated sunlight. A recent biomedical study on the stability of a SARS-CoV-2 isolate [13] found no influence of temperature variations, a moderate sensitivity to the variation of simulated sunlight and relative humidity [13], and high sensitivity to saliva properties [13, 14]. The effect of indoor ambient humidity on the risk of acute respiratory illness was studied by

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Han et al [15] over 3 years, reporting a negative association of acute respiratory illness at low absolute humidity levels during cool seasons [15]. Controversial results by Kormuth et al [16], testing the lifetime of influenza virus in stationary droplets and suspended aerosols in a humidity-controlled chamber, reported high infectivity regardless of the humidity level. Further studies outlined a virus inactivation potential to undetectable levels for certain types of oral rinses, verified with saliva suspension tests [17].

Recent investigations returned to the fundamentals with a recommendation for a 1 to 2-m social distancing limit, while utilizing high-quality face coverings to further mitigate the risk of contracting an airborne infection [18–20]. A reusable, 3-layer cloth face covering was found to match the filtering efficiency of 3-layer disposable coverings under ideal conditions [21]. Quantitative impaction air samples were taken by Bischoff et al at 1 ft (0.305 m), 3 ft (0.610 m), and 6 ft (1.829 m) from the patient, reporting a significant transmission risk due to the presence of small droplets and aerosols (diameter < 4.7 µm) [22]. However, a comprehensive review study of droplet and airborne travel distance from human respiratory function documented the wide variance in results of existing research [23], outlining the need for a new study to document the effect of face coverings with quantitative droplet detection technology. Hence, the present human research study was conducted to quantify and compare the droplet/aerosol content and sizes at various distances from 2 respiratory events, speaking and coughing. The data were gathered using 3 measurement techniques simultaneously, planar particle imagery, phase doppler interferometry, and an aerodynamic particle sizer. The measurements are reported for no face covering, a cotton single-layer cloth face covering, and a 3-layer disposable face covering. The results quantitatively verify what was reported in a recent distance study [24] in the context of a group, and indicate that, with face coverings, a physical distance of 3 ft (0.914 m) will have similarly low exposure to exhaled droplets/aerosols as 6 ft (1.829 m) without a face covering.

METHODS

Table 1 and Table 2 list all equipment and participant demographics as they pertain to the study. Figure 1 depicts a schematic of the equipment's and participants' orientation relative to each other. The experiment consisted of each participant reciting a phrase and simulating a cough each for 5 minutes without face covering, with a cotton single-layer cloth covering, and with a 3-layered disposable covering. The phrase was "The quick brown fox jumps over the lazy dog into a field of pretty playful perpetually purple pandas." The phrase is a pangram (containing every letter of the alphabet) and has "puh," "ple," and "pra" pronunciations, which create large droplets that travel longer distances [10]. The experiments were performed in a dust-free environment to minimize ambient particulate noise. The temperature of the room was maintained at 20°C with 35% relative humidity. The cloth face coverings (Hanes) were single-layer, 100% moisture-wicking cotton fabric, while the disposable face coverings (Bailey) were 3-layer fabric with a mean pore size of 15 µm. The face coverings are designed to reduce human aerosol and droplet emission by absorption and/or filtration, depending on the mesh pore size, material, and disposability of the face covering.

A high-power illumination source was used to illuminate a 1.5 × 1.5 ft (0.457 × 0.457 m) planar region. Aerosols/droplets entering this region produced light scatter that was captured by a 5 MP camera recording at 30 fps. This allowed sufficient light scatter of the expelled droplets. An opaque background was used to generate greater contrast. A phase doppler interferometer (PDI; Artium Technologies 1D-PDI) and aerodynamic particle sizer (APS; TSI Model 3321) were placed at the back center of the imaging domain (3 in [7.6 cm] from the edge of the planar region) and were used to record the aerosol/droplet size distribution and velocity (Figure 1A). The equipment remained stationary and distance data were obtained by the participant moving in 1-ft (0.305-m) increments from the capture region. The experimental data were recorded and processed by J. R. at the University of Central Florida.

There were 7 marked locations for the fixed displacements, each 1 ft (0.305 m) apart in the axial direction (Figure 1). The horizontal x-axis of the processed data and imaging material was aligned with the mouth level of the respective participant. Data were recorded up to 0.5 ft (0.152 m) above and below centerline along the entire axial downstream coordinate. Data up to 1.5 ft (0.457 m) above and below centerline were acquired at the 1-ft (0.305-m) and 2-ft (0.610-m) axial positions by adjusting

Table 1. Experiment Specifications

Equipment	Specifications	Use	Placement
Light source	532 nm, 150 mJ	Particle illumination	ROI
Camera	5 MP, 30 fps	Capture of particle scatter	1.52 m from ROI
PDI	0.5 < diameter < 1000 µm	Particle distribution/velocity	ROI
APS	0.3 < diameter < 500 µm	Particle distribution	ROI
Cloth face covering	Single layer, 100% cotton	Exhausted particle reduction	Over participant's nose and mouth
Disposable face covering	Triple layer, 15-µm mesh	Exhausted particle reduction	Over participant's nose and mouth

Abbreviations: APS, aerodynamic particle sizer; PDI, phase doppler interferometer; ROI, region of interest.

