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## Inward and outward effectiveness of cloth masks, a surgical mask, and a face shield

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Jin Pan, Charbel Harb, Weinan Leng, Linsey C. Marr

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1 **Inward and outward effectiveness of cloth masks, a surgical**  
2 **mask, and a face shield**

3 Jin Pan, Charbel Harb, Weinan Leng, Linsey C. Marr\*

4 Civil and Environmental Engineering, Virginia Tech, Blacksburg, VA 24061

5 \*Corresponding author: [lmarr@vt.edu](mailto:lmarr@vt.edu)

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## 7 **Abstract**

8 We evaluated the effectiveness of 11 face coverings for material filtration efficiency, inward  
9 protection efficiency on a manikin, and outward protection efficiency on a manikin. At the most  
10 penetrating particle size, the vacuum bag, microfiber cloth, and surgical mask had material  
11 filtration efficiencies >50%, while the other materials had much lower filtration efficiencies.  
12 However, these efficiencies increased rapidly with particle size, and many materials had  
13 efficiencies >50% at 2  $\mu\text{m}$  and >75% at 5  $\mu\text{m}$ . The vacuum bag performed best, with efficiencies  
14 of 54-96% for all three metrics, depending on particle size. The thin acrylic and face shield  
15 performed worst. Inward protection efficiency and outward protection efficiency were similar for  
16 many masks; the two efficiencies diverged for stiffer materials and those worn more loosely (e.g.,  
17 bandana) or more tightly (e.g., wrapped around the head) compared to a standard earloop mask.  
18 Discrepancies between material filtration efficiency and inward/outward protection efficiency  
19 indicated that the fit of the mask was important. We calculated that the particle size most likely to  
20 deposit in the respiratory tract when wearing a mask is  $\sim 2 \mu\text{m}$ . Based on these findings, we  
21 recommend a three-layer mask consisting of outer layers of a flexible, tightly woven fabric and an  
22 inner layer consisting of a material designed to filter out particles. This combination should  
23 produce an overall efficiency of >70% at the most penetrating particle size and >90% for particles  
24 1  $\mu\text{m}$  and larger if the mask fits well.

25

## 26 **Introduction**

27 Amid mounting evidence that COVID-19 is transmitted via inhalation of virus-laden aerosols  
28 (Allen and Marr 2020; Asadi et al. 2020; Hadei et al. 2020; Morawska et al. 2020; Prather, Wang  
29 and Schooley 2020), universal masking has emerged as one of a suite of intervention strategies for  
30 reducing community transmission of the disease. There is a correlation between widespread mask  
31 wearing (The Economist 2020), or at least interest in masks (Wong et al. 2020), and lower  
32 incidence of COVID-19 by country and between mask mandates and county-level COVID-19  
33 growth rates in the US (Lyu and Wehby 2020), but a causal relationship has not been confirmed.

34 Due to a shortage of medical masks and respirators, some public health agencies have  
35 recommended the use of cloth face coverings. While there have been numerous studies on the  
36 ability of surgical masks and N95 respirators to filter out particles, far less is known about the  
37 ability of cloth masks to provide both inward protection to reduce the wearer's exposure and  
38 outward protection for source control. Ideally, a randomized controlled trial would be conducted,  
39 but in the absence of such evidence, we can evaluate the ability of masks to block particles under  
40 controlled conditions.

41 Reviews on the use of masks in both healthcare and non-healthcare settings to reduce transmission  
42 of other respiratory diseases mostly show a protective effect. A systematic review and meta-  
43 analysis of interventions against respiratory viruses found that wearing simple masks was highly  
44 effective at reducing transmission of severe acute respiratory syndrome (SARS) in five case  
45 control studies (Jefferson et al. 2008). In contrast, a review of 10 randomized controlled trials of  
46 mask wearing in non-healthcare settings concluded that there was not a substantial effect on

47 influenza transmission in terms of risk ratio, although most of the studies were underpowered and  
48 compliance was not perfect (Xiao et al. 2020). A systematic review of interventions against SARS-  
49 CoV-2 and the coronaviruses that cause SARS and Middle East respiratory syndrome found that  
50 the use of face masks could result in a large reduction in the risk of infection (Chu et al. 2020).

51 Laboratory studies have demonstrated the ability of surgical masks to provide both inward and  
52 outward protection against viruses. Testing of eight different surgical masks on a manikin with  
53 influenza virus in droplets/aerosols of size 1–200  $\mu\text{m}$  found that the amount of virus detected  
54 behind the mask was reduced by an average of 83%, with a range of 9% to 98% (Makison Booth  
55 et al. 2013). The ability of a mask to block influenza virus was correlated with its ability to block  
56 droplets/aerosols containing only phosphate buffered saline (PBS) and bovine serum albumin  
57 (BSA). Surgical masks used for source control on influenza patients during breathing and coughing  
58 reduced the amount of virus released into the air in coarse ( $> 5 \mu\text{m}$ ) and fine ( $\leq 5 \mu\text{m}$ ) aerosols by  
59 96% and 64%, respectively (Milton et al. 2013). In a follow-up study, surgical masks blocked the  
60 release of seasonal coronaviruses in coarse and fine aerosols to undetectable levels, while they  
61 blocked influenza virus in most but not all patients (Leung et al. 2020).

62 There have been some studies of cloth masks, which have been found to be less protective than  
63 surgical masks in most, but not all, cases. A variety of cloth materials mounted in a filter holder  
64 removed 49% to 86% of aerosolized bacteriophage MS2, compared to 89% removal by a surgical  
65 mask (Makison Booth et al. 2013). According to fit tests on 21 adults in the same study, homemade,  
66 100% cotton masks provided median inward filtration efficiencies of 50%, compared to 80% for  
67 surgical masks. The filtration efficiencies of 44 materials and medical masks, challenged with  
68 sodium chloride (NaCl) particles of diameter 0.03–0.25  $\mu\text{m}$ , ranged from  $<10\%$  for polyurethane

69 foam to nearly 100% for a vacuum cleaner bag (Drewnick et al. 2020). Cloth masks, sweatshirts,  
70 t-shirts, towels, and scarves evaluated in a TSI Automated Filter Tester had filtration efficiencies  
71 of 10–60% against polydisperse NaCl particles ranging in size from 0.02 to 1.0  $\mu\text{m}$ ; the towels  
72 performed best (Rengasamy, Eimer and Shaffer 2010). Homemade masks made from tea cloths  
73 and worn by volunteers had a median inward filtration efficiency of 60%, compared to 76% for a  
74 surgical mask (van der Sande, Teunis and Sabel 2008). Pieces of a bandana, veil, shawl,  
75 handkerchief, and cotton t-shirt mounted in a filter holder and challenged with volcanic ash  
76 particles were found to have filtration efficiencies of 18% to 43% in terms of mass concentration  
77 (Mueller et al. 2018).

