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The source control effect of personal protection equipment and physical barrier on short-range airborne transmission

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ABSTRACT

In order to control the spread of Covid-19, authorities provide various prevention guidelines and recommendations for health workers and the public. Personal protection equipment (PPE) and physical barrier are the most widely applied prevention measures in practice due to their affordability and ease of implementation. This study aims to investigate the effect of PPE and physical barriers on mitigating the short-range airborne transmission between two people in a ventilated environment. Four types of PPE (surgical mask, two types of face shield, and mouth visor), and two different sizes of the physical barrier were tested in a controlled environment with two life-size breathing thermal manikins. The PPE was worn by the source manikin to test the efficiency of source control. The measurement results revealed that the principles of PPE on preventing short-range droplet and airborne transmission are different. Instead of filtering the fine droplet nuclei, they mainly redirect the virus-laden exhalation jet and avoid the exhaled flow entering the target's inhalation region. Physical barriers can block the spreading of droplet nuclei and create a good micro environment at short distances between persons. However, special attention should be paid to arranging the physical barrier and operating the ventilation system to avoid the stagnant zone where the contaminant accumulates.

1. Introduction

Coronavirus disease 2019 (Covid-19) caused by severe acute respiratory syndrome coronavirus 2 (SARS-Cov-2) has spread worldwide since December 2019, leading to an ongoing pandemic. Recently, the Delta Variant a highly contagious SARS-CoV-2 virus strain accelerated the pandemic. The Centers for Disease Control and Prevention (CDC) described Delta as more transmissible than the common cold and influenza and indicated it as contagious as chickenpox [1]. Understanding the transmission routes of the diseases and their characteristic allows for the identification of effective prevention and control measures. World Health Organization (WHO) provided an overview of the possible transmission routes of SARS-Cov-2, including contact, droplet, airborne, fomite, fecal-oral, bloodborne, mother-to-child, and animal-to-human transmission [2]. Among all the transmission routes, the most critical and widely discussed ones are fomite, droplet, and airborne transmission. Fomite transmission occurs when susceptible individuals contact the surface and objects contaminated by respiratory

secretions or droplets expelled by infected individuals. Viable SARS-CoV-2 virus has been found on those surfaces for periods ranging from hours to days, depending on the ambient environment and the type of surface [3–5]. Droplet transmission occurs when viruses travel on relatively large respiratory droplets formed from coughing, sneezing, talking, or singing. Most of the large respiratory droplets fall on nearby surfaces within 1 m [6–8]. Direct airborne transmission occurs when exhaled flow from the infected person enters the breathing zone of the target person and is inhaled by the target person. Indirect airborne transmission occurs when the exhalation flow disperses and mixes with the room air before it enters the breathing zone and is inhaled by the target person, which is especially critical in space with inadequate ventilation combined with high occupancy levels and extended exposure periods. The threshold distance of approximately 1–1.5 m between the infected and target person is normally used to distinguish these two transmission routes [7]. A recent study by Chen et al. [9] suggested that short-range airborne transmission mode dominates exposure of respiratory infection during close contact.

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In order to control the spread of COVID-19, authorities provide various prevention guidelines and recommendations for health workers and the public. WHO [10], CDC [11] addressed that appropriate use of personal protective equipment (PPE) should be regarded as one of the primary prevention measures to patients and healthcare providers. Wearing a face mask or visor/shield in indoor public space or transport is also introduced as a recommendation or mandatory rule in more than 70 countries over the world [12]. PPE imposes a barrier between the wearer/user and the environment, which can protect the wearer's body from injury or infection. The PPE used in the COVID-19 context mainly includes surgical mask, respirator, face shield/visor, eye goggles, gloves, gown [13]. Apart from gloves and gowns, the other PPE are mainly used to protect the facial area and related mucous films (nose, eyes, and mouth) from sprinkles, showers, and splash of body liquids during medical procedures or aerosols during respiration, coughing, speaking process. In areas experiencing PPE shortages, using physical barriers including glass or plexiglass screens is also introduced as an intervention to a health setting or public setting [10].

However, whether the current prevention measures can effectively control or prevent the transmission of infectious diseases is still under debate. Recently, many studies investigated the effect of PPE in decreasing the risk of infection. Fischer et al. [14] used a laser sheet illumination technique to compare the effectiveness of different face masks in filtering respiratory droplets. They observed that some masks, such as neck gaiters or bandanas offer very little protection during speech. Bandiera et al. [15] also addressed the droplet transmission route and quantified the droplets ejected by an anatomically realistic manikin with a surgical mask or a single-layer cotton face covering in speaking and coughing conditions. Their results indicated that face covering presents consistent efficacy at blocking respiratory droplet and provide the possibility to moderate social distancing policy. However, the airborne transmission route was not considered in the above studies. Bandiera et al. [15] pointed out that the effectiveness of face covering might be overestimated if the airborne transmission is a significant driver of infection. Ueki et al. [16] investigated the effectiveness of face masks against droplet and aerosol transmission. A droplet/aerosols simulator was developed to represent human respiration and cough with various types of face masks (cotton masks, surgical masks, and N95 masks). They found out that surgical masks and even N95 masks were not able to completely block the transmission of virus droplets/aerosols even when completely sealed. The efficacy of face shields against cough aerosol droplets was investigated by Lindsley et al. [17] from a cough simulator. Their results showed that face shields can substantially remove the large droplet (8.5 μm), but smaller particles (3.4 μm) can remain airborne longer and flow around the face shield to be inhaled potentially.

The above studies mainly investigate the effect of PPE on mitigating the droplet and combined droplet/airborne transmission. Their results indicated that PPE performs efficiently on filtering large droplets, however, does not perform in the same manner for the small aerosols. Therefore, this study aims to address the airborne transmission route, especially in a short range, and compare the efficacy of commonly applied PPE and physical barriers on migrating the cross-infection.