Table 2. Statistical Participant Information

				Zero-Exposure Distance, ft (90% CI)		
Participant	Age, y	Height, ft	Sex	No Cover	Cloth Cover	Disposable Cover
1	28	5.67	Male	4.3 (±0.22)	2.1 (±0.12)	0.5 (±0.01)
2	25	5.83	Male	4.4 (±0.24)	2.2 (±0.14)	0.5 (±0.03)
3	26	5.58	Male	4.3 (±0.19)	2.0 (±0.20)	0.5 (±0.01)
4	24	5.75	Male	4.5 (±0.31)	2.1 (±0.11)	0.4 (±0.01)
5	23	5.75	Male	4.4 (±0.25)	1.8 (±0.05)	0.5 (±0.02)
6	29	5.67	Male	4.4 (±0.23)	2.0 (±0.18)	0.5 (±0.01)
7	26	5.42	Male	4.2 (±0.28)	1.9 (±0.10)	0.5 (±0.03)
8	22	5.92	Male	4.5 (±0.19)	2.1 (±0.02)	0.4 (±0.01)
9	30	5.75	Male	4.1 (±0.22)	2.0 (±0.04)	0.5 (±0.01)
10	31	6	Male	4.5 (±0.33)	2.1 (±0.13)	0.3 (±0.02)
11	27	6.08	Male	4.5 (±0.26)	2.2 (±0.14)	0.5 (±0.03)
12	28	5.67	Female	4.4 (±0.22)	1.8 (±0.13)	0.4 (±0.02)
13	27	5.5	Female	4.4 (±0.21)	1.7 (±0.04)	0.5 (±0.01)
14	21	5.58	Female	4.5 (±0.30)	2.1 (±0.15)	0.5 (±0.02)

Abbreviation: CI, confidence interval.

the equipment along the vertical direction. For speech, the participants stood at the marked location and recited the phrase for 5 minutes. The exhaled aerosols/droplets were illuminated and captured by the camera, while simultaneously measured using the PDI and APS. Subsequently, the participant moved backwards to the next marked location and began reciting the phrase while data were recorded. Participants were asked to speak as loudly as possible, and their decibel levels were recorded. The average decibel rating was 87.8 ± 5.05 dB throughout the tests. This was repeated until the participant reached the final location. The process was repeated with the cloth and disposable face coverings. An example of how these data were segmented and compiled is shown in Figure 1B. The experiments were repeated for a cough, with the participant simulating a cough for 5 minutes. The participants were asked to keep the rate of their coughs close to 10 coughs per minute and maintain intensity. The experiments were repeated at each location and with all types of face coverings. To verify near-constant droplet emission levels of a single participant throughout the test procedure, a reference dataset was collected in reverse order, initializing the data collection at 6 ft (1.829 m) distance and having the participant subsequently move forward.

The images were postprocessed to create pseudo–long-exposure images that represent the aerosol/droplet path lines, generated by superimposing a 2-dimensional temporal moving average at a given location from each participant and combining the locations into a particle exposure image (Figure 1B). Aerosol/droplet loading was then calculated by normalizing the intensity of the exposure image and total counts of aerosols/droplets by the intensity and counts in the region behind the point of origin. Only 1 × 1 ft (0.305 × 0.305 m) of the 1.5 × 1.5 ft (0.457 × 0.457 m) segments were used to compile the images. This accounts for differences and movements of participants during recording and the Gaussian character of the light source.

The study was designed with power analysis to ensure sufficient participants to evaluate a hypothesis. The number of participants was based on the analysis of sample sizes for 2 independent samples, 3 ft (0.914 m; μ_1) and 6 ft (1.829 m; μ_2), assuming a continuous outcome. With a confidence level of 95% and 80% power, the probabilities yield a type I error of 5% (α) and type II error of 20% (β). An estimated standard deviation (σ) of 3.5 ft (1.067 m), extracted from previous studies [23], was used. In Equation 1, common values for 1-tail assessments of $Z_{1\text{-}\alpha/2}$ and $Z_{1\text{-}\beta}$ are used, that is 1.96 and 0.840, respectively. δ is 3 ft (0.914 m; $|\mu_1 - \mu_2|$) and represents the size of the effect that is clinically worthwhile to detect. The power analysis, given as

