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Breathing, virus transmission, and social distancing—An experimental visualization study

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ABSTRACT

With the outbreak of COVID-19 in many countries, public awareness related to the droplet mode of virus transmission is well documented and communicated. With a large spike in COVID-19 positive cases and the mortality rate, most of the general public are following preventive measures such as wearing masks, maintaining social distancing, and frequent hand washing. However, recently, it has been reported that the virus may also transmit through aerosolized particles of diameter $<10\ \mu$m. The majority of the past research focuses on understanding droplet generation and transport through the most violent spasmodic expiration: coughing and sneezing. However, "breathing," the most common phenomenon, is scarcely studied as a virus transmission source. In the present study, we report an experimental visualization of the droplet's transport through breathing to quantify the reach of a typical breath for various exhale to inhale ratios. The efficacy of various standard (surgical, five-layered, and N95) and non-standard (homemade) protective measures such as face masks and face shields is also evaluated. An exhaled breath at E:I = 1:1 can travel up to 4 ft in 5 s; however, this reach reduces to 3 ft for E:I = 1:2. Two-layer homemade and commercial cotton masks are unable to completely impede the leakage of the droplet in the forward direction. A combination of a two-layer mask and face shield is also not effective in preventing the leakage and diffusion of the droplets. The surgical mask alone is not recommended during normal conversations as the leakage of the droplets is noticeable. A commercial N95 mask completely impedes the leakage of the droplets in the forward direction. However, the leakage of the droplets from the gaps between the mask and the nose is observed to be significant. A commercial five-layered mask is observed to be the most effective preservative measure with minimum leakage of the droplets.

INTRODUCTION

The COVID-19 outbreak is now spread all over the world. This global pandemic has influenced economics significantly, and many countries are still finding ways to bring the economy to normal. This global pandemic has motivated many to report studies related to possible sources and modes of COVID-19 transmission (Dbouk and Drikakis, 2020a; 2020b), transmission risk (Agrawal and Bhardwaj, 2020; Li *et al.*, 2020a; Wang *et al.*, 2020; Mittal *et al.*, 2020; Pendara and Páscoab, 2020; Das *et al.*, 2020; and Fontes *et al.*, 2020), and innovative preventive measures (Bhardwaj and Agrawal, 2020a; 2020b, Chen *et al.*, 2020; Akagi *et al.*, 2020; Akhtar *et al.*, 2020; and Li *et al.*, 2020b). With the relaxation of stringent lockdown measures in many countries, techno-economical activities are resuming, and communities have begun to reopen. The majority of the general population have now adopted different face masks as a protective measure in their day-to-day activities and social distancing. However, it is of concern to note that many countries are observing the second and third waves of COVID-19 (Harris and Moss, 2020). There could be many aspects to this second wave, including ignorance, large gatherings, and working in a group in closed spaces for a long duration. One major factor for this could be a limited understanding of all possible transmission modes of COVID-19. Over the past year, most of the emphasis was on spreading awareness among common people to wear a mask and maintain a social distance of 6 ft and do frequent hand washing (World Health Organization, 2020; Centers for Disease Control, 2020). The basis for formulating such guidelines is the assumable mode of COVID-19 virus transmission, the "droplet mode." However, recently, it has been reported that the airborne mode of virus transmission may also play a dominant role under certain circumstances (Eissenberg *et al.*, 2020; Domingo *et al.*, 2020; Morawska and Cao, 2020; Morawska and Milton, 2020; Lewis, 2020; and Ishii *et al.*, 2021).

Social distancing and face mask are considered the most prominent ways to combat the spread of COVID-19 (World Health Organization, 2020; Centers for Disease Control, 2020). However, the minimum distance between the infected person and the host is disputable (Qureshi *et al.*, 2020). Many recent studies highlighted that a minimum social distancing of 6 ft is not adequate during coughing and sneezing (Bourouiba, 2020; Setti *et al.*, 2020) without protective measures. The experimental visualization study by Bourouiba (2020) suggests that the turbulent cloud generated during coughing and sneezing can travel up to 23–26 ft. Arumuru *et al.*, (2020) also reported a sneeze's reach as ~25 ft. A recent computational study by Pendara and Páscoab (2020) reported a minimum social distancing of 13 ft during coughing and sneezing. Verma *et al.* (2020a; 2020b) simulated coughing experimentally and reported that the particle emulated during coughing could travel ~8 ft without protective measures.