On the other hand, many of the literature studies [16,17] simulated the droplet or airborne transmission process by a head simulator in an isolated chamber without the consideration of the flow elements around the human body and surrounding environment. The previous studies [18,19] indicated the thermal plume generated by the human body has a significant impact on the development of respiration flow, especially when the exhalation has a relatively low momentum, like the respiration process. In addition, the surrounding environment around the human, such as temperature, humidity, flow velocity, and turbulence, strongly influence the travel distance [7,20] and survival time of the virus [21, 22]. Therefore, it is essential to create a realistic micro- and surrounding environment when investigating the airborne transmission process.

Full-scale experiments were conducted in this study with two life-

size breathing thermal manikins in a controlled chamber with commonly applied air distribution systems, to represent the practical working environment. The prevention measures tested in this study included four types of PPE (surgical mask, two types of face shield, and mouth visor), and two different sizes of physical barrier. They are widely applied in practice during COVID-19 due to their affordability and ease of implementation. The PPE were worn by a source manikin, which simulated a spreader or a superspreader. Literature reported that approximately 80% of transmission were caused by 10% infected individuals [23]. Transmission clusters and superspreaders events played an important role in SARS-Cov-2 transmission. Therefore, the source control on the infected individuals was addressed here. We visualized the exhaled flow development with and without PPE/physical barriers by smoke test, and measured the exposure index of the target by tracer gas technique. Previous studies showed that the transport behavior of tracer gas is similar to fine droplet nuclei with the size < 5 μm [7, 24–26]. It needs to notice that the study focused on investigating the effect of PPE on mitigating the airborne transmission caused by fine droplet nuclei, especially their impact on directing the airflow in the microenvironment and consequent transport in the indoor environment. The filtration effect on the droplet was not included here.

2. Methodology

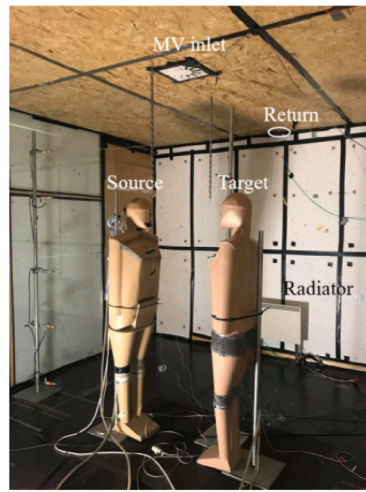
2.1. Full-scale test room

The study was carried out in a full-scale IEA Annex 20 test room [27] with the dimension of 4.2 m, 3.6 m and 2.5 m in length, width and height, see Fig. 1. Two air distribution systems were installed in the test room: mixing ventilation (MV) and displacement ventilation (DV). A ceiling mounted swirl diffuser was used as the inlet for mixing ventilation, and a wall-mounted semicircular diffuser was used as the inlet for displacement ventilation. Both inlet diffusers were well tested and documented in previous studies [28–30]. The return opening was placed on the ceiling next to the end wall. Two breathing thermal manikins stood face-to-face in the center of the test room. One simulated the infected individual (source) and the other simulated the susceptible individual (target). A radiator located in the wall opposite to the DV inlet was used to maintain a certain vertical temperature gradient.

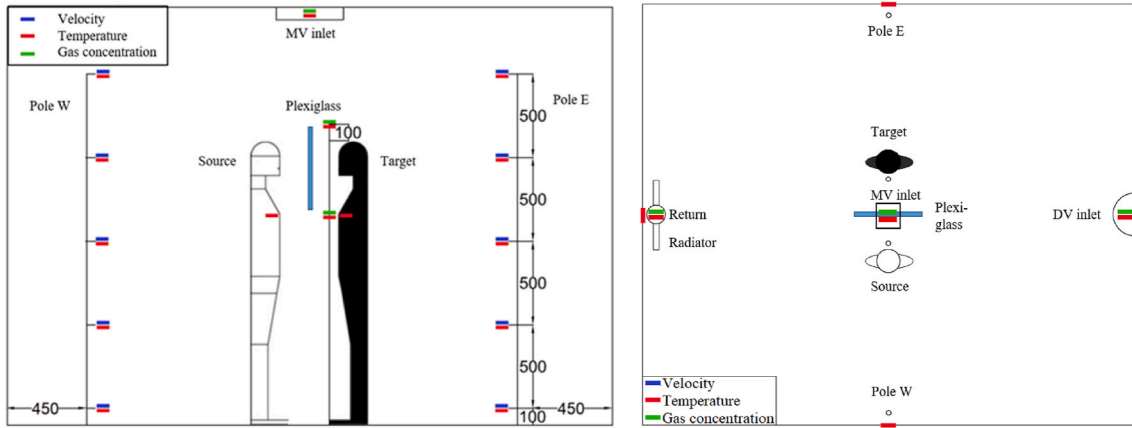
2.2. Breathing thermal manikins

Two life-size breathing thermal manikins were used in this study to present one source and one target individual. The manikins were 1.68 m in height and with a surface area of 1.44 m^2 . The geometry of the manikins represent average-sized females, and detailed dimensions refer to E. Bjørn [31]. The torso of the manikins was installed with heating wires to generate heat load. The activity level of 1.4 met was assumed in this study to represent a standing person with light office work, which corresponds to a sensible heat load of 53.7 W/m^2 . The latent heat load was excluded from this study since the manikins do not have diffusion of water vapor and evaporation of sweat as humans.