78 N95 respirators and cloth masks serve different purposes, so the testing procedure for N95s is not  
79 necessarily well-suited for cloth masks. An N95 must be able to protect an individual worker in  
80 high-risk situations. A critical component of its efficacy is the fit test to ensure that the respirator  
81 seals completely to the face with no leaks. On the other hand, the overall goal of wearing cloth  
82 masks during the COVID-19 pandemic is to reduce community transmission. Cloth masks provide  
83 some degree of both source control and exposure reduction. While an N95 must block at least 95%  
84 of NaCl particles of the most penetrating size, 0.3  $\mu\text{m}$ , cloth masks can be effective if they remove  
85 at least some particles, particularly those of the size that is most relevant for transmission.  
86 Although we do not yet know which size particles are most important, we can make some  
87 inferences from existing studies. SARS-CoV-2 and other viruses are carried by particles ranging  
88 in size from  $<1 \mu\text{m}$  to  $>5 \mu\text{m}$  (Chia et al. 2020; Liu et al. 2020; Yan et al. 2018; Yang, Elankumaran  
89 and Marr 2011). A SARS-CoV-2 virion is 0.1  $\mu\text{m}$  in diameter, but it is carried in respiratory  
90 droplets that also contain salts, proteins, and other components of respiratory fluid. Even if all the

91 water evaporates, the mass of the non-volatile components is expected to be orders of magnitude  
92 larger than that of any viruses that might be present (Marr et al. 2019), so the size of a particle  
93 carrying an intact virus must be quite a bit larger than 0.1  $\mu\text{m}$ . The smaller mode of respiratory  
94 particles produced during breathing and speaking is centered around 1  $\mu\text{m}$ , and there are relatively  
95 few particles smaller than 0.5  $\mu\text{m}$  (Johnson et al. 2011). Influenza transmission between ferrets  
96 has been shown to be mediated by particles larger than 1.5  $\mu\text{m}$  (Zhou et al. 2018). Thus, it seems  
97 prudent to evaluate mask performance over a range of particle sizes, particularly those larger than  
98 0.3  $\mu\text{m}$ .

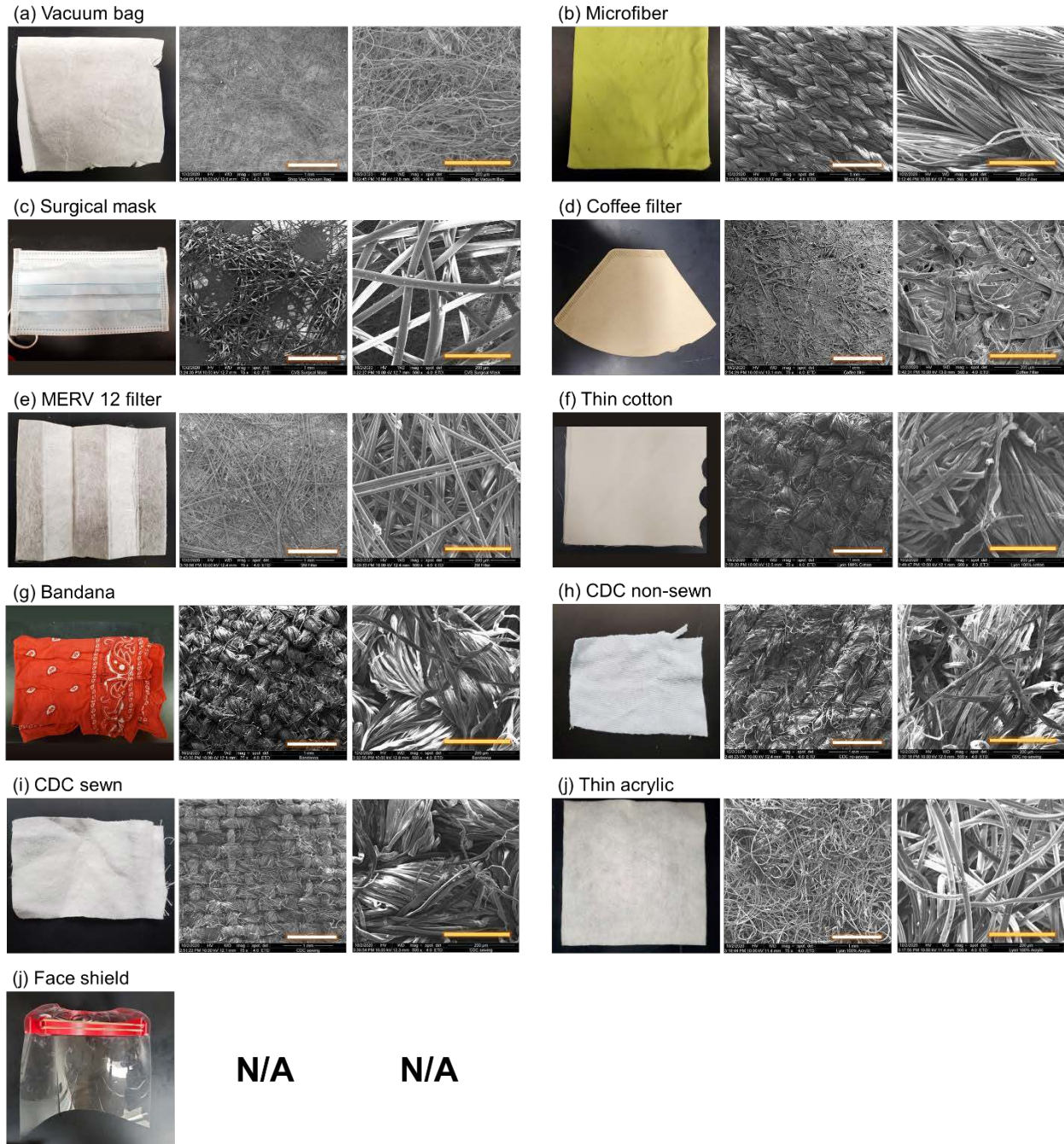
99 Given the advice of public health agencies for the general public to wear face coverings and the  
100 paucity of knowledge about their effectiveness, the objective of this study is to evaluate the  
101 efficiency of cloth masks compared to a surgical mask and a face shield at blocking particles over  
102 a wide range of sizes. We first measure the filtration efficiency of materials under ideal conditions  
103 and then investigate both inward and outward protection efficiency of the materials when worn as  
104 masks on a manikin. We expect that efficiency on a manikin will be lower than in a filter holder  
105 due to leakage around the mask and that outward efficiency will be higher than inward efficiency  
106 due to differences in velocity of the particles as they approach the material. The results of this  
107 study will contribute to understanding how universal masking might reduce transmission of  
108 COVID-19 and other respiratory diseases.

