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## Investigation of Mask Efficiency for Loose-Fitting Masks against Ultrafine Particles and Effect on Airway Deposition Efficiency

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### Abstract

Ultrafine particle (i.e., smaller than 100 nm) in the ambient air is a significant public health issue. The inhalation and deposition of ultrafine particles in the human airways can lead to various adverse health effects. Loose-fitting types of masks are commonly used by the general public in some developing countries for protecting against ultrafine particles in the ambient environment. This research conducted a series of laboratory chamber experiments using two sets of particle sizers and two mannequin heads to study the mask efficiency of selected loose-fitting masks. Results acquired demonstrated that the cloth mask showed a low mask efficiency against ultrafine particles with the mask efficiency generally less than 0.4. The KN95 presented a better mask efficiency among all tested masks with the mask efficiency overall larger than 0.5. In addition, the effect of mask-wearing on the change of ultrafine particle airway deposition efficiency was also investigated in this study. The ultrafine particle deposition efficiency in the airway section studied was found to decrease due to mask-wearing, and the decreases of the deposition efficiencies were similar among all loose-fitting masks tested.

### Keywords

Mask efficiency; Loose-fitting mask; Ultrafine particle; Airway deposition efficiency

## 1 INTRODUCTION

Ultrafine particles are airborne particulate matter (aerosol) with particle diameters less than 100 nm. Many human activities and industrial processes are known to generate ultrafine particles as byproducts, and most of the ultrafine particles are released into the ambient environment such as the diesel engine exhausts and power plant emissions. Ultrafine particles in the ambient air inevitably can be inhaled by the general public. The inhalation and deposition of ultrafine particles in the human airways can lead to a variety of adverse

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health effects. Based on the published literature, exposure to ultrafine particles in the environment could cause coughing, peak expiratory flow decreasing, asthma, bronchitis, and chronic obstructive lung disease (Schraufnagel 2020; Leikauf et al., 2020). Evidence also has shown that ultrafine particles attribute to cardiovascular diseases (Schulz et al., 2005; Daiber et al., 2020). Moreover, mortality rates were found to be associated with both short-term and long-term exposure to ultrafine particles (Stafoggia et al., 2017; Ostro et al., 2015). In the laboratory study, exposure to elemental carbon ultrafine particles proved to induce allergic airway inflammation and neuropathological effects (Alessandrini, et al., 2009; Allen et al., 2017). Based on the above, ultrafine particles in the ambient environment are considered a significant environmental health issue.

It is known that several developing countries in Asia have severe particulate matter issues including ultrafine particles (Dejchanchaiwong et al., 2020; Huyen et al., 2021; Liu, et al. 2018). Mask-wearing by the general public is a common practice in these countries to protect themselves from inhaling particulate matters into the lungs (Cherrie et al., 2018). However, there are different types of masks sold in the market and online stores, and the efficiencies of these masks in protecting against airborne particle matter, especially ultrafine particles, are usually unknown. It is widely accepted that the aerodynamic behavior of ultrafine aerosol is more similar to gases than particles due to their tiny masses. Thus, ultrafine particles can follow closely the airstream to penetrate the mask or bypass the mask through gaps between the face and the mask, and then eventually enter the wearer's respiratory tract. In contrast, large particles with considerable masses such as dust and droplets in the air are relatively easier to be filtrated by common masks through the inertial and interception filtration mechanisms. Therefore, from the viewpoint of environmental health, it is essential to investigate the efficiency of the masks used by the general public in certain developing countries to provide useful reference information for protecting against ultrafine particles.

Mask efficiency studies have been published throughout the years for masks used in different professions such as the health care surgical masks (Deerrick and Gomersall, 2005; Oberg and Brosseau, 2008; Grinshpun et al., 2010) and the occupational N95 masks (Balazy et al., 2006; Huang et al., 2007; Rengasamy et al., 2008). Only a small number of mask tests were carried out for masks used by the general public to protect against air pollution (Rengasamy et al., 2010; Jung et al., 2014; Shakya et al., 2017). The short of experiments might be due to the lack of a standard test method for the loose-fitting type of masks. Recently, due to the COVID-19 pandemic, a considerable amount of mask evaluation tests were conducted for protection against virus-laden aerosol (Zangmeister et al., 2020; Konda et al., 2020; Drownick et al., 2020). However, very few of these published experiments carefully considered the temporal and spatial variations of the particle concentration in their experiments and integrated such change into the mask efficiency calculation. Besides, no experiment above was designed to study the mask efficiency and the fate of the particle that penetrated the mask such as the particle respiratory deposition efficiency under mask-wearing. In light of this, this study attempted to conduct a series of mask evaluation tests in a chamber using two sets of particle sizers and two silicone mannequin heads. One of the mannequins was installed with a realistic human airway replica to investigate the mask efficiency as well as the alteration of the respiratory deposition efficiency due to

mask-wearing. Loose-fitting masks were selected as test masks, and ultrafine particles were employed as the challenge particles. The purpose of testing loose-fitting masks is because common masks used by the general public to protect against airborne particulate matter and ultrafine particles are loose-fitting masks. Results acquired from this study can provide valuable reference information regarding the efficiency of some loose-fitting masks against ultrafine particles and understand the change of ultrafine particle respiratory deposition due to mask-wearing.

## 2 MATERIAL AND METHODS

### 2.1 Test Masks

Four different types of loose-fitting masks designed to protect against airborne particulate matter were selected as the test masks. The masks were evaluated in this study for their efficiency against ultrafine particles and also for their effects on changing the respiratory deposition efficiency in the human upper airways. The selected masks were the cloth mask, the breathing valve mask (a mask with a breathing valve), the smart mask (a mask with an electronic fan installed), and the KN95 mask. These masks are available for purchase through a variety of online and retail stores. For comparison, the surgical mask commonly used during the COVID-19 pandemic and the occupational N95 mask (without fitting test) were also tested in this study as references. Fig. 1 shows the four test masks and the two reference masks used in this study.

