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# Airborne infection risk of nearby passengers in a cabin environment and implications for infection control

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**ABSTRACT**

*Background*: Expiratory droplets cause high infection risk to nearby passengers via airborne route. *Methods*: We built a two-row four-seat setup to simulate a public transport cabin. A cough generator and a nebulizer were used to simulate the cough and talk processes respectively. Exposure and infection risk of nearby passengers was studied. The effect of gasper jet and backrest on risk mitigation was investigated.

*Results*: For the activity of coughing, the front passenger has much higher infection risk, which was around four times of that of other passengers, because of the concentration surge in the inhalation zone. For talking, the nearby passengers have similar infection risk because nearby passengers were all exposed to concentration surges with similar peak value. Gasper jet of the infected passenger and higher backrest can extinguish or reduce the concentration surge of front passengers and reduce the infection risk due to coughing and talking droplets.

*Conclusion*: The passengers near the infected passenger have very high infection risk. The overhead gasper and a higher backrest can reduce the exposure and mitigate the risk of infection. It is believed that the control measures to protect nearby passengers are urgently needed in public transport cabins.

**Keywords**: Public transport; Covid-19; Personalized ventilation; Backrest; Gasper jet

## 1.Introduction

Due to the outbreaks of the infectious diseases, such as the SARS-2003, H1N1-2009, and COVID-19, study of respiratory disease transmission risk attracts a lot of research interest [1-3]. The public transport cabin environment is a common place to cause respiratory disease transmission because close contacts among passengers are unavoidable during rush hour [4-6]. Coughing and talking are two typical respiratory activities releasing numerous respiratory droplets with different initial velocities. Pathogen-laden airborne droplets can reach the lower respiratory tract by inhalation and cause infections [7,8]. The infection risk of the passenger near an infected passenger is expected to be much higher than that of the passengers far away because of the higher droplet concentration. Researchers indicated that airborne transmission in close contact is an important route for the

COVID-19 [9,10]. Most infected cases in air travel were associated with sitting within two rows of an infected passenger [4,6,11]. Thus, understanding the infection risk of nearby passengers and control is important for reducing infection in the public transport cabin.

Many studies have been conducted on expiratory droplet dispersion in public transport cabins, such as aircraft cabins, trains, and buses. Sze-To et al. [12] experimentally studied the dispersion of cough droplets in an aircraft cabin. They found that the cough droplets took 20-30 s to reach the area of two rows. Wan et al. [13] modelled the fate of poly-dispersed expiratory droplets in an aircraft cabin environment by numerical simulation. Gupta et al. [14] studied the transport of expiratory droplets in an aircraft cabin using a computational fluid dynamics (CFD) simulation. They showed that the droplet fraction can be reduced to 12% within 4 minutes due to background ventilation. Zhu et al. [15] studied the dispersion of breathing droplets in a bus using CFD simulations. Airborne transmission among passengers was affected by the air distribution, position of return/exhaust, and seat arrangement. Lei and Li [16] studied the dispersion of cough droplets in a high-speed rail cabin using CFD simulations. Yang et al. [17] studied the effects of diffuser types on the contaminant transport in high-speed train cabins by CFD simulations.

Studies mentioned above mainly focused on the expiratory droplet dispersion in the whole cabin with different background ventilations. However, the infection risk of the region near the infected passenger could be higher and is dominated by many other localized factors. For example, in a cabin environment, the backrest surface of a seat may partially or fully block the expiratory jets behind it depending on the backrest's height and the distance between the seats of the two successive rows. A study revealed that a flat plate can block a cough jet by turning the cough flow downward and upward [18]. Similarly, a backrest surface can effectively block the cough jet and prevent droplet spray. In addition, the overhead gasper jet for the infected passenger was found to bend the cough jet to the ground [19]. In an aircraft cabin, the gasper jets greatly increased the local airflow velocity and changed the contaminant distribution [20]. Another research also found that a downward plane jet dividing a chamber in half can reduce the exposure to airborne droplets in the other half of the chamber [21]. These studies indicated the strong effects of the backrest and gasper jets on cough jet and droplet deposition/distribution, while their effects on blocking airborne droplets and reducing infection risk of nearby passengers were not investigated in these studies and remain unknown.

In this work, a two-row four-seat setup and an air duct system were built to simulate a public transport cabin environment. The objectives are to evaluate the infection risks of passengers near the infected passenger and investigate the effects of geometric setup and gasper jet on protecting nearby passengers. A cough generator and a nebulizer were employed to simulate the respiratory activities of coughing and talking, respectively. The expiratory droplet concentrations in the inhalation zones were measured. Then the infection risk of the nearby passengers was studied.