## 109 **Methods**

### 110 *Masks*

111 We tested nine materials that were fashioned into masks, one surgical mask, and one face shield,  
112 shown in Figure 1. To make the masks, we cut materials into 15.5 cm × 10 cm rectangles and  
113 securely taped them to a frame tailored from a surgical mask, except for two designs that followed  
114 instructions from the US Centers for Disease Control and Prevention (CDC). These included a  
115 sewn mask made of two layers of a 200-thread count cotton pillowcase and a non-sewn mask cut  
116 from a cotton t-shirt (Centers for Disease Control and Prevention 2020). The instructions for the  
117 non-sewn mask used in this study have been supplanted with an updated design involving a large  
118 square of fabric and rubber bands. The surgical mask had a single layer and was advertised to meet  
119 ASTM level 1 specifications, which require  $\geq 95\%$  filtration efficiency of particles larger than 1  
120  $\mu\text{m}$ . We characterized the texture and structure of the masks using a scanning electron microscope  
121 (FEI Quanta 600 FEG). Because it is not possible to generate or characterize particles spanning a  
122 wide range of sizes with a single experimental setup, we designed several different protocols for  
123 testing masks, optimizing among different types of equipment and detection limits, as described  
124 below.





125

126 Figure 1. Ten mask materials and a face shield. SEM images are shown at two scales: the white scale bar represents 1  
127 mm and the yellow one represents 200 μm. There are no SEM images for the face shield, which was made of a plastic  
128 sheet.

129 ***Material filtration efficiency***

130 Evaluation of the materials for filtration efficiency followed a protocol based on National Institute  
131 of Occupational Safety and Health (NIOSH) testing procedures. Using a Collison 3-jet nebulizer  
132 (BGI MRE-3, BGI Inc., MA, USA), we generated challenge particles of size 0.04 to 1  $\mu\text{m}$  from a  
133 2% NaCl solution. The particles filled a 280 L polyethylene chamber (Sigma AtmosBag, Sigma-  
134 Aldrich, ON, Canada), in which we placed a small fan to promote mixing. The temperature and  
135 humidity inside the chamber were 22  $^{\circ}\text{C}$  and 25-35% RH, respectively. We measured particle  
136 concentrations and size distributions using a scanning mobility particle sizer (SMPS 3936, TSI  
137 Inc., MN, USA), with the particle density set to 2.165  $\text{g}/\text{cm}^3$  (NaCl) to convert from mobility  
138 diameter to aerodynamic diameter. We cut out circular pieces of each material to mount in a 25  
139 mm stainless steel filter holder (Advantec, Cole Parmer, IL, USA) that was connected to a vacuum  
140 line whose flow rate was maintained at 2.7 L/min by a mass flow controller (32907-53, Cole  
141 Parmer, IL, USA). The SMPS sampled from this line at a rate of 0.3 L/min, producing a total flow  
142 rate of 3.0 L/min and a corresponding face velocity of 10 cm/s through the material. Clean make-  
143 up air flow to the chamber was provided through a high-efficiency particulate air filter capsule  
144 (12144, Pall Corporation, MA, USA). We checked the material filtration efficiency of an N95  
145 respirator and the microfiber cloth with and without a Kr-85 radioactive neutralizer (3012, TSI  
146 Inc., MN, USA) or soft x-ray neutralizer (XRC-05, HCT CO., Ltd, Republic of Korea) after the  
147 nebulizer, and did not find significant differences (Figures S1-S3), so we did not employ a  
148 neutralizer in subsequent tests. To calculate the size-resolved filtration efficiency, we compared  
149 measurements with the material in the filter holder to those made with an empty filter holder, as  
150 shown in equation (1), where  $FE$  is the material filtration efficiency;  $D_P$  is the particle diameter;

151  $C_{blank}$  is the concentration of challenge particles measured downstream of the empty filter holder,  
152 and  $C_{material}$  is the concentration of particles downstream of the material:

$$FE(D_p) = \left(1 - \frac{C_{material}(D_p)}{C_{blank}(D_p)}\right) \times 100\% \quad (1)$$

153 We conducted these experiments in triplicate using three different pieces cut from each material.

154 In addition to challenging the masks with submicron particles generated by the Collison nebulizer,  
155 we also tested larger particles ranging in size from 2 to 5  $\mu\text{m}$ . We generated these from a 2% NaCl  
156 solution using a flow focusing monodisperse aerosol generator (FMAG, TSI Inc., MN, USA). We  
157 measured the particles using an aerodynamic particle sizer spectrometer (APS 3321, TSI Inc., MN,  
158 USA). Because the APS samples at a flow rate of 1.0 L/min, we adjusted the vacuum line to 2.0  
159 L/min to produce a total flow rate of 3.0 L/min, the same as used for testing smaller particles.  
160 Clean make-up air was also applied as described above. We calculated the filtration efficiency  
161 according to equation (1) in triplicate. We also measured the pressure drop of each material in the  
162 filter holder using a differential pressure gauge (Minihelic II 2-5005, Dwyer Instruments, IN,  
163 USA).