### 2.2 Human upper airway replicas and mannequin heads

The airway replica used for studying the ultrafine particle respiratory deposition efficiency is a 3D-printed human upper airway replica containing an oral cavity, oropharynx, larynx, trachea, and the Tracheobronchial (TB) airways down to parts of the 6<sup>th</sup> lung generation. The airway replica was made of conductive PLA filament (Proto-pasta, ProtoPlant, Vancouver, WA, USA) to prevent the electrostatic effect on particle deposition. The replica was installed inside an airway container to become a simplified airway system with a TB airway replica down to the 6<sup>th</sup> lung generation (R6). The inner surface of the airway replica was coated with a thin layer of silicone oil to prevent the re-entrainment of deposited particles. This simplified airway system was used previously in our lung deposition experiments for acquiring aerosol respiratory deposition data (Su et al., 2019a and 2019b).

In this study, two mannequin heads were used in the experiments. The mannequin heads are made of silicon rubber having the soft-touch texture as skin, and they have face features including eyes, nose, lips, and ears. To use the mannequin head for conducting mask efficiency experiments, the mouth of the mannequin head was inserted (reversely) with an oval-shaped mouthpiece of a medical nebulizer with the mouthpiece opening matching the lips of the mannequin. The test masks were managed to be worn on one of the mannequin heads with the mask ear loops hooking on ears under a normal mask-wearing situation. To study the effect of mask-wearing on the change of ultrafine particle respiratory deposition, the oral airway of the simplified airway system, R6, was installed inside the mannequin head designated for wearing test masks with the oral airway opening connecting to the

mouthpiece. Fig. 2 shows the components of the simplified airway system and the silicone mannequin head incorporated with the simplified airway system.

### 2.3 Experimental set-up

The experiments were conducted in a stainless-steel chamber with the main testing zone in a dimension of 61 cm (L)  $\times$  61 cm (W)  $\times$  61 cm (H). The two silicone mannequin heads were placed side-by-side in the chamber. The mannequin head wearing the test mask was named test mannequin, which was the one installed with the simplified airway system (R6). Prior to each experiment, the test mannequin was double-checked by the researcher to ensure the nose and mouth of the test mannequin head were well covered by the test mask and the nasal strip were snugly in contact with the upper nose. In this way, leakages from the mask-face gaps could be minimized and the variability of the result could be reduced. The other identical mannequin head worked as the reference (reference mannequin). The reference mannequin head had an oral-to-throat airway replica connected to the mouthpiece as the test mannequin head but without TB airways.

Sodium Chloride (NaCl) particles in the size range of 10 to 200 nm were used as the challenge ultrafine particles in the experiments for studying the mask efficiency and the respiratory deposition efficiency. The ultrafine NaCl particles were generated by a laboratory atomizer (3079A, TSI Inc., Shoreview, MN, USA). The generated NaCl aerosol first passed through several drying columns and then delivered into the test chamber through its pyramid top. Two sets of Scanning Mobility Particle Spectrometers (SMPS+C, GRIMM Aerosol Technology, Germany) were employed as particle sizers to measure simultaneously the particle size distribution (number concentration, # cm<sup>-3</sup>, by particle size) of ultrafine particles entered both mannequin heads. Fig. 3 shows the schematic of the experimental set-up of the study. For the test mannequin head, particle size distributions were measured at the location of the oral airway inlet in two conditions of wearing and non-wearing masks. The particle size distributions were also measured at the location of the R6 airway outlet under two conditions (with and without wearing masks). For the reference mannequin head, the particle size distributions were measured only at the oral airway inlet without wearing a mask. All experiments were conducted at an inspiratory flow rate of 15 L min<sup>-1</sup> for both mannequin heads controlled by individual rotameters. Experiments were repeated at least five times for each experimental condition to obtain good estimates of the mean and standard deviation.

### 2.4 Estimation of the Mask efficiency

According to the experimental design in this study, particle size distributions measured at the test mannequin head have to be corrected based on the reference mannequin head in order to take into account the possible temporal and special change of the particle concentration inside the chamber. Based on this, define  $C_{oral,d}$  to be the particle size distribution (# cm<sup>-3</sup> by particle size) measured at the oral airway inlet of the test mannequin head without wearing masks, and  $C_{ref\_oral,d}$  is the particle size distribution measured at the reference mannequin head at the same time while the  $C_{oral,d}$  is measured. Given that the  $C_{oral,d}$  is the baseline for calculating the mask efficiency and the respiratory deposition efficiency, particle size distributions measured at the test mannequin head in other experimental conditions and

locations have to be corrected according to  $C_{ref\_oral,d}$  and the corresponding measurement at the reference mannequin head:

$$C'_{oral+mask,d} = C_{oral+mask,d} \times \left( \frac{C_{ref\_oral,d}}{C_{ref\_oral+mask,d}} \right) \quad (1)$$

$$C'_{R6,d} = C_{R6,d} \times \left( \frac{C_{ref\_oral,d}}{C_{ref\_R6,d}} \right) \quad (2)$$

$$C'_{R6+mask,d} = C_{R6+mask,d} \times \left( \frac{C_{ref\_oral,d}}{C_{ref\_R6+mask,d}} \right) \quad (3)$$

where  $C_{oral+mask,d}$  is the measured particle size distribution at the oral airway of the test mannequin head with wearing masks, and  $C'_{oral+mask,d}$  is the corrected  $C_{oral+mask,d}$  by reference measurements.  $C_{ref\_oral+mask,d}$  is the particle size distribution obtained at the reference mannequin head when  $C_{oral+mask,d}$  is measured.  $C_{R6,d}$  and  $C'_{R6,d}$  are respectively the measured and reference-corrected particle size distributions at the outlet of the R6 without wearing masks.  $C_{ref\_R6,d}$  is the particle size distribution measured at the reference mannequin head when  $C_{R6,d}$  is measured.  $C_{R6+mask,d}$  and  $C'_{R6+mask,d}$  are respectively the measured and corrected particle size distributions at the R6 outlet of the test mannequin with wearing masks.  $C_{ref\_R6+mask,d}$  is the particle size distribution obtained at the reference mannequin head when  $C_{R6+mask,d}$  is measured.