Coughing and sneezing are violent spasmodic expiration in which the velocity of the expelled droplets and the turbulent cloud is high. However, these events have a low occurrence frequency. On the other hand, breathing is a continuous process, which can generate aerosols (Asadi *et al.*, 2019; Leung *et al.*, 2020; and Scheuch, 2020). The infected person's exhaled breath may carry virus-bearing aerosol droplets, which may remain suspended in the air. The aerosol particle aerodynamic diameter varies from 0.3 to 100 μm. However, the primary source of infection is the respirable-size in the range <10 μm. (Wang and Du, 2020; Fennelly, 2020; Gralton *et al.*, 2011; and Leung *et al.*, 2020) reported the presence of COVID-19 in human exhaled breath in people with acute respiratory illness. They also reported that virus samples in aerosol particles are not significantly reduced by wearing a surgical mask. However, the surgical mask was found to be effective in filtering large droplets. The important parameter to decide the social distancing is the reach and spread of the droplet and aerosol particles generated during coughing, sneezing, and talking. However, considerable attention is not paid toward breathing as one of the possible virus transmission sources from an infected person to a healthy host. In addition, there is limited information available on the efficacy of various standard and non-standard face masks in filtering respiratory viruses under various parametric breathing conditions such as the frequency of breathing and exhale to inhale ratios. Hence, the present study's objective is to visualize breathing experimentally and to quantify the droplets' reach and spread during breathing. Such a study is extremely important to understand the transmission and spreading of the virus from an infected person to a healthy host. In the present COVID-19 scenario, this study can be used as an educational tool to educate and spread awareness among common people and help policymakers frame new guidelines to combat the spread of COVID-19. We also evaluated the efficacy of various standard and non-standard protectives measures such as face masks and shields under different breathing patterns. Such a study is equally useful in the present COVID-19 pandemic, where the scientific community is indulged in understanding all possible routes of transmission and possible preventive measures.

EXPERIMENTAL SETUP

An in-house developed mechanical breathing simulator is used to simulate breathing. The breathing simulator output is connected to the 10 mm nozzle fitted precisely in a standard mannequin's nose. The breathing simulator is shown in Fig. 1. The breathing simulator consists of a piston–cylinder arrangement mounted on a guided rail. The piston is operated by a stepper motor. The stepper motor can be configured to achieve different breathing frequencies [Breath Per Min (BPM)], displacement volumes, and Exhale to Inhale (E:I) ratios. The tidal/displacement volume we considered in the present study is ~500 ml, which corresponds to the average tidal volume of healthy adults (Weiss *et al.*, 2016). The breathing frequency is selected as BPM = 15, which corresponds to the average breathing frequency of a healthy adult (Lehrer *et al.*, 2000). We considered two different E:I ratios (1:1, 1:2) to simulate different breathing patterns.

The outlet of the breathing simulator is connected to a settling chamber filled with fog. The fog is generated using a mixture of distilled water (70%) and glycerin (30%) by a commercial fog generator. The estimated diameter of the fog droplets is in the range of 1–10 μm. Based on the Stokes law, the settling velocity of 10 μm diameter droplets is 0.003 m/s, which is similar to that in experiments reported by Verma *et al.* (2020b). A diode laser of 532 nm wavelength in conjunction with an appropriate lens is used to generate a laser sheet aligned along the exit of the nose, as shown in Fig. 1. The droplets emulated by the breathing simulators scatter sufficient laser light, which is captured by a video camera. The droplets are emulated from the mannequin nose from a height of 5 ft 8 in. The estimated Reynolds number of the flow is Re ~500. The volume flow rate variation during breathing at 15 BPM at various E:I ratios is shown in Fig. 2. The stepper motor is programmed appropriately to generate the piston movement to achieve a similar breathing pattern as reported by Bautsch *et al.* (2019). With an increase in the E:I ratio for a given breathing cycle (exhale and inhale), the inhalation duration increases. Hence, with an increase in the E:I ratio, the inhaled volume is expelled in a shorter interval.

RESULTS AND DISCUSSION

The fundamental basis for deciding a safe social distance to prevent the possible transmission of infection is the reach of droplets

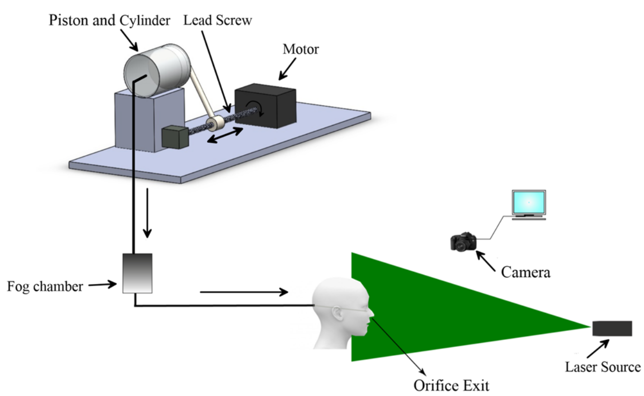


FIG. 1. Schematic of the breathing simulator.

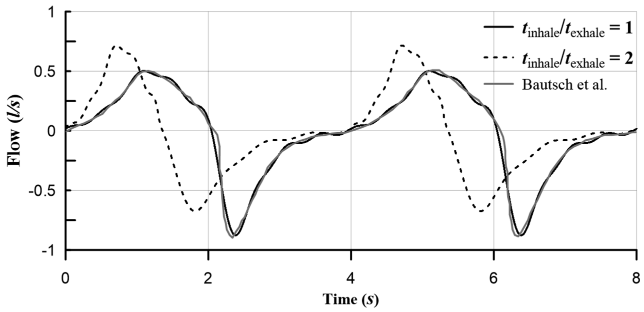


FIG. 2. Flow rate variation during breathing.