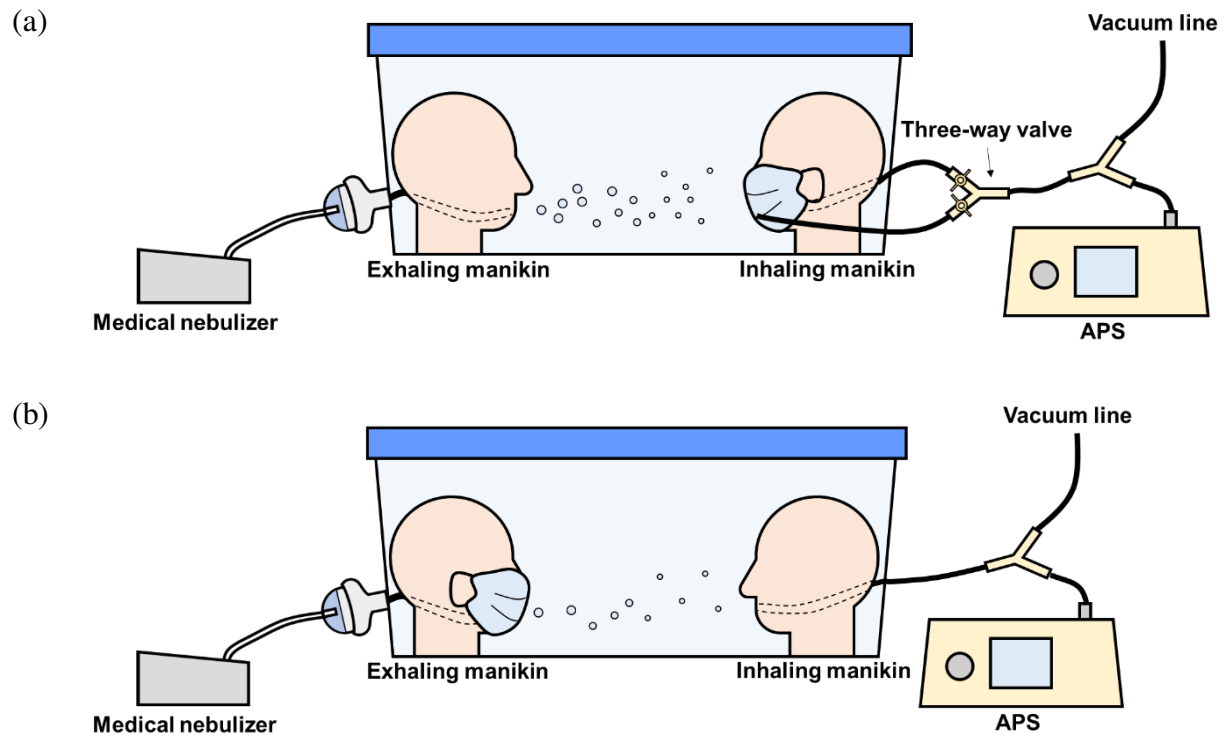
#### 164 **Inward and outward protection efficiency at close distance**

165 We evaluated both inward and outward protection efficiency of face coverings using two manikins  
166 mounted on opposite sides of a 57-L acrylic chamber (51 cm  $\times$  34 cm  $\times$  33 cm), mimicking the  
167 situation of close talking, with a mouth-to-mouth distance of 33 cm (Figure 2a, b). The “exhaling”  
168 manikin was connected to a medical nebulizer (AIRIAL) filled with 2% NaCl solution, that  
169 produced a flow rate of 10 L/min through 0.79 cm i.d. tubing. The “inhaling” manikin was

170 connected to both the APS and a vacuum line, with flow rates of 1 L/min and 14 L/min,  
171 respectively, resulting in a total flow rate of 15 L/min through 1 cm i.d. tubing. Make-up air entered  
172 the chamber around the top perimeter, to minimize disruption to air flow that might be introduced  
173 by a port, and had a background particle concentration of at most 0.5% of that generated in the  
174 chamber by the nebulizer. The air velocity at both manikin's mouths was 3.2–3.4 m/s, similar to  
175 that of breathing and talking (Gupta, Lin and Chen 2010; Xie et al. 2009). To minimize losses of  
176 particles, we used conductive tubing in lengths as short as possible.

177 To evaluate inward protection efficiency, we attached face coverings to the inhaling manikin  
178 (Figure 2a, Figure S4) and tested two scenarios. In scenario 1, we ran the medical nebulizer for 3  
179 s through the exhaling manikin, generating particles of size 0.5–2  $\mu\text{m}$ . Using a three-way valve,  
180 we set up the APS to sample either through the inhaling manikin's mouth or through tubing whose  
181 inlet was placed outside the face covering, near the manikin's mouth. The flow rate through the  
182 inhaling manikin remained constant at 15 L/min. We then waited 30 s for particle concentrations  
183 to decay below the upper limit of detection of the APS, switched the valve to sample from outside  
184 the mask, and measured the size distribution in the chamber for 5 s, denoted  $C_{c1}$ . We then switched  
185 the valve so that the APS sampled through the inhaling manikin's mouth and measured particles  
186 that penetrated the mask, denoted  $C_m$ . To account for the continually decaying particle  
187 concentration in the chamber, we then switched back to measuring particles in the chamber again,  
188 denoted as  $C_{c2}$ . The difference between  $C_{c1}$  and  $C_{c2}$  was less than 10% in all cases. Therefore, we  
189 used the average of  $C_{c1}$  and  $C_{c2}$  to represent  $C_c$  at the time when we measured  $C_m$ . We calculated  
190 the inward protection efficiency based on equation (1), replacing the numerator with  $C_m(D_P)$  and  
191 the denominator with  $C_c(D_P)$ . The temperature and humidity inside the chamber were 22 °C and  
192 50–70% RH, respectively. In a separate experiment, we demonstrated that the three-way valve and

193 the location of sampling inlets did not bias the calculation. There was no difference in the  
194 concentration and size distribution of particles whether the APS sampled directly from the chamber  
195 or through the inhaling manikin without the mask. Measurements in scenario 2 followed a similar  
196 protocol as in scenario 1 except that the medical nebulizer ran for 30 s instead of 3 s to generate  
197 larger particles, up to 5  $\mu\text{m}$ , thanks to coagulation.



198 Figure 2. Schematic of experimental setup for determining (a) inward protection efficiency and (b) outward protection  
199 efficiency.

200 To evaluate outward protection efficiency, we removed the three-way valve and connected the  
201 APS and vacuum line directly to the inhaling manikin (Figure 2b). In each test, we ran the medical  
202 nebulizer for 30 s and then allowed particle concentrations to decay, as in scenario 2 of the inward  
203 protection protocol, and we measured the chamber concentration ( $C_{cl}$ ) using the APS at 1-s  
204 resolution. After introducing the HEPA-filtered air to flush particles from the chamber, we then



205 put the mask or face shield on the exhaling manikin and ran the medical nebulizer for 30 s again  
206 to measure the concentration ( $C_m$ ). Then we flushed the chamber again, ran the nebulizer to  
207 measure the chamber concentration  $C_{c2}$ , and calculated the average  $C_c$  as described in scenario 1.  
208 We calculated the outward protection efficiency according to equation (1) as well. We conducted  
209 all measurements in triplicate.

