Filtration Performance and Fiber Shedding Behavior in Common Respirator and Face Mask Materials

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ABSTRACT

Wearing respirators and face masks is effective for protecting the public from COVID-19 infection. Thus, there is a need to evaluate the performance of the commonly used respirators and face masks. Two experimental systems were developed to investigate seven different mask materials, which have a fiber size range from 0.1 µm (100 nm) to 20 µm (20,000 nm). One of the systems is a computer-controlled setup for measuring the filtration performance, including size-dependent filtration efficiency and pressure drop, while the other system is for testing the fiber shedding behavior of the materials. The technique of scanning electron microscope (SEM) was applied to observe the dimensions and structures of those materials, which are made of nonwoven-fabrics electret-treated media, cotton woven fabrics, or nanofiber media. The study indicated that the 3M N95 respirator has the best overall filtration performance with over 95% efficiency and low pressure drop of 74.1 Pa. The two commercial cotton face masks have the worst filtration performance in general, with a filtration efficiency of around 25%. No broken fibers from the seven tested respirator and face mask materials were discovered; however, dendrite structures likely shed by the SHEMA97 face mask with a size comparable to its nanoscale fibers were identified. The reason for this phenomena is presented.

Keywords: Face mask, Filtration efficiency, Breathability, Fiber shedding, Fiber structures

1 INTRODUCTION

Since the widespread outbreak of the COVID-19 pandemic at the beginning of 2020, its impact to society, globally has been significant, including its economy, social activities, and public health. (Barouki et al., 2021; Chowdhury et al., 2021; Mueller et al., 2020; Padhan and Prabheesh, 2021; Pokhrel and Chetri, 2021; Ranjbari et al., 2021; Sarkodie and Owusu, 2021). During the pandemic, wearing respirators or face masks has become the new norm for people to effectively impede COVID-19 transmission (Mitze et al., 2020; Cheng et al., 2021; Howard et al., 2021; Li et al., 2021b). Thus, investigations on respirators and face masks are important as guidance for the public in combating the pandemic.

Researchers have discussed many aspects about respirators and face masks, such as standards, materials, testing and decontamination methods (Rengasamy et al., 2017; Chua et al., 2020; Forouzandeh et al., 2021; Ju et al., 2021). The filtration efficiency is one major factor that evaluates the material’s ability to filter airborne particles, bacteria, and viruses, while the pressure drop of a respirator or face mask indicates the breathability of the material. Therefore, an examination on the filtration performance of a respirator or face mask material should be conducted on both
the filtration efficiency and pressure drop. A few studies have been carried out to investigate the filtration efficiencies and pressure drop of N95 respirators and surgical face masks (Jung et al., 2014; Dugdale and Walensky, 2020; Sickbert-Bennett et al., 2020; Whiley et al., 2020; Joo et al., 2021; Steinbrook, 2021). Meanwhile, the performance of materials as alternatives to commercial face masks has also been explored (Konda et al., 2020; Ou et al., 2020; Bagheri et al., 2021; Dhanraj et al., 2021; Hao et al., 2021; Kwong et al., 2021; Morais et al., 2021). These studies suggested that multiple layers of a face mask can improve the performance and provide some level of protection, surgical masks, other N95 alternatives, and face masks treated by certain decontamination methods can still provide adequate protection against COVID-19 transmission, and improved fit between the mask and the wearer’s face increased efficacy of the respirator/face mask. However, currently there is still limited evidence available regarding a comparison of the filtration performance of various common respirator and face mask materials which takes into account a wide fiber size range from hundreds of nanometers to tens of microns (10s of thousands of nanometers).

Besides the filtration performance, the potential risk of inhaling shed fibers in micro/nanoscale should also be considered when evaluating respirator and face mask materials, since research indicates that inhalation of micro/nanoplastic have adverse effect on human health (Prata, 2018). Study on fiber shedding from respirators and face masks have been rarely reported. Han and He (2021) called for research efforts to assess the shedding of micro/nanoplastic debris from respirator and face mask materials. Since then, researchers have shown fiber shedding characteristics of face masks under certain treatments, such as immersion in liquid solutions, UV light exposure, mechanical agitation, and in reusability studies (Rathinamoorthy and Balasaraswathi, 2022; Asadi et al., 2020; Chen et al., 2021; Morgana et al., 2021; Saliu et al., 2021; Shen et al., 2021; Wang et al., 2021). They found that these treatments all can cause disposable face masks to become significant sources of micro/nanoplastics to the environment. Li et al. (2021a) conducted breathing simulation experiments to observe and count microplastics that could come from both the air and the face masks themselves. Their results indicated that respirators/face masks, especially N95 respirators, can significantly decrease the inhalation risk of fiber-like microplastic when they are used as directed. But so far, no experimental system has been developed to systematically test shed fibers directly from untreated respirator and face mask materials and evaluate its potential to harm the wearer’s health.