FIG. 4. Snapshot of the jet for E:I = 1:1. Multimedia view: https://doi.org/10.1063/5.0045582.1

generated during coughing, sneezing, and talking. However, breathing is often not paid attention, which generates aerosolized particles that may contain an influenza virus-like COVID-19. In the present study, we documented the reach of a typical continuous breath at 15 BPM for E:I ratios 1:1 and 1:2. The reach of a typical breath at 15 BPM and E:I = 1:1 is shown in Fig. 3 and Fig. 4 (Multimedia view). The visualization study highlights that droplets generated from continuous breathing travel ~4 ft in a quiescent environment in 5 s. The reach of the breath is influenced by the E:I ratio; with an increase in the E:I ratio to 1:2, the droplets' reach reduces to ~3 ft, as shown in Fig. 5 and Fig. 6 (Multimedia view). The exhalation time reduces with an increase in the E:I ratio; this increases the local Reynolds number, which leads to a larger radial spread, and hence, the jet streamwise reach reduces.

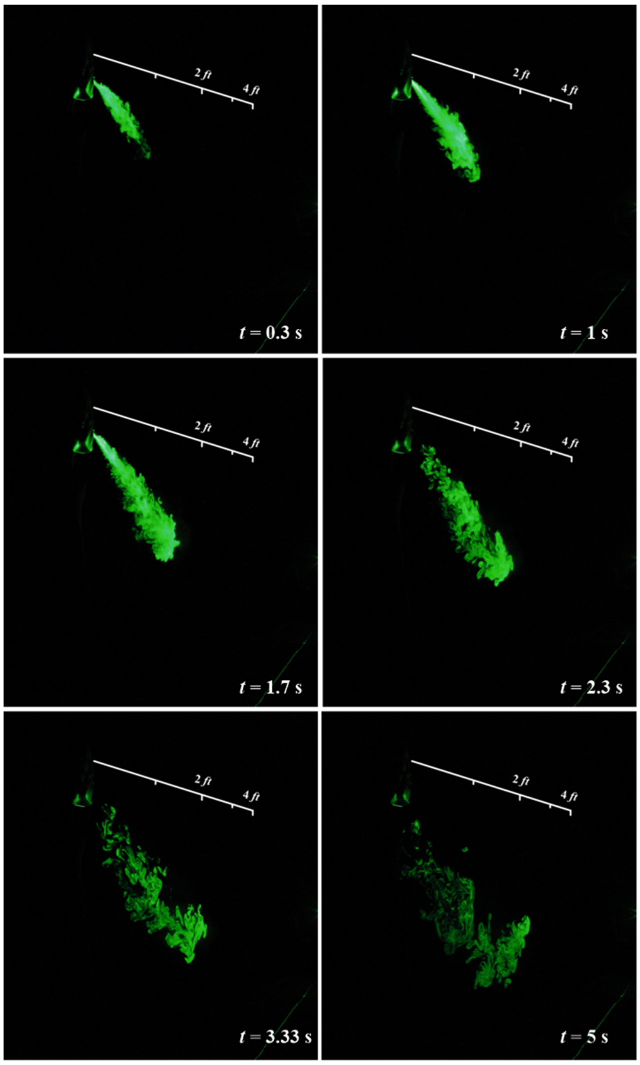


FIG. 3. Reach of the turbulent jet and droplet for E:I = 1:1.

The time evolution of the breath cloud is shown in Fig. 7. Initially, the cloud undergoes a deceleration with exit velocity around 5–1.5 m/s in 0.45 s; thereafter, the cloud travel speed remains nearly constant at 2 m/s.

The reach of the droplets documented in Figs. 3 and 5 suggests maintaining at least a social distancing of 4 ft during normal conversations without any protective measures. The widely recommended social distancing of 6 ft is adequate during normal conversations and day-to-day activities when the droplets are generated only by breathing; however, as reported by other recent studies (Bourouiba, 2020; Arumuru *et al.*, 2020; Verma *et al.*, 2020a; and Pendara and Páscoab, 2020), during coughing and sneezing, 6 ft is not sufficient without protective measures.

The commonly used protective measures such as face masks have become an integral part of life, and the majority of the common population are using them. However, the efficacy of these masks under the influence of breathing is scarcely reported in the literature. Hence, in the present study, we evaluated the efficacy of various face masks (homemade, two-layered, five-layered, surgical, and N95) and face shields, during breathing.

The leakage of thermal plumes of droplets from a two-layered triangle mask is shown in Fig. 8. A minor leakage was observed for E:I = 1:1 from the front. However, for the E:I ratio 1:2, because of longer inhalation, escape of thermal plumes is restricted to a greater extent, and no noticeable leakage is observed.

Intuitively, the purpose of using a face shield is to completely restrict the jet's forward movement and to direct the expelled jet downward, which is completely achieved for E: = 1:1, as shown in Fig. 9. However, for E:I = 1:2, due to the higher momentum of ejected turbulent jets, they are separating from the bottom edge of the face shield and further traveling to 1.5 ft in the forward direction, as shown in Fig. 10. The present investigation concludes the face shield