### 210 *Droplet deposition analysis*

211 We evaluated the ability of the face coverings to block droplets larger than 20  $\mu\text{m}$ , which is the  
212 upper limit of the APS, using a modified droplet deposition analysis (DDA) (Johnson et al. 2011;  
213 Xie et al. 2009). The setup was similar to that of the outward protection protocol but with an air  
214 brush (MP290001AV, Campbell Hausfeld, OH, USA) in place of the medical nebulizer to generate  
215 larger droplets (Lindsley et al. 2013). We connected the air brush to HEPA-filtered air and a gas  
216 regulator set at 165.5 kPa, resulting in a total flow rate of 10 L/min, the same as the flow rate of  
217 the medical nebulizer. We filled the air brush with 2% NaCl solution and red food dye at a ratio  
218 of 4:1. We taped five glass slides (75 mm  $\times$  25 mm) to the face of the inhaling manikin. We pre-  
219 cleaned each slide using 70% isopropyl alcohol wipes.

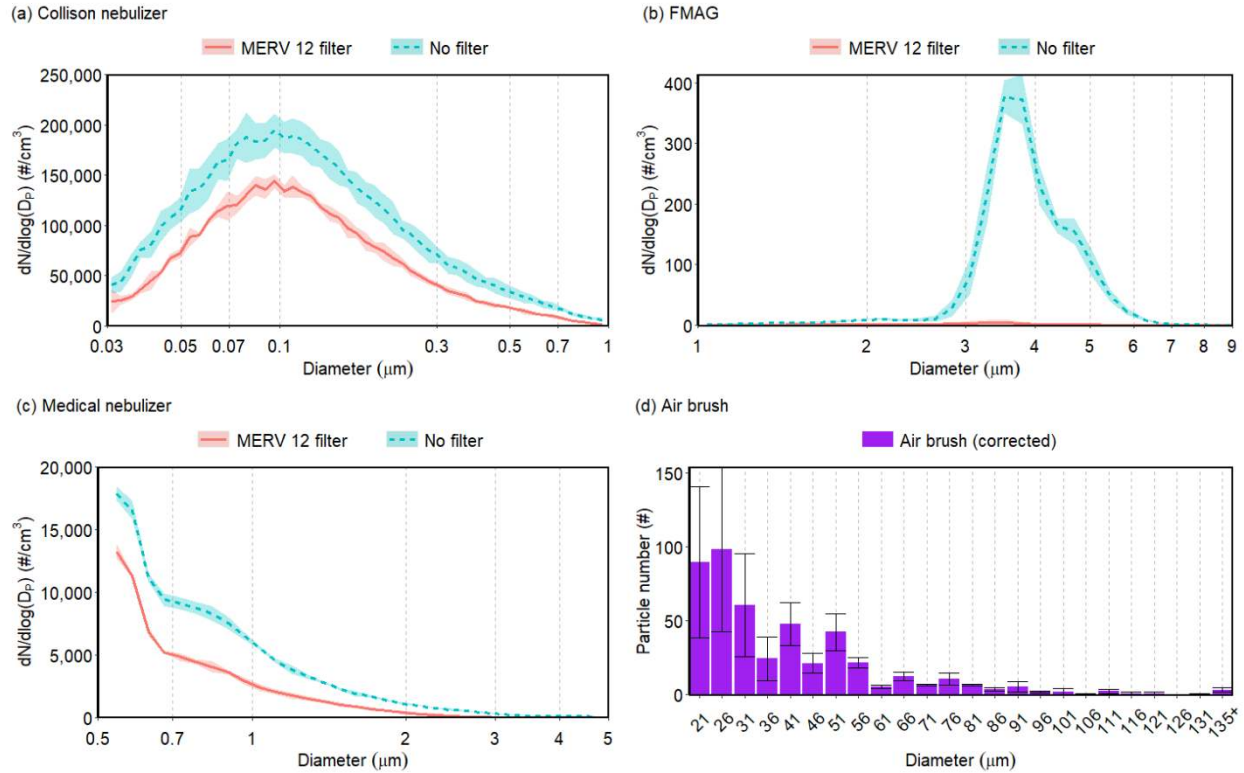
220 First, we sprayed the air brush for 3 s without the face covering on the exhaling manikin. We then  
221 removed the glass slides from the inhaling manikin and inspected them under an optical  
222 microscope at 10 $\times$  magnification (EVOS FL Auto, Life Technologies, CA, USA). We put the face  
223 covering on the exhaling manikin and repeated the same steps. To identify droplets on the slides,  
224 we processed the images using ImageJ and then manually counted the stains and measured their  
225 size with a limit of detection of 12.3  $\mu\text{m}/\text{pixel}$ . Because the droplets spread upon impaction with  
226 the slides, we corrected their size assuming a spread factor of 1.5, the ratio of the size of the stain

227 to the original diameter of the droplet (Johnson et al. 2011). We conducted all measurements in  
228 triplicate.

## 229 **Results**

### 230 *Size of challenge particles*

231 We used four different types of aerosol generators to cover a broad size range and to accommodate  
232 different setups. The Collison nebulizer and FMAG, used to determine material filtration  
233 efficiency, generated particles ranging in size from 0.04 to 1  $\mu\text{m}$  and from 2 to 5  $\mu\text{m}$ , respectively  
234 (Figure 3a, b). The Collison nebulizer produced particles with a geometric mean diameter (GMD)  
235 of 0.12  $\mu\text{m}$  and geometric standard deviation (GSD) of 1.4, and the FMAG a GMD of 4  $\mu\text{m}$  and  
236 GSD of 1.21. The figure also shows the size distribution measured downstream of a MERV 12  
237 filter to illustrate the data used to calculate filtration and protection efficiencies. The medical  
238 nebulizer produced particles ranging in size from 0.5 to 5  $\mu\text{m}$ ; the GMD was below the detection  
239 limit of the APS (Figure 3c). As the medical nebulizer covered a relatively large size range, we  
240 chose to use it to evaluate the inward and outward protection efficiencies (Figure 3c). The air brush  
241 generated large particles ranging in size from 20  $\mu\text{m}$  to greater than 135  $\mu\text{m}$  (Figure 3d).