The present study is aimed to determine the filtration performance of various common respirators and face masks with a wide range of fiber sizes and identify potential fiber shedding directly from those materials. This paper first discusses the two experimental systems developed for filtration performance measurements and fiber shedding behavior observations, respectively. Then the seven respirator and face mask materials tested by the experimental systems are introduced with their SEM images displayed. Results on both the filtration performance and fiber shedding behavior investigations are presented and analyzed in the Results and Discussion section. At the end of the paper, a summary of the current research work is given.

2 METHODS

2.1 Filtration Performance Testing System

The computer-controlled testing system for measuring the size-dependent filtration efficiency and pressure drop of respirator and face mask materials was developed in the Particle Technology Lab (PTL) at the University of Minnesota. The system applies the size-resolved fractional efficiency measurement technique, which has been described in detail by Ou et al. (2020). The schematic of the experimental setup is given in Fig. 1, which is cited from the paper. Fig. 2 shows the photos of the apparatus for our testing setup. The system is capable of testing size-dependent filter collection efficiency from 20 nm to 1000 nm, under a variety of filtration velocities. A LabView algorithm adjusts the Differential Mobility Analyzer (DMA) voltage, sheath flow rate and aerosol inlet/outlet flow rates, and changes the switching valve to monitor the upstream/downstream particle number concentrations with a Condensation Particle Counter (CPC). The aerosol generator applied here is a Collison type atomizer (TSI 3076, Shoreview, MN). The polydisperse NaCl aerosol was first generated by atomizing a solution of NaCl in Deionized water. The polydisperse aerosol then flowed through a diffusion dryer to remove excess moisture from the atomizer solution so
Fig. 1. Schematic of the filtration performance measurement setup (Ou et al., 2020).

Fig. 2. Photos showing the apparatus of the computer-controlled filtration performance testing system.

that the humidity level of the aerosol was controlled below the deliquescence relative humidity of NaCl. A Po-210 radioactive neutralizer (0.5 mCi) and a DMA were used as a size selector and only allowed NaCl particles with a narrow mobility range to be extracted. The monodisperse particles were then passed through another Po-210 neutralizer (0.5 mCi) to bring the charge level of these particles to a Boltzmann equilibrium charge distribution, a steady state distribution best representing the charge level of ambient aerosols. The neutralized test particles are then mixed with dilution air and sent into the filter holder for filtration efficiency measurements. A 57-mm diameter circle was cut from each respirator/face mask material, and placed inside a stainless-steel filter holder with gaskets sealing to stop any leakage. The efficiency of the tested material was measured by sampling the aerosol concentrations at both the upstream and downstream of the filter holder with a CPC. After each measurement, the fractional filtration efficiency (FE) of the sample is calculated by

\[ FE = 1 - \frac{C_{\text{dn}}}{C_{\text{up}}} \left( \frac{C_{\text{blank, dn}}}{C_{\text{blank, up}}} \right) \]  

where \( C_{\text{up}} \) and \( C_{\text{dn}} \) are the number concentrations of NaCl particles at the upstream and
downstream of the sample, respectively, and \( C_{\text{blank,up}} \) and \( C_{\text{blank,dn}} \) are the number concentrations of NaCl particles at the upstream and downstream of the material when no sample is inserted in the filter holder, respectively. Filtration efficiencies for particle sizes from 30 nm to 400 nm were measured for each respirator/face mask, which contains the Most Penetrating Particle Size (MPPS) of both electret and mechanical filtration materials. A filtration velocity of 10.5 cm s\(^{-1}\) was chosen for all the experiments, which equals to 85 L min\(^{-1}\) at a filtration area of 135 cm\(^2\). The flowrate of 85 L min\(^{-1}\) is the standard rate at which NIOSH certifies N95s, and 135 cm\(^2\) is the lower end of filtration surface area of typical commercial N95 respirators. The pressure drop across each material was measured by a calibrated pressure transducer located across the filter holder.