Both manikins were connected with an artificial lung to generate periodical breathing. The breathing frequency was 16 min^{-1} and the pulmonary ventilation rate was 9.32 l/min, corresponding to an average female with an activity level of 1.4 met. The exhalation was through the mouths and inhalation was through the noses, and the facial structure of the manikins can be seen in Fig. 2. The nostrils consisted of two circular openings with a diameter of 12 mm and tilted toward the chest with an angle of 45°. The mouth consisted of a circular opening with a diameter of 12 mm and the mouth outflow was horizontal for isothermal flow. This manikin complies with the important characteristics and requirements for a breathing thermal manikin as proposed by Melikov [32], which can be regarded as a 'standard' manikin. The characteristic of exhaled flow by the manikin was validated by those of the human subject, and the results showed that the manikin can simulate human



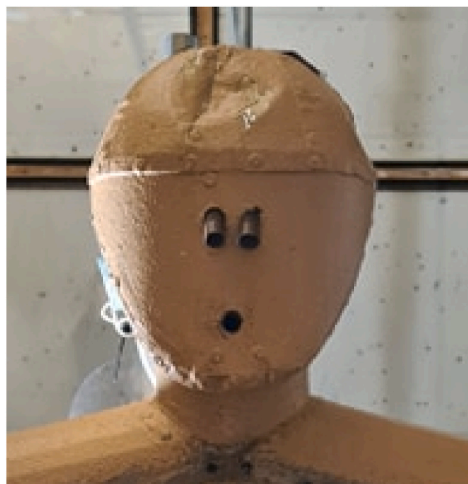
(a)



(b)

(c)

Fig. 1. The setup in the test room (a) Photo of the test room with two manikins (b) Illustration of the measurement sensors and their locations from the side (c) Illustration of the measurement sensors and their locations from the above.



(a)



(b)

Fig. 2. Facial structure of two breathing thermal manikins (a) Source manikin (b) Target manikin.

breathing to a certain satisfying degree [33]. The respiratory phase was set up as the worst scenario that the source manikin exhales exactly when the target manikin inhales, as illustrated in Fig. 3. Based on Bjørn's study [31], the exhalation temperature through the mouth is 34 °C when the ambient temperature is around 20 °C. In the full-scale experiments, the exhaled air was not saturated with water vapor, therefore, a correction on the exhaled temperature should be made in order to compensate for the density difference [31]. The exhalation temperature of 37 °C was used in this study.

2.3. Measurement and sensor locations

CO₂ was used as a tracer gas to simulate the exhaled droplet nuclei from an infected source. The CO₂ was dosed directly to the exhaled flow of the source manikin. INNOVA Multi-gas Samplers 1303 and Monitor 1412 were used to measure concentration in the ventilated room and personal exposure. The sampling tubes were placed around the micro-environment of the manikins: target inhalation, target chest, 10 cm above target's head, source exhalation. Besides the sampling points around manikins, two sampling tubes were located at ventilation inlets (both MV and DV), and the other was located at the outlet, see Fig. 1.

The exposure risk of the target person is evaluated by the susceptible exposure index, defined by Qian [34] and Li [7]. The susceptible exposure index, ε_i , is expressed as eq (1):

$$\varepsilon_i = \frac{c_i - c_s}{c_r - c_s} \quad (1)$$

Where C_i , C_r , and C_s are concentrations at the inhaled air of the target manikin, return opening (outlet), and supply opening (inlet). A high ε_i indicates a high exposure risk by the target to the airborne substances exhaled by the source. If the room air is fully mixed, ε_i will be 1. It needs to note that the susceptible exposure index is the reciprocal of the local air quality index commonly used to describe the ventilation effectiveness [35].

Besides contaminant distribution, the temperature and velocity distributions were measured in the test room, where the location of sensors can be seen in Fig. 1. Temperature measurement aims to verify if the ventilation systems perform as they were designed to be: fully mixing in MV and thermal stratification in DV. Air velocity measurement aims to validate the comfort level in the occupied zone, which should be below 0.15 m/s.

Finally, smoke tests were conducted to visualize the exhaled flow development in the micro-environment of the manikin and the dispersion of droplet nuclei in the ventilated room. A Stairville Hz-200 Compact Hazer generator was used to supply smoke to source manikin's exhalation. The smoke tests were only carried out in the cases with MV.

2.4. Prevention measures and measurement cases

Four types of PPE and two types of physical barriers were tested in this study. PPE includes surgical mask, open face shield, closed face shield, and mouth visor, as shown in Fig. 4. PPE was only worn by the

source manikin to test the efficiency of source control. The detailed properties of PPE are introduced as below:

- Surgical mask: The surgical mask is a 3-layer Type IIR Mask with the size of 17.5 × 9.5 cm, and is made of polypropylene and non-woven fabric. The bacterial filtration efficiency (BFE) is larger than 98% and breathing resistance is less than 49 Pa/cm². The mask is CE-certified according to EN 14683:2005 [36].
- Open face shield: The face shield covers the mouth, nose, and eyes with a width of 27 cm and a length of 25 cm. It is made of plastic, with a padded headband for comfort and a removable visor that can be cleaned and replaced. It can be worn multiple times.
- Closed face shield: Anti-splash protective face shield with the width of 27 cm and the length of 20 cm. The closed face shield is similar to the open one, the major difference is that the air or droplet can not enter or leave from the top of the shield. It is closed at the forehead with a foam cushion and is pressing against the forehead with an elastic strap behind the head.
- Mouth visor: The mouth visor only covers the mouth and nose area, with a width of 14 cm and a length of 7 cm. It is made of plastic and can be reused.

Besides PPE, another widely applied prevention measure during COVID-19 is the physical barrier. Physical barriers can provide visual and physical separation between people to prevent physical contact, and are commonly applied for workstations that social distancing is not able to maintain. In this study, the physical barriers were made of plexiglass with two different dimensions: 0.5 × 0.5 m and 1 × 1 m. The plexiglass was placed between two manikins, and the center of the plexiglass was aligned with the center of the manikin breathing zone (1.5 m height), as shown in Fig. 1 (b).