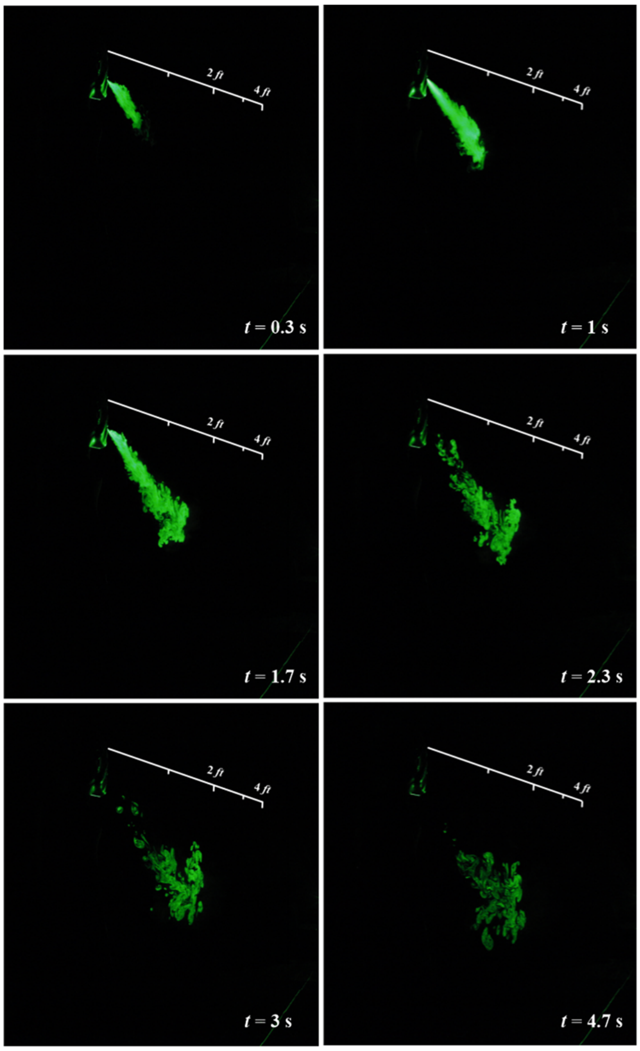


FIG. 5. Reach of the turbulent jet and droplet for E:I = 1:2.

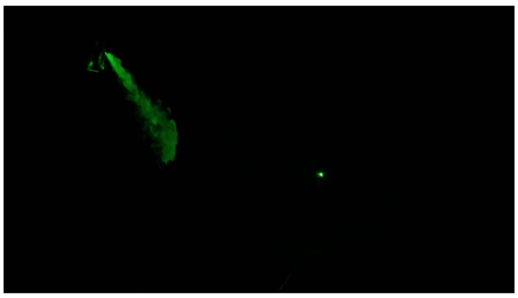


FIG. 6. Snapshot of the jet for E:I = 1:2. Multimedia view: https://doi.org/10.1063/5.0045582.2

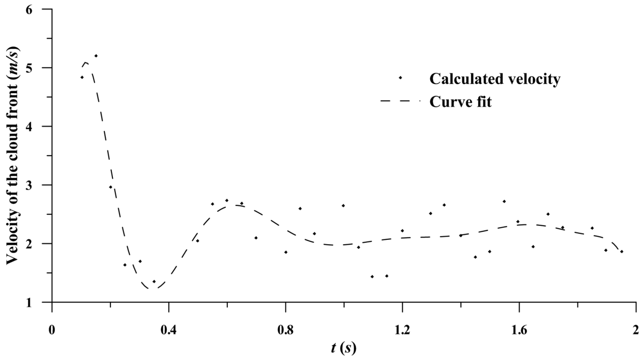
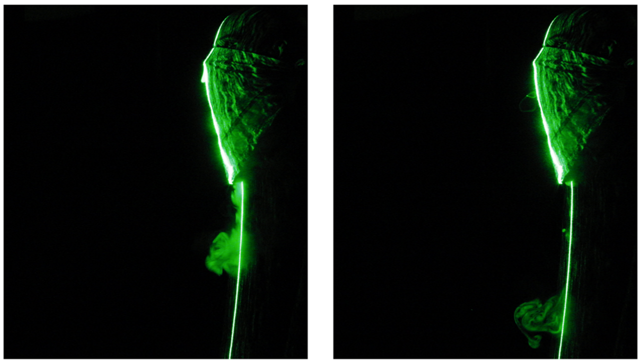


FIG. 7. Time evolution of the breath cloud.

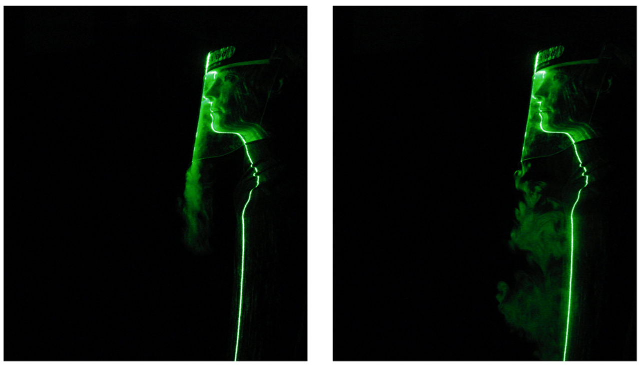


(a) (b)

FIG. 8. Leakage of respiratory jets from a two-layered triangle mask at (a) t = 2 s and (b) t = 4 s during breathing for E:I = 1:1.

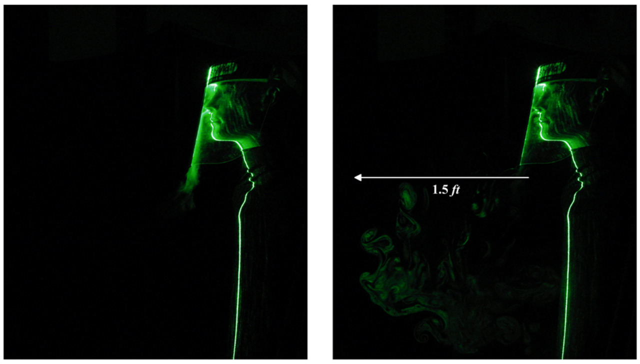
alone is not sufficient to mitigate the dispersal of the turbulent jet in the forward direction during breathing.