Based on the above, the mask efficiency can be defined as the ratio of the reduced number of particles due to mask-wearing to the number of particles that enter the oral airway without a mask. The mask efficiency in this study covers the filtration efficiency produced by the mask material as well as the inevitable particle leakage due to the nature of the loose-fitting mask. The mask efficiency can be calculated by:

$$E_{mask,d} = \frac{C_{oral,d} - C'_{oral+mask,d}}{C_{oral,d}} = 1 - \frac{C'_{oral+mask,d}}{C_{oral,d}} \quad (4)$$

where  $E_{mask,d}$  is the efficiency (0 to 1.0) of the mask against an ultrafine particle with a particle diameter of  $d$ , and  $C_{oral,d} - C'_{oral+mask,d}$  expresses the reduced particle number entered the oral airway.

## 2.5 Estimation of the mask-wearing effect on respiratory deposition efficiency

The aerosol deposition efficiency in an airway section is defined as the ratio of the particles deposited within an airway section to the total particles entered that airway section. Thus, in this study, the deposition efficiency in the entire R6 without mask-wearing can be calculated as:

$$D_{R6,d} = \frac{C_{oral,d} - C'_{R6,d}}{C_{oral,d}} = 1 - \left( \frac{C'_{R6,d}}{C_{oral,d}} \right) \quad (5)$$

Similarly, the deposition efficiency in R6 with mask-wearing can be calculated as:

$$D_{R6+mask,d} = \frac{C'_{oral+mask,d} - C'_{R6+mask,d}}{C'_{oral+mask,d}} = 1 - \left( \frac{C'_{R6+mask,d}}{C'_{oral+mask,d}} \right) \quad (6)$$

It is worth noting that the denominator in Eq. (6) is the particle size distribution measured at the oral airway inlet when masks are wearing ( $C'_{oral+mask,d}$ ) in order to represent those particles actually entered the airway and contributed to the deposition efficiency. Based on the above, the change of deposition efficiency ( $D_{mask,d}$ ) in R6 due to mask-wearing can be calculated by Eq. (6) – Eq. (5):

$$\Delta D_{mask,d} = \left( 1 - \left( \frac{C'_{R6+mask,d}}{C'_{oral+mask,d}} \right) \right) - \left( 1 - \left( \frac{C'_{R6,d}}{C'_{oral,d}} \right) \right) = \frac{C'_{R6,d}}{C'_{oral,d}} - \frac{C'_{R6+mask,d}}{C'_{oral+mask,d}} \quad (7)$$

For Eq. (7), a positive value of  $\Delta D_{mask,d}$  indicates the deposition efficiency of ultrafine particles in the upper airway increased because of wearing a mask, and a negative value represents the deposition efficiency decreased after wearing a mask. In this way, the effect of mask-wearing on the deposition efficiency can be revealed and compared for different masks tested.

### 3 RESULTS

Fig. 4 demonstrates a typical data set measured during an experiment. As can be seen, the particle size distribution acquired at the test mannequin head (Fig. 4a) varied according to the condition of mask-wearing and also by the location of measurement taken. For a given particle size, the  $C'_{oral,d}$  (i.e., the particle concentration measured at the oral airway inlet without wearing masks) showed the highest concentration among all measurements. The  $C'_{G6,d}$  expressed a relatively higher concentration than the  $C'_{oral+mask,d}$ , and the  $C'_{G6+mask,d}$  showed an overall lowest concentration among all data. In contrast, the particle size distribution measured at the reference mannequin head (Fig. 4b) showed similar results throughout the entire experiment with only slight fluctuations.

Fig. 5 shows mask efficiency against the ultrafine particle for test and reference masks calculated by Eq. (4). For all loose-fitting masks, the mask efficiency decreased as the diameter of the ultrafine particle increased. The KN95 presented a generally high mask efficiency ( $> 0.5$ ) within the particle size range studied, which was better than all the other loose-fitting masks tested. The smart mask showed a high mask efficiency (around 0.7) in the small particle size range, but as the particle size increased, the mask efficiency dropped quickly to around 0.2 at 200 nm. The cloth mask and breathing valve mask both showed relatively low mask efficiencies, but the cloth mask was the lowest among the four loose-fitting masks. The average mask efficiency was 0.34 for the breathing valve mask, and the average was 0.2 for the cloth mask. For the reference masks, the mask efficiency of the surgical mask demonstrated a similar result compared to the four test masks with the highest value around 0.6 at 10 nm and the lowest value around 0.3 at 200 nm. The reference N95 mask showed an overall high mask efficiency even though no fit test was applied. The mask efficiency of N95 was 0.84 on average for the particle size range studied.