### 2.2 Fiber Shedding Behavior Testing System

Another experimental system was built in the PTL at the University of Minnesota to directly identify whether respirator and face mask materials shed fibers during use. Fig. 3 presents the schematic diagram of the testing system. It was equipped with a pulse generator to generate high pulse pressure at the upstream of the testing filter holder. The samples of the tested respirator and face mask materials were cut into 47-mm circles and sealed inside the stainless-steel testing filter holder. Downstream of the testing filter holder, an Isopore membrane filter was mounted inside the sampling filter holder. During each pulsing cycle, the compressed air with high pulse pressure from the system upstream could potentially break the fibers of the materials and push the broken fibers onto the downstream sampling filter. The bellows were set between the two filter holders, which was to absorb the excessive airflow during each pulse and gradually release the airflow back to the sampling filter when each pulsing cycle ends. A vacuum pump was connected downstream of the sampling filter holder to balance the system flow rate. A pressure transducer was installed to monitor the pressure drop across the tested respirator and face mask materials. A LabView computer program was developed to control the pulsing cycles of the compressed air from the pulse generator. The highest pulse pressure of the current setup is 3.5 kg cm\(^{-2}\) (1 kg cm\(^{-2}\) = 98.07 kPa or 14.2 PSIG), with a pulse duration of 0.1 seconds (s) and a pulse frequency of 0.25 s\(^{-1}\). Fig. 4 shows a photo of the fiber shedding experimental system.

Each fiber shedding experiment was conducted continuously for 24 hours, during which the system generated 21,600 pulses in total. Once the testing experiments were over, the downstream Isopore membrane filters were prepared as SEM samples, which are shown in Fig. 5. The black color is from the conductive tape which pasted the Isopore filters onto the SEM sample holder. Then the samples were coated with conductive material and taken for SEM scanning sessions. The SEM images were scanned through to identify any broken fiber structure shed by the tested samples.

**Fig. 3.** Schematic of the testing system for fiber shedding behaviors of respirator and face mask materials.
3 MATERIALS

Seven different respirator and face mask materials were investigated during the study, which are shown in Table 1 with their material types and fiber size ranges listed. The first three respirators/face masks are nonwoven-fabrics electret-treated media, while the next two materials are made of cotton woven fabrics. The last two materials have the fiber size range in nanometer, so we refer to them as nanofiber materials in this paper. The Cummins EX101 filtration material was applied for new mask designs as viable alternatives to traditional N95 respirators (Griffin et al., 2022). According to the table, the respirator and face mask materials investigated in the study have a wide spread of fiber size ranges from 100 nm (0.1 µm) to 20 µm.

Fig. 6 presents the SEM images for all the seven materials with dimensions and fiber structures shown on the images. The size range listed here is based on the dimensional measurements conducted during the SEM scanning sessions. The magnification magnitude for each image is shown at the bottom. One thing to be noted is that these materials all have multiple layers. The SEM scanning was carried out on the layer that performs the main filtration function for each material. For instance, the Cummins EX101 material has four layers, and Fig. 6(g) shows the layer with the finest fiber size (hundreds of nanometers) which contributes the most to its filtration efficiency. The SHEMA97 face mask has the finest fiber size among the seven materials, and the two cotton face masks have the largest fiber size, as indicated in Table 1.
Table 1. Respirator and face mask materials investigated in the study.

<table>
<thead>
<tr>
<th>Name/brand</th>
<th>3M N95 9010</th>
<th>Airpop face mask</th>
<th>Surgical face mask</th>
<th>GAP</th>
<th>Athleta</th>
<th>SHEMA97</th>
<th>Cummins EX101</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material type</td>
<td>Electret</td>
<td>Electret</td>
<td>Electret</td>
<td>Cotton</td>
<td>Cotton</td>
<td>Nanofiber</td>
<td>Nanofiber</td>
</tr>
<tr>
<td>Fiber size range</td>
<td>0.98 µm–4.38 µm</td>
<td>0.552 µm–4.47 µm</td>
<td>1.25 µm–9.81 µm</td>
<td>12.3 µm–23.7 µm</td>
<td>11.6 µm–15.6 µm</td>
<td>0.089 µm–0.111 µm</td>
<td>454 nm–1.64 µm</td>
</tr>
</tbody>
</table>

