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Deposition features of inhaled viral droplets may lead to rapid secondary transmission of COVID-19

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Inhaled viral droplets may immediately be expelled and cause an escalating re-transmission. Differences in the deposition location of inhaled viral droplets may have a direct impact on the probability of virus expelling. This study develops a numerical model to estimate the region-specific deposition fractions for inhalable droplets (1–50 μm) in respiratory airways. The results identified a higher deposition fraction in the upper airways than the lower airways. Particularly for droplets larger than 10 μm, the relatively high deposition fraction in the oral/laryngeal combined region warns of its easy transmission through casual talking/coughing. Moreover, considering droplet sizes’ effect on virus loading capacity, we built a correlation model to quantify the potential of virus expelling hazards, which suggests an amplified cascade effect on virus transmission on top of the existing transmission mechanism. It therefore highlights the importance of considering the instant expelling possibilities from inhaled droplets, and also implies potentials in restricting a rapid secondary transmission by measures that can lower down droplet deposition in the upper airways.

1. Introduction

The COVID-19 pandemic caused by severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) has affected more than 36 million people and caused over 1 million deaths (Weekly Operational Update on COVID-19: 9 October 2020, 2020). According to current evidence, COVID-19 virus is primarily transmitted between people through respiratory droplets via coughing, sneezing, breathing/talking. Deep understandings of the underlying virus transmission patterns, particularly from the airborne/aerosol transmission perspective, are widely considered to play key roles in containing the spread of this disease (Klompas, Baker, & Rhee, 2020). Currently, extensive studies have been devoted to the human-to-human transmission of virus-laden aerosols originally expelled from infected (symptomatic/asymptomatic) carriers, who can become highly infectious as early as 3 days prior to the onset of symptoms. However, emerging evidence also suggested that SARS-CoV-2 can spread to wider areas and suspend longer time than expected, possibly facilitated by a secondary transmission mechanism (Nishiura et al., 2020; Shen et al., 2020). It remains unclear that how the inhale viral droplets depositing in close contact people’s respiratory system may infect human or contaminate environment (fomite transmission) that are out of the social distance. This might be the cause of an escalating secondary transmission (re-transmission), especially in high traffic areas such as airport terminals, schools, restaurants and hospitals. To gain a deeper understanding, this study develops a numerical model to estimate the escalating transmission rate, which can help relevant professional outline the virus re-transmission mechanism.

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Inhaled droplets are proven to deposit in either upper airways or lower airways depending on particle size and respiratory intensity (Shang, Dong, Inthavong, & Tu, 2015). Previous investigations (Morawska et al., 2009) have indicated that particles expelled from the close contact during coughing and talking serve as primary vehicles for respiratory virus transmission, with typical starting concentrations 10 times higher than those generated during breathing. Thus, it is reasonable to deduce that inhaled respiratory viruses trapped in upper airways (extending from oral cavity to larynx) are more easily to be expelled into the air than those deposited in lower airways, which lead to direct and indirect contact transmissions. Unlike adequate attentions paid within the social distance, transmissions outside the social distance is usually overlooked but it can easily and immediately become a secondary transmission due to a medium person (Fig. 1). Therefore, the deposition features of virus-laden droplets in the respiratory airway can directly impact on the probability of a secondary transmission. Particularly, if high deposition fractions of virus-laden droplets are expected in upper airways, raised alert levels to the contagiousness of this virus are recommended to implement adequate preventive measures to help prevent potential re-transmission. In this study, we investigated region-specific deposition fractions of inhalable droplets (1–50 μm) in the respiratory system from an aerodynamic perspective. Our contribution is to establish a better understanding of the virus spreading procedure in the transmission chains, especially the role of the secondary contacts in high populated areas.

2. Material and methods

2.1. Computational geometry and numerical setups

We used the Computational Fluid Dynamics (CFD) method to simulate the particle dynamics in respiratory airways. Current CT-image based realistic respiratory airway model consists of the upper airway (the nasal cavity, oral cavity, nasopharynx, oropharynx and larynx) and the lower airway (trachea, main bronchi and segmental bronchi up to 15 generations) (Fig. 2).