Fig. 6 compares the effect of mask-wearing on the change of ultrafine particle respiratory deposition efficiency. The alteration of the deposition efficiency due to wearing a mask was calculated based on Eq. (7). It can be seen that changes in the deposition efficiency were generally in negative value, implying the deposition efficiency of the ultrafine particle in the airway (R6) was decreased because of mask-wearing. The smaller the particle size, the more decrease in deposition efficiency would be. For the four loose-fitting masks tested, decreases of the deposition efficiencies were basically less than 0.1. However, for the reference surgical and N95 masks, the decrease of the deposition efficiency could reach 0.3 in the small particle size range. Overall, the cloth mask showed a relatively smaller decrease in deposition efficiency, and the N95 presented a comparatively more decrease in deposition efficiency among all masks studied.

## 4 DISCUSSION

As can be seen in Fig. 5, the size-dependent mask efficiency increased as the particle size decreased. This result indicates the fact that the major mechanism for masks to prevent ultrafine particles from entering the human airways is diffusion. The high mask efficiency in the small particle size regime specifies that small particles are relatively easier than the larger particles to be captured by the mask material via diffusion. Also shown in Fig. 5 is that the patterns of the mask efficiency of the four test masks were found to be similar to the pattern of the surgical mask rather than that of N95. This is a reasonable result since the four test masks and the surgical mask are all loose-fitting masks. It is known that, for loose-fitting masks, parts of the inhaled air can “leak” into the wearer’s airways through gaps between the mask and the face without actually passing through the mask material (bypassing the mask). Consequently, although it is expected that masks should have a high mask efficiency against ultrafine particles because of the diffusion mechanism, the actual efficiency is compromised by the unavoidable air leakage carrying with ultrafine particles due to loose-fitting. Therefore, the mask efficiency against ultrafine particles for loose-fitting masks is normally lower than expected. For all loose-fitting masks tested in this study, the size-dependent mask efficiencies were less than 0.7 in general. Among the four test masks, cloth masks are made of materials with low particle filtration efficiency (Pan et al., 2021). Therefore, with the combined effect of loose-fitting and inefficient material, the cloth mask showed the lowest efficiency of all tested masks. In contrast, the N95 (reference mask) is designed with many occupational health features to protect workers from inhaling hazardous aerosol in the workplace. The N95 mask is characterized by its tight-fitting design (face seal, nose clip, and stretchable straps) and the material of the N95 is dense with high particle filtration efficiency (Qian et al., 1998). Therefore, N95 showed a generally high mask efficiency ( $> 0.7$ ) compared to those loose-fitting masks tested. On the other hand, KN95 is considered a loose-fitting mask, but the mask material of KN95 possesses a relatively better particle filtration efficiency (Yim et al., 2020). As a result, KN95 presented a superior mask efficiency among all loose-fitting masks tested in this study including the surgical mask.

As indicated previously, a considerable amount of mask evaluation studies were designed for tight-fitting masks such as N95. Relative fewer loose-fitting masks such as cloth masks were evaluated. The reason for the lack of experiment might be due to the fact that no conventional test protocol for evaluating loose-fitting masks was developed. As a result,

different experimental designs, setup, and test conditions could lead to different types of gaps and leakages, and the mask efficiency obtained for loose-fitting masks could be discrepant. Nevertheless, a mask performance evaluation study carried out by Shakya et al. (2017) presented that the mask efficiency of the test cloth masks were 0.15 to 0.25 for particles of 30 nm, and 0.30 to 0.35 for particles of 100 nm. Another published mask performance research for cloth masks with common fabric materials (Rengasamy et al., 2010) showed that the penetration efficiency of the breath health cloth mask was around 70% to 80% for particles in the range of 20 to 100 nm implying the associated mask efficiency is around 0.30 to 0.20. These published mask efficiencies are similar to the cloth mask (0.25 to 0.15) and the breathing valve mask (0.35 to 0.25) found in this study under the same particle size range (Fig. 5). Data listed above demonstrate that cloth masks indeed possess in general a low mask efficiency against ultrafine particles.

In contrast, there is a standard fit test procedure and commercial devices are also available for evaluating the mask efficiency or protection factor of tight-fitting masks based on the designed function of the mask. However, the N95 in this study is in the role of a reference mask but not the subject mask for testing and the mask efficiency of N95 was tested without implementing the fit test. The experiments were conducted under the practical condition that the N95 was purchased and worn by the general public without a fit test. In reality, it seems inapplicable for the general public to go through the strict fit test process before wearing a tight-fitting mask. Thus, without a proper fit test, the leakage is predictable when using the N95, which will make the mask efficiency decrease to a certain extent. The effect of the leakage can be seen in Fig. 5 that the mask efficiency of N95 was not able to achieve above 0.95 as designed by the manufacturer.

It is worth noting that again, in this study, the mask efficiency experiments were designed for common mask usage to protect people from inhaling ultrafine particles in the outdoor environment, rather than for protecting the general public against virus-containing aerosol such as coronavirus. Therefore, the efficiency of wearing double layers of masks were not tested in this study. In fact, people seldom wear two layers of masks against air pollutions in the environment for the reason of high air resistance and uncomfortableness. However, it can be reasonably expected that two layers of the same type of masks or any combination of two different types of masks will provide a better mask efficiency to prevent ultrafine particles from entering the wearers' airways. Besides, although the effect of the inhalation flow rate on the mask efficiency was not investigated in this study, the result could be expected according to the principle of aerosol filtration. It is known that diffusion is the dominant filtration mechanism for a mask to block ultrafine particles. A large inhalation flow rate will generate a high air velocity to bring ultrafine particles fast passing through the mask, resulting in less particle deposition due to a lack of time and chance for the particles to be captured by the fiber of the mask material. In contrast, a small inspiratory flow rate will generate a low air velocity, which will allow ultrafine particles to have relatively more time to pass through the mask and increase the chance to be captured by the mask material. Thus, theoretically, mask efficiency should be higher in a low inspiratory flow rate than that in a high inspiratory flow rate. This phenomenon has been proved in several mask studies on N95 and cloth masks (Balazy et al., 2006; Eninger et al., 2008; Rengasamy et al., 2010; Shakya et al., 2017). Therefore, it could be reasonably predicted that if an inspiratory flow



rate higher than  $15 \text{ L m}^{-1}$  was employed to conduct the experiments in this study, the mask efficiency obtained could be less than the data shown in Fig. 5.

