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Simplified Models for Exhaled Airflow from a Cough with the Mouth Covered

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Abstract
Covering a cough can be useful in reducing the transmission of airborne infectious diseases. However, no simple method is available in the literature for predicting the exhaled airflow from a cough with the mouth covered. This investigation used smoke to visualize the airflow exhaled by 16 human subjects. Their mouths were covered by a tissue, a cupped hand, a fist, and an elbow with and without a sleeve. This study then developed simplified models for predicting the airflow on the basis of the smoke visualization data. In addition, this investigation performed numerical simulations to assess the influence of mouth coverings on the receptor's exposure to exhaled particles. It was found that covering a cough with a tissue, a cupped hand, or an elbow can significantly reduce the horizontal velocity and cause the particles to move upward with the thermal plumes generated by a human body. In contrast with an uncovered cough, a covered cough or a cough with the head turned away may prevent direct exposure.

Keywords: Computational fluid dynamics (CFD); Tissue; Cupped hand; Fist; Elbow with sleeve; Particle deposition

Practical implications
This study developed simplified models for predicting the exhaled airflow from a cough with the mouth covered. The proposed models can easily be used to investigate the risk of transmission of airborne infectious diseases in enclosed environments.

1. Introduction

Transmission of airborne infectious diseases in indoor environments has been a major public health concern for decades (Li et al., 2007). Common airborne infectious diseases include tuberculosis, influenza, and severe acute respiratory syndrome (SARS). Droplets carrying infectious viruses can be generated by exhalation activities such as breathing, coughing, talking, and sneezing by an infected person (Nicas et al., 2005). The size of these droplets ranges from sub-micrometer to super-micrometer (Morawska, 2006). These exhaled particles can be transported in the air and then inhaled by susceptible individuals (Morawska, 2006). It is essential to predict the dispersion of exhaled particles in enclosed environments in order to improve air distribution design and reduce the risk of transmission of airborne infectious diseases.

There are a number of experimental studies focusing on the person-to-person contaminant transport in enclosed environments. For example, Qian et al. (2006) and Yin et al. (2011) compared the effectiveness of mixing and displacement ventilation in controlling person-to-person contaminant transport in hospital wards. Lai and Wong (2010, 2011) investigated person-to-person particle transport in laboratory chambers with mixing and displacement ventilation. Nielsen et al. (2010) compared the person-to-person contaminant exposure in a hospital ward with different ventilation rates. Olmedo et al. (2012) investigated the effect of person-to-person distance on exhaled contaminant transport in a simulated room. Lindsley et al. (2012) assessed a health care worker's exposure to coughed particles exhaled by a patient in a simulated medical examination room. In these studies, the index person was assumed to cough or breathe directly without covering the mouth.

In recent years, computational fluid dynamics (CFD) has been widely used in predicting the transport of exhaled particles indoors. For instance, Li et al. (2005) simulated the transmission of SARS during the largest nosocomial outbreak in Hong Kong. Chen et al. (2010) predicted the transmission of infectious diseases from patient to health care worker in a dental clinic. He et al. (2011) modeled the exhaled particle transmission between occupants under various ventilation strategies in a typical office room. Gupta et al. (2011) computed the transport of particles exhaled by the index patient seated in the middle of a seven-row, twin-aisle, fully occupied aircraft cabin. Zhu et al. (2011) numerically assessed the risk of airborne influenza infection in a bus microenvironment. Zhang and Li (2012) modeled the dispersion process of respiratory particles released by the coughing of an individual in a fully-occupied high-speed rail cabin. Again, all of these studies assumed that the index person coughed or breathed directly without covering the mouth.

In reality, however, people usually cover their mouths with a hand or a tissue when they cough or sneeze. In health care facilities, patients with respiratory illness are usually asked to wear a mask. Center for Disease Control and Prevention (CDC) has also strongly recommended the public to "cover your cough" (CDC, 2009), since it may reduce the risk of transmission of airborne infectious diseases.

For masks such as surgical and N95 masks, there are numerous studies focusing on its effectiveness of removing exhaled particles. For instance, Gupta (2010) conducted a systematic review on the performance of N95 masks and concluded that the penetration through the N95 masks including the face seal leakages to be 10%. However, for surgical masks, Green et al. (2012) found that the removal efficiency of bioaerosols only ranged from 48% to 76%. Milton et al. (2013) showed that the surgical masks can remove 96% of coarse influenza virus aerosols (> 5 μm) but only 55% of fine influenza virus aerosols (≤ 5 μm). Davies et al. (2013) further compared the surgical and homemade mask, and found that the surgical mask was 3 times more effective in blocking transmission than the homemade mask. Furthermore, the fit performance of a mask can significantly affect the effectiveness of removing exhaled particles (Mansour and Smaldone, 2013). In addition to particle removal achieved by masks, other influencing factors about masks were also investigated. Tang and colleagues applied the real-time schlieren and shadowgraph imaging method to visualize the airflow from a cough with and without a mask (Tang et al., 2008; Tang and Settles, 2009; Tang et al., 2009). They found that a N95 mask can block the formation of the cough jet and a surgical mask can redirect the jet in a less harmful direction. Lai et al. (2012) measured the receptor's exposure in an environmental chamber and concluded that the separation between the source and the receptor was the most influential parameter affecting mask protection. Moreover, it was found that masks on the receptors offered less protection when compared with masks on the sources (Diaz and Smaldone, 2010; Mansour and Smaldone, 2013).

Compared with masks, there are few studies addressing the effectiveness of other mouth coverings, such as a tissue or a hand. Tang and colleagues again used the real-time schlieren and shadowgraph imaging method to extensively visualize the airflow from a cough/sneeze with the mouth covered by a tissue, cupped hand, fist, novel 'coughcatcher' device (Tang et al., 2011) and elbow (Tang et al., 2012). The qualitative schlieren and shadowgraph imaging experiments show that covering a cough can significantly reduce the horizontal velocity of the exhaled airflow. However, air jets were still observed from the leakage points between the face and covering. The videos/images produced by Tang and colleagues significantly improve the public understanding on the airflow from a cough/sneeze with the mouth covered.