## 2. Materials and methods

### 2.1. Experimental setup and studied parameters

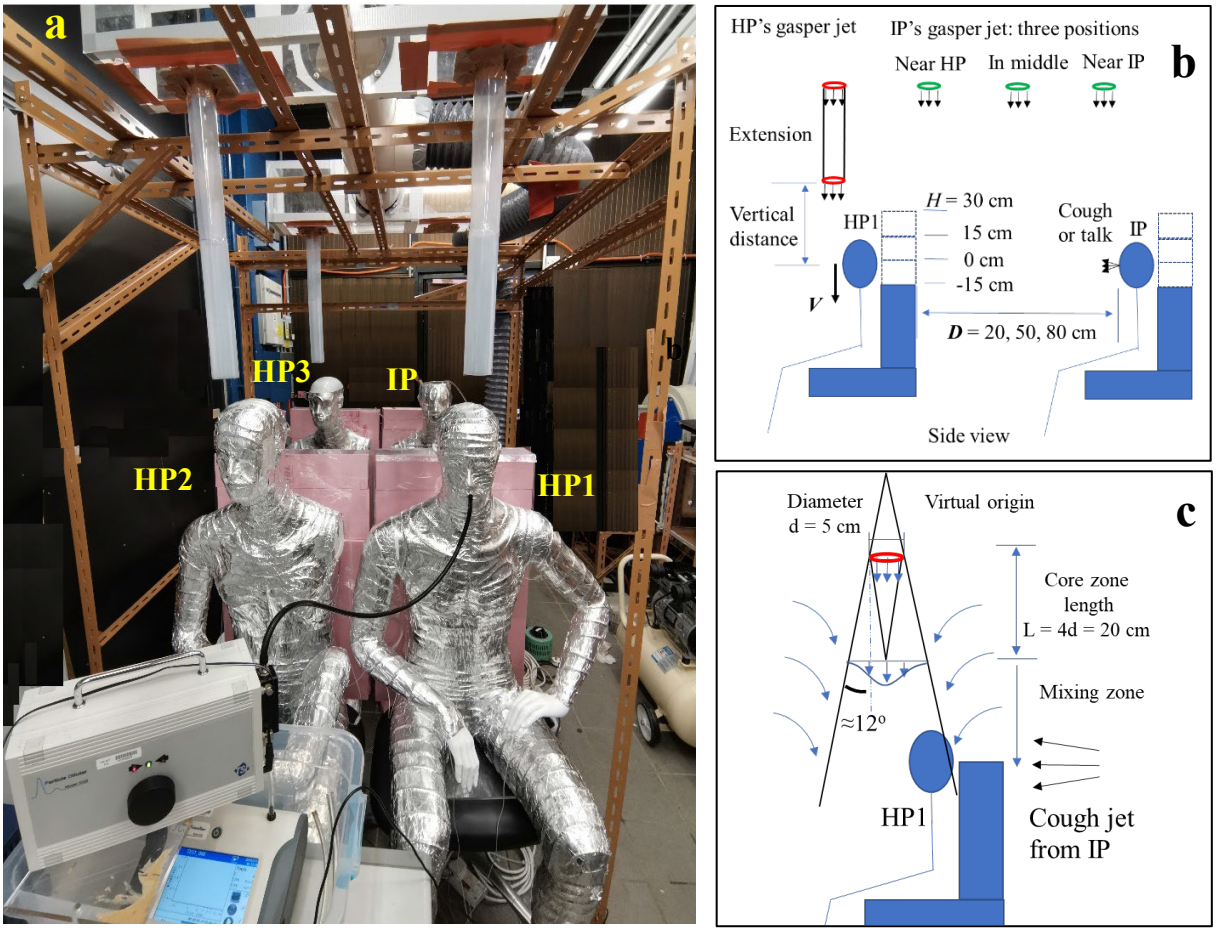



Fig. 1. (a) Experimental setup and schematic diagrams of (b) experimental setup and (c) studied parameters

A two-row four-seat setup and an air duct system were built and located in a conditioned room with controlled temperature of 21±1 °C and relative humidity of 70%±3%. Four identical thermal

manikins were placed at each seat with heat release of 75 W to simulate seated persons with moderate activities. The thermal manikin at the rear left-hand seat was considered as an infected passenger and denoted as IP. Three other manikins were considered as healthy passengers and denoted as HP1, HP2, and HP3 respectively, as shown in Fig. 1a. The gaspers had the diameter of 5 cm which is the same as that in buses.

Three different distances, *D*, between the backrest and cough generator of 20, 50, and 80 cm were considered (Cases 1-3 in Table 1). Four different relative heights, *H*, between the backrest and passenger's mouth of -15, 0, 15, and 30 cm were investigated (Cases 2 and 4-6 in Table 1). To evaluate the effect of IP's and HP's gaspers, either IP's or HP's gasper was separately turned on or off with the velocity of 1.5 m/s (Cases 5 and 7-9). Three positions of the IP's gasper were studied (Cases 11 and 13-14) as shown in Fig. 1b. Three velocity of IP's gasper (IP's gasper position at Middle) was studied (Cases 2 and 10-12). The gasper jet velocity was measured near the passenger's mouth.

The schematic diagram of the gasper jet was shown in Fig. 1c. The core zone length of the gasper jet was around four times of the outlet diameter [22,23]. When the gasper was closer to the passenger, it may improve the quality of breathing air. Thus, circular ducts with specific length were attached to the HP's gaspers to reduce the vertical distance, as shown in Fig. 1a and Fig. 1b. Five vertical distances of 80 cm, 55cm, 30 cm, 20 cm, and 10 cm were studied (Cases 5 and 15-23 in Table 1). For each vertical distance, the gasper jet velocity near the mouth was kept at a constant value of 1.5 m/s or 2.5 m/s to sustain a similar value with real condition in public transport cabins. The studied cases for cough activities were summarized in Table 1, while that of talking activity were shown in Table 2.