The main reason for the decrease in the respiratory deposition efficiency caused by mask-wearing is not definite at this moment. One possible reason might be attributed to the change of the airflow field due to wearing a mask. It is known that mask-wearing causes air resistance which can alter or re-arrange the flow field around the mouth and inside the head airways (oral cavity to the throat). The flow field change can affect the particle trajectory and then change the respiratory deposition efficiency to a certain degree. The other reason for the decrease in the respiratory deposition efficiency might be attributed to the decrease in the test particle concentration. The total number of ultrafine particles entering the R6 was reduced significantly after the mask-wearing, which might result in a decrease in deposition efficiency in the airway. This phenomenon can be demonstrated by the data shown in Fig. 5 and Fig. 6. As can be seen in Fig. 5, the N95 showed a much higher mask efficiency than the cloth mask, which allows very few ultrafine particles to enter the human airway. In Fig. 6, the deposition efficiency shows a prominent decrease in wearing N95 than in wearing the cloth mask. For the cloth mask, groups of ultrafine particles can enter the wearer's mouth as a result of the loose-fitting leakage (shown in Fig. 5 as the low mask efficiency), which allows a considerable amount of ultrafine particles to enter the airway. With the particle number entering the airway being not drastically discrepant between wearing and not wearing the cloth mask, the decrease of the deposition efficiency could therefore be limited as shown in Fig. 6. However, it is worth reminding that the definition of respiratory deposition efficiency is the ratio of the particle number deposited in the airway to the total inhaled particle number. The airway section used in this study for calculating the deposition efficiency is only from the mouth to the 6<sup>th</sup> lung generation. Therefore, the decrease of the respiratory deposition efficiency in the above airway section implies an increase in the penetration efficiency to the lower airways. Nevertheless, since the total number of inhaled ultrafine particles has been reduced considerably due to mask-wearing, the increase of penetration efficiency caused by the decrease of airway deposition efficiency should not lead to significant ultrafine particle deposition in the further lower airways. Further studies on topics of particle trajectory changes and fates of inhaled particles in airways due to mask-wearing such as the research done by Xi et al. (2021) are needed. The investigation could be implemented by using computational fluid dynamics (CFD) numerical simulation to improve the understanding of the effect of mask-wearing on the decrease of respiratory deposition efficiency of ultrafine particles found in this study.

In this study, experiments of mask efficiencies were conducted under a steady inspiratory flow rate of  $15 \text{ L min}^{-1}$  through mouth breathing due to restrictions of laboratory facilities, available airway replicas, as well as the research scope. Data obtained under such experimental conditions might limit its applications. Although this experimental condition is unable to represent some of the ambient ultrafine particle exposure scenarios in Asian cities such as walking and riding on the street with masks on, the experimental condition used in this study could describe a potential exposure scenario as a person wearing a mask (mouth breathing) standing outdoor and waiting for a bus (low breathing rate). Future studies are needed and would be focused on carrying out mask evaluation tests under different inspiratory flowrates to investigate the mask efficiencies under different outdoor

activities. With the data of the mask efficiency as a function of the inspiratory flow rate available, a more realistic mask efficiency based on a cyclic flow rate could be studied in detail by integrating individual mask efficiencies according to the flow rates in different inhalation stages. In this way, the discrepancy between the mask efficiencies obtained from a steady inspiratory flow rate and a cyclic flow rate can then be revealed. In this research, the particle deposition data were obtained only down to the 6<sup>th</sup> lung generation (G6) in the TB airways. Given that the deposition of ultrafine particles in the human airways is mainly in the lower respiratory tract, the information provided from the data acquired in this study is considered incomplete. However, the data obtained still contribute to providing initial results as references for later data comparison. Therefore, for the future study on the change of ultrafine particle respiratory deposition due to mask-wearing, lung deposition experiments will be conducted using the human TB airway replica with more lung generations (G11) and a representative alveolar region to provide more useful information for investigating the change of airway deposition efficiency caused by mask-wearing.

## 5 CONCLUSION

This study conducted a set of chamber experiments to study the mask efficiency against ultrafine particles for selected loose-fitting masks. In addition, the effect of mask-wearing on the change of airway deposition efficiency was also investigated. Results acquired presented that mask efficiencies were similar among the loose-fitting masks tested including the surgical mask. The cloth mask showed a low mask efficiency in general against ultrafine particles due to the combined effect of loose-fitting and inefficient material. The KN95 presented a better mask efficiency among all tested masks with the mask efficiency generally larger than 0.5. The deposition efficiencies of ultrafine particles in the airway were found to be decreased due to mask-wearing. The N95 which has an overall high mask efficiency showed a relatively more decrease in the deposition efficiency than the loose-fitting masks tested. Further studies are needed to investigate in detail the decrease of respiratory deposition efficiency caused by mask-wearing found in this study.