Although great effort has been made on experimental studies about covering a cough, there are surprisingly few numerical studies available in the literature. Li et al. (2012) used CFD simulations to investigate the effects of mouth covering on a co-occupant's exposure under three commonly employed ventilation systems. They concluded that covering the mouth could interrupt the horizontal transport of exhaled air and protect the co-occupant from direct exposure to the coughed particles. Their work has provided a new avenue in studying the effects of a mouth covering on the dispersion of exhaled particles. However, in their simulations, a small plate (0.20 m in length × 0.12 m in height) located 0.03 m in front of the infector's mouth was used to represent the mouth covering. The plate may not be representative of actual mouth coverings used in daily life. Thus, to obtain more realistic information about person-to-person contaminant transport in indoor environments, it is important to correctly predict the exhaled airflow from a cough with the mouth covered.

To predict the exhaled airflow from a cough with the mouth covered, one option is to directly build a realistic geometry of the mouth covering, such as a tissue, a cupped hand, a fist, or an elbow. However, it would be very difficult to identify the air leakage points between the face and mouth covering. Furthermore, the complicated geometry of the mouth covering would necessitate a large number of grids in CFD simulations and result in significant computing costs.

Therefore this investigation aims to develop simplified models for predicting the exhaled airflow from a cough with the mouth covered.

2. Visualization of exhaled airflow from a cough with the mouth covered

2.1 Experimental methods

In order to understand the characteristics of exhaled airflow from a cough with the mouth covered, this study used tobacco smoke to visualize the airflow from 16 human subjects (15 males and 1 female). The median diameter of tobacco smoke particles is about 0.2 μm (Klepeis and Nazaroff, 2002) and the temperature of exhaled tobacco smoke is close to that of pure exhaled air (Gupta et al., 2009). Thus, the exhaled smoke flow should closely follow the cough airflow. The subjects were healthy smokers, and the experimental procedures were approved by an institutional review board for human subject experimentation. The subjects were informed of the objectives of this research and the associated risks. Each subject signed a consent form before participating in the experiment. The pictures of the exhaled flows were obtained by moderate-speed photography at a frequency of 80 Hz. Five types of mouth covering methods were tested: a tissue, a cupped hand, a fist, and an elbow with a sleeve and without a sleeve, as well as an uncovered cough. Each test was repeated at least twice for each subject. The subjects were asked to exhale smoke through a single cough. To ensure high-quality flow visualization, a light source and a dark background were used. The pictures were taken from both the front and side view. However, the results showed that the exhaled airflow visualized from the front view was much more limited than that from the side view. Therefore, this study only discusses the characteristics of coughed airflow from the side view.

2.2 Characterizing exhaled airflow from a cough with the mouth covered

In representative photographs of a cough covered by a tissue (Figure 1), the transient exhaled airflow profiles can be seen in detail. A forward jet penetrated the tissue, and an upward jet escaped from the upper leakage point between the face and tissue. Further visualization results are provided in Figure 2. Some subjects exhaled both forward and upward jets, as shown in Figure 2(a), while others exhaled only a forward jet or only an upward jet, as shown Figures 2(b) and 2(c), respectively. The visible horizontal transport distance of the smoke was quantitatively estimated using the digital color Y'UV model. Averagely, the visible smoke flow from a cough covered by a tissue can travel by 0.10 m in the horizontal direction. Note that the estimated visible horizontal transport distance does not necessarily represent the actual stopping distance of the cough air, since the smoke may be too weak to be detected outside the "edge" of the visible smoke. This parameter is provided for comparison between different covering methods.

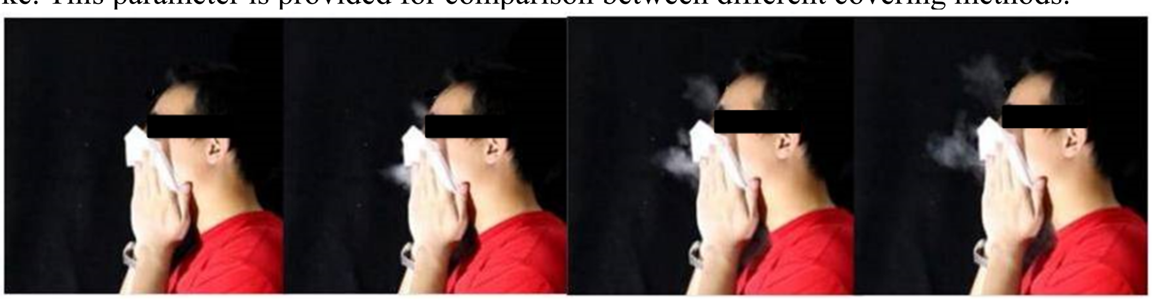


Figure 1 Representative photographs of a cough covered by a tissue.

(a) (b) (c)

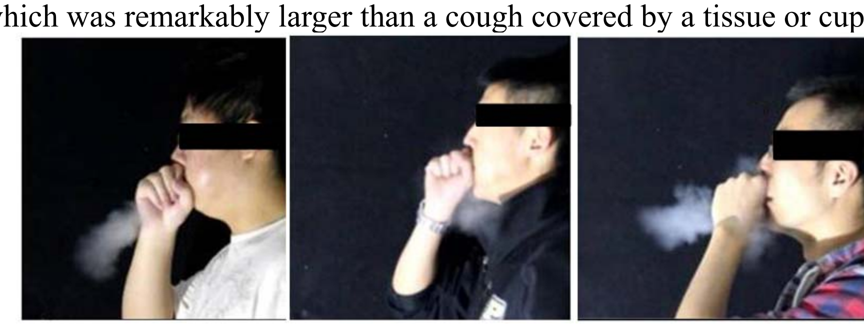
Figure 2 Visualization of a cough covered by a tissue (a) with both forward and upward jets, (b) with only a forward jet, and (c) with only an upward jet.

When a cough was covered by a cupped hand, upward and downward jets escaped the upper and lower leakage points, respectively, between the face and hand. Moreover, the upward jet tended to move forward to some extent. The visualization results (Figure 3) indicate that the cough could lead to both upward and downward jets, only an upward jet, or only a downward jet. The average horizontal transport distance for a cough covered by a cupped hand was 0.13 m.