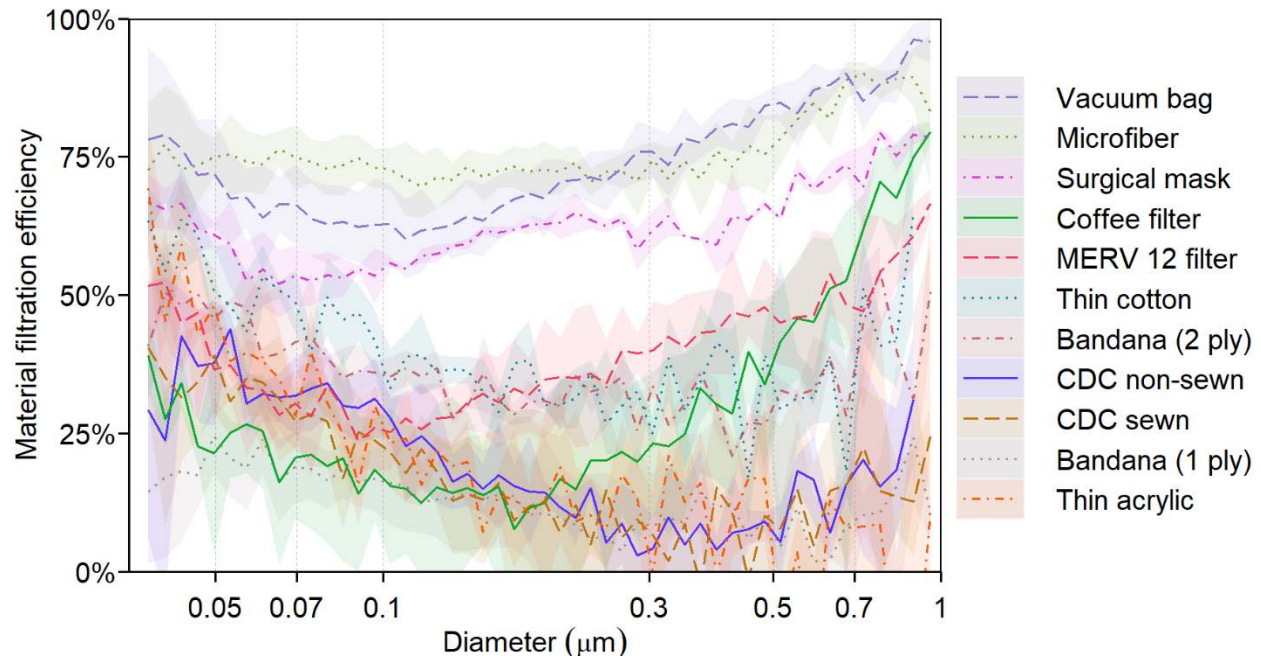
242

243 Figure 3. Concentration and size distribution of particles as a function of aerodynamic diameter generated by (a)  
244 Collision nebulizer, (b) FMAG, (c) medical nebulizer, without a filter (blue dashed line) or downstream of a MERV  
245 12 filter (red solid line), and (d) air brush. In panel (d), the diameter was corrected from the measured size of the  
246 droplet stains on the slide by a factor of 1.5. Shading and error bars represent the standard deviations of triplicates.

### 247 ***Material filtration efficiency***

248 We tested the material filtration efficiency of nine common homemade mask materials and one  
249 surgical mask. We did not test the face shield because it does not allow air flow through it. Figure  
250 4 shows results obtained using the Collision nebulizer and SMPS over the size range 0.04 to 1  $\mu$ m.  
251 The efficiency curves exhibit the expected U shape with a minimum in most cases in the range  
252 0.1–0.3  $\mu$ m, where no collection mechanism is especially efficient (Hinds 1999).