The details of mesh generation and airflow simulation methods were explained in the authors’ previous studies (Dong et al., 2019; Shang, Dong, Tian, Inthavong, & Tu, 2019), which investigated airflow dynamics and nanoparticle deposition characteristics using the same realistic airway model. To better revealing the regular inhalation conditions in the crowded environment, the oral–nasal inhalation scenario mode B (Dong et al., 2019), which inhales air through nostrils and mouth opening simultaneously, was selected in this study. The external sphere was set as pressure inlet with the pressure of zero. Each group of outlets of lobar bronchi was set as velocity outlets that sucked the airflow, with the flow rate weights adopted in Shang et al. (2019) and measured by Horsfield, Dart, Olson, Filley, and Cumming (1971). The details of boundary conditions are listed in Appendix. The By adopting this high-intensity inhalation as the worst case scenario, i.e. highest possibility of inhaling and expelling, the results are anticipated to assist in precaution decisions. The $k – \omega$ SST turbulence model was used for the laminar–turbulent transitional flow. Micron-particles with selective diameters of 1, 2, 3, 5, 7, 10, 15, 20, 30 and 50 μm were used for particle transport and deposition simulations.
The equations and numerical schemes of particle tracking simulation were explained in the study of Gu et al. (2019). The concept of inhalability is adopted to better estimate inhaled particle depositions, which is defined as the number of inhaled particles over the number of particles released for each particle size. To accurately calculate the inhalability and regional deposition efficiencies, 100,000 particles for each size were passively released from a spherical surface with a radius of 3 cm, that is adequate to enclose both the nasal and oral openings and also small to ensure a compact particle source being continuously released.

2.2. Determination of droplet sizes

The size of expelled droplets could be diversely ranging from 1 μm to 1000 μm (Chao et al., 2009). The historical threshold of size for the droplet transmission is 5–10 μm, larger than which the droplet would quickly drop to the ground within 1 m (World Health Organization, 2014). However, recent studies strongly suggested that the criteria to distinguish between aerosol and droplet transmissions should be significantly increased to 100 μm, larger than which the droplet would fall to the ground within 2 m (Prather et al., 2020). On the other hand, the droplet inhalability drastically decreases as the droplet size exceeds 50 μm. Therefore in this study, 50 μm was considered as a cut-off diameter to distinguish the inhalable droplets and focused on 1–50 μm droplets. The reference data from Chao et al. (2009) indicated a size distribution of aerosol droplets from coughing, ranging from 1 to 1000 μm (Fig. 3a). The original unit of the number fraction was “number of particles per unit ln(μm)”. To have a convenient viral load
Fig. 3. Droplet number-size distribution from a typical cough. (a) log-scale distribution reproduced and fitted from the experimental results of Chao et al. (2009), (b) converted to the linear scale for convenient calculation.

Table 1
Inhalability and deposition efficiency (DE) of inhaled particles depositing in the oral/laryngeal combined region.

| Size (μm) | 1  | 2  | 3  | 5  | 7  | 10 | 15 | 20 | 30 | 50 |
|-----------|----|----|----|----|----|----|----|----|----|----|
| Inhalability (%) | 99.2 | 99.2 | 99.2 | 98.9 | 98.5 | 98.1 | 97.3 | 96.4 | 52.5 | 13.9 |
| Oral/laryngeal DE (%) | 6.2 | 6.9 | 8.5 | 19.4 | 41.2 | 58.2 | 51.6 | 57.4 | 54.4 | 45.5 |

calculation, Fig. 3b converts the unit of number fraction from logarithm scale to linear scale “number of particles per unit μm”. The fitted equation of the particle number size distribution is,

\[
\text{number fraction} = \frac{a}{\sigma \sqrt{2\pi}} \times \exp \left(-\frac{1}{2} \left(\frac{\log(ds) - \log(\mu)}{\sigma}\right)^2\right)
\]

(1)

where \(ds\) is the droplet size in μm, fitted parameters are \(a = 0.43\), \(\sigma = 0.54\) and \(\mu = 13.5\).

Integrations of number fraction indicate that 1–50 μm particles account for 85.1% of total number of particles in size range 1–1000 μm.

3. Results

3.1. Particle deposition at upper and lower airways

The inhalability for each particle size is defined as the number of inhaled particles over the number of particles released. Our CFD simulation results showed small droplets (1–20 μm) present nearly 100% inhalability. As the droplet size exceeds 20 μm, the inhalability drastically drops and reaches 14.0% for 50 μm droplets (Table 1).

Fig. 4 depicts a distinct influence of particle sizes over deposition fractions and locations in the airways. Although large droplets have much higher deposition fraction over the whole respiratory system (100%, 81.9% and 12.1% for 50, 10 and 1 μm droplets, respectively), the locations where large and small droplets tend to deposit are remarkably different. Large droplets tend to stay at the upper airway (the nasal cavity, the oral cavity and the larynx), while small droplets are less likely to stay in this region. Overall, the upper airway receives more droplet deposition than the lower airway, with ratios of 4 : 1 and 15 : 1 for 1 μm and 10 μm respectively, in accordance to deposition fraction 9.5% and 76.7% in the upper airway to 2.4% and 5.1% in the lower airway (Fig. 4). While for 50 μm droplets, the deposition in the upper airway is 100%.