(a) (b) (c)

Figure 3 Visualization of a cough covered by a cupped hand (a) with both upward and downward jets, (b) with only an upward jet, and (c) with only a downward jet.

When a cough was covered by a fist, jets moved through the hole in the subject's fist (Figure 4(a)), through the side leakage points between the fist and face (Figure 4(b)), or through both locations (Figure 4(c)). The average horizontal transport distance for a cough covered by a fist was 0.30 m, which was remarkably larger than a cough covered by a tissue or cupped hand.



(a) (b) (c)

Figure 4 Visualization of a cough covered with a fist (a) with a jet through the hole in the fist, (b) with jets through the leakage points between the face and fist, and (c) with both types of jets.

When a cough was covered by an elbow with a sleeve, there was a relatively strong upward jet and a relatively weak downward jet through the leakage points between the face and elbow (Figure 5). An elbow with a sleeve can significantly redirect the exhaled airflow.

Figure 5 Visualization of a cough covered by an elbow with a sleeve.

Without a sleeve, the jet can move further than with a sleeve, as illustrated in Figure 6. Therefore, the effectiveness of covering a cough by an elbow without a sleeve is worse than that with a sleeve. The average horizontal transport distance for a cough covered by an elbow without a sleeve (0.25 m) was relatively larger than that with a sleeve (0.18 m). As a reference, this study also visualized the airflow from an uncovered cough. The average horizontal transport distance for an uncovered cough was 0.38 m.

Figure 6 Visualization of a cough covered by an elbow without a sleeve.

3. Simplified models for the airflow from a cough with the mouth covered

From the images captured in the experiments, the jet velocity and direction from the coughs can be determined, and these parameters can be used as boundary conditions for modeling person-to-person contaminant transport in ventilated spaces. This section details the determination of jet velocity and direction.

3.1 Methods for determining jet velocity, direction, and flow ratio

Figure 7 shows an example of the first image captured after the start of exhalation. Because the image capture frequency was 80 Hz, the image was captured at t = 0.0125 s. The distance traveled by the jet was Δs, which was quantitatively determined using the digital color Y'UV model. It was found that the peak velocity occurred at the very beginning of exhalation, and thus the peak velocity of the jet can be calculated by

$$V = \frac{\Delta s}{\Delta t} \quad (1)$$

where Δt is equal to 0.0125 s.

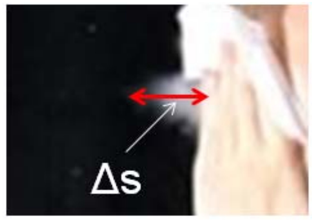


Figure 7 An example of the first image captured after the start of exhalation.

To verify the method, this investigation also visualized the airflow from an uncovered cough and compared it with detailed measurement data from Gupta et al. (2009). The average calculated peak velocity (11.8 m/s for 15 males and 1 female) agrees reasonably well with the measurement data (12.6 m/s for 25 males). Thus, this method can be used to determine the jet velocity from a cough with the mouth covered.

The direction of the jet's central line was visually approximated as a line that equally divided the smoke in the two-dimensional plane as shown in Figure 8. Two angles, θ_1 and θ_2, were used to describe the direction of the jets. For cases in which two jets were observed, the ratio of the airflow rates can be estimated by the volumes of the two smoke jets.

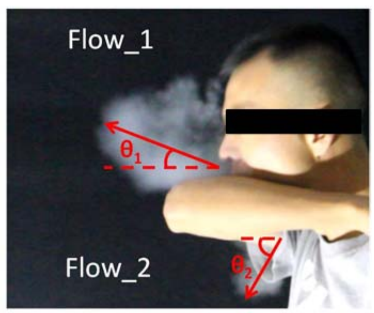


Figure 8 Directions of jets' central lines.

3.2 Initial jet velocity, direction, and flow ratio results and simplified models

The average, 10th percentile, and 90th percentile of initial jet velocity, direction, and flow ratio were determined for coughs with the mouth covered, as shown in Figure 9. The average velocities of the forward and upward jets from a cough covered by a tissue were 2.6 and 3.8 m/s, respectively, which were lower than in the other cases. Since the use of tissues can also prevent the transmission of infectious diseases by eliminating direct contact with hands, covering a cough with a tissue should be the best approach. Covering a cough with a cupped hand is the second best approach, with an average upward jet velocity of 6.3 m/s and an average angle of 59.2^{o}. When coughs were covered by an elbow with and without a sleeve, the average initial jet velocity was similar between them, but the average angle with a sleeve was relatively large. Thus, the sleeve is beneficial for redirecting the airflow and reducing the risk of horizontal transport of exhaled particles. Covering a cough with a fist is probably the worst approach, with a relatively high velocity of 8.5 m/s and a small angle of 25.8^{o}.