The measurement scenarios are listed in Table 1. The cases without prevention measures are used as baselines to compare the effect of different prevention measures. The efficiencies of prevention measures were tested under two air distribution principles (MV and DV) with varying distances between two manikins (separation distance). In all cases, the air change rate was 5.6 h⁻¹ and the room average air temperature was kept at 23 ± 2 °C, which aims to create a comfortable indoor environment in the occupied zone. The heat sources in the room consisted of manikins and a radiator, with a total heat load of 500 W. The same boundary conditions were also used in our previous studies for investigating the airborne transmission in the room with different air distribution strategies [7,30,37]. All measurements were conducted under quasi-steady state. After the indoor temperature and CO₂ concentration reached stabilization, we recorded the data for at least 4 h. The susceptible exposure index is calculated based on the average concentrations during the measured period.

3. Results

3.1. The effect of separation distance

The effect of separation distance on the exposure risk was measured

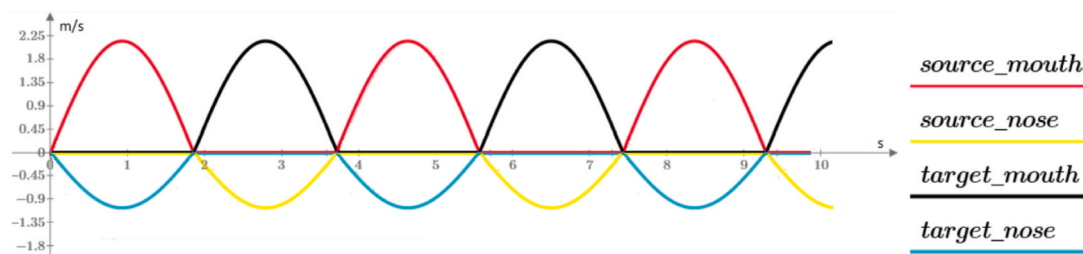


Fig. 3. Sinusoidal breathing function and respiratory phases of source and target manikins (positive value represent exhalation, negative value represent inhalation).



Fig. 4. Four types of PPE worn by the source manikin (a) Surgical mask (b) Open face shield (c) Closed face shield (d) Mouth visor.

Table 1
Overview of measurement scenarios.

Prevention measure		Air distribution principle	Distance between the manikins [m]
Without prevention (Baseline)	N/A	MV; DV	0.35; 0.5; 0.8; 1.1; 1.5 ^a
PPE	Surgical mask	MV; DV	0.35; 0.5; 0.8
	Open face shield	MV; DV	0.35; 0.5; 0.8
	Closed face shield	MV; DV	0.35; 0.5; 0.8
Physical barrier	Mouth visor	MV; DV	0.35; 0.5; 0.8
	Plexiglass 0.5 × 0.5 m	MV; DV	0.35; 0.5; 0.8
	Plexiglass 1 × 1 m	MV; DV	0.35; 0.5; 0.8

^a 1.5 m is only for displacement ventilation.

with both air distribution systems. Fig. 5 shows the vertical temperature distributions in different scenarios. Thermal stratifications are found in all cases with DV, with a temperature gradient around 2.1–2.5 °C/m. The vertical temperature differences are less than 0.2 °C in all MV cases, which indicates a good mixing has been reached in the space.

Fig. 6 shows the susceptible exposure index as a function of the distance between the two manikins. Different trends are observed with the two air distribution principles. Fast decay of the exposure with the increase of separation distance is with DV, while the exposure does not present strong dependency on the separation distance with MV. High exposure indexes up to 3 are measured in close proximity with DV, while decreasing rapidly to 0.5 when the distance increases to 0.8 m. These

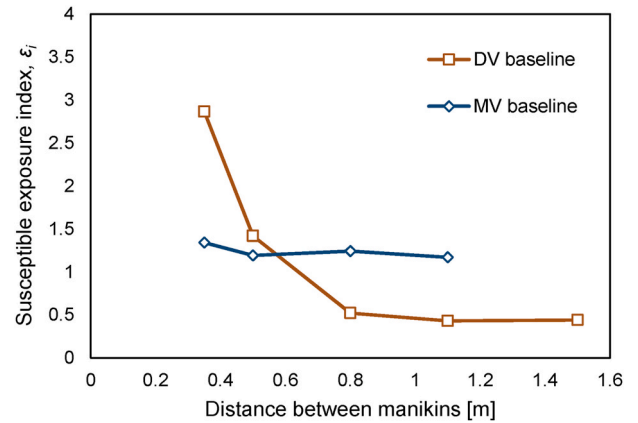


Fig. 6. Susceptible exposure index as a function of separation distance with both air distribution systems.

results agree well with the finding by Li. et al. and Nielsen et al. [7,29], that direct exposure mainly takes place within 1 m distance in DV, and the exposure can be lower than full mixing at a remote distance because the target inhales the air from the lower zone through its thermal boundary layer. In the scenario with MV, the direct exposure in close proximity is not as high as in DV. The susceptible exposure index is 1.34 at 0.35 m distance and reduces to 1.17 at 1.1 m distance, which indicates the source manikin’s exhalation jet does not penetrate to the target’s breathing zone. The high exposure in close proximity in DV further proves the lock-up phenomenon as reported in previous studies [24,38,39]. Exhaled contaminants are locked at the breathing zone due to