$$N = \frac{\left(Z_{1-\frac{\alpha}{2}} + Z_{1-\beta}\right)^2 * \sigma^2}{|\mu_1 - \mu_2|^2} = 10.67 \tag{1}$$

indicates that at least 11 participants are required. In this study, a total of 14 participants were included. The sex of the participants were 11 male and 3 female, their heights varied from 165.1 cm to 185.4 cm, and participants' ages varied from 21 to 31 years (Table 2). Data presented in Table 2 and Table 3 include the 90% confidence interval, in parentheses. With face coverings in use, the data become a strong function of the face covering itself, reducing the parameter sensitivity to demographic variability. The effect of minimized distance and confidence intervals as a function of the quality of the face covering can be tracked in Table 3).

RESULTS

Outcomes of the speech and cough studies are presented, both conducted without any face covering, with a cotton single-layer cloth face covering, and with a 3-layer disposable face covering.

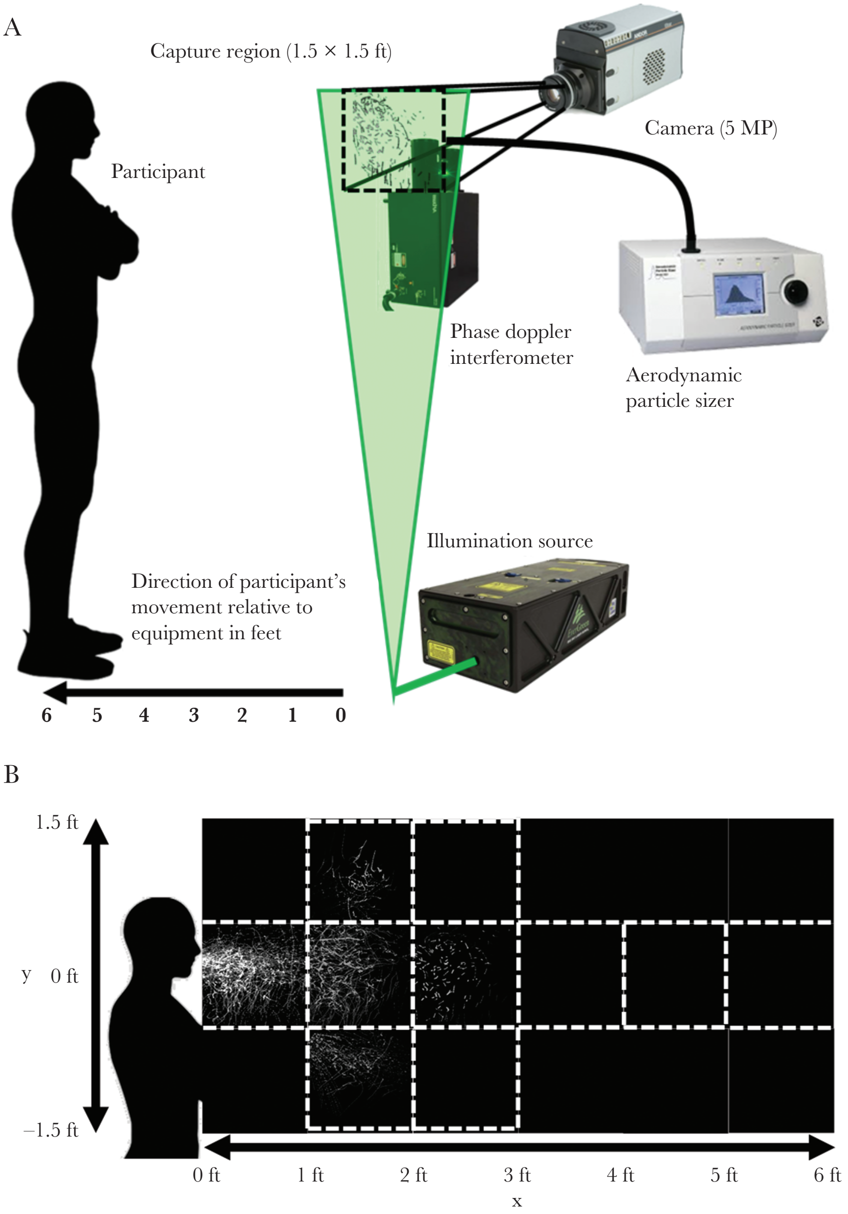

Figure 1. Experimental approach: (*A*) diagram of experimental set up with labeled equipment; and (*B*) acquisition grid used to obtain distance data.