Table 1 Studied cases for the activity of coughing

| Cases | Distance of two rows (*D*) (cm) | Relative height of backrest (*H*) (cm) | HP gasper jet velocity (m/s) | Vertical distance between HP gasper and HP mouth (cm) | IP gasper jet velocity (m/s) | IP gasper position |
|---|---|---|---|---|---|---|
| 1 | 20 | 0 | 0 | | 0 | - |
| 2 | 50 | | | | | - |
| 3 | 80 | | | | | - |
| 4 | | -15 | | | | - |

| | | | | | | |
|---|---|---|---|---|---|---|
| 5 | 50 | 15 | 0 | 80 | 0 | - |
| 6 | | 30 | | | | - |
| 7 | 50 | 0 | 1.5 | | 0 | Near IP |
| 8 | | | 1.5 | | 1.5 | |
| 9 | | | 0 | | 1.5 | |
| 10 | 50 | 0 | 0 | | 0.75 | Middle |
| 11 | | | | | 1.5 | |
| 12 | | | | | 2.5 | |
| 13 | 50 | 0 | 0 | | 1.5 | Near HP |
| 14 | | | | | | Near IP |
| 15 | 50 | 0 | 2.5 | 80 | 0 | - |
| 16 | | | 1.5 | 55 | | |
| 17 | | | 2.5 | | | |
| 18 | | | 1.5 | 30 | | |
| 19 | | | 2.5 | | | |
| 20 | | | 1.5 | 20 | | |
| 21 | | | 2.5 | | | |
| 22 | | | 1.5 | 10 | | |
| 23 | | | 2.5 | | | |

Table 2 Studied cases for the activity of talking

| Cases | Distance of two rows (*D*) (cm) | Relative height of backrest (*H*) (cm) | HP gasper jet velocity (m/s) | HP gasper jet velocity (m/s) | Vertical distance of HP gasper and mouth (cm) (with HP gasper velocity of 1.5m/s) |
|---|---|---|---|---|---|
| 1 | 20 | 0 | 0 | 0 | 80 |
| 2 | 50 | | | | |
| 3 | 80 | | | | |
| 4 | 50 | -15 | 0 | 0 | |
| 5 | | 15 | | | |
| 6 | | 30 | | | |
| 7 | 50 | 0 | 1.5 | 0 | |
| 9 | | | 0 | 1.5 | |
| 14 | 50 | 0 | 1.5 | 0 | 20 |
| 15 | | | | | 10 |

### 2.2. Expiratory droplet release and experimental procedures

A cough generator was used to simulate a real cough, which was the same one used in our previous work [18]. In the experiment, the IP 'coughed' 3 times with a time interval of 5 seconds, and each cough lasted 1 second. A Collison Nebulizer (BGI, Inc., Waltham, MA, USA) was used to simulate a 30 second talking process [24,25]. An optical particle sizer (OPS, Model 3330, TSI, USA), combined with a diluter (Model 3332, TSI, USA), was used to measure the number and mass concentration of the airborne droplets of 0.3-10 μm in diameter. Droplet concentrations in the three HP's inhalation zones were measured separately. The measurement for each HP was repeated three times. The detailed information about expiratory droplet generation and measurement was shown in Supplementary Information.

### 2.3. Infection risk

The mass exposure to airborne droplets was calculated by the following equation [26]:

$$E = \int_0^t m(t)dt \tag{1}$$

where $E$ is the mass exposure, $m(t)$ is the mass concentration in the inhalation zone measured by the OPS, and $t$ is the measurement time. The droplet density was set as 1 g/cm$^3$ in calculating the mass from droplet volume. In the cough and talk experiments, $t$ was 360 s and 1800 s respectively.

Research indicated that the carried viral load in aerosols/droplets is reasonably proportional with aerosol volume (i.e. aerosol mass) [18,27]. The mass exposure can then be used to evaluate the viral exposure by considering the virus survivability in the aerosols. Therefore, in this work the viral dose in the upper and lower respiratory tracts via inhalation, denoted as $D_u$ and $D_l$, was calculated by Equations (2) and (3), respectively.

$$D_u = p \cdot \beta_u \cdot c \cdot \frac{1}{\varphi} \cdot \frac{1}{\rho} \cdot E \cdot S \tag{2}$$

$$D_l = p \cdot \beta_l \cdot c \cdot \frac{1}{\varphi} \cdot \frac{1}{\rho} \cdot E \cdot S \tag{3}$$

where $p$ is the pulmonary rate and was set as 0.48 m$^3$/h, $\beta_u$ and $\beta_l$ are the deposition fractions for upper and lower respiratory tracts and were set as 0.4 and 0.1 respectively [28], $c$ is the viable virus concentration in saliva, $\rho$ is the density of droplet and was set as 1 g/cm$^3$, $\varphi$ is the ratio of aerosol volume after to before evaporation with value of around $10^{-1}$ [18], and $S$ is the virus survivability

in airborne droplets. The viral load of SARS-CoV-2 in saliva of infected people varies from $10^0$ copies/mL up to $10^9$ copies/mL with median of around $10^{5\text{-}6}$ copies/mL [29]. The survivability of SARS-CoV-2 is around $10^{-1}$ in aerosols [30]. Thus, in this work, the overall value of $(c \cdot \frac{1}{\varphi} \cdot S)$ was chosen as $10^5$ copies/mL in this work.