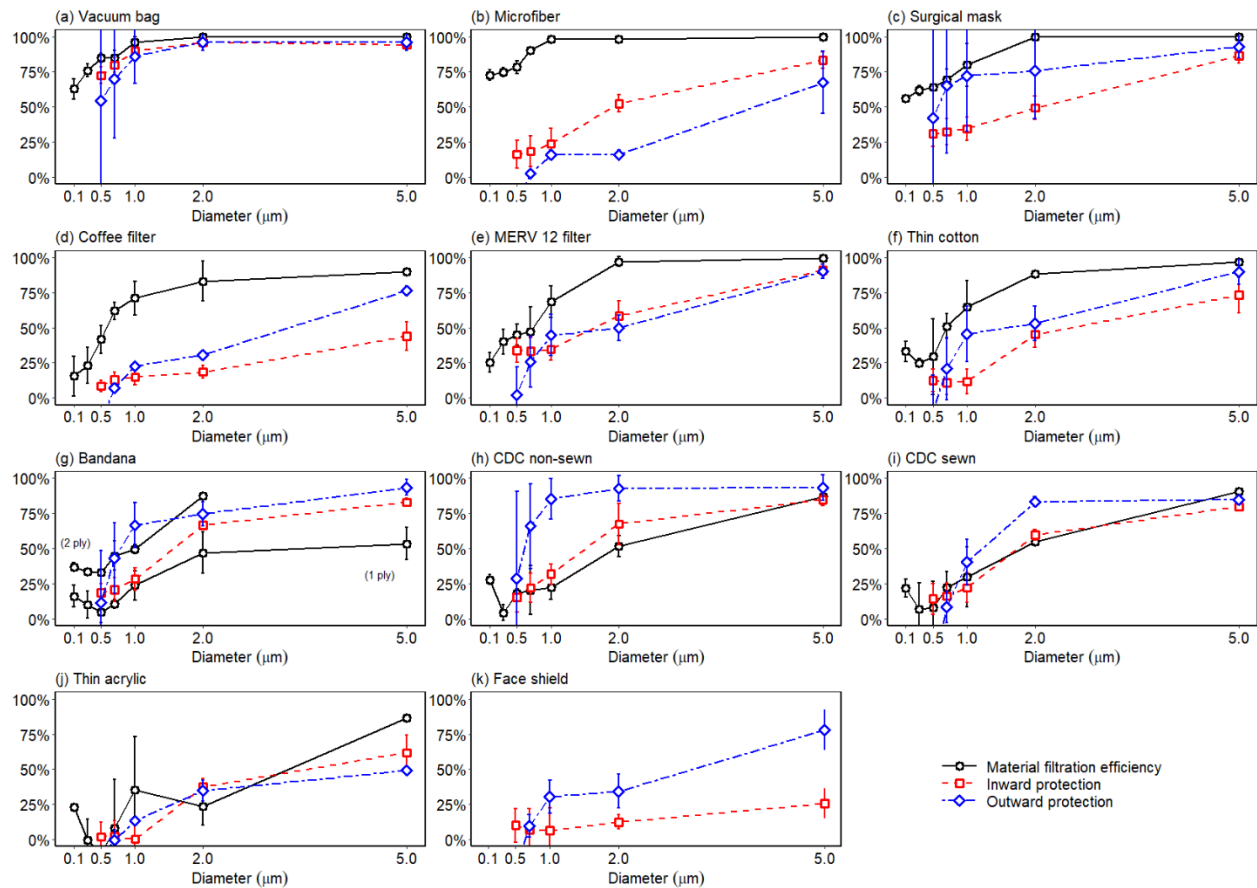




253  
254 Figure 4. Material filtration efficiency of 10 mask materials as a function of aerodynamic diameter. The bandana  
255 appears twice because it was tested in both 1-ply and 2-ply configurations. Shading represents the standard deviations  
256 of triplicates.

257 The vacuum bag and microfiber performed best, with a minimum efficiency of 60%. Other studies  
258 have also reported that vacuum bags have high filtration efficiencies (Drewnick et al. 2020;  
259 Zangmeister et al. 2020), whereas the performance of microfiber varies depending on the  
260 manufacturer and fabric structure (Drewnick et al. 2020; Zhao et al. 2020). Following the top two,  
261 the surgical mask was ~50–75% efficient over this size range, falling with the range reported for  
262 surgical masks in previous studies (Makison Booth et al. 2013; Oberg and Brosseau 2008;  
263 Zangmeister et al. 2020; Zhao et al. 2020). The minimum efficiency of the coffee filter was only  
264 10% for particles at 0.17 μm, lower than the reported value of 34.4% in another study (at a face  
265 velocity of 6.3 cm/s) (Zangmeister et al. 2020), but its efficiency rapidly increased with particle  
266 size to 75% for particles at 1 μm. The MERV 12 filter reached its lowest efficiency of 25% at 0.1  
267 μm and had an efficiency > 50% at the extremes shown in Figure 4. Common fabrics, including

268 the thin cotton and bandana (2 ply), had low efficiencies, mostly between 30% and 50%. The  
269 fabrics fashioned into the CDC non-sewn and CDC sewn masks, bandana (1 ply), and thin acrylic  
270 had even lower efficiencies of 5–40% for submicron particles.



271  
272 Figure 5. Inward and outward protection efficiency of 10 masks and a face shield. The face shield was not tested for  
273 material filtration efficiency because it did not allow air flow through the material. Error bars represent the standard  
274 deviations of triplicates.

275 Most of the materials exhibited a much better material filtration efficiency for particles >1 μm than  
276 for smaller ones, as shown by the black solid line in Figure 5. The vacuum bag, microfiber, surgical  
277 mask, and MERV 12 filter achieved 90% or higher efficiency at 2 μm, and thin cotton and coffee  
278 filter were around 80% efficient at this size. The 2-ply bandana performed much better than the 1-

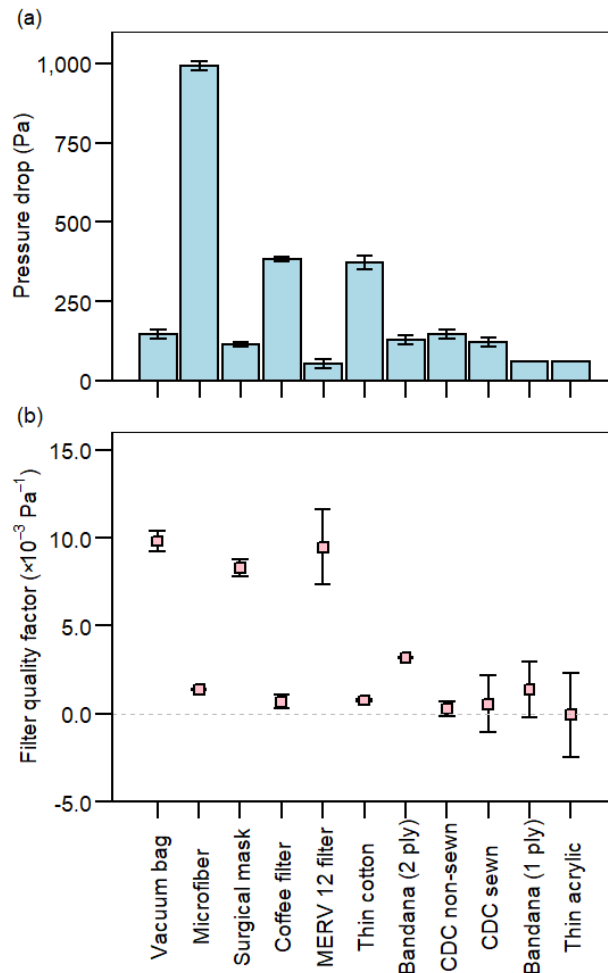
279 ply bandana, with efficiencies of ~75% and <40% at 2  $\mu\text{m}$ , respectively. The CDC non-sewn and  
280 CDC sewn mask materials had efficiencies of ~50% at 2  $\mu\text{m}$ , and their efficiencies increased with  
281 particle size to up to 75% at 5  $\mu\text{m}$ . The thin acrylic still ranked at the bottom. Its efficiency was  
282 <30% at 2  $\mu\text{m}$  but reached 75% at 5  $\mu\text{m}$ .