Speech Study

Figure 2 shows the effect of the face covering on the distance traveled by the aerosols/droplets ejected from participants during speech. All plots in Figure 2 show time-averaged aerosol/droplet path lines from all participants. The spatial loading for each distance marker is represented by the color map and

Table 3. Summarized Results From All Experimental Test Cases and Participants With 90% Confidence Intervals in Parentheses

Mode	Face Cover, Type	Average Exhausted Diameter, µm	Maximum Exhausted Distance, ft	Average Exhausted Velocity, m/s	Expelled Volume, mL
Speech	None	11.5 (±1.10)	1.25 (±0.08)	5.3 (±0.32)	3.5 (±0.29)
	Cloth	1.5 (±0.11)	0.61 (±0.04)	1.9 (±0.14)	0.05 (±4e-3)
	Disposable	0.8 (±0.06)	0.15 (±0.01)	0.8 (±0.05)	0.002 (±2e-4)
Cough	None	13.2 (±1.30)	1.37 (±0.09)	12.1 (±0.74)	4.3 (±0.41)
	Cloth	1.9 (±0.14)	0.67 (±0.04)	4.8 (±0.33)	0.07 (±5e-3)
	Disposable	0.7 (±0.07)	0.15 (±0.15)	0.9 (±0.08)	0.001 (±1e-4)

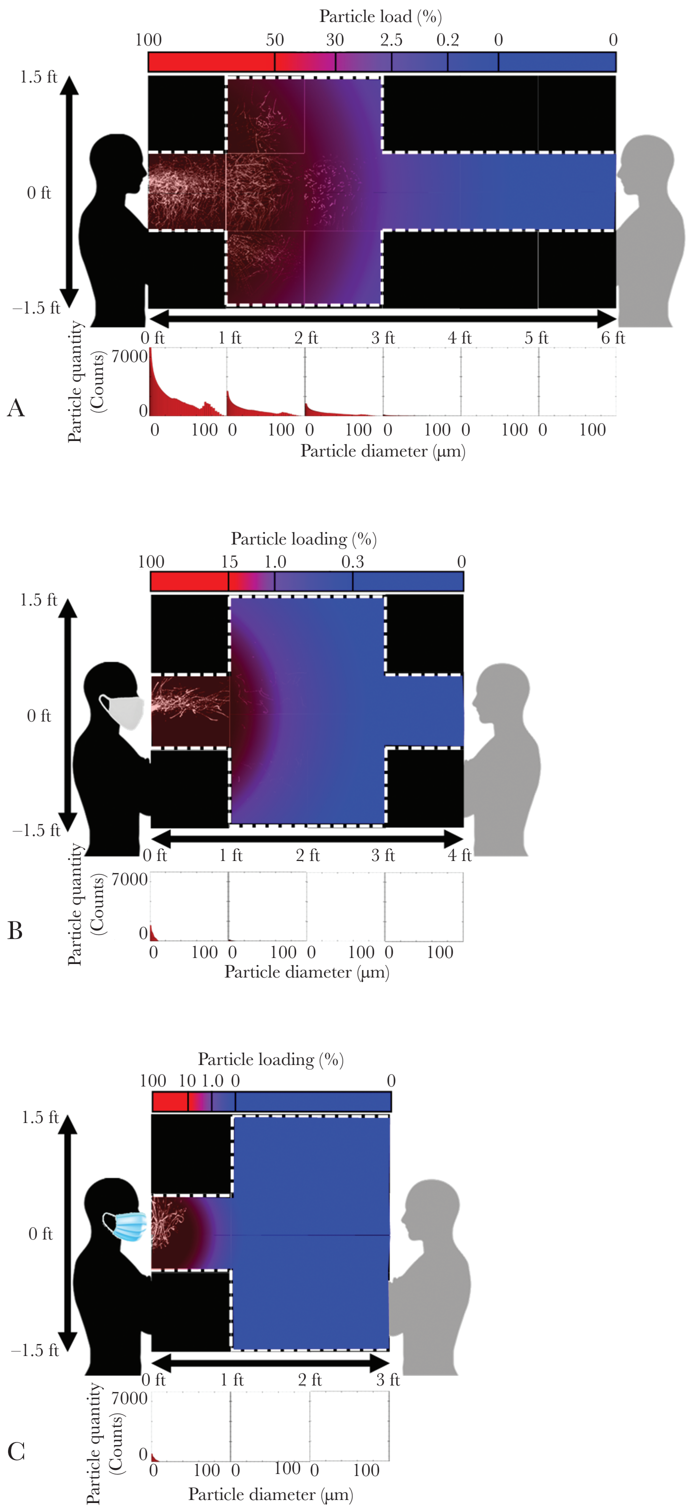

Figure 2. Path line images of compiled speech recordings (*A*) without a face covering; (*B*) with a cotton cloth covering; and (*C*) with a 3-layer mesh disposable covering.

is the percentage of counted particles along the axial direction, normalized by the amount at 0 ft. Two-dimensional particle imagery fields and size distributions are overlayed and aligned to the axial direction. Figure 2A shows data associated with no face covering, Figure 2B a cloth face covering, and Figure 2B a disposable face covering.