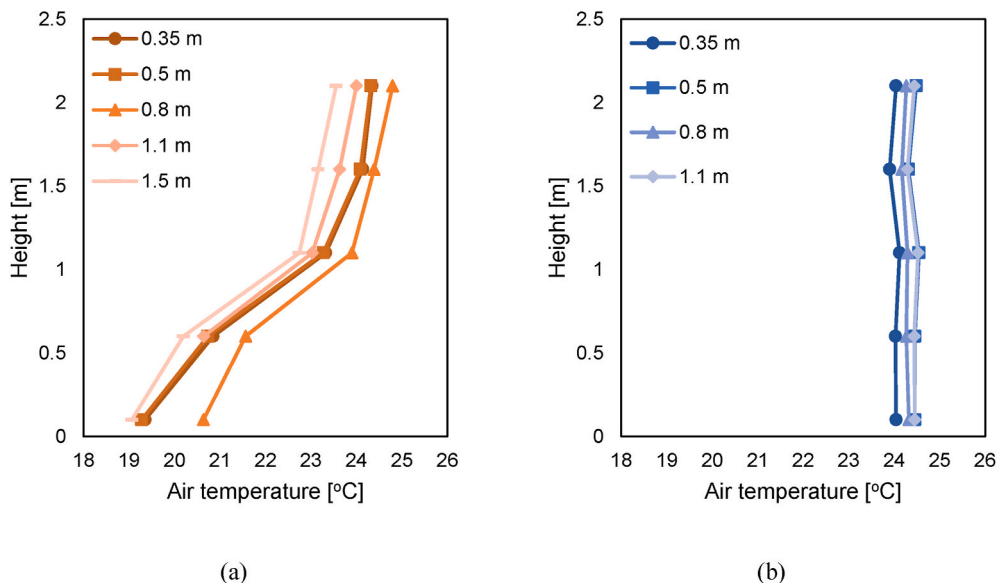


Fig. 5. Vertical temperature distribution in the test room in the room with different air distribution systems and with different separation distances (a) DV (b) MV.

thermal stratifications, and can travel a long distance along the horizontal direction.

3.2. The effect of personal protective equipment (PPE)

Fig. 7 and Fig. 8 present the susceptible exposure index under the scenarios where the source manikin is without PPE (baseline) and with different types of PPE in the room with two air distribution systems, respectively. For DV (Fig. 7), it is clear to see that all investigated PPE reduce the exposure significantly at the short distances (<0.8 m). PPE reduce the momentum of the source manikin's exhalation jet and avoid the direct penetration of the exhalation jet to the target manikin's inhalation region, where the exposure index towards to 1. By comparing the efficiency of different types of PPE, it is surprising to see that open face shield and mouth visor are the most efficient PPE for preventing airborne exposure at 0.35 m distance, followed by closed face shield and surgical mask. The efficiencies of the four types of PPE are similar at the distance of 0.5 m and 0.8 m, where the susceptible exposure indexes reduce to around 0.7. For MV (Fig. 8), all PPE show similar efficiency in preventing the airborne exposure, the susceptible exposure indexes are reduced to approximately 1 at all distances. It shows that the use of PPE promotes the mixing level under both air distribution scenarios.

In order to understand the principle of PPE on mitigating the airborne transmission, the smoke tests were used to visualize the exhaled flow development in the micro-environment of the source manikin with and without PPE in MV, as seen in Fig. 9. Fig. 9 (a) shows that the exhaled airflow can be treated as partly an instantaneous turbulent air jet and partly as a vortex flow. The airstream gradually grows in size due to the mixing with the surrounding air. The jet trajectory shows an upwards curve because of the higher exhalation temperature compared with the ambient temperature. The penetration length of the exhaled flow depends on many parameters, such as human activity level, shape and the opening area of the mouth, room temperature, and velocity distribution. In the scenario with MV (in the conditions by the current study), the exhaled flow rises up within 0.35 m distance and therefore, the target does not exposure to the high contaminant exhalation directly. The inhaled air of the target manikin is mainly from the lower zone brought up by the thermal plume generated by the body.

It is clear to see that the use of PPE breaks the development of the exhalation jet. When the source manikin wears a mask, Fig. 9 (b), most of the exhaled flow escapes from the gap between mask and nose, and the exhaled flow risks up along the manikin's face and enters the upper zone of the test room. A small amount of exhaled flow leaks from gaps on the side of the face and moves backward. In the case with DV, the leakage flow from the side might be locked-up in the breathing zone and inhaled by the target, which results in the exposure index slightly higher than 1 at the close proximity (0.35 m). Fig. 9 (c) shows the open face shield redirects the forward exhalation jet and almost all the exhaled flow leaves from the top gap between the plastic shield and the forehead, and moves upwards. Different from the open face shield, the exhaled

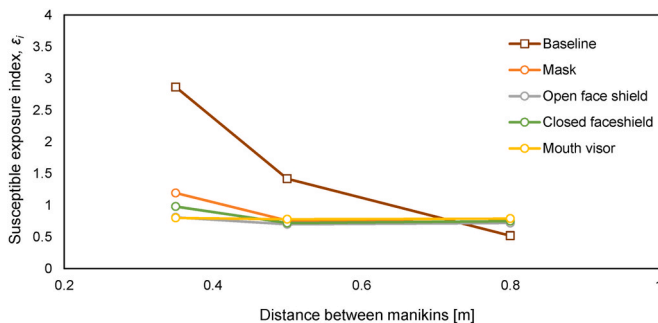


Fig. 7. Susceptible exposure index with different types of PPE worn by source manikin in DV.

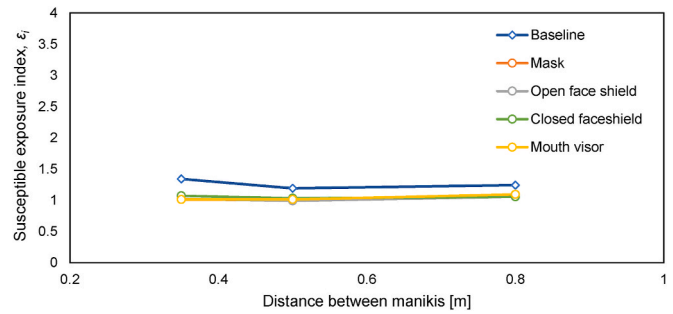


Fig. 8. Susceptible exposure index with different types of PPE worn by source manikin in MV.

flow can not leave from the top because it is closed at the forehead with a foam cushion. The exhaled flow is redirected by the face shield and move downwards, which leaves from the space between the shield and the chin, Fig. 9 (d). The low momentum downwards flow rises up again in front of the chest due to the temperature difference with the ambient air and thermal plume from the body, which presents a risk of exposure to the target manikin in close proximity. The last investigated PPE is the mouth visor. Even the mouth visor does not cover the entire face, it efficiently disturbs the exhalation jet and changes the flow direction. The exhaled flow rises up along the manikin's face and moves upwards instead of spreading in the breathing zone, as shown in Fig. 9 (e).