Another notable difference is observed within the upper airway, i.e. in the nasal cavity and the oral/laryngeal combined region. For viral droplets at 1, 10 and 50 μm, the depositions in the nasal cavity are 3.3%, 18.5% and 54.5% comparing to 6.2%, 58.2% and 45.5% in the oral/laryngeal combined region (Fig. 2). For droplets at 1 μm and 10 μm, much lower deposition fractions in the nasal cavity suggest reduced infectivity by normal breathing than coughing. However, 50 μm droplets result in a notably high deposition fraction of 54.5% in the nasal cavities and a comparable rate of 45.5% in the oral/laryngeal combined region, suggesting a high risk of rapid expelling through casual respiration and talking, especially with the fact that larger particles usually carry more virus loads.

3.2. Inhaled virions potential for expelling

The virus can be assumed evenly distributed before being ejected from coughing as studies (Stadnytskyi, Bax, Bax, & Anfinrud, 2020) suggested that viral droplets contain a virus RNA load of average \(7 \times 10^6\) copiers per millilitre. However, the virus load in individual droplets also varies due to their volume differences according to different droplet sizes. Therefore, the following
discussions apply the fact that the studied three particle sizes contain different numbers of virions, i.e. a 10 μm droplet contains about 1000 times viruses of that in a 1 μm droplet. Specifically, when considering the particle size distribution in Fig. 3, 10 μm droplets ejected from a cough carry 864 times more viruses than those in 1 μm droplets.

The expelling potential $P$ for inhaled virions is defined as,

$$P = \frac{\int_{x=1}^{50} NF(x) IH(x) DE(x) \left( \frac{1}{6} \pi x^3 \right) dx}{\int_{x=1}^{50} NF(x) \left( \frac{1}{6} \pi x^3 \right) dx} \times 100\% \quad (2)$$

where $NF(x)$ is the number fraction distribution against the particle size (diameter) as illustrated in Fig. 3. $IH(x)$ is the inhalability (number of inhaled particles over number of particles released). $DE(x)$ is the droplet deposition efficiency in the oral cavity, oropharynx and larynx, where the virons can be easily re-expelled by talking and coughing. Thus, apart from the background concentration, $P$ can be used for quantifying the potential of virus expelling hazards. Based on a steady-state assumption, our CFD model reveals a expelling rate of 14.9%, which represents a substantial chance for inhaled virons to be immediately re-transmitted into the air and may worsen the infectiousness due to the overlay effect in virus concentration.

4. Discussion

Epidemic models are fundamental to modelling and forecasting the spread of COVID-19, which usually describe individuals associated with the spread of coronavirus through three stages: susceptible, infected and recovered (Lauer et al., 2020). This paper suggests an amplified cascade effect on virus transmission among individuals exposed to COVID-19, which is independent of the incubation period for the virus (at least five days Hoque, 2020 before a person feels symptoms) as it may occur instantly after virus inhalation. Therefore, this paper demonstrates an important influential factor to be included by existing epidemic models, which helps in model calibration and enables us to reproduce and predict the dynamic evolution of the epidemic. This paper also highlights the significance of fully implemented and sustained social distancing measures on containing widespread community transmission of COVID-19.

Although face masks are proven efficient in lowering the transmission, there are still concerns about the limited effectiveness of a mask or face covering (Betsch et al., 2020; Brooks, Butler, & Redfield, 2020). Nevertheless, even without efficient respirators (such as N95), some substitutions (scarf, clothes or homemade masks) are still helpful in filtering particles in micron-scale range, e.g. cotton, natural silk, and chiffon can provide above 50% protection in the entire 10 nm to 6 μm range (Konda et al., 2020). By lowering down the virus deposition in the upper airways, the risk of a rapid re-transmission can be significantly limited.

On the other hand, due to the far-reaching economic consequence of strict social distancing measures, political leaders and policy makers are facing unprecedented challenges to consider relaxing them as early as possible. However, the model presented here demonstrates that relaxing these measures in the absence of pharmaceutical interventions may allow the pandemic to reemerge shortly, particular in densely populated areas.

5. Conclusions

While most studies are focused on the SARS-CoV-2 airborne/aerosol transmission, limited research has been conducted to investigate the potential re-transmission caused by the immediate expelling of inhaled viral droplets via casual talking/coughing. This paper addressed the deposition features of viral droplets ranging between 1 and 50 μm in the respiratory system, especially the oral/laryngeal combined region in the upper airway.
The droplets ranging from 1 to 50 μm shows higher deposition in the upper airway comparing to the lower airway, particularly for large size droplets (i.e. 50 μm). Notably, for droplet sizes larger than 10 μm, the relatively high deposition fraction (> 40%) in the oral/laryngeal combined region warns of the easy expelling of the virus through casual talking/coughing. To include the droplet size effect in terms of virus loading capacity, an expression was proposed to estimate the fraction of expelled 1–50 μm viral droplets potential for re-transmission. The predicted expelling potential P of 14.9% suggests an amplified cascade effect on virus transmission on top of existing direct or indirect human-to-human transmission mechanism.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix

See Table 2.

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