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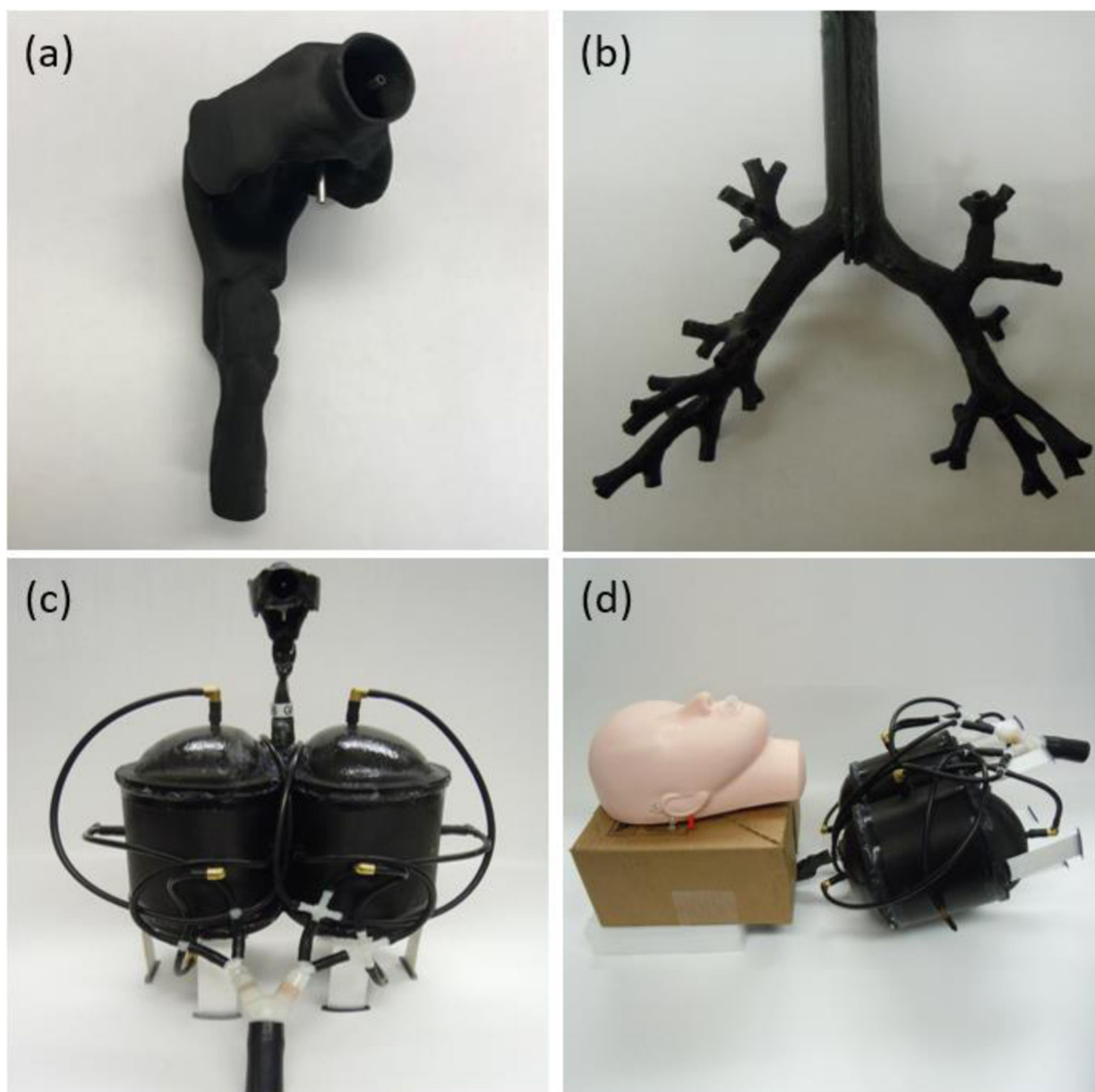
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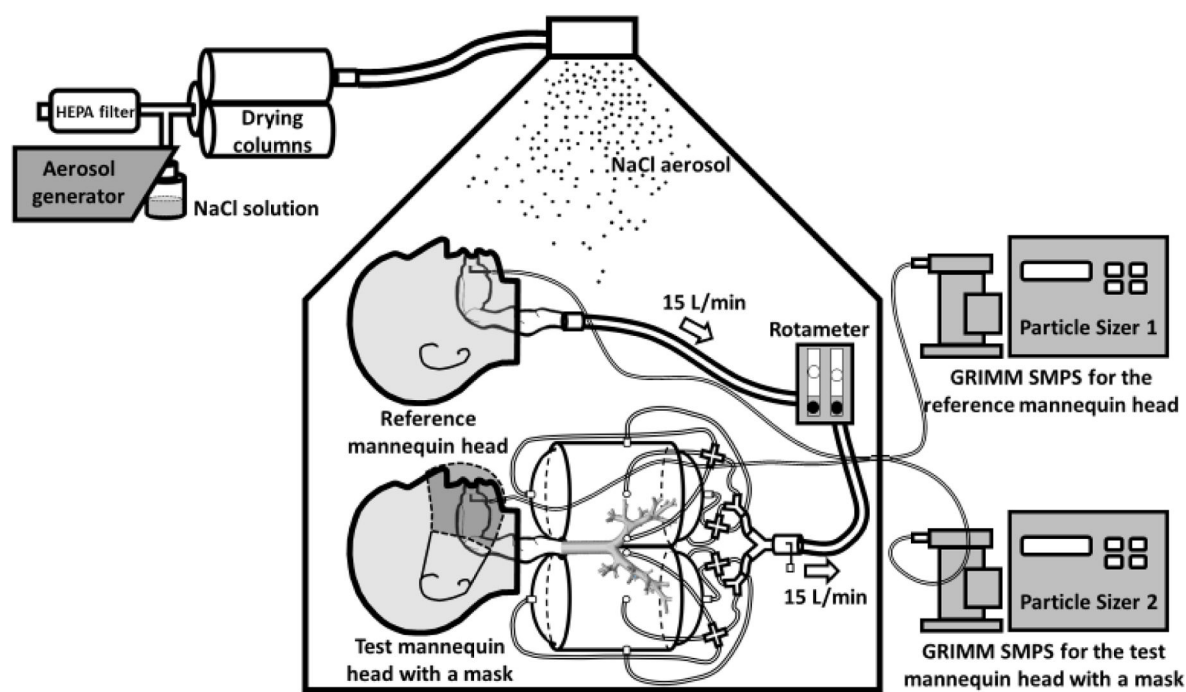


**Fig. 1.**  
The loose-fitting masks tested in this study: (a) cloth mask, (b) breathing valve mask, (c) KN95 mask, (d) smart mask, and the two reference masks: (e) surgical mask, (f) N95 mask.