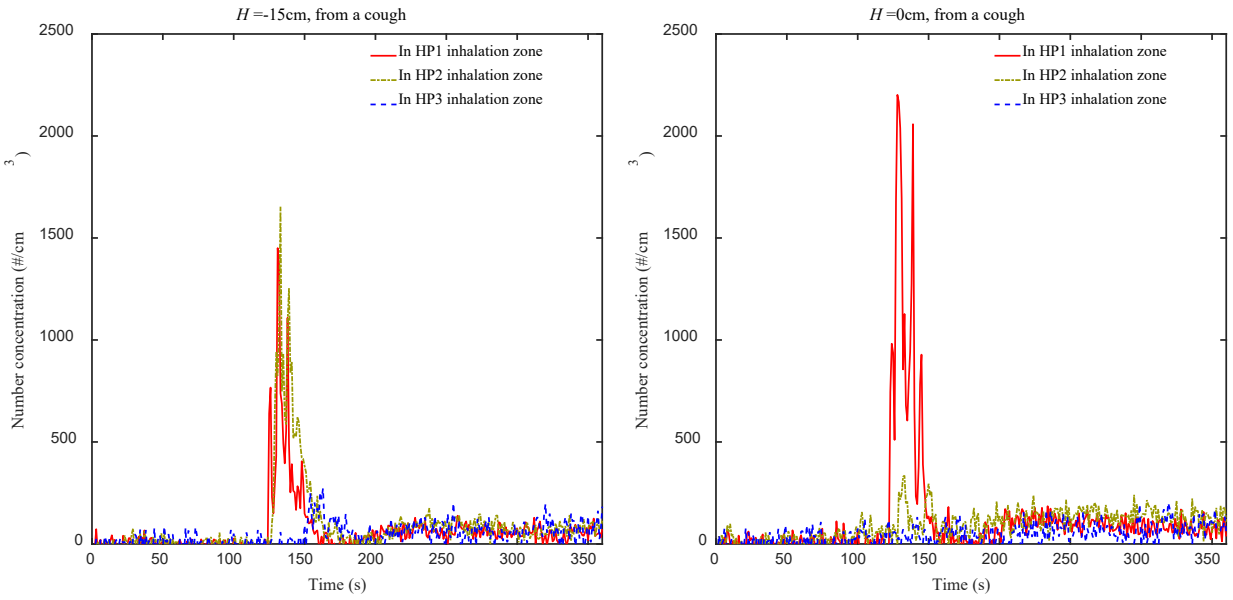
The infection risk was then calculated by the dose-response model.

$$IR = 1 - exp[-(r_u \cdot D_u + r_l \cdot D_l)] \quad (4)$$

where $IR$ is the infection risk, and $r_u$ and $r_l$ are the fitting parameters evaluating infectivity of the pathogen in upper and lower respiratory tracts respectively; they were respectively chosen as 0.0025 and 2.4755 based on the ID50 of 280 PFU and 0.28 PFU in upper and lower respiratory tracts of mice for SARS-CoV-1 virus [31,32]. Many parameters in the above equations vary depending on timeline of infection, population, and surrounding environment, such as the viral load, survivability, and infectivity. The moderate parameter values were employed to estimate the infection risk of the most common situation.

## 3. Results and discussion

### 3.1 Real-time number concentration of cough droplets in inhalation zone



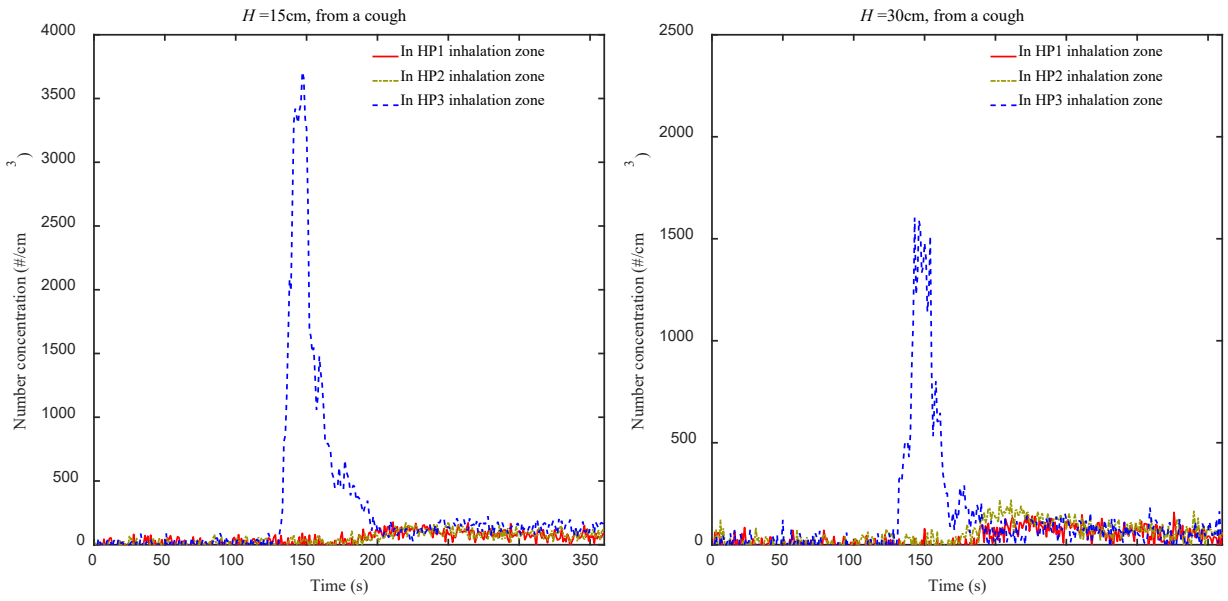
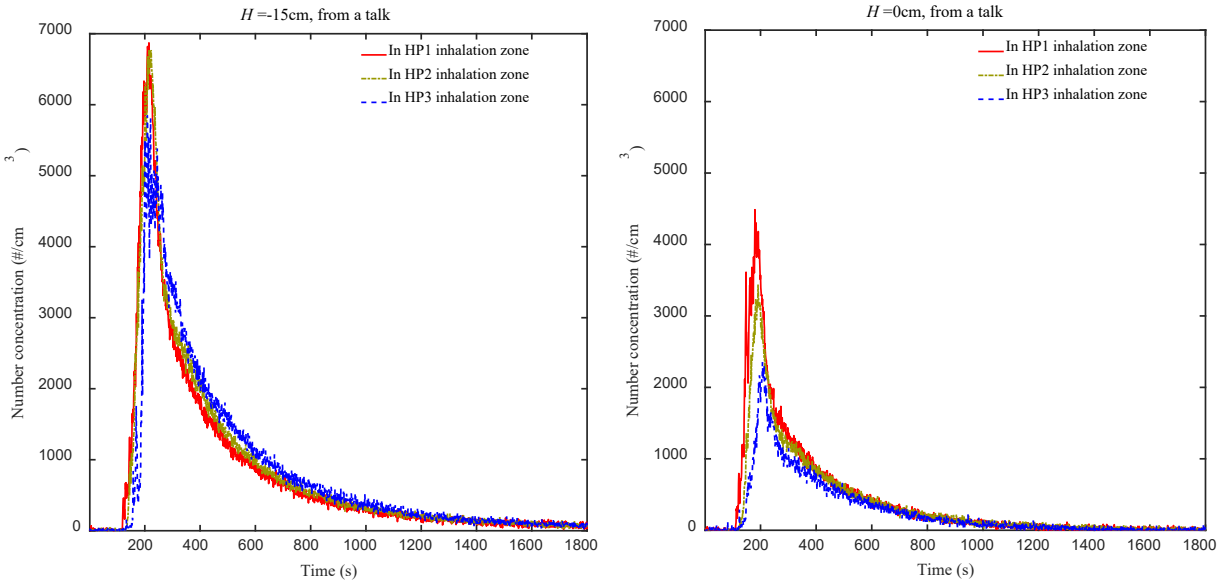