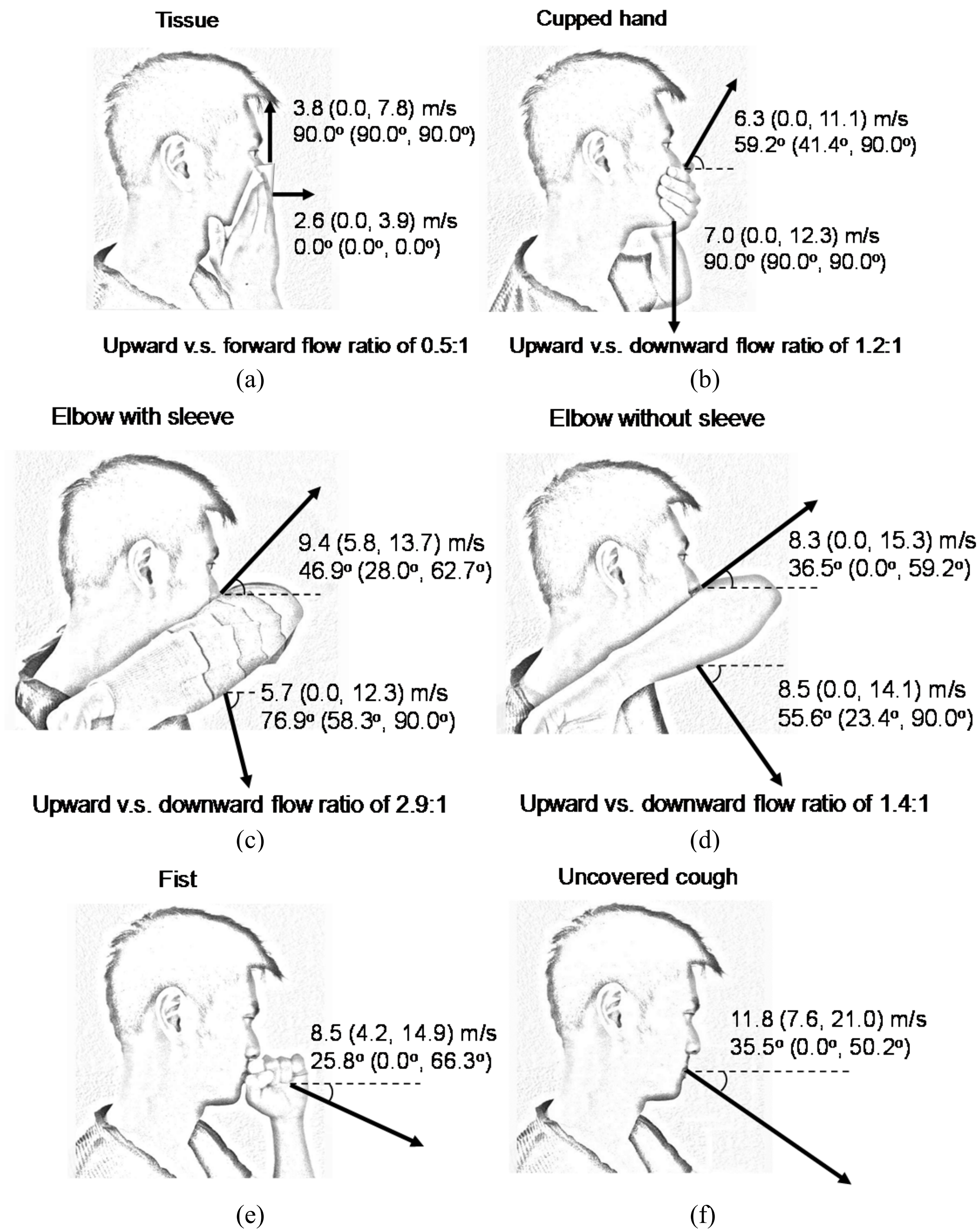


Figure 9 Average jet velocity, direction, and flow ratio for coughs covered by (a) a tissue, (b) a cupped hand, (c) an elbow with a sleeve, (d) an elbow without a sleeve, and (e) a fist; and (f) an uncovered cough. The numbers in parentheses are the 10th and 90th percentiles, respectively.

A covered mouth can be represented by a simplified method that separates the opening into four equal sections with a total area of 8 cm^2, as shown in Figure 10. The jet velocity and direction are defined at two of these sections, and the other two sections are defined as solid walls. Thus, the remaining area of the opening is 4 cm^2, which is the actual area of a mouth opening (Gupta et al., 2009). The various mouth coverings (Figure 10) are defined according to the following rule. If the angle shown in Figure 9 is larger than 45°, the jet is defined at the upper or lower section of the opening, whereas, if the angle is smaller than 45°, the jet is defined at the upper-front or lower-front section of the opening. Under this simplification, the complicated geometries of mouth coverings are avoided, and the models can be used more easily for engineering applications.

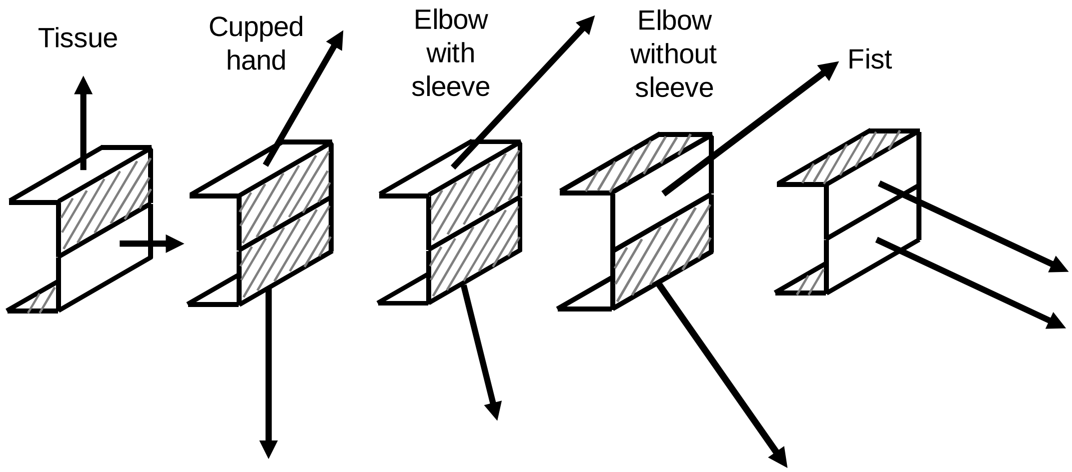


Figure 10 Definition methods for different mouth coverings in CFD simulations.

4. Model verification and case study

This investigation designed multiple cases and applied the proposed simplified models to calculate the particle concentration distribution as a function of time. The CFD results were then qualitatively compared with the images of smoke flow in order to verify the models to some extent. Finally, this study explored the influence of mouth coverings on the receptor's exposure.