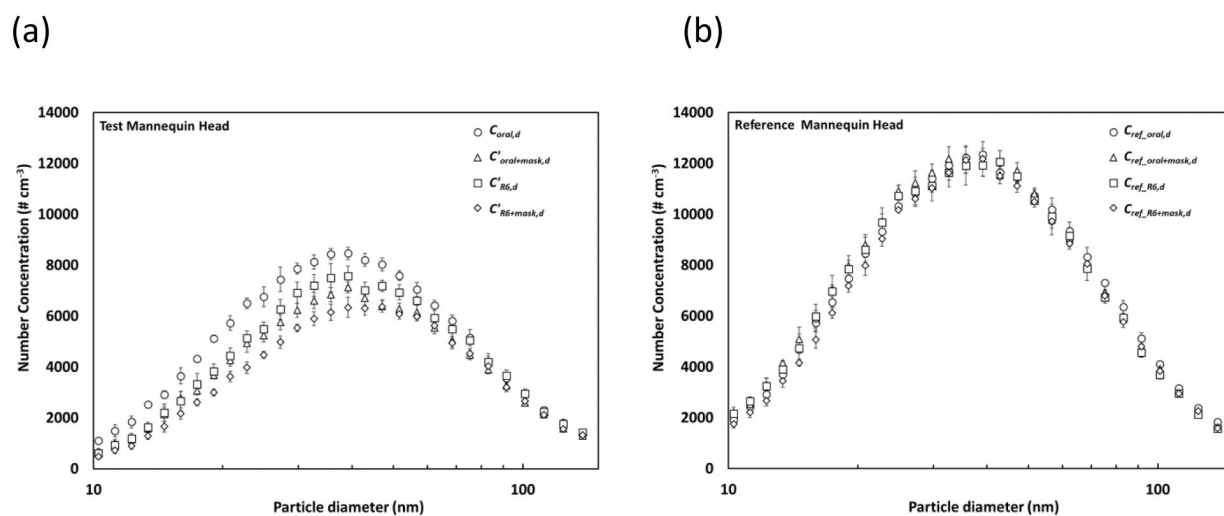


**Fig. 2.**  
(a) human oral airway replica, (b) TB airway replica down to parts of the 6<sup>th</sup> lung generation, (c) simplified airway system (R6), and (d) simplified airway system with a silicone mannequin head.