Fig. 2. Airborne droplet concentration in inhalation zones from a cough under four backrest heights

Fig. 2 shows the real-time airborne droplet concentration in the inhalation zones from a cough under four relative heights of backrest. The gaspers for four passengers were all turned off. The IP 'coughed' 3 times with a time interval of 5 seconds, and each cough lasted 1 second. The first cough started at the moment of 120 second. When $H$ = -15 cm, the backrest was 15 cm lower than the cough, and the cough jet travelled over the backrest and reached the front row. A sharp concentration surge appeared at HP1's and HP2's inhalation zones within few seconds after the cough. When $H$ = 0 cm, the concentration peak appeared only in the HP1's inhalation zone. When $H$ = 15 and 30 cm, the concentration peak appeared at the HP3's inhalation zone. It means that increasing the backrest height effectively eliminates the concentration peak of passengers in the front row (HP1 & HP2) but generates a concentration peak for the side passenger (HP3). The high concentration lasted around 30-60 seconds with the peak value of 1500 #/cm$^3$ - 3500 #/cm$^3$. After the concentration peak, three HPs were exposed to a relatively low concentration with a similar value for different studied $H$ values. It means that the airborne droplets in the space of nearby seats were uniformly distributed during this period. In addition, for the $H$ of 15 cm and 30 cm, it is seen that the concentrations for HP1 and HP2 increased at the moment of around 180 second, indicating that the airborne droplets took around 60 seconds to reach the inhalation zones of the front passengers by turbulent dispersion in spite of the block of the backrest.

As the increase of distance, *D*, between two rows from 20 cm to 50 cm and to 80 cm, the peak concentration in inhalation zones decreased gradually from 4000 to 2200 and to 1600 #/cm$^3$. When the gasper of the IP was turned on, the concentration surge for front HP1 was extinguished but a concentration surge for side HP3 appeared (peak value of 16000 #/cm$^3$). Then when the gasper of HP3 was also turned on, the peak concentration was greatly reduced to around 3000 #/cm$^3$, indicating the protection ability of overhead gasper. It was also found that when the IP's gasper was smaller and at the middle position, the concentration peak of HP3 was smaller (1000 #/cm$^3$). In this work, we also shorten the vertical distance between gasper and passenger. It was found that only when the gasper was around or less than 10 cm close to the inhalation zone, the concentration surge of HP1 was reduced to less than 1000 #/cm$^3$ indicating protection ability. The detailed airborne droplet concentration and discussion was shown in Figure S1-S5 in Supplementary Information.