Fig. 6. SEM images showing the dimensions and structures of 3M N95 particulate respirator 9010, Airpop face mask, surgical face mask, GAP face mask, Athleta face mask, SHEMA97 face mask and Cummins EX101 filtration material. The left column presents the images with higher magnification, and the right column with lower magnification.
4 RESULTS AND DISCUSSION

4.1 Filtration Performance

To evaluate the filtration performance of the above respirator and face mask materials, their filtration efficiencies and pressure drops were measured. For each material, five measurements were conducted, and the averaged measurement results on the filtration efficiencies and pressure drops are presented in Fig. 7 and Table 2, respectively. As indicated in the figure, the 3M N95 particulate respirator 9010 (3M N95) has the highest filtration efficiency over the majority of the studied particle size range from 0.05 µm to 0.3 µm, followed by the Airpop face mask and the
Cummins EX101 material. The 3M N95 respirator and Airpop face mask have similar most penetrating particle size (MPPS) at around 0.05 μm, while the Cummins EX101 has the MPPS at around 0.1 μm. This is because they are different types of filtration materials with the former two being electret-treated media and the later one is nanofiber media. According to Figs. 6(a) and 6(b), the 3M N95 respirator and Airpop face mask have similar fiber dimensions and structures, contributing to the similarity of their efficiency curves. Although the Cumming EX101 has high filtration efficiency, its pressure drop is also the highest among all the tested materials. The surgical face mask, which is one commonly used face mask during the COVID-19 pandemic, has a filtration efficiency between 70–85% over the size range studied. The two cotton face masks of GAP and Athleta have the lowest filtration efficiency among all seven tested materials. Meanwhile, the two cotton materials also yield quite high pressure drops. The efficiency level of the SHEMA97 nanofiber face mask falls in between the surgical face mask and the cotton face masks, and it has the lowest pressure drop. Its low efficiency and low pressure drop is caused by the high porosity of the nanofiber material, which can be observed in Fig. 6(f). In general, with the fiber size of a filter material increases, the filtration efficiency decreases.

In addition, figure of merit is a suggested performance factor that combines the measured filtration efficiency and pressure drop together to characterize the overall performance of a respirator/face mask material. It is defined by the following equation.

\[
F = \frac{\ln(1 - EF)}{\Delta P} \times 100
\]  

(2)

where \( EF \) is the filtration efficiency and \( \Delta P \) is the pressure drop of the material. Fig. 8 shows the calculated values of figure of merit for the seven materials. The 3M N95 respirator has the best...
overall performance, followed by the Airpop face mask, while the two commercial cotton face masks have the worst overall performance.

4.2 Fiber Shedding Performance

Experiments were performed to understand if there are broken fibers directly shed from the studied materials. The tests were conducted for each material with three different upstream pulse pressures of 1.0, 2.0 and 3.0 kg cm$^{-2}$ (1.0 kg cm$^{-2}$ = 98.07 kPa or 14.22 PSIG). The pressure drop cycle across the Cummins EX101 filtration material was illustrated in Fig. 9. At a pulse pressure of 3.0 kg cm$^{-2}$, the pressure drop across the material can reach over 1000 Pa. As mentioned previously, during the filtration efficiency measurements the average pressure drop across the Cumming EX101 material is 319 Pa at a testing airflow velocity of 10.5 cm s$^{-1}$, equivalent to the standard flow rate at which NIOSH certifies N95 respirators. Thus, the airflow velocity subjected to the face mask materials at an upstream pulse pressure of 3.0 kg cm$^{-2}$ in our testing system has far exceeded the face velocity of a face mask when the wearer is breathing. Therefore, it is reasonable to set up the upstream pulse pressure to be 1.0, 2.0 and 3.0 kg cm$^{-2}$ for the current shedding tests.