3.3. The effect of physical barrier

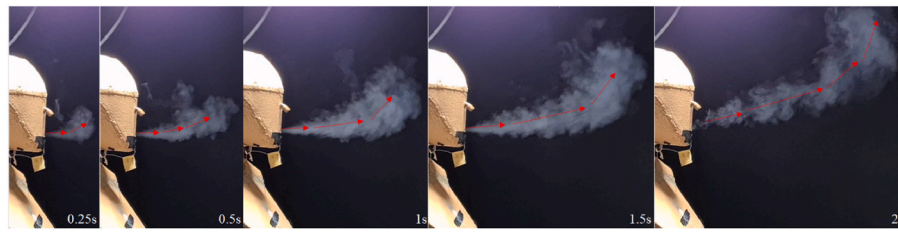
The effects of physical barriers on preventing airborne transmission in a short distance are presented in Fig. 10. Both sizes of plexiglass efficiently mitigate direct airborne exposure in the short distance (<0.8 m) in DV. The susceptible exposure indexes are reduced to below 0.6 at all distances, which indicates the air quality inhaled by the target is better than the fully mixed scenario. The physical barrier does not make a significant difference in the cases with MV, the susceptible exposure indexes slightly reduce to 1 at all distances, indicating a better mixing of contaminant air and supply air than the case without the physical barrier. The measured results show that the physical barriers preserve the good micro environment in all distances between persons. The size of the plexiglass does not play an important role in this study. However, it needs to notice both plexiglasses are large enough to block the exhalation jet penetrating the target's breathing zone, as proved by the smoke visualization Fig. 11. Further study is recommended to identify the minimum effective size of the physical barrier. On the other hand, the relative location of physical barriers to the breathing zone could have a large impact on the effectiveness of physical barriers, which is also recommended to investigate in the future study.

4. Discussion

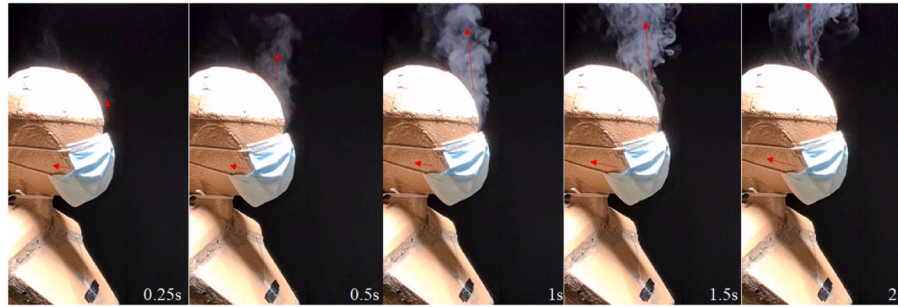
4.1. Mixing and displacement ventilation

The measured results show that there is a significant difference in the airborne cross-infection risk in the room with MV and DV, and the prevention measures perform differently with these two air distribution systems.

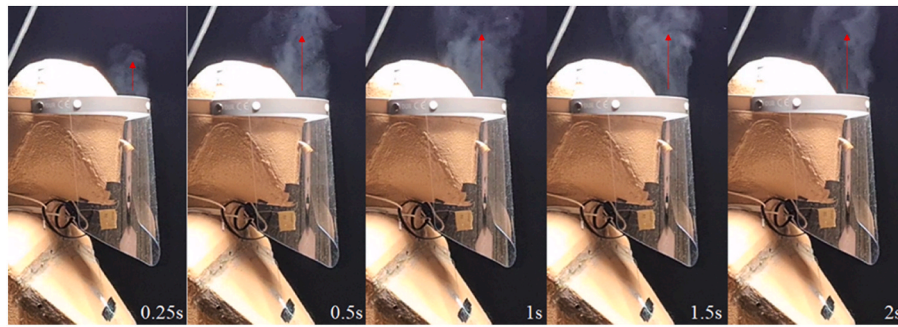
In the current conditions, DV generates a high direct exposure risk to a susceptible individual in the short-distance (<0.8 m) due to the lock-up phenomenon. When the separation distance is larger than the penetration length of the exhaled flow, the exposure reduces remarkably and shows a lower exposure than with the fully mixing ventilation. In DV, the air quality inhaled by the target strongly depends on both ventilation related parameters and person-related parameters, for example, the vertical temperature gradient [7,24,38], the position, height, and orientation of the persons [24,25,37], the persons' behavior and



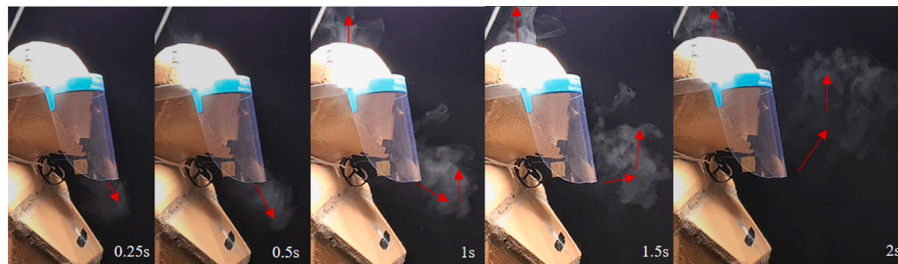
(a)



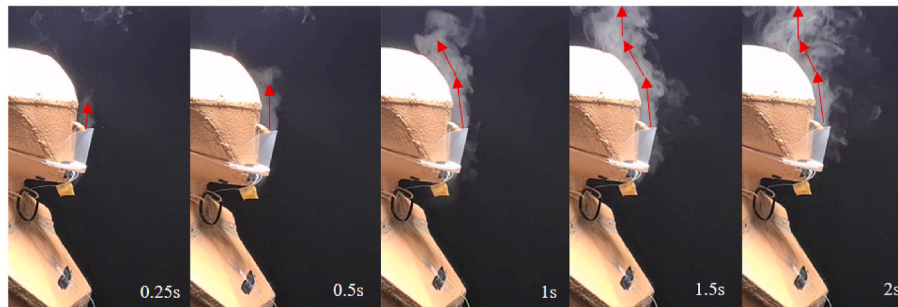
(b)



(c)



(d)



(e)

Fig. 9. Smoke visualization of exhaled flow development with and without PPE under MV (a) Without PPE (baseline), (b) Surgical mask, (c) Open face shield, (d) Closed face shield, (e) mouth visor.