### 3.2 Real-time number concentration of airborne talking droplets in inhalation zone



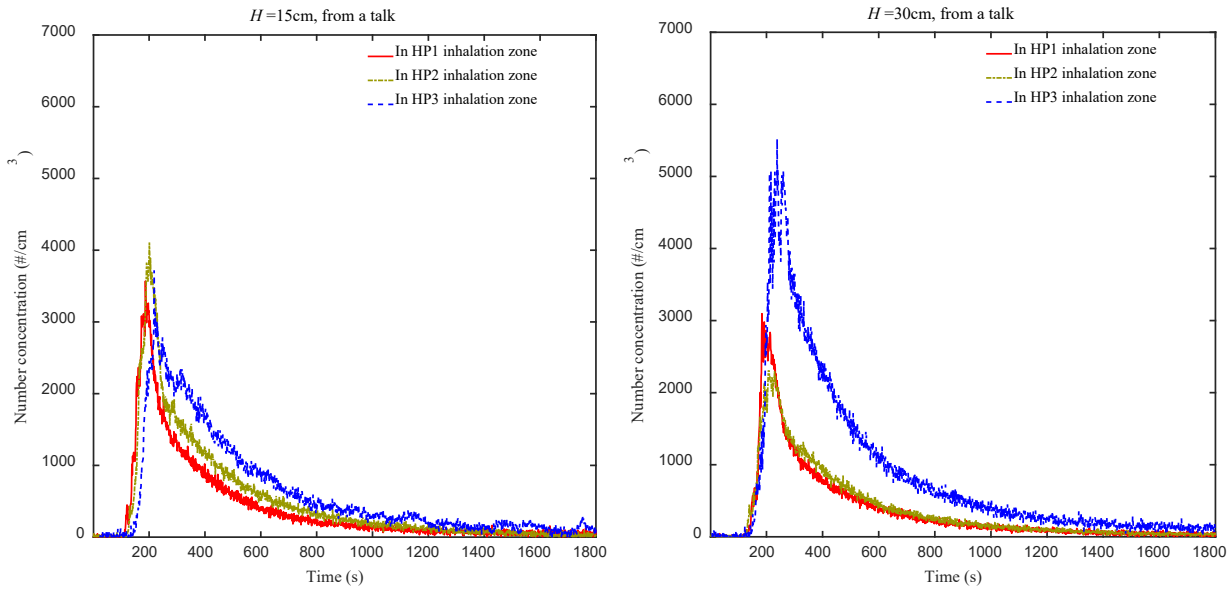



Fig. 3. Airborne droplet concentration in inhalation zone from a talk under four backrest heights

Fig. 3 shows the real-time number concentration of airborne droplets from a talk activity at four backrest heights. The gaspers for passengers were all turned off. For all the backrest heights, the concentration in the inhalation zones of all three HPs increased simultaneously and then decreased with a similar decay rate. It should be because the talk droplets relied on the turbulent dispersion to reach the inhalation zone of HPs due to the relatively low releasing velocity, in contrast that cough droplets with higher velocity first reached inhalation zone of front HP1 by bulk flow as shown in Section 3.1. As the increase of *H* from 0 to 15 cm and to 30 cm, the concentration peak for HP1 and HP2 was moderately decreased from around 4500 to 4000 and to 3000 #/cm$^3$. The concentration peak for HP3 was increased gradually from 2000 to 3500 and to 5000 #/cm$^3$. It indicates that increasing the backrest height can moderately reduce the concentration peak of passengers in front row, but it increased the concentration peak of the side passenger.

As the increase of distance, *D*, between two rows from 20 cm to 80 cm, the peak concentration in inhalation zones slightly decreased from 4500 to 3500 #/cm$^3$. When the IP's gasper was turned on, a concentration surge also appeared to HP3, which is similar with the cough droplets in section 3.1. When the vertical distance between gasper and passenger was shorten, the peak concentration of HP1 was increased greatly, which is different from the cough droplets. The detailed airborne droplet concentration and discussion was shown in Figure S6-S7 in Supplementary Information.

### 3.3 Infection risk and implications

3.3.1 Infection risk due to the cough droplets

Table 3 Estimated infection risk of nearby HPs to cough droplets for different studied parameters

| Parameters | | HP1 | HP2 | HP3 | Parameters | | HP1 | HP2 | HP3 |
|---|---|---|---|---|---|---|---|---|---|
| ***H*** **(cm)** | **-15** | 0.41 | 0.36 | 0.1 | ***V*** **of IP gasper (m/s)** | **0** | 0.76 | 0.22 | 0.12 |
| | **0** | 0.76 | 0.23 | 0.12 | | **0.75** | 0.21 | 0.22 | 0.41 |
| | **15** | 0.18 | 0.1 | 0.4 | | **1.5** | 0.14 | 0.11 | 0.49 |
| | **30** | 0.16 | 0.22 | 0.24 | | **2.5** | 0.27 | 0.20 | 0.50 |
| ***D*** **(cm)** | **20** | 0.72 | 0.42 | 0.54 | **Vertical distance (cm) / velocity of HP gasper (m/s)** | **80/1.5** | 0.44 | 0.16 | 0.25 |
| | **50** | 0.76 | 0.22 | 0.12 | | **55/1.5** | 0.82 | 0.27 | 0.17 |
| | **80** | 0.70 | 0.38 | 0.19 | | **30/1.5** | 0.86 | 0.42 | 0.21 |
| **IP off** | **HP off** | 0.76 | 0.22 | 0.12 | | **20/1.5** | 0.60 | 0.20 | 0.04 |
| **IP on** | **HP off** | 0.31 | 0.27 | 0.93 | | **10/1.5** | 0.25 | 0.24 | 0.04 |
| **IP off** | **HP on** | 0.44 | 0.16 | 0.25 | | **80/2.5** | 0.67 | 0.53 | 0.28 |
| **IP on** | **HP on** | 0.23 | 0.24 | 0.36 | | **55/2.5** | 0.81 | 0.19 | 0.15 |
| **Position of IP gasper** | **Near IP** | 0.31 | 0.27 | 0.93 | | **30/2.5** | 0.84 | 0.27 | 0.17 |
| | **Middle** | 0.14 | 0.11 | 0.49 | | **20/2.5** | 0.48 | 0.21 | 0.04 |
| | **Near HP** | 0.08 | 0.02 | 0.93 | | **10/2.5** | 0.22 | 0.23 | 0.06 |

The infection risk of HPs to cough droplets under different cases were listed in Table 3. For the case of *H*=0 cm (gaspers off), the infection risk of HP1 was around 0.76 and was around 3-6 time of the risks of HP2 and HP3 which were 0.23 and 0.12 respectively. When *H* was increased from 0 cm to 30 cm, the risk of HP1 was reduced from 0.76 to 0.16, while the risk of HP3 was increased from 0.1 to 0.4 because of the generation of a concentration surge for HP3. Infection risk of HP2 varied from 0.1 to 0.2 for different heights of backrest. The distance *D* does not have significant effect on the infection risk. Therefore, it was suggested that the backrest should be higher than passenger's head and the minimum height should cover the head.