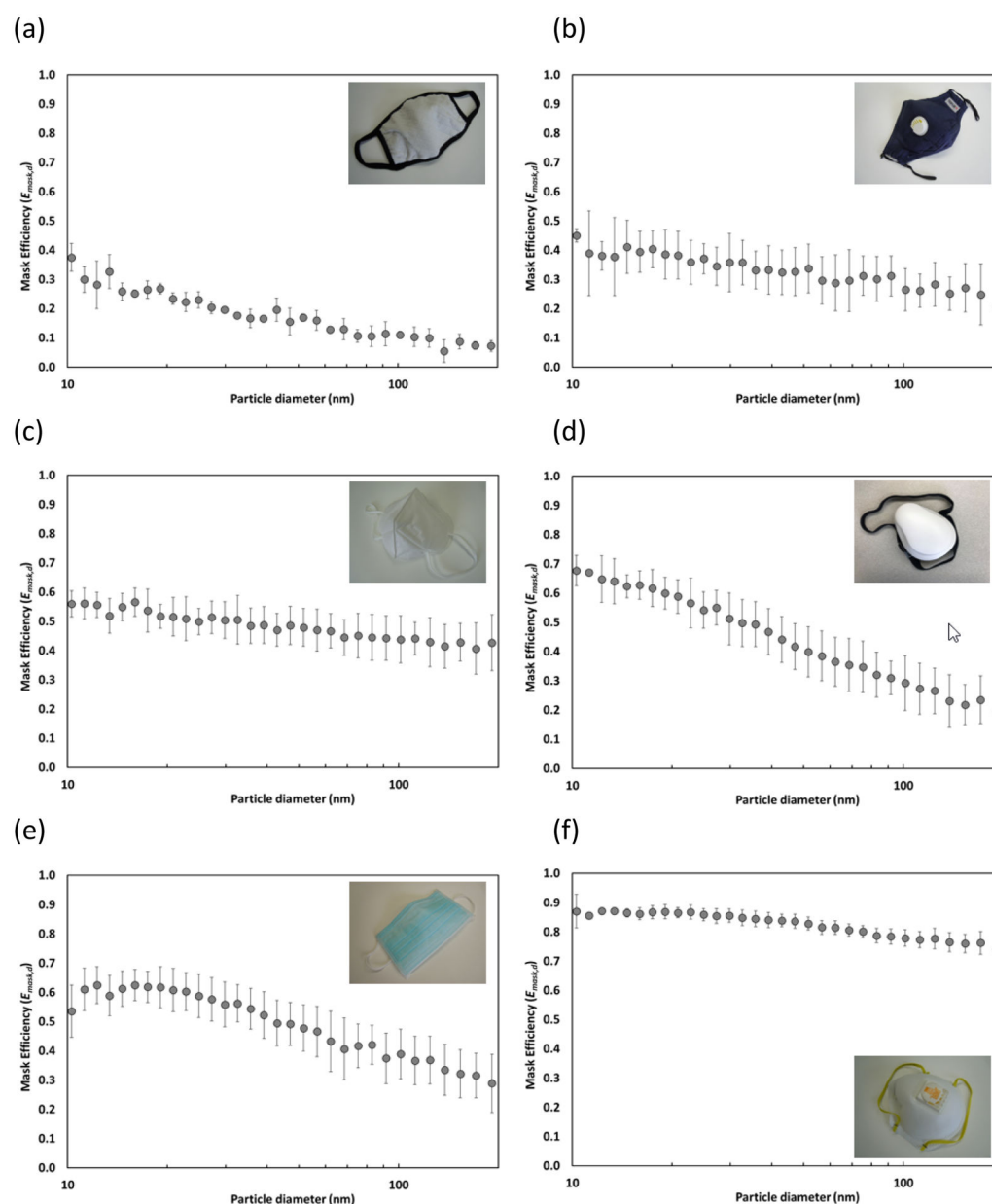




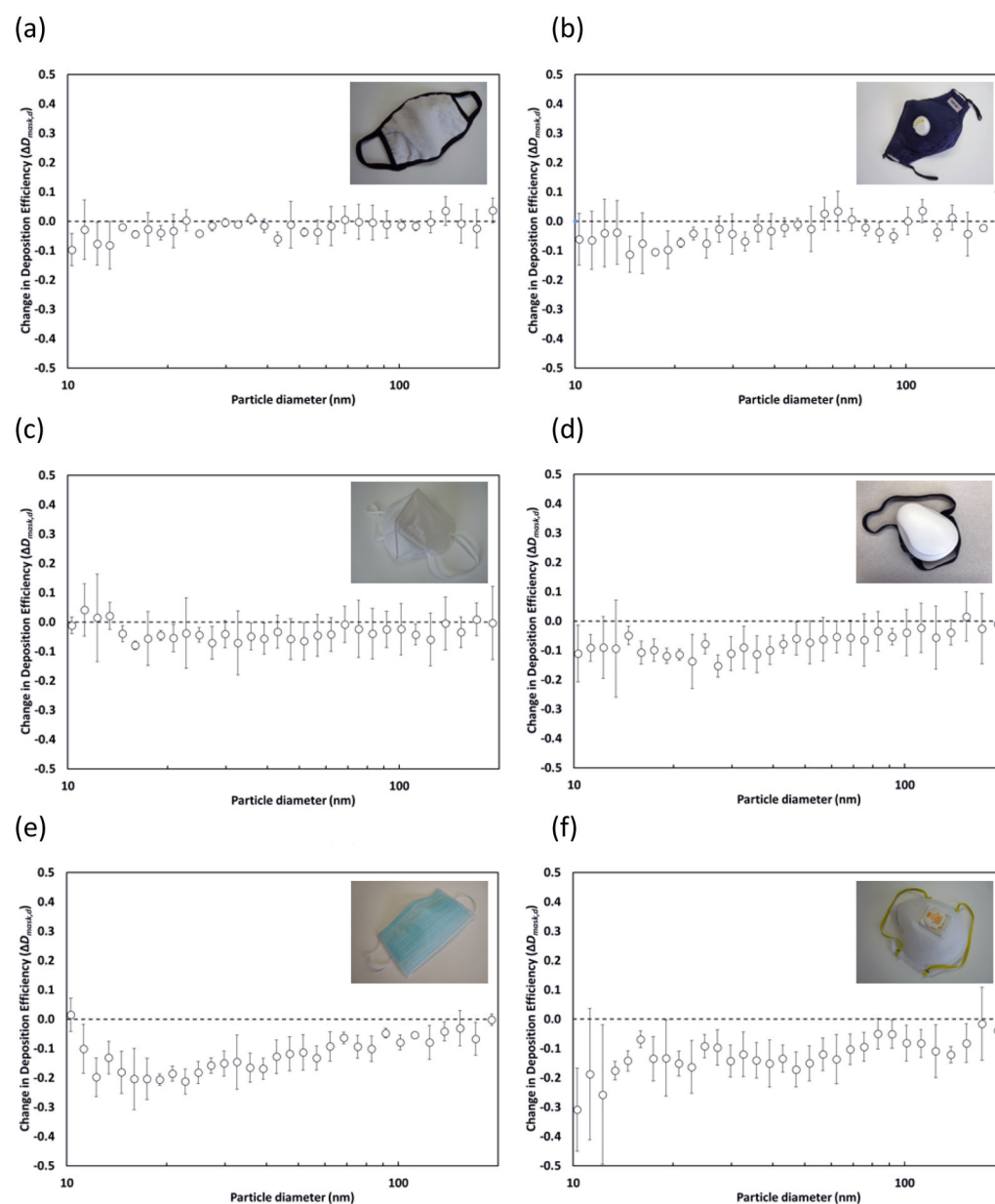
**Fig. 3.**  
The experimental set-up of the study.

**Fig. 4.**

The measured particle size distribution at (a) the test mannequin head, and at (b) the reference mannequin head (error bars represent the standard deviation.)



**Fig. 5.** The mask efficiency of the tested and reference masks (a) cloth mask, (b) breathing valve mask, (c) KN95 mask, (d) smart mask, (e) surgical mask, and (f) N95 mask (error bars represent the standard deviation.)

**Fig. 6.**

The effect of wearing masks on the ultrafine particle airway deposition efficiency (a) cloth mask, (b) breathing valve mask, (c) KN95 mask, (d) smart mask, (e) surgical mask, and (f) N95 mask (error bars represent the standard deviation.)