No Face Covering

When no face covering was worn (Figure 2A), a high concentration of aerosols/droplets was visible up to 4.1 ft (1.250 m) downstream. Due to the limited forward momentum generated by speech, aerosols/droplets took a randomized path with little alignment to the horizontal axis. However, the bulk motion of aerosols/droplets remained relatively aligned to the forward direction. Maximum vertical fluctuations of y = ±1.2 ft (0.366 m) were recorded at an axial distance between 1 ft (0.305 m) and 2 ft (0.610 m). At 1 ft (0.305 m), the PDI counted a total of 250 000 aerosols/droplets in the range of 0 to 100 µm, with a peak of 7300 counts at 1 µm, signifying the maximum aerosol concentration. At 100 µm diameter, a second peak of 1200 droplets was measured, a local maximum that represented the larger droplet fraction. The overall measured count decreased along the axial direction, reaching 40% reduction from origin after 2 ft (0.610 m) distance, 5% after 3 ft (0.914 m), and 0.15% after 4 ft (1.219 m).

Cloth Face Covering

Tests with a single-layered cloth face covering (Figure 2B) returned a lower number of detectable aerosols/droplets. At 1 ft (0.305 m), a total of 29 000 counts of aerosols/droplets were detected, signifying a reduction of 88.4% relative to the counts at 1 ft (0.305 m) without a face covering. The large droplet fraction (approximately 100 µm) was filtered entirely by the face covering, with the largest detected droplet being 21 µm. Approximately 1400 units at the small scale (approximately 1 µm) were able to penetrate through the face covering (a reduction of 80.8% in aerosols), leaving traces visible up to 1 ft (0.305 m) axial distance. Few aerosols/droplets remained detectable downstream, with total count dropping to 2500 at the 2 ft (0.610 m) marker and none detected at the 3 ft (0.914 m) marker. The planar particle imagery data show that at least 1 aerosol/droplet was present up to 2.1 ft (0.64 m). The use of a cloth face covering reduced aerosol/droplet concentration and reduced propagation distance from 4 ft (1.219 m) to 2 ft (0.610 m).

Disposable Face Covering

When a 3-layer disposable face covering was worn (Figure 2C), the emission downstream of the face covering was further reduced. Like the cloth face covering, the disposable covering filtered out the large-scale droplets entirely. No aerosols/droplets were detected at 1 ft (0.305 m) and thus the PDI and APS systems were moved to 0.5 ft (0.152 m). At this location, a total of 15 000 counts of aerosols/droplets were recorded (a 94% reduction from without a face covering). A limited amount of about 600 units at the small-scale range (approximately 1 µm) was recorded, with the largest recorded droplet being 11 µm. From the particle planar imagery, the maximum aerosol/droplet travel distance was 0.5 ft (0.152 m). Because the disposable face covering had limited adjustability, the images show a minor amount of undirected path lines to originate from the chin area and from both sides at the nose. However, due to the high filtering efficiency of disposable face coverings, horizontal emission downstream of the face covering was negligible and reduced travel distance to 0.5 ft (0.152 m).

Cough Study

The study was repeated for a series of cough events. Figure 3 is structured similarly to Figure 2, showing no face covering (Figure 3A), cloth face covering (Figure 3B), and disposable face covering (Figure 3C). A comparable aerosol/droplet count was recorded relative to speech [10].

No Face Covering

The cough event without face covering yielded the maximum emission travel of 4.5 ft (1.372 m) per the planar particle imagery data. A cough (Figure 3) showed more aligned aerosol/droplet traces relative to speech (Figure 2). The bulk of the path lines were concentrated along the horizontal distance, traveling through the first domain with a moderate divergence angle of ± 10°. The recorded propagation shows a reduced extent in the vertical directions. Despite the focused horizontal propagation, a high concentration of falling droplets was recorded in the lower sampling squares (−0.5ft ≤ y ≤ −1.5ft). This was confirmed with the APS and PDI data, showing a more distinct droplet fraction relative to the speech result [25]. Coughing produced a total count of 300 000 aerosols/droplets (a 20% increase over speech) at the 1 ft (0.305 m) location with higher concentration of large-scale droplets, 2000 counts (versus 1200 counts during speech). The large-scale droplet peak for coughing was found to be at 90 µm, whereas for speech it was at 100 µm.