The surgical mask is one of the most popular preventive measures adopted by the general public. The leakage of the turbulent plume from the front is clearly observed for E:1 = 1:1. The influence



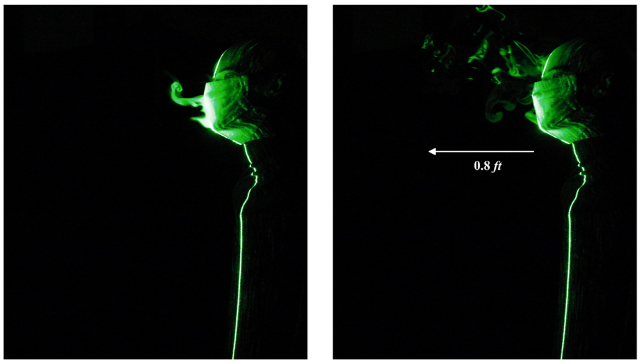
(a) (b)

FIG. 9. Leakage of respiratory secretions from the face shield at (a) t = 1 s and (b) t = 2 s during breathing for E:I = 1:1.



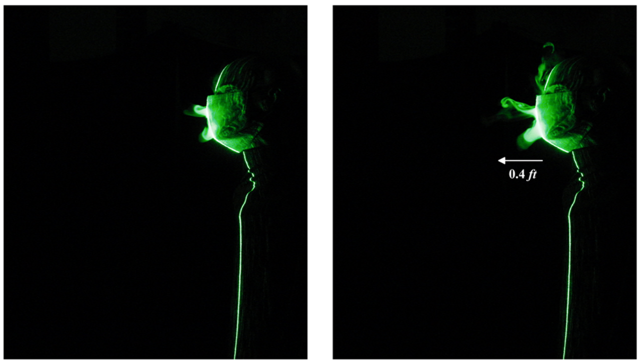
(a) (b)

FIG. 10. Leakage of respiratory secretions from the face shield at (a) t = 1 s and (b) t = 6 s during breathing for E:I = 1:2.



(a) (b)

FIG. 11. Leakage of respiratory jets from a surgical mask at (a) t = 2 s and (b) t = 5 s during breathing for E:I = 1:1.



(a) (b)

FIG. 12. Leakage of respiratory jets from a surgical mask at (a) t = 1 s and (b) t = 2 s during breathing for E:I = 1:2.

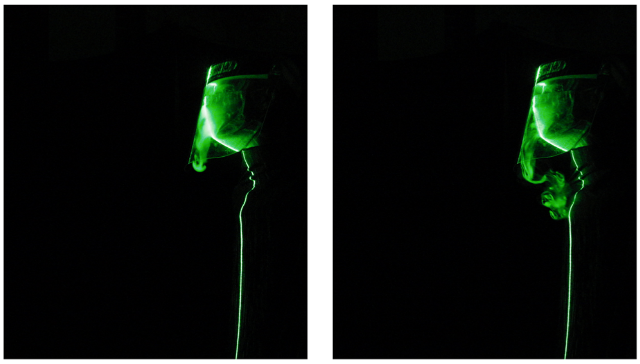
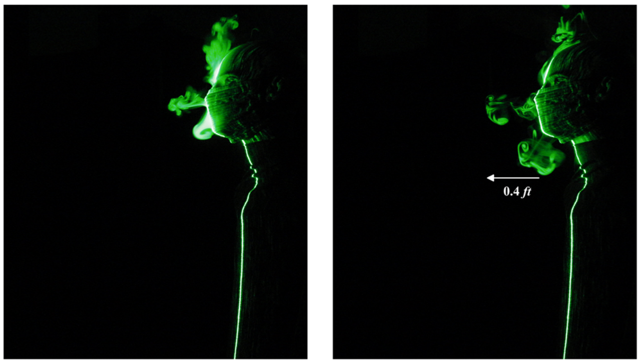

(a) (b)

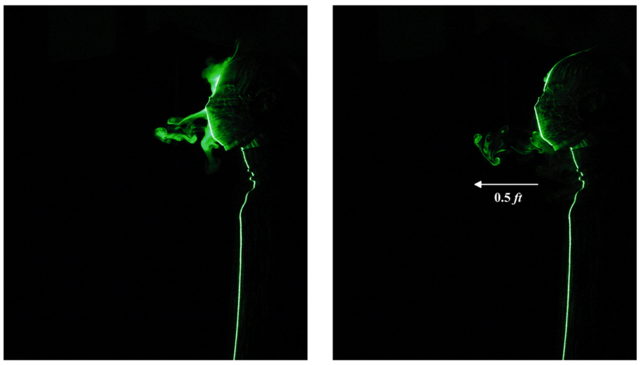
FIG. 13. Escape of exhalation jets from a surgical mask with a face shield at (a) t = 2 s and (b) t = 4 s during breathing for E:I = 1:2.

of thermal buoyancy further rises the jet upward, and the jet travels up to 0.8 ft, as shown in Fig. 11. An increase in jet velocity for E:I = 1:2 has displaced the ejected jet downward, as shown in Fig. 12, with negligible influence of buoyancy. A face shield in conjunction