4.1 Case setup

Figure 11 illustrates the configuration of the room used in this study. The room was 3.0 m in length, 3.0 m in width, and 2.3 m in height. There were two persons sitting face to face, with a distance of about 1.0 m between their noses. The person on the left was assumed to be the index person, while the one on the right was the receptor. The index person was assumed to have a single cough at time zero. The room was ventilated by a mixing ventilation system with an air change rate of 3 ACH. The temperature of the supplied air was 21°C, and the surface temperature of the persons was 32°C. All the walls were adiabatic. Eight cases were investigated, including a cough covered by a tissue, a cupped hand, a fist, an elbow with a sleeve, and an elbow without a sleeve, an uncovered cough with average and maximum velocity and a hypothetical release of particles with zero velocity. The total particle emission rates were exactly the same for all cases. This study assumed a constant exhaled velocity for a cough. The constant velocity was assumed to be the peak velocity. The cough duration was set at 0.15 s so that the cough expired volume matches with the measurement data by Gupta et al. (2009). A particle size of 1.0 μm was assumed in order to represent fine particles. The densities of particles were assumed to be uniform.

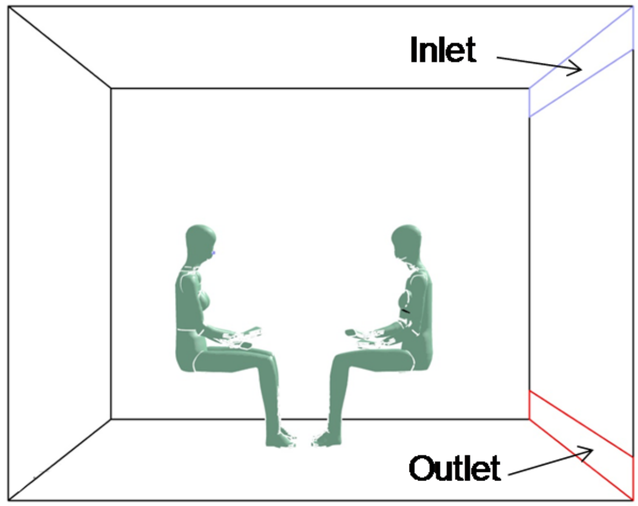


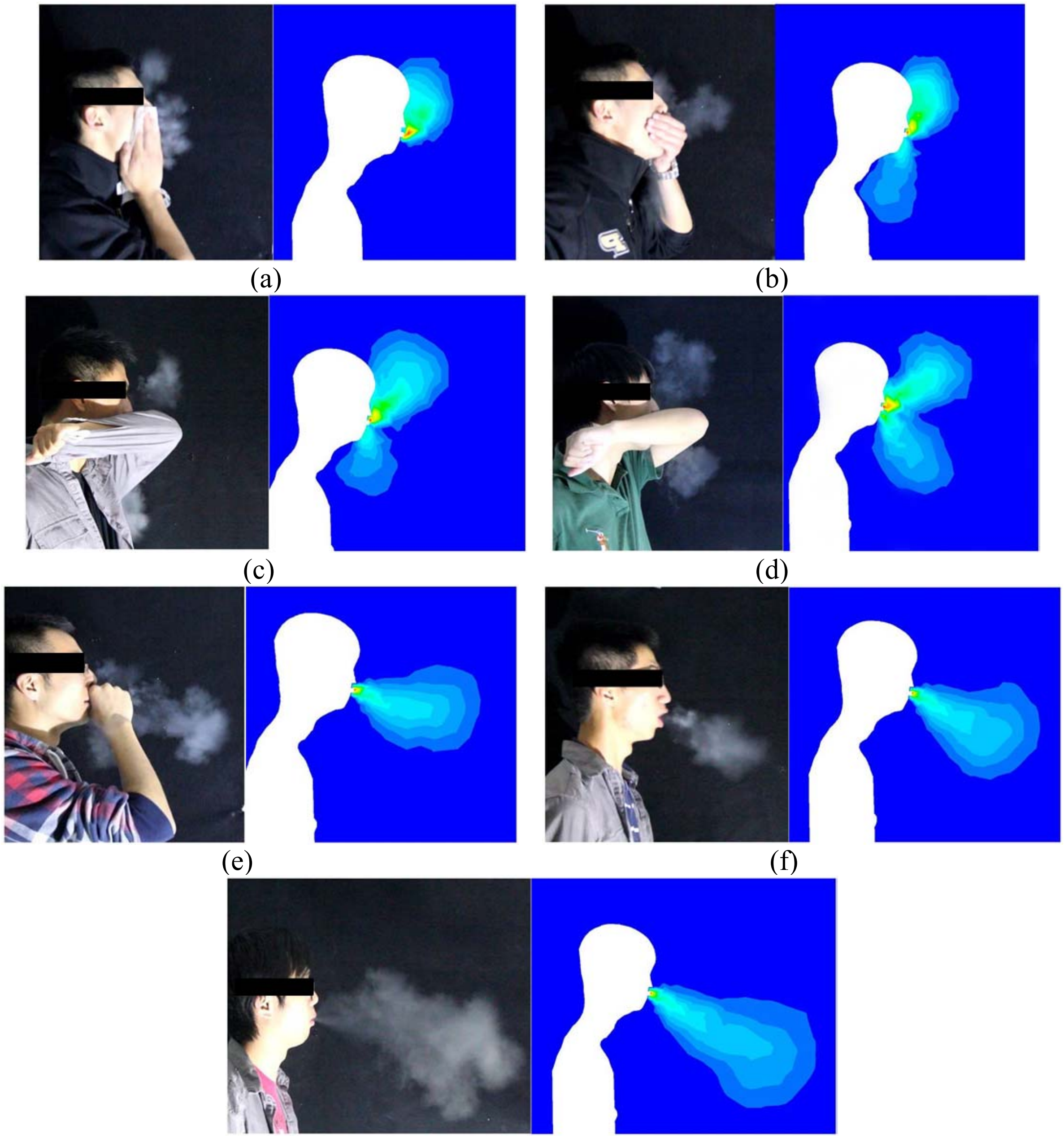
Figure 11 Configuration of the room used in this study.

4.2 Simulation models

The renormalization group (RNG) k-ε model (Choudhury, 1993) was used to calculate the airflow and turbulence, as recommended by Wang and Chen (2009). The standard logarithmic law wall function was adopted to connect the solution variables at the near-wall cells with corresponding quantities on the walls. The Eulerian drift-flux model was used to calculate the dispersion of exhaled particles. The numerical simulations were conducted using the CFD program, ANSYS Fluent 12.1 (ANSYS, 2010). A user-defined function (UDF) was implemented to realize the Eulerian model. The effect of particle deposition onto the walls is negligible at a particle size of 1.0 μm (Zhao et al., 2009). The evaporative process is almost instantaneous for droplets with a diameter smaller than 3 μm (Chen and Zhao, 2010). Three grid resolutions (669,109, 1,446,790, and 2,937,128) were tested for CFD grid independence. The resolution of 1,446,790 was sufficiently fine to capture the turbulent flow in the room.