Either turning on the IP's gasper or the HP's gasper can reduce the infection risk of HP1 from 0.76 to around 0.23-0.44. But turning on the IP's gasper jet greatly increased the risk of HP3 from 0.22 to 0.93. Once the IP's gasper was turned on, its velocity and position do not have much effect on the infection risks for HPs. When both HP's and IP's gaspers were turned on, the high risk of HP3 was reduced to 0.36. Therefore, it was suggested that the passengers (both the IP and HP) should turn on the overhead gaspers to reduce the infection risks when traveling by public transportation. Particularly, when the IP's gasper was turned on, the side passenger should also turn on his or her gasper.

When the vertical distance between the gasper and inhalation zone was decreased from 80 to 30 and then to 10 cm (with velocity of 1.5 m/s), the infection risk of HP1 was increased firstly from around 0.44 to around 0.86 and then decreased to 0.25. The changing trend is similar with the concentration peak value for HP1 in Fig. 5. The infection risk of HP2 was similar for difference vertical distances. The infection risk of HP 3 was greatly decreased to 0.04 at vertical distance of 20 and 10 cm. With the velocity of 2.5 m/s, the infection risk of HP1 was similar with that for 1.5 m/s.

3.3.2 Infection risk due to the talk droplets

The infection risk of HPs to talk droplets under different cases were listed in Table 4. For *H*=0 cm, the infection risks of all HPs were similar. As the increase of *H* from -15 to 30 cm, the risk of HP1 and HP2 was decreased from around 0.6 to 0.4. For a larger distance of *D*=80 cm, the risk of HP1 and HP2 was slightly lower. When IP's or HP's gasper was turned on, the infection risk of HP1 and HP2 was reduced slightly, but the risk of HP3 was increased to around 0.7. When the vertical distance between HP's gasper and inhalation zone was reduced, the infection risk of HP1

and HP2 was increased. This was different from the cases exposed to cough droplets, in Section 3.3.1. More detailed studies are needed to reveal the underlying mechanism.

Table 4 Estimated infection risk of nearby HPs to talk droplets for different studied parameters

| **Parameters** | | **HP1** | **HP2** | **HP3** | **Parameters** | | **HP1** | **HP2** | **HP3** |
|---|---|---|---|---|---|---|---|---|---|
| ***H*** **(cm)** | **-15** | 0.54 | 0.57 | 0.6 | **IP off HP off** | | 0.46 | 0.43 | 0.36 |
| | **0** | 0.46 | 0.43 | 0.36 | **IP on HP off** | | 0.38 | 0.41 | 0.71 |
| | **15** | 0.39 | 0.51 | 0.46 | **IP off HP on** | | 0.35 | 0.40 | 0.74 |
| | **30** | 0.38 | 0.44 | 0.59 | **Vertical distance (cm)** | 80 | 0.35 | 0.40 | 0.74 |
| ***D*** **(cm)** | **20** | 0.42 | 0.25 | 0.35 | | 20 | 0.78 | 0.77 | 0.29 |
| | **50** | 0.46 | 0.43 | 0.36 | | 10 | 0.82 | 0.84 | 0.51 |
| | **80** | 0.30 | 0.27 | 0.48 | - | | | | |

Our work has some limitations. Some parameters in a public transport cabin were not considered, such as background airflow, human walking, and wearing a mask. It is expected that they can affect the droplet dispersion and infection risk of nearby passengers. Human walking can introduce bulk flow of air and may transport more aerosols to passenger's inhalation zone. Wearing a mask can redirect the forward cough jet and affect the aerosols transported to passenger's inhalation zones. In addition, the tool virus for SARS-CoV-2 was not added in the aerosolized saliva solution. The viral exposure is estimated based on mass of aerosols. In actual disease transmission the viral exposure may be more complex than the estimation, although it is a commonly used method for risk analysis. Further research is needed to simulate the actual transmission situation in a cabin environment.

In conclusion, the airborne infection risk of nearby passengers was calculated. The front passenger HP1 has much higher infection risk than the other nearby passengers. The backrest covering the head and IP's gasper jet can block the cough and talk droplets and reduce the infection risk of the front passenger HP1. The backrest and IP's gasper jet increased the infection risk of HP3, while

HP's gasper jet can reduce the risk of HP3 by decreasing the concentration peak of HP3. Reducing the vertical distance between gasper and inhalation zone decreased the infection risk from cough droplets but increased the risk from talk droplets. The results will help understand the infection risk and control in public transport cabins.

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**Authorship contribution statement**

**C.T. Wang**: Investigation; Data curation; Formal analysis; Writing - original draft; Writing – review & editing. **J.C. Xu**: Investigation; Data curation; Writing – review & editing. **S.C. Fu**: Conceptualization; Data curation; Writing – review & editing; Supervision. **Christopher Y.H. Chao**: Conceptualization; Writing – review & editing; Funding acquisition; Resources; Supervision.

**Declarations of competing interests**

Authors have no competing interests to declare.

**References**

[1] Dye C, Gay N. Modeling the SARS epidemic. Science 2003;300:1884-5.

[2] Cowling BJ, Ip DK, Fang VJ, Suntarattiwong P, Olsen SJ, Levy J et al. Aerosol transmission is an important mode of influenza A virus spread. Nat Commun 2013;4:1935.

[3] Liu Y, Ning Z, Chen Y, Guo M, Liu Y, Gali NK et al. Aerodynamic analysis of SARS-CoV-2 in two Wuhan hospitals. Nature 2020;582:557-60.

[4] Edelson PJ, Phypers M. TB transmission on public transportation: a review of published studies and recommendations for contact tracing. Travel Med Infect Dis 2011;9:27-31.

[5] Mangili A, Gendreau MA. Transmission of infectious diseases during commercial air travel. Lancet 2005;365:989-96.