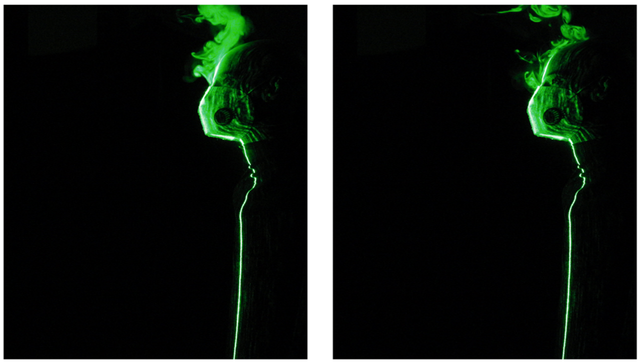
(a) (b)

FIG. 14. Leakage of respiratory jets from a two-layered cotton mask at (a) t = 2 s and (b) t = 4 s during breathing for E:I = 1:1.



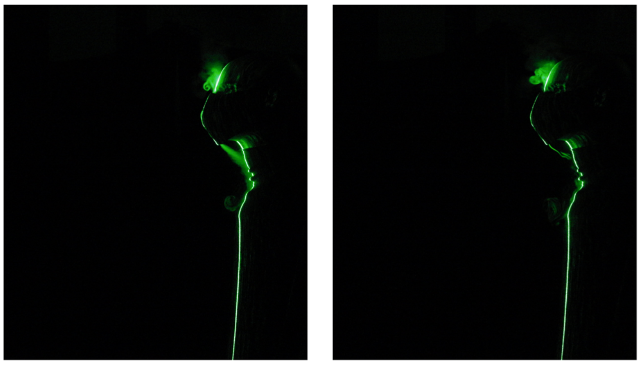
(a) (b)

FIG. 15. Leakage of respiratory jets from a two-layered cotton mask at (a) t = 2 s and (b) t = 4 s during breathing for E:I = 1:2.



(a) (b)

FIG. 16. Leakage of respiratory jets from an N95 mask at (a) t = 2 s and (b) t = 4 s during breathing for E:I = 1:1.



(a) (b)

FIG. 17. Spraying of respiratory droplets from a five-layered anti-pollution face mask at (a) t = 2 s and (b) t = 3 s during breathing for E:I = 1:2.

with a surgical mask exhibits the stoppage of exhalation jets in the forward direction, as shown in Fig. 13. However, the settling of the droplets below the face shield is noticeable. Hence, this combination is not recommended in hospitals and other places where strict social distancing guidelines are difficult to be followed.

In the present pandemic time, people are widely using commercial cotton masks purely based on the washable and reusable aspects of these masks. These masks are competing with surgical and N95 masks as a cheaper alternative protective measure. Hence, in the present study, the efficacy of these commercial two-layered cotton masks is also evaluated. It is observed that significant jets are escaping from surfaces of the mask for E:I = 1:1 (Fig. 14) and the volume of leakage jets has reduced to a certain extent for E:I = 1:2 (Fig. 15), which may be due to the prominent suction effect at higher E:I ratios. The present investigation suggests the commercial two-layered cotton masks should not be considered the preferred choice to prevent the transmission of aerosol particles from an infected individual. However, for such non-standard masks, the leakage depends on the quality of the fabric, porosity, and fitment.

The N95 mask is considered one of the most effective preventive measures. As the name suggests, these masks are designed

TABLE I. Summary of different masks, types of materials used, number of layers or threads/inch present, and the maximum distance traveled by the droplets.

Type of mask	Material	Number of layers or threads/in.	E:I ratio	Maximum distance traveled by droplets (ft)
Without mask	...	...	1:1 1:2	$\sim$4 $\sim$3
Two-layered bandana mask	Cotton	50 threads/in.	1:1 1:2 1:2	Negligible
Face shield	Polycarbonate	...	1:1 1:2	... 1.5
Surgical mask	Synthetic polymer fibers	Five layered	1:1 1:2	0.8 0.4
Surgical mask with face shield	Polypropylene	Three layered	1:1 1:2	Negligible
N95	...	...	1:1 1:2	Negligible
Double-layered homemade cotton mask	Cotton	Two layered	1:1 1:2	0.4 0.5
Double-layered homemade cotton mask with face shield	Cotton	...	1:1 1:2	0.4 Negligible
Five-layered N95 face mask	Melt blown fabric	Five layered	1:1 1:2	Negligible

to trap 95% of the emission of the smaller aerosol particles. Arumuru *et al.* (2020) demonstrated a significant leakage of a human sneeze from the mask's top gap with the nose, traveling up to 2 ft in the backward direction. In the present study, we noticed a significant leakage of the exhaled breath from the top gap between the mask and the nose, as shown in Fig. 16. The droplets are unable to penetrate in the forward direction from the N95 mask due to its higher hydraulic resistance; however, the leakage from the gaps is observed to be significant.