4.3 Verification of the simplified models

Figure 12 provides a qualitative comparison of the CFD simulation results (at 0.05 s) with images of the smoke flows. The experimental images of (a) to (f) depict the coughs with an initial jet velocity and direction that is close to the average values shown in Figure 9. The experimental image of (g) depicts an uncovered cough with an initial jet velocity that is the maximum of the initial jet velocities of all uncovered coughs. The proposed simplified models can predict the general trend of exhaled airflow reasonably well. For instance, the models predicted the relatively weak jet generated by a cough covered by a tissue. For a cough covered by a cupped hand and an elbow, the model correctly predicted an upward and a downward jet. Furthermore, the model reflects the fact that covering a cough with an elbow with a sleeve can redirect the airflow more significantly than an elbow without a sleeve. In addition, the predicted horizontal jet from a cough covered by a fist was the strongest jet from coughs with the various mouth covering methods. This result agrees with the experimental observations. Thus, these simplified models can be used to predict the airflow from a cough with the mouth covered.



(g)

Figure 12 Qualitative comparison of airflow in experimental images and as depicted by simplified models, from coughs covered by (a) a tissue, (b) a cupped hand, (c) an elbow with a sleeve, (d) an elbow without a sleeve, and (e) a fist; and uncovered coughs with (f) average velocity and (g) maximum velocity.

4.4 Influence of mouth coverings on receptor's exposure

The background airflow distribution predicted by CFD simulation shows that there was no strong advective airflow moving from the index person to the receptor. This feature allows us to examine the influence of a cough and mouth coverings on receptor's exposure with minimized impact of background advective airflow. The particle concentration distribution at t = 5.0 s is shown in Figure 13 for each of the eight cases. Videos showing the particle transport from t = 0 to 5.0 s are provided in the Figure S1. For a hypothetical release of particles with zero velocity and for coughs covered by a tissue, a cupped hand, and an elbow, the exhaled particles moved upward with the thermal plumes generated by human bodies. For these cases, the horizontal transport distances of the particles at this moment were less than 0.5 m. For a cough covered by a fist and an uncovered cough with an average velocity, the particles penetrated the thermal plumes and moved forward to some extent. The horizontal transport distance of the particles for covering by a fist was about 0.7 m. For an uncovered cough with a maximum velocity, the particles directly entered the breathing zone of the receptor, i.e. the horizontal transport distance of the particles was at least 1.0 m. The results indicate that the mouth coverings, with the exception of the fist, can significantly reduce the horizontal air velocity and cause the particles to move upward with the thermal plumes. Furthermore, when the horizontal air velocity is sufficiently high, or the person-to-person distance sufficiently small, the particles can directly enter the breathing zone of the receptor and result in serious exposure.