[6] Mohr O, Askar M, Schink S, Eckmanns T, Krause G, Poggensee G. Evidence for airborne infectious disease transmission in public ground transport–a literature review. Euro Surveill 2012;17:20255.

[7] Varghese SK, Gangamma S. Particle deposition in human respiratory system: deposition of concentrated hygroscopic aerosols. Inhal Toxicol 2009;21:619-30.

[8] Hofmann W. Modelling inhaled particle deposition in the human lung-A review. J Aerosol Sci 2011;42:693-724.

[9] Chen W, Zhang N, Wei J, Yen H, Li Y. Short-range airborne route dominates exposure of respiratory infection during close contact. Build Environ 2020;176:106859.

[10] Zhang R, Li Y, Zhang AL, Wang Y, Molina MJ. Identifying airborne transmission as the dominant route for the spread of COVID-19. Natl Acad Sci USA 2020;117:14857-63.

[11] Hertzberg VS, Weiss H. On the 2-row rule for infectious disease transmission on aircraft. Ann Gob Health 2016;82:819-23.

[12] Sze To GN, Wan MP, Chao C, Fang L, Melikov A. Experimental study of dispersion and deposition of expiratory aerosols in aircraft cabins and impact on infectious disease transmission. Aerosol Sci Tech 2009;43:466-85.

[13] Wan MP, Sze To GN, Chao C, Fang L, Melikov A. Modeling the fate of expiratory aerosols and the associated infection risk in an aircraft cabin environment. Aerosol Sci Tech 2009;43:322-43.

[14] Gupta JK, Lin C, Chen Q. Transport of expiratory droplets in an aircraft cabin. Indoor Air 2011;21:3-11.

[15] Zhu S, Srebric J, Spengler JD, Demokritou P. An advanced numerical model for the assessment of airborne transmission of influenza in bus microenvironments. Build Environ 2012;47:67-75.

[16] Zhang L, Li Y. Dispersion of coughed droplets in a fully-occupied high-speed rail cabin. Build Environ 2012;47:58-66.

[17] Yang L, Li M, Li X, Tu J. The effects of diffuser type on thermal flow and contaminant transport in high-speed train (HST) cabins–a numerical study. Int J Vent 2018;17:48-62.

[18] Wang CT, Fu SC, Chao CY. Short-range bioaerosol deposition and recovery of viable viruses and bacteria on surfaces from a cough and implications for respiratory disease transmission. Aerosol Sci Tech 2021;55:215-230.

[19] Wang CT, Xu JC, Fu SC, Chan KC, Chao CYH. Respiratory bioaerosol deposition from a cough and recovery of viable viruses on nearby seats in a cabin environment. Indoor Air 2021;31:1913-1925.

[20] Li B, Duan R, Li J, Huang Y, Yin H, Lin C et al. Experimental studies of thermal environment and contaminant transport in a commercial aircraft cabin with gaspers on. Indoor Air 2016;26:806-19.

[21] Cao G, Liu S, Boor BE, Novoselac A. Dynamic interaction of a downward plane jet and a cough jet with respect to particle transmission: An analytical and experimental study. J Occup Environ Hyg 2017;14:618-31.

[22] Xia LP, Lam KM. Velocity and concentration measurements in initial region of submerged round jets in stagnant environment and in coflow. J Hydro-environ Res 2009;3:21-34.

[23] Or CM, Lam KM, Liu P. Potential core lengths of round jets in stagnant and moving environments. J Hydro-environ Res 2011;5:81-91.

[24] Chao CYH, Wan MP, Morawska L, Johnson GR, Ristovski ZD, Hargreaves M et al. Characterization of expiration air jets and droplet size distributions immediately at the mouth opening. J Aerosol Sci 2009;40:122-33.

[25] Xu J, Fu S, Chao CY. Performance of airflow distance from personalized ventilation on personal exposure to airborne droplets from different orientations. Indoor Built Environ 2020:1420326X20951245.

[26] Morawska L, Afshari A, Bae GN, Buonanno G, Chao CYH, Hänninen O et al. Indoor aerosols: from personal exposure to risk assessment. Indoor Air 2013;23:462-87.

[27] Zuo Z, Kuehn TH, Verma H, Kumar S, Goyal SM, Appert J et al. Association of airborne virus infectivity and survivability with its carrier particle size. Aerosol Sci Tech 2013;47:373-82.

[28] Yeh H, Cuddihy RG, Phalen RF, Chang I. Comparisons of calculated respiratory tract deposition of particles based on the proposed NCRP model and the new ICRP66 model. Aerosol Sci Tech 1996;25:134-40.

[29] Julin CH, Robertson AH, Hungnes O, Tunheim G, Bekkevold T, Laake I et al. Household Transmission of SARS-CoV-2: A Prospective Longitudinal Study Showing Higher Viral Load and Increased Transmissibility of the Alpha Variant Compared to Previous Strains. Microorganisms 2021;9:2371.

[30] Van Doremalen N, Bushmaker T, Morris DH, Holbrook MG, Gamble A, Williamson BN et al. Aerosol and surface stability of SARS-CoV-2 as compared with SARS-CoV-1. N Engl J Med 2020;382:1564-7.

[31] Watanabe T, Bartrand TA, Weir MH, Omura T, Haas CN. Development of a dose-response model for SARS coronavirus. Risk Anal 2010;30:1129-38.

[32] Lei H, Li Y, Xiao S, Lin C, Norris SL, Wei D et al. Routes of transmission of influenza A H1N1, SARS CoV, and norovirus in air cabin: Comparative analyses. Indoor Air 2018;28:394-403.