During this unprecedented period, it is important to choose an appropriate mask that can contain the transmission of the virus through respiratory processes. It is a common belief that increasing the number of layers of the mask can fully restrict the emanation of droplets. We tested the filtration efficiency of a commercial five-layered mask that includes a carbon layer. Although no leakage is observed in the onward direction, still jets are spraying out from the gaps between the chin and the mask, as shown in Fig. 17. Part of the jets is also escaping from the gap between the nose and the mask. It is interesting to note that, with an increase in the number of protective layers, which is related to masks' hydraulic resistance to flow, the forward movement of the droplets is restricted; however, the openings between the mask, nose, and chins become the least resistance paths for droplet leakage. Hence, a more quantitative study related to the hydraulic resistance of the masks under the influence of unavoidable leakage and its consequence on human health needs to be conducted in detail. The summary of the present study is presented in Table I.

The present study highlighted that most of the commonly used protective measures such as face masks and shields are unable to prevent the escape of droplets generated during breathing. The leaked aerosol particle may contain the virus, which may trigger the airborne transmission of the disease. Under these circumstances, the conventional CO_2 level measurement in confined space for assessing the air quality index may not be sufficient to regulate the airflow (Persily and Jonge, 2017). We propose that, in the present scenario, considering that all the occupants inside a closed room wear a mask and considering 5%–10% leakage of the aerosol particle in each breathing cycle, the amount of fresh air circulation rate can be decided. This will minimize aerosol particle concentrations in a closed space, and the potential risk of airborne virus transmission may reduce.

CONCLUSIONS

Breathing as a potential source of virus transmission is seldom studied in the literature. In the present study, we report the reach of a typical breath for various Exhale to Inhale (E:I) ratios. The maximum reach of a breath for E:I = 1:1 is up to 4 ft; however, this reach reduces to 3 ft for E:I = 1:2. Two-layer homemade and commercial cotton masks are unable to impede the leakage of the droplet in the forward direction. However, a combination of a two-layer mask and face shield is effective in preventing the leakage of droplets. The surgical mask alone is not recommended during normal conversations as the leakage of the droplets is noticeable. A commercial N95 mask completely impedes the leakage of the droplets in the forward direction. However, the leakage of the droplets from the gaps between the mask and the nose is observed to be significant. A commercial five-layered mask is observed to be the most effective preservative measure with minimum leakage of the droplets. The present study highlights that with an increase in the number of protective layers, which is related to masks' hydraulic resistance to flow, the forward movement of the droplets is restricted; however, the openings between the mask, nose, and chins become the least resistance paths for droplet leakage. The present study highlights that there is a need for innovation in face mask design, which can present the leakage of the droplets with adequate human comfort. New guidelines need to be formulated for deciding the air circulation rate in confined space considering the leakage of the aerosol particle from protective measures.

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DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

REFERENCES

Agrawal, A. and Bhardwaj, R., "Reducing chances of COVID-19 infection by a cough cloud in a closed space," Phys. Fluids **32**, 101704 (2020).

Akagi, F., Haraga, I., Inage, S.-I., and Akiyoshi, K., "Effect of sneezing on the flow around a face shield," Phys. Fluids **32**, 127105 (2020).

Akhtar, J., Garcia, A. L., Saenz, L., Kuravi, S., Shu, F., and Kota, K., "Can face masks offer protection from airborne sneeze and cough droplets in close-up, face-to-face human interactions?—A quantitative study," Phys. Fluids **32**, 127112 (2020).

Arumuru, V., Pasa, J., and Samantaray, S. S., "Experimental visualization of sneezing and efficacy of face masks and shields," Phys. Fluids **32**, 115129 (2020).

Asadi, S., Wexler, A. S., Cappa, C. D., Barreda, S., Bouvier, N. M., and Ristenpart, W. D., "Aerosol emission and superemission during human speech increase with voice loudness," Sci. Rep. **9**, 2348 (2019).

Bautsch, F., Männel, G., and Rostalski, P., "Development of a novel low-cost lung function simulator," Curr. Dir. Biomed. Eng. **5**, 557–560 (2019).

Bhardwaj, R. and Agrawal, A., "Likelihood of survival of coronavirus in a respiratory droplet deposited on a solid surface," Phys. Fluids **32**, 061704 (2020a).

Bhardwaj, R. and Agrawal, A., "Tailoring surface wettability to reduce chances of infection of COVID-19 by a respiratory droplet and to improve the effectiveness of personal protection equipment," Phys. Fluids **32**, 081702 (2020b).

Bourouiba, L., "Turbulent gas clouds and respiratory pathogen emissions: Potential implications for reducing transmission of COVID-19," JAMA **323**, 1837–1838 (2020).

Centers for Disease Control, CDC guidelines on social distancing, available at https://www.cdc.gov/coronavirus/2019-ncov/preventgetting-sick/socialdistancing.html, 2020.

Chen, Z., Jr., Garcia, G., Arumugaswami, V., and Wirz, R. E., "Cold atmospheric plasma for SARS-CoV-2 inactivation," Phys. Fluids **32**, 111702 (2020).

Das, S. K., Alam, J.-E., Plumari, S., and Greco, V., "Transmission of airborne virus through sneezed and coughed droplets," Phys. Fluids **32**, 097102 (2020).

Dbouk, T. and Drikakis, D., "On coughing and airborne droplet transmission to humans," Phys. Fluids **32**, 053310 (2020a).

Dbouk, T. and Drikakis, D., "Weather impact on airborne coronavirus survival," Phys. Fluids **32**, 093312 (2020b).