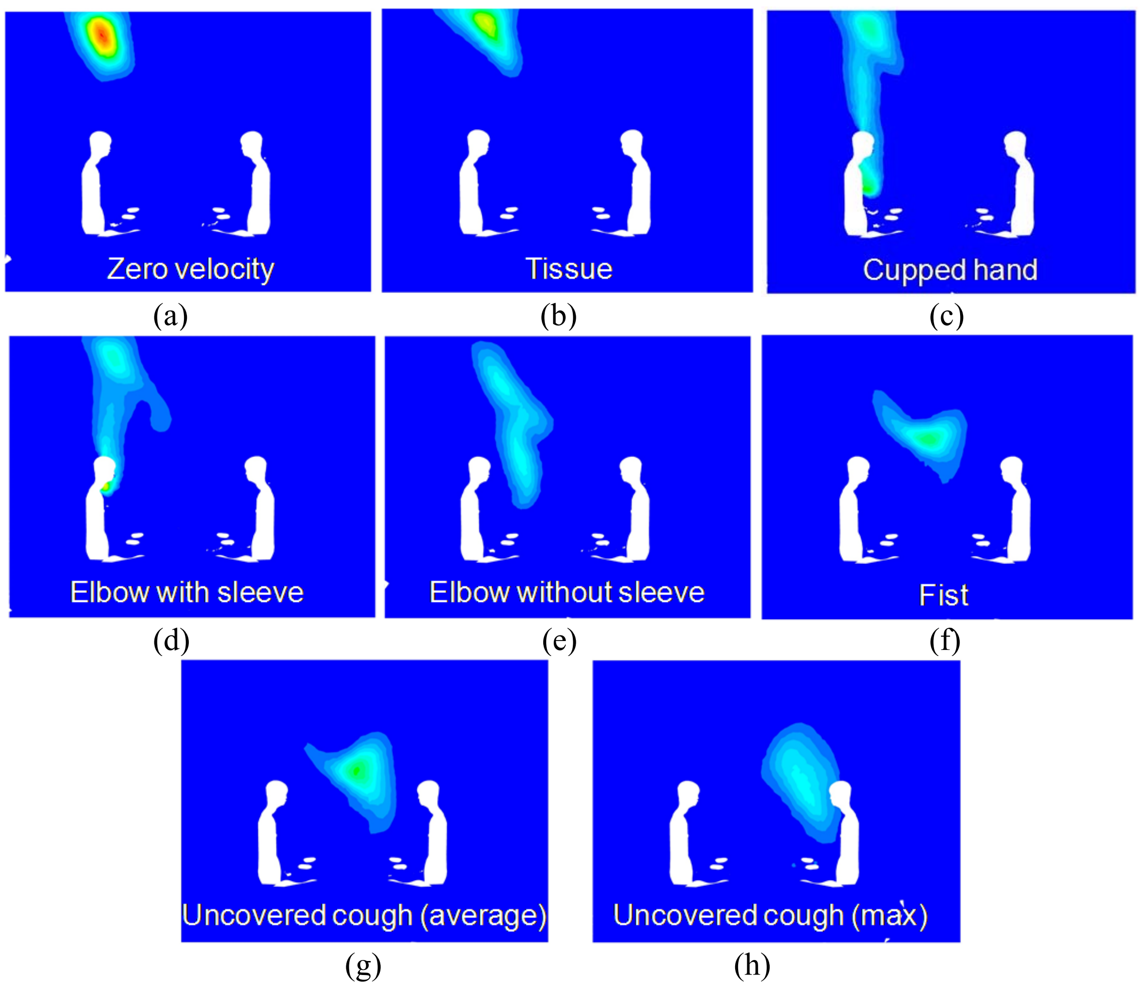


Figure 13 Comparison of particle concentration distributions at 5.0 s for (a) a hypothetical release of particles with zero velocity; coughs covered by (b) a tissue, (c) a cupped hand, (d) an elbow with a sleeve, (e) an elbow without a sleeve, and (f) a fist; and uncovered coughs with (g) average velocity and (h) maximum velocity.

Figure 14 compares the normalized particle concentration as a function of time in the breathing zone of the receptor for the eight cases. The particle concentrations were normalized by the maximum concentration observed in the breathing zone of the receptor among all the cases. For uncovered coughs, the exhaled particles directly entered the breathing zone of the receptor. The receptor also experienced indirect exposure because the particles dispersed throughout the room and again reached the receptor. However, if the mouth was covered, the receptor experienced only indirect exposure.

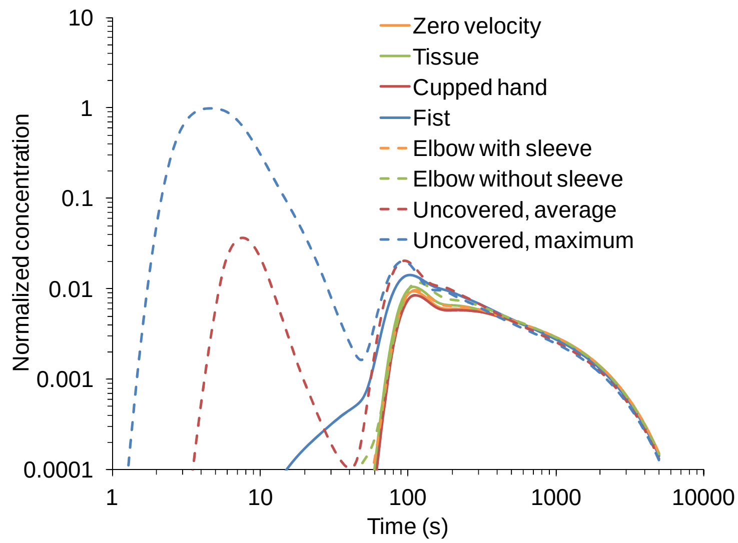


Figure 14 Comparison of particle concentration as a function of time in the breathing zone of the receptor for the eight cases.

As compared with the particle concentration as a function of time, the total exposure of the receptor may be more important for estimating the risk of infection. This study calculated the inhaled dose, ID, by

$$ID = \int_{t=0}^{t'} C(t)dt \cdot q \quad (2)$$

where C(t) is the particle concentration in the breathing zone of the receptor, t is the time, q is the breathing flow rate which was set at 0.00053 m^3/s, which corresponds to the ISO standard for an adult 1.88 m tall with a mass of 85 kg engaged in moderate work (ISO, 2007). The inhaled dose was further separated into direct exposure from 0 to 50 s and indirect exposure from 50 to 5000 s, as shown in Figure 15. All the inhaled doses were normalized by the total inhaled dose for an uncovered cough with maximum velocity. The results show that, for an uncovered cough with maximum velocity, direct exposure was 44.7% of the total exposure. However, if the mouth was covered, no direct exposure was observed. Thus, covering a cough can eliminate approximately 45% of the total exposure as compared with an uncovered cough with maximum velocity. Interestingly, the indirect exposure for all the cases was similar to that of a hypothetical release of particles with zero velocity, which indicates that indirect exposure was determined primarily by the ventilation rather than the cough itself.

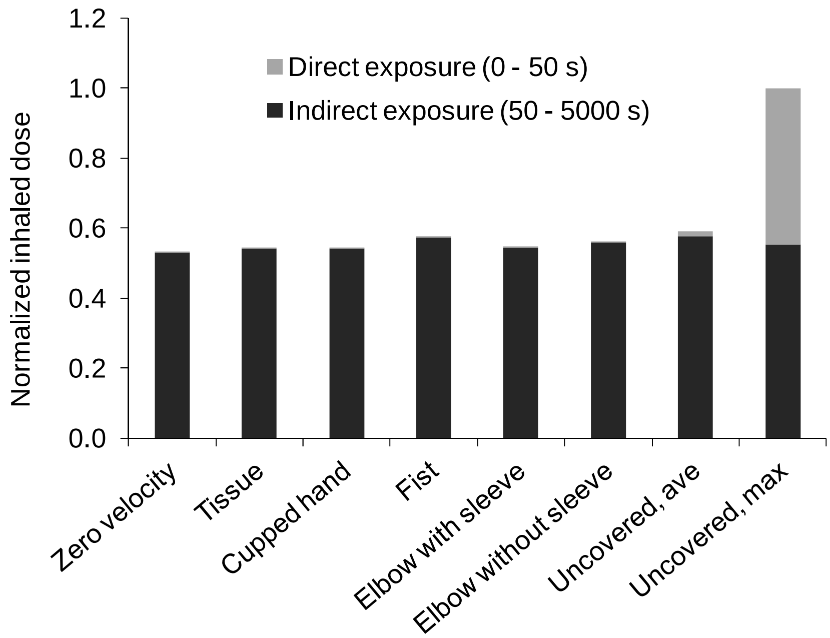


Figure 15 Comparison of inhaled dose for the eight cases.