Cloth Face Covering

When coughing into a single-layer cloth face covering (Figure 3B), a different expulsion pattern was visualized. A moderate horizontal trajectory was noticed in the first domain, yielding an approximate divergence angle of y = ±25°. The vertical propagation resulted in significant detectable intensities in the outer squares (y ≤ ±1.5 ft) between 1 ft (0.305 m) and 2 ft (0.610 m) axial distance. Coughing into a cloth face covering forces aerosols/droplets to deflect due to the resistance of the face covering. The expulsion exits through the crevices at the top and bottom ends of the covering, located by the nose and chin. As a result, the maximum axial penetration of one given aerosol/droplet recorded by planar particle imagery was 2.2 ft (0.671 m) in the upper and lower quadrants of the recording domain. The cloth filtered out large-scale droplets entirely with a maximum droplet diameter captured of 24 µm. A reduction of 89.0% of total aerosols/droplets counts were recorded, with 0 aerosols/droplets detectable after 2 ft (0.610 m) according to the PDI and APS instruments.

Disposable Face Covering

Like speech, high filtering efficiency of the 3-layer disposable face covering was recorded for the cough, and a propagation distance of 0.5 ft (0.152 m) axial distance was observed. The cough particles did not leave the near field of the disposable face

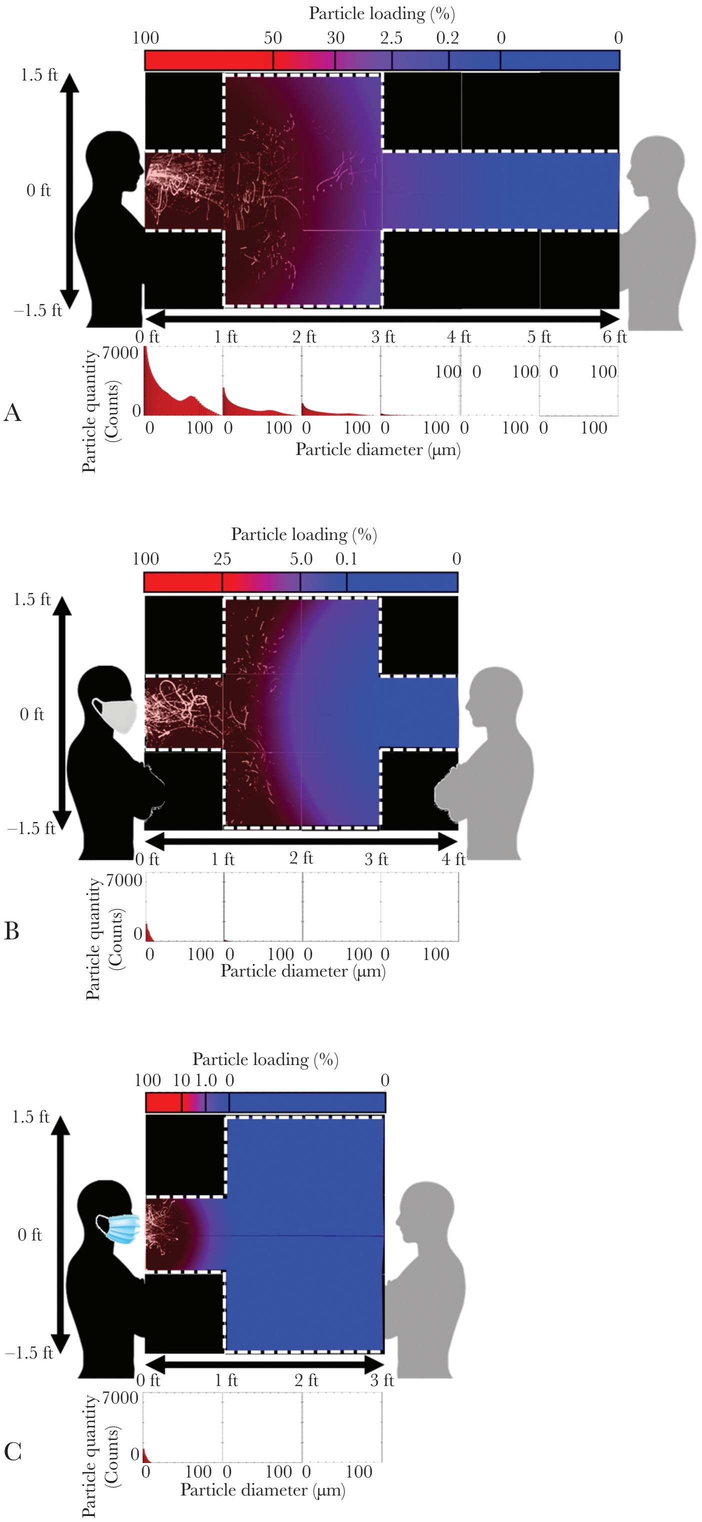

Figure 3. Path line images of compiled cough recordings (*A*) without a face covering; (*B*) with a cotton cloth covering; and (*C*) with a 3-layer mesh disposable covering.

covering. Figure 3C shows a very limited number of aerosols/droplets left the face covering and were detected by the imaging system. The total count remained low and did not differ significantly (4% deviation) from speech.