Domingo, J. L., Marquès, M., and Rovira, J., "Influence of airborne transmission of SARS-CoV-2 on COVID-19 pandemic. A review," Environ. Res. **188**, 109861 (2020).

Eissenberg, T., Kanj, S. S., and Shihadeh, A. L., "Treat COVID-19 as though it is airborne: It may be," AANA J. **88**, 29 (2020).

Fennelly, K. P., "Particle sizes of infectious aerosols: Implications for infection control," Lancet Respir. Med. **8**, 914–924 (2020).

Fontes, D., Reyes, J., Ahmed, K., and Kinzel, M., "A study of fluid dynamics and human physiology factors driving droplet dispersion from a human sneeze," Phys. Fluids **32**, 111904 (2020).

Gralton, J., Tovey, E., McLaws, M. L., and Rawlinson, W. D., "The role of particle size in aerosolised pathogen transmission: A review," J. Infect. **62**, 1–13 (2011).

Harris, P. and Moss, D., "Reflections on the impact of coronavirus on public affairs," J. Public Aff. **20**, e2205 (2020).

Ishii, K., Ohno, Y., Oikawa, M., and Onishi, N., "Relationship between human exhalation diffusion and posture in face-to-face scenario with utterance," Phys. Fluids **33**, 027101 (2021).

Lehrer, P. M., Vaschillo, E., and Vaschillo, B., "Resonant frequency biofeedback training to increase cardiac variability: Rationale and manual for training," Appl. Psychophysiol. Biofeedback **25**, 177–191 (2000).

Leung, N. H. L., Chu, D. K. W., Shiu, E. Y. C., Chan, K. H., McDevitt, J. J., Hau, B. J. P. *et al.*, "Respiratory virus shedding in exhaled breath and efficacy of face masks," Nat. Med. **26**, 676 (2020).

Lewis, D., "Mounting evidence suggests coronavirus is airborne-but health advice has not caught up," Nature **583**(7817), 510–513 (2020).

Li, Y.-Y., Wang, J. X., and Chen, X., "Can a toilet promote virus transmission? From a fluid dynamics perspective," Phys. Fluids **32**, 065107 (2020a).

Li, Z., Wang, H., Zhang, X., Wu, T., and Yang, X., "Effects of space sizes on the dispersion of cough-generated droplets from a walking person," Phys. Fluids **32**, 121705 (2020b).

Mittal, R., Meneveau, C., and Wu, W., "A mathematical framework for estimating risk of airborne transmission of COVID-19 with application to face mask use and social distancing," Phys. Fluids **32**, 101903 (2020).

Morawska, L. and Cao, J., "Airborne transmission of SARS-CoV-2: The world should face the reality," Environ. Int. **139**, 105730 (2020).

Morawska, L. and Milton, D. K., "It is time to address airborne transmission of COVID-19," Clin. Infect. Dis. **71**, 2311 (2020).

Pendar, M.-R. and Páscoa, J. C., "Numerical modeling of the distribution of virus-carrying saliva droplets during sneeze and cough," Phys. Fluids **32**, 083305 (2020).

Persily, A. and Jonge, L. D., "Carbon dioxide generation rates for building occupants," Indoor Air **27**, 868–879 (2017).

Qureshi, Z., Jones, N., Temple, R., Larwood, J. P. J., Greenhalgh, T., and Bourouiba, L., "What is the evidence to support the 2-metre social distancing rule to reduce COVID-19 transmission," accessed on https://www.cebm.net/covid-19/what-is-the-evidenceto-support-the-2-metre-social-distancing-rule-to-reduce-covid-19-transmission, 2020.

Scheuch, G., "Breathing is enough: For the spread of influenza virus and SARS-CoV-2 by breathing only," J. Aerosol Med. Pulm. Drug Delivery **33**, 230–234 (2020).

Setti, L., Passarini, F., Gennaro, G. D., Barbieri, P., Perrone, M. G., Borelli, M., Palmisani, J., Gilio, A. D., Piscitelli, P., and Miani, A., "Airborne transmission route of COVID-19: Why 2 meters/6 feet of inter-personal distance could not be enough," Int. J. Environ. Res. Public Health **17**, 2932 (2020).

Verma, S., Dhanak, M., and Frankenfield, J., "Visualizing droplet dispersal for face shields and masks with exhalation valves," Phys. Fluids **32**, 091701 (2020a).

Verma, S., Dhanak, M., and Frankenfield, J., "Visualizing the effectiveness of face masks in obstructing respiratory jets," Phys. Fluids **32**, 061708 (2020b).

Wang, J. and Du, G., "COVID-19 may transmit through aerosol," Ir. J. Med. Sci. **189**, 1143–1144 (2020).

Wang, J.-X., Li, Y.-Y., Liu, X.-D., and Cao, X., "Virus transmission from urinals," Phys. Fluids **32**, 081703 (2020).

Weiss, C. H., Baker, D. W., Weiner, S., Bechel, M., Ragland, M., Rademaker, A., Weitner, B. B., Agrawal, A., Wunderink, R. G., and Persell, S. D., "Low tidal volume ventilation use in acute respiratory distress syndrome," Crit. Care Med. **44**, 1515–1522 (2016).

World Health Organization, "Advice for public—Maintain at least 1 meter (3 feet) distance between yourself and anyone who is coughing or sneezing," available at https://www.who.int/emergencies/diseases/novelcoronavirus-2019/advice-for-public, 2020.