4.5 Influence of turning the head away on receptor's exposure

The results above demonstrate the benefits of covering a cough. Covering can prevent direct exposure, which suggests that turning the head away may also reduce direct exposure. The person on the left in Figure 11 was assumed to have turned her head by 90^{o} when she coughed. Three cases were calculated in which the head was turned away, including an uncovered cough with an average velocity and maximum velocity, and a cough covered by an elbow with a sleeve. Figure 16 compares the total exposure when the head was turned away with the total exposure when there were face-to-face uncovered coughs. If the index person turned her head away, the receptor experienced only indirect exposure. Moreover, the total exposure when the head was turned away was similar to that of a hypothetical release of particles with zero velocity. It should be noted that although turning the head away can prevent direct exposure, it cannot remove the coughed particles in the same way that covering a cough can do. Therefore, covering a cough is still a better choice. It is likely that turning the head away while simultaneously covering the mouth is the best way to reduce the risk of infection.

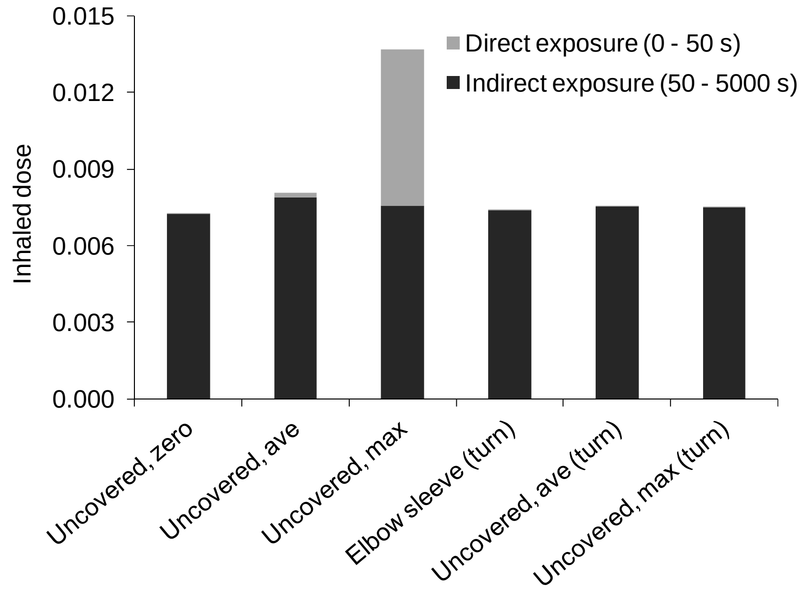


Figure 16 Comparison of the inhaled dose when the head was turned away with the inhaled dose when there were face-to-face uncovered coughs.

5. Limitations

There are a number of limitations to the present study, beginning with the use of smokers as human subjects. Smokers may suffer from chronic obstructive pulmonary disease (COPD) so that their respiratory patterns may be different from non-smokers (Decramer et al., 2012). Typically, a smoker may generate a larger volume of cough air than a non-smoker (Tang et al., 2012). Therefore, this study recruited “healthy” smokers who reported no COPD in their consent forms to minimize this influence, although the experimental results may still be somewhat biased. Another limitation was that only 1 female subject was recruited in this study due to the difficulty of finding female smokers. Thus, the proposed models should work better for males than females. To avoid the influence of smokers as human subjects, Tang and colleagues proposed to use the real-time schlieren and shadowgraph imaging method to visualize the exhaled airflow (Tang and Settles, 2009; Tang et al., 2008; 2009; 2011; 2012). This method does not require the introduction of visualization media such as tobacco smoke. Furthermore, as shown in Tang et al. (2008, 2009), this method can obtain instantaneous velocity vectors of a cough. Thus, it is hoped that this investigation will encourage the researchers who have access to the schlieren and shadowgraph imaging systems to develop similar models as presented in this study based on the advanced experimental technique.

This study developed the simplified models based on the average values of initial jet velocity and direction. As shown in Figure 9, the initial jet velocity and direction can vary significantly among subjects. Thus, the proposed simplified models predict the general patterns of airflow from a cough with the mouth covered, other than the pattern for a particular person. Furthermore, this study limited the models to two dimensions since the exhaled airflow visualized from the front view was much more limited than from the side view. This assumption may result in a certain error since there might be some small airflow in the third direction. Moreover, this study did not consider the effect of the speed with which the user can put their hands/tissues into effective position to cover the cough. It was reported that this factor could significantly affect the effectiveness of covering a cough (Tang et al., 2011). In addition, the movement of the head when coughing may also affect the airflow movement (Tang et al., 2011), which was not included in the present analysis.

In addition, this investigation did not consider the effect of virus survival on the receptor's exposure. There are several environmental parameters affecting the survival of virus, such as humidity, temperature, ultraviolet (UV) radiation and ozone reaction (Weber and Stilianakis, 2008). For instance, given the first-order inactivation rate reported by Hemmes et al. (1960), in an environment with a relative humidity at 15 to 40%, 21.9% of the influenza A virus would be inactivated after 30 minutes in the air. This implies that, although covering a cough cannot avoid the indirect exposure, it can delay the exposure so that a portion of virus could be inactivated. Thus, this characteristic further enhances the effectiveness of covering a cough on the receptor's exposure to virus particles.

6. Conclusions

This investigation used smoke to visualize the airflow exhaled by a cough from 16 human subjects with covered mouths. On the basis of the smoke data, simplified models were developed for predicting airflow. Finally, the effects of a mouth covering on the receptor's exposure were discussed. Within the scope of this research, the following conclusions can be drawn:

(1) The proposed simplified models can be used to predict the airflow from a cough when the mouth is covered.

(2) Covering a cough with a tissue, a cupped hand, or an elbow can significantly reduce the horizontal velocity and cause the exhaled particles to move upward with the thermal plumes generated by human bodies.

(3) Covering a cough or turning the head away can prevent the receptor's direct exposure.

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Supporting Information

Additional Supporting Information may be found in the online version of this article:

Figure S1. Videos of particle transport from t = 0 to 5.0 s for (a) a hypothetical release of particles with zero velocity; coughs covered by (b) a tissue, (c) a cupped hand, (d) an elbow with a sleeve, (e) an elbow without a sleeve, and (f) a fist; and uncovered coughs with (g) average velocity and (h) maximum velocity.

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