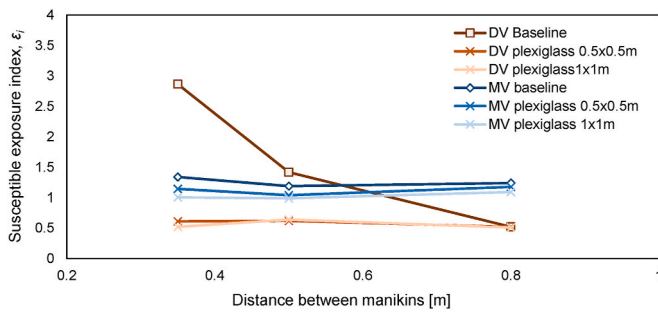


Fig. 10. Susceptible exposure index with different sizes of plexiglass in the room with DV or MV.

activities [40,41]. Therefore, although DV is considered as an effective air distribution principle in many applications, it can be problematic in connection with infection control because its performance could vary significantly under different boundary conditions. However, with the help of PPE and physical barrier, the exposure risk is remarkably reduced in all distances with DV. The high momentum exhaled air jet is disturbed, and rises above the breathing zone due to the temperature difference to the ambient air and the thermal plume. The person mainly inhales air from the lower zone that has superior quality than full-mixed air. DV combined with prevention measures, such as PPE or physical barrier, presents the possibility to be applied as an efficient strategy for infection control.

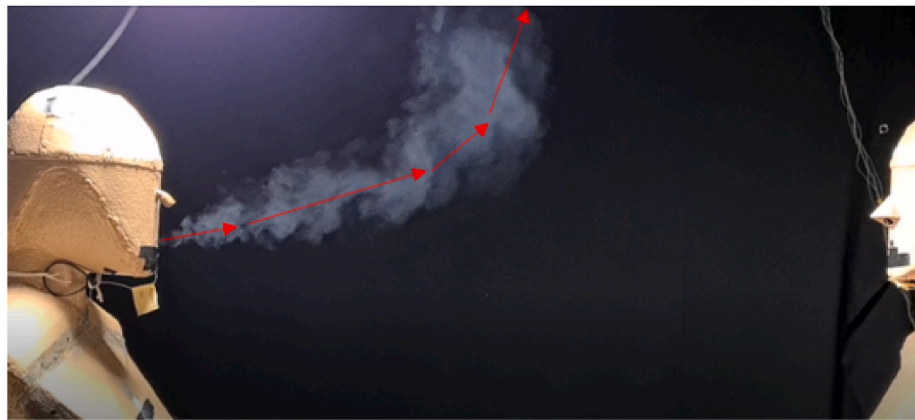
In this study, no direct airborne exposure is identified in close proximity with mixing ventilation, which is because the exhalation jet rises upward before it reaches the inhalation region of the target, as shown in Fig. 9 (a). The exhalation jet develops as an upwards curve, that can be described by the following equations [42]:

$$\frac{z}{\sqrt{A_0}} = 0.0354 Ar_0 \left(\frac{x}{\sqrt{A_0}}\right)^3 \sqrt{\frac{T_0}{T_\infty}} \quad (2)$$

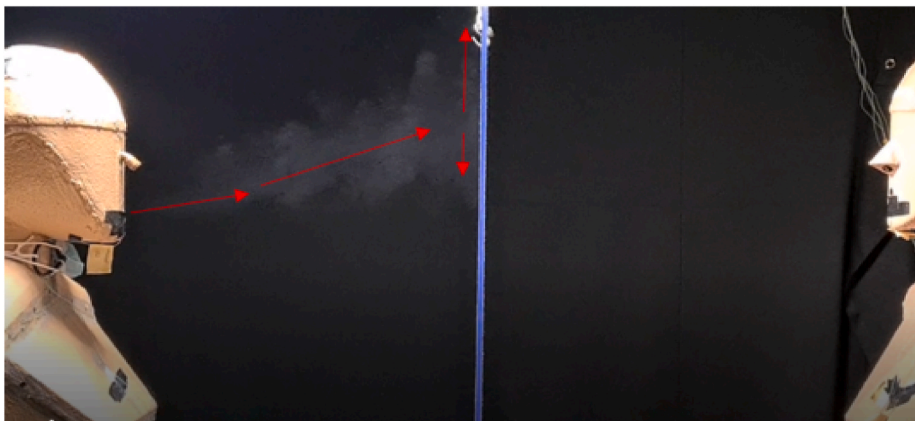
$$Ar_0 = \frac{g \sqrt{A_0} \Delta \rho}{u_0^2 \rho_0} \quad (3)$$

Where z is the vertical centerline position; A_0 is the area of the source mouth; Ar_0 is the Archimedes number; T_0 is the initial jet temperature; T_∞ is the ambient temperature; g is the gravitational acceleration; ρ_0 is the jet initial density; $\Delta \rho$ is the density difference between the jet and ambient air; x is the horizontal distance between the source and the target, u_0 is the initial velocity at the source mouth outlet.