For each fiber shedding test, the experimental system generated pulsing airflow to attack the materials for 24 hours. Then the downstream Isopore membrane sampling filter was brought for SEM scanning to identify if there are any broken, shed fibers. Fig. 10 shows the examples of the SEM images of the sampling filters for the tests on both the Cummings EX101 material and Airpop face mask at different upstream pulse pressures. The black dots in the images are pores with a 2 µm diameter on the Isopore membrane filter. Only a small amount of contaminants coming from the upstream airflow and system apparatus can be observed, and no broken fiber shed from the materials themselves was found. After conducting the shedding tests for all the seven respirator and face mask materials, the same conclusion was drawn that none of these materials shed fibers at the current attacking airflow velocity which already exceeds the breathing airflow velocity for respirators/face masks under actual use conditions.

In addition, an interesting phenomena was discovered for the SHEMA97 nanofiber face mask. Many dendrite structures with the size comparable to the nanofiber of the material were found on the Isopore membrane sampling filter. Fig. 11 shows the SEM images of the dendrite structures on the sampling filter. To further explore this phenomenon, the tested samples of the material
was brought back for SEM scanning. The dendrite structures were also found on the nanofibers of the tested SHEMA97 face mask material, as shown in Fig. 12. The compressed air at the upstream of the system was discovered to contain a small amount of contaminants. It is likely that the contaminants can agglomerate and form larger particles in the shape of dendritic structures.

![Graph](image)

**Fig. 9.** Measured pressure drops across the Cummings EX101 material as a function of time with three different upstream pulse pressures of 1.0, 2.0 and 3.0 kg cm\(^{-2}\) (1.0 kg cm\(^{-2}\) = 98.07 kPa or 14.22 PSIG).

![SEM Images](image)

**Fig. 10.** SEM images of the Isopore membrane sampling filters after the shedding tests for the Cummings EX101 material with an upstream pulse pressure of (a) 1.0 kg cm\(^{-2}\), (b) 2.0 kg cm\(^{-2}\) and (c) 3.0 kg cm\(^{-2}\), and for the Airpop face mask with a pulse pressure of (d) 3.0 kg cm\(^{-2}\). Two SEM images of clean Isopore membrane filters are presented in (e) and (f) as a control.
Fig. 11. SEM images of the dendrite structures found on the Isopore membrane sampling filters after the shedding tests for the SHEMA97 face mask.

Fig. 12. SEM images showing the dendrite structures growing on the nanofibers of the SHEMA97 face mask material with comparable size to the nanofibers.

the fibers of the filtration material. Once they become large enough, the structures were shed by the face mask material and captured by the downstream Isopore membrane sampling filter. A control test with clean upstream compressed air was also conducted, and no dendrite structures were found on either the downstream Isopore sampling filter or the nanofibers of the tested...
SHEMA97 face mask materials themselves. However, further investigations should be carried out to confirm this hypothesis.

5 CONCLUSIONS

We investigated the filtration performance and fiber shedding behaviors of seven different respirator and face mask materials in the fiber size range of 0.1 µm (100 nm) to 20 µm (20,000 nm). The microscope images of the materials obtained by applying the SEM technique were presented. A computer-controlled testing system was built to measure size-dependent filtration efficiencies and pressure drops for these materials, while an experimental setup was developed to generate high pulse pressure to perform direct fiber shedding tests. It was found that the 3M N95 respirator and the Airpop face mask have the best overall filtration performance. The fiber shedding experiments illustrated that the seven materials have no broken fiber shedding at the upstream pulse pressures of 1.0, 2.0 and 3.0 kg cm–2, which generates an attacking airflow velocity already exceeding the breathing airflow velocity under actual use conditions. The experimental results also revealed many dendrite structures with the size comparable to the nanofibers of the SHEMA97 face mask found on the Isopore membrane sampling filters, which was likely caused by the growing of the contaminants in the upstream airflow on the nanofibers of the material during the shedding experiments.

One limitation of the study is that the SEM samples prepared from the Isopore membrane filters sample a small portion of the entire sampling filters, which makes it difficult to evaluate the shed fibers from the tested respirator and face mask materials in a quantitative manner, although this method can tell if substantial fiber shedding happens during the testing periods. In order to quantitatively investigate the fiber shedding characteristics of respirator and face mask materials, novel experimental methods should be developed. In addition, as mentioned by a few articles cited in the introduction section, certain treatments can increase the microfiber release from disposable face masks. Therefore, future research is needed to explore different treated or worn face masks and perform quantitative analysis on their fiber shedding behaviors.

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REFERENCES