Population Statistics

Table 3 shows a list of relevant parameters that summarizes all tests and participants. To capture both aerosol/droplet size distribution and expelled quantity into a single quantity, the total expelled volume was calculated using Equation 2 where V_{Total} represents the total expelled volume at the point of origin, n represents the bin number, C_n is the total counts at bin n, and d_n is the diameter of an aerosol/droplet at bin n.

$$V_{Total} = \sum_{1}^{n} C_n \frac{1}{6} \pi d_n^3 \qquad (2)$$

From Table 3, speech particles were smaller than cough particles, but when either face covering was used, the mean sizes were similar. Coughing propagated further than speech for the cases where no face covering or cloth face coverings were used, but the use of a disposable face covering normalized both events to a maximum distance of 0.5 ft (0.152 m). Coughing produced higher expelled velocities (approximately 2 times that of speech) for cases with no face covering or cloth covering but normalized to less than 1 m/s when a disposable face covering was used. Coughing produced more expelled volume than speech with no face covering and the cloth face covering but were very similar in quantity when the disposable face covering was used. It is important to note a reduction of over 98% in expelled volume when using either face covering.

DISCUSSION

The current recommendation for social distancing in the United States is based on the initial CDC guideline of 6 ft (1.829 m) irrespective of using face coverings and considered safe. Findings from this study indicate that when face covering is used, equivalent 6 ft (1.829 m) aerosol/droplet exposure is recorded at a shorter distance. The furthest propagation measured from this study was from a cough event without any face covering and did not travel any further than 4.5 ft (1.372 m) axial distance. The use of cloth face coverings showed the ability to reduce the propagation distance to 2–2.2 ft (0.610–0.671 m). Additionally, the use of a disposable face covering allowed further reduction of the axial propagation distance to 0.5 ft (0.152 m). The disposable face covering performed better than the cloth face covering due to the smaller crevices remaining further away from the mouth.

Both speech and cough emission output consisted of a high-count, small diameter (approximately 1μm) aerosol fraction as well as a low-count droplet fraction at approximately 100 μm diameter without a face covering. Differences in the size and evaporation characteristics between speech and cough experiments were subordinate and strongly governed by the effect of the face covering. With respect to the speech case count at 1 ft (0.305 m) distance without a face covering, the count was reduced by a factor of 8.7 with the cloth covering, and by a factor of 16.5 by wearing the disposable covering. Differences were shown with an analysis of the spatial distribution pattern: cough particulate showed a greater perpendicular spread and more directed particle paths, indicated by the higher exhaust velocity of the cough event. The largest amount of perpendicular (± y) effects were produced by coughing with a cloth face covering, showing a redirection of droplet emission across a ± 25° divergence angle. Measurements indicate that with a face covering, there is a reduction in expelled volume (Table 3). The expelled volume reduction indicates that the point where zero risk to exposure happen at a closer distance to the host. In Table 2 the zero-exposure distance for each participant is reported for no covering, cloth covering, and disposable covering. This would be the location where there is zero exposure to aerosols/droplets, determined with the planar particle imagery and confirming that the PDI detected no data past this point. The results show that the zero risk to emission exposure one would experience at 6 ft (1.829 m) from an individual without a face covering is experienced at 2.2 ft (0.671 m) with a cloth face covering, and 0.5 ft (0.152 m) with a disposable face covering, indicating that utilization of a face covering is effective at reducing exposure to aerosols/droplets expelled from a host.

CONCLUSIONS

Zero exposure to aerosols/droplet without a face covering occurs at a maximum of 4.5 ft (1.372 m) for cough and speech respiratory events. This study quantified that face coverings exhibit different distribution and velocity characteristics in comparison to without a face covering for both cough and speech. The cloth face covering tended to deflect aerosols/droplets causing a more vertical spread, most notable during a cough. All face covering types reduce expelled volume and propagation distance, with the disposable face covering being the most effective at reducing both. Thus, the human research study of aerosol/droplet propagation distance from the human respiratory events highlights 3 ft of physical distancing with face coverings to be equally as effective as 6 ft of physical distancing without a face covering.

Notes

Author contributions. J. R. and J. D. contributed to the development, data acquisition, and processing of experimental data, as well as compilation of figures and tables. B. S. wrote a large portion of the paper, including revisions and formatting work. M. K. served as the principal investigator and provided a complete review. K. A. served as the corresponding author, coordinating the experimental and publication effort.