The bending angle of the curve is a function of Ar_0 , where the angle increases with the increasing of the temperature difference between exhaled air and ambient air, and decreases with the increasing of the initial exhalation velocity. Therefore, the exposure risk at close proximity in MV strongly depends on the room temperature and the activity level of the person. For example, when people are talking, coughing and singing, the exhalation jet will travel longer in the breathing zone and have a higher chance of penetrating the target's inhalation region than when they are just breathing [40,43], which present a higher direct



(a)



(b)

Fig. 11. Smoke visualization of exhaled flow dispersion in the room with and without a physical barrier in MV (a) Without physical barrier (b) With plexiglass 0.5 × 0.5 m

exposure risk. On the other hand, the current study considered the indoor temperature within the comfort range. In some situations, for example, industrial spaces, the room temperature is close to exhaled air temperature, which results in the exhalation jet developing in the horizontal direction and entering the target's breathing zone directly.

4.2. Airborne and droplet prevention

The principles of PPE on preventing short-range droplet and airborne transmission are different. A surgical mask can efficiently filter the large droplet, where the filtration effectiveness is larger than 95% for particles $> 3 \mu\text{m}$ based on EN 14683 [44]. The other types of PPE are mainly used to block the respiratory droplets spreading from the source to others. However, the PPE does not filter the fine droplet nuclei or block their spreading in the same manner as droplets [17]. They mainly work by disturbing the virus-laden airflow exhaled by the infected source and changing the movement direction to avoid direct airborne exposure by the targets.

Another issue related to the use of physical barriers is that their impact on the airflow distribution in the space is difficult to predict, which depends on the size and location of the physical barrier, room layouts, and air distribution principles. The presence of a physical barrier might reduce the dilution or replacement of the contaminant air, and results in a stagnant zone where the contaminant will accumulate. TNO [45] investigated the effect of different arrangements of physical barriers integrated with different ventilation systems on reducing the aerosol exposure risk in a restaurant layout. The results showed that ventilation rate is the most determining parameter to the exposure risk. The use of physical barriers can improve the situation with high (11 h^{-1}), medium ventilation rate (8 h^{-1}), but it can worsen the situation at the low ventilation rate (4 h^{-1}). It is recommended to use physical barriers with the provision that the ventilation rate is higher than the minimal requirement by the current building regulations or standards.

4.3. Limitations of this study

First, this study used tracer gas to simulate the exhaled droplet nuclei from the infected person. Even though previous studies proved that tracer gas can be used reliable to simulate fine particles ($< 5 \mu\text{m}$) in measurements of airborne transmission [7,24,25], there are still certain limitations when measuring the efficacy of PPE. As mentioned by Y. Li [46] that the effectiveness of surgical mask is due to both filtration and jet blockage. The filtration effect of surgical mask on droplet nuclei (aerosol) and virus is neglected by the use of tracer gas. All contaminants are regarded as escaping from the PPE without depositing on the PPE surface. Therefore, this study mainly investigated the effect of PPE on redirecting the exhaled flow instead of filtering the aerosol and virus, where the efficacy of PPE might be underestimated.

Second, the susceptible exposure index was selected as an indicator for this study, which demonstrates the exposure risk of a target individual compared with the ambient environment. This indicator is suitable for simple and fast predictions of the exposure risk of pathogens by experiments or simulations, but it does not consider the infectivity of a specific disease agent. The dose-response model and the Wells-Riley model are widely applied to predict the infection risk over time. They consider the infectivity and viability of the pathogen and pathogen concentration in the respiratory fluid, however, they are challenging to use at the beginning of the pandemic with the absence of infection data [47].

5. Conclusions and further research

The airborne cross-infection risk between two people in a short distance was investigated in a full-scale test room with two air distribution systems (MV and DV). The source control effects of prevention measures widely applied during Covid-19 were tested, including four different

types of PPE (surgical mask, open face shield, closed face shield, and mouth visor) and two physical barriers of different sizes.

In the scenario without prevention measures, air distribution principle showed significant impacts on the exposure risk. High direct exposure risk was observed in the short-distance with DV because the high contaminant exhaled flow was locked in the breathing zone due to thermal stratification. However, when the separation distance was larger than the penetration length of the exhaled flow, the exposure reduces remarkably and shows a lower exposure than with the fully mixing ventilation. No direct exposure in close proximity was identified with MV in this study. However, the exposure risk strongly depends on the trajectory of exhaled air jet, it will change with the temperature difference between exhaled flow and ambient, and persons' activity, such as singing, talking, and coughing.

The principles of PPE on preventing short-range droplet and airborne transmission are different. Instead of filtering the fine droplet nuclei, they mainly redirect virus-laden exhalation jet and avoid the exhaled flow entering the target's inhalation region. Open face shield and mouth visor presented better performance on mitigating airborne exposure in the very short distance ($< 0.5 \text{ m}$) than closed face shield and surgical mask, especially in the case with DV. Physical barriers can block the spreading of droplet nuclei and create a good micro environment at all distances between persons. However, special attention should be paid on arranging the physical barrier and operating the ventilation system to avoid the stagnant zone where the contaminant accumulates.

There are two basic approaches of engineering control, one is source control and the other is susceptible control. This study mainly investigated the effect of PPE worn by source manikin, which focuses on source control. Actually, the PPE is currently recommended to be worn by the public in the closed enclosure. It is important to investigate the protective effect of PPE worn by the target and both. Secondly, in most hospital and healthcare settings, it is recommended to wear a surgical mask together with a face shield or eye protection. The combined effect of PPE should be considered in future study. Finally, the airborne transmission due to the breathing process is discussed in this study. Different activities, such as singing, talking, and coughing, will generate different exhalation jets, which consequently will influence the direct exposure in the short distance.

CRediT authorship contribution statement

Chen Zhang: Writing – review & editing, Writing – original draft, Methodology, Investigation, Funding acquisition, Conceptualization. **Peter V. Nielsen:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Li Liu:** Writing – review & editing, Methodology, Funding acquisition, Conceptualization. **Emilie Tranegaard Siger:** Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation. **Sarah Ghoreishi Mikkelsen:** Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation. **Rasmus L. Jensen:** Writing – review & editing, Supervision, Conceptualization.

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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