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References

1. Tang J, Liebner T, Craven B, Settles G. A schlieren optical study of the human cough with and without wearing masks for aerosol infection control. J R Soc Interface **2009**; 6:S727–36.
2. Cowling BJ, Ip DKM, Fang VJ, et al. Aerosol transmission is an important mode of influenza A virus spread. Nat Commun **2013**; 4:1935.
3. Bourouiba L. Turbulent gas clouds and respiratory pathogen emissions: potential implications for reducing transmission of COVID-19. JAMA **2020**; 323:1837–8.
4. Bourouiba L, Dehandschoewercker E, Bush John WM. Violent expiratory events: on coughing and sneezing. J Fluid Mech **2014**; 745:537–63.
5. Gupta S, Hayek SS, Wang W, et al. Factors associated with death in critically ill patients with coronavirus disease 2019 in the US. JAMA Intern Med **2020**; 180:1436–47.
6. Richardson S, Hirsch JS, Narasimhan M, et al. Presenting characteristics, comorbidities, and outcomes among 5700 patients hospitalized with COVID-19 in the New York City area. JAMA **2020**; 323:2052–9.
7. McKee M, Stuckler D. If the world fails to protect the economy, COVID-19 will damage health not just now but also in the future. Nat Med **2020**; 26:640–2.
8. Wu JT, Leung K, Lam TTY, et al. Nowcasting epidemics of novel pathogens: lessons from COVID-19. Nat Med **2021**; 27:388–95.
9. Carvalho T, Krammer F, Iwasaki A. The first 12 months of COVID-19: a timeline of immunological insights. Nat Rev Immunol **2021**; 21:245–56.
10. Jennison MW. Atomizing of mouth and nose secretions into the air as revealed by high-speed photography. AAAS publication no. 17. Washington, DC: American Association for the Advancement of Science, **1942**:106–28.
11. Weaver GH. Droplet infection and its prevention by the face mask. J Infect Dis **1919**; 24:218–30.
12. Ratnesar-Shumate S, Williams G, Green B, et al. Simulated sunlight rapidly inactivates SARS-CoV-2 on surfaces. J Infect Dis **2020**; 222:214–22.
13. Schuit M, Biryukov J, Beck K, et al. The stability of an isolate of the SARS-CoV-2 B.1.1.7 lineage in aerosols is similar to three earlier isolates. J Infect Dis **2021**; 224:1641–8.
14. Binder RA, Alarja NA, Robie ER, et al. Environmental and aerosolized severe acute respiratory syndrome coronavirus 2 among hospitalized coronavirus disease 2019 patients. J Infect Dis **2020**; 222:1798–806.
15. Han L, Ran J, Chan K-H, et al. Indoor environmental factors and acute respiratory illness in a prospective cohort of community-dwelling older adults. J Infect Dis **2020**; 222:967–78.
16. Kormuth KA, Lin K, Prussin AJ, II, et al. Influenza virus infectivity is retained in aerosols and droplets independent of relative humidity. J Infect Dis **2018**; 218:739–47.
17. Meister TL, Brüggemann Y, Todt D, et al. Virucidal efficacy of different oral rinses against severe acute respiratory syndrome coronavirus 2. J Infect Dis **2020**; 222:1289–92.
18. Nicas M, Nazaroff WW, Hubbard A. Toward understanding the risk of secondary airborne infection: emission of respirable pathogens. J Occup Environ Hyg **2005**; 2:143–54.
19. Siegel JD, Rhinehart E, Jackson M, Chiarello L; Health Care Infection Control Practices Advisory Committee. 2007 guideline for isolation precautions: preventing transmission of infectious agents in health care settings. Am J Infect Control **2007**; 35:S65–164.
20. Morawska L. Droplet fate in indoor environments, or can we prevent the spread of infection? Indoor Air **2006**; 16:335–47.
21. Robinson JF, Rios de Anda I, Moore FJ, Reid JP, Sear RP, Royall CP. Efficacy of face coverings in reducing transmission of COVID-19: calculations based on models of droplet capture. Phys Fluids **2021**; 33:043112.
22. Bischoff WE, Swett K, Leng I, Peters TR. Exposure to influenza virus aerosols during routine patient care. J Infect Dis **2013**; 207:1037–46.
23. Bahl P, Doolan C, de Silva C, Chughtai AA, Bourouiba L, MacIntyre CR. Airborne or droplet precautions for health workers treating coronavirus disease 2019? [published online ahead of print 16 April 2020]. J Infect Dis doi: 10.1093/infdis/jiaa189.
24. van den Berg P, Schechter-Perkins EM, Jack RS, et al. Effectiveness of 3 versus 6 ft of physical distancing for controlling spread of coronavirus disease 2019 among primary and secondary students and staff: a retrospective, statewide cohort study. Clin Infect Dis **2021**; 73:1871–8.
25. Wells WF. On air-borne infection: study II. Droplets and droplet nuclei. Am J Epidemiol **1934**; 20:611–8.