283 Figure 6 shows the pressure drop across all materials, measured at a flow rate of 3.0 L/min through  
284 a sample 25 mm in diameter. Microfiber had the highest pressure drop, nearly 1000 Pa, followed  
285 by the coffee filter and thin cotton at ~380 Pa. The pressure drop through the other materials was  
286 <150 Pa, among which the thin acrylic and MERV 12 filter had the lowest values, ~70 Pa. We  
287 further related the pressure drop to the material filtration efficiency using a filter quality factor ( $Q$ ),  
288 as defined by equation (2) (Hinds 1999; Podgórski, Bałazy and Gradoń 2006), where  $FE(D_P)$  is  
289 the material filtration efficiency at a particle size of  $D_P$ , and  $\Delta P$  is the pressure drop:

$$Q(D_P) = -\frac{\ln(1 - FE(D_P))}{\Delta P} \quad (2)$$

290 We chose 0.3  $\mu\text{m}$  as the representative particle size for the calculation of  $Q$  for ease of comparison  
291 with other studies (Figure 6b). Since pressure drop is directly correlated with the breathability of  
292 the material, a high  $Q$  means a high filtration efficiency can be achieved with a low pressure drop,  
293 indicating that the material is efficient and easy to breathe through. The vacuum bag and MERV  
294 12 filter, which are both designed to filter out particles, had the highest  $Q$  of all the materials  
295 ( $\sim 10 \times 10^{-3} \text{ Pa}^{-1}$ ). The surgical mask also performed well, with an average  $Q$  of  $7.6 \times 10^{-3} \text{ Pa}^{-1}$ , not  
296 significantly different from  $Q$  of the previous two. These results are comparable to those reported  
297 in another study conducted under similar conditions (Zangmeister et al. 2020). The  $Q$  values of

298 the thin cotton, bandana (2 ply), and the other fabrics were  $<5 \times 10^{-3} \text{ Pa}^{-1}$ , similar to previously  
299 reported values (Zangmeister et al. 2020; Zhao et al. 2020). Notably, an increase in the number of  
300 layers of the bandana resulted in an increase in  $Q$ .



301  
302 Figure 6. Pressure drop and filter quality factor at  $0.3 \mu\text{m}$  of 10 mask materials, sorted on the basis of material filtration  
303 efficiency (Figure 4). The bandana appears twice because it was tested in both 1-ply and 2-ply configurations. Error  
304 bars represent standard deviations of triplicates. In panel (a), there are no error bars for the last two materials as the  
305 measurements fell below the detection limit of the pressure gauge.

306 SEM images of the materials' structure can partly explain the differences in the performance. The  
307 vacuum bag, which had the highest material filtration efficiency, had the smallest-diameter fibers

308 and such a compact structure that the pores or intervals between fibers were the least perceptible  
309 among all the materials (Figure 1a). The fibers of the microfiber cloth were also more tightly  
310 woven than those of other materials (Figure 1b), resulting in good filtration efficiency. The  
311 materials with low efficiency were generally loosely woven, such as the bandana (1 ply), 200-  
312 thread-count pillow case used for the CDC non-sewn mask, cotton t-shirt used for the CDC sewn  
313 mask, and thin acrylic (Figure 1g-j). However, the tightness of the weave was not the only factor  
314 influencing the filtration efficiency. For example, the fiber intervals were large for the surgical  
315 mask, yet it was composed of multiple layers of different materials (Zhao et al. 2020), which made  
316 it unique from other materials. That fabric structure alone does not explain filtration efficiency  
317 also applies to the filter quality factors. For instance, the vacuum bag had a compact texture yet a  
318 low pressure drop, resulting in a high  $Q$  value. Likewise, the surgical mask was not tightly woven,  
319 but it was more efficient and thus had a higher  $Q$  than many other materials. The number of layers  
320 (Drewnick et al. 2020), the properties of the fibers including diameter and electrostatic charges  
321 (Konda et al. 2020; Ou et al. 2020; Podgórski, Bałazy and Gradoń 2006; Zangmeister et al. 2020),  
322 and the material composition (Zangmeister et al. 2020; Zhao et al. 2020) all contribute to  
323 differences in filter quality factors.

#### 324 ***Inward and outward protection efficiency***

325 In this study, the inward protection efficiency (*IPE*) quantifies the capability of a mask, as worn  
326 on a manikin, to protect the wearer by filtering out particles moving in the inward direction through  
327 the mask, from the surrounding air to the wearer's respiratory tract. The outward protection  
328 efficiency (*OPE*) quantifies the capability of a mask for source control, to filter out particles  
329 moving in the outward direction through the mask, from the wearer to the surrounding air. After  
330 being made into a mask, the vacuum bag still ranked first for protection efficiency in both

331 directions, with its *IPE* and *OPE* curves close to the material filtration efficiency curve (Figure  
332 5a), especially for particles larger than 1  $\mu\text{m}$ . Both *IPE* and *OPE* were  $>50\%$  at 0.5  $\mu\text{m}$  and  $>90\%$   
333 for particles larger than 2  $\mu\text{m}$ . However, there were large variations in *OPE* for particles smaller  
334 than 0.7  $\mu\text{m}$ . The *IPE* and *OPE* were also similar to the respective material filtration efficiency for  
335 the CDC-sewn and thin acrylic masks (Figure 5i, j), though their performance was much worse  
336 than that of the vacuum bag. The *OPEs* of the CDC sewn mask and thin acrylic mask were  $\sim 75\%$   
337 and  $\sim 50\%$ , respectively, for particles larger than 2  $\mu\text{m}$ , and both masks were not effective at  
338 blocking particles smaller than 0.7  $\mu\text{m}$ . Notably, the *OPE* of the CDC sewn mask was slightly  
339 higher than its *IPE* at 2.0  $\mu\text{m}$ , whereas no significant differences ( $p>0.05$ ) between *OPE* and *IPE*  
340 were observed across all sizes for the thin acrylic mask.

341 In contrast, the microfiber and coffee filter masks had a much worse *IPE* and *OPE* than their  
342 material filtration efficiency (Figure 5b, d), indicating leakage and a poor fit. The *OPE* for the  
343 microfiber mask was  $<25\%$  for particles smaller than 2  $\mu\text{m}$ , a difference of  $>50$  percentage points  
344 compared to its material filtration efficiency. Its *IPE* was slightly better but still 20–50 percentage  
345 points lower than its material filtration efficiency for particles smaller than 2  $\mu\text{m}$ . Similar trends  
346 were also observed for the coffee filter, except that its *OPE* was slightly higher than its *IPE* at  
347 particle sizes larger than 2  $\mu\text{m}$ .

348 For the surgical mask, thin cotton, and MERV 12 filter, the differences between *OPE* or *IPE* and  
349 material filtration efficiency were moderate, usually within 25 percentage points (Figure 5c, e, f).  
350 The *OPEs* of the surgical mask and thin cotton mask were higher than their *IPEs* but not  
351 significantly; and these efficiencies were lower than the corresponding material filtration  
352 efficiency. In particular, the average *OPE* of the surgical mask was substantially better than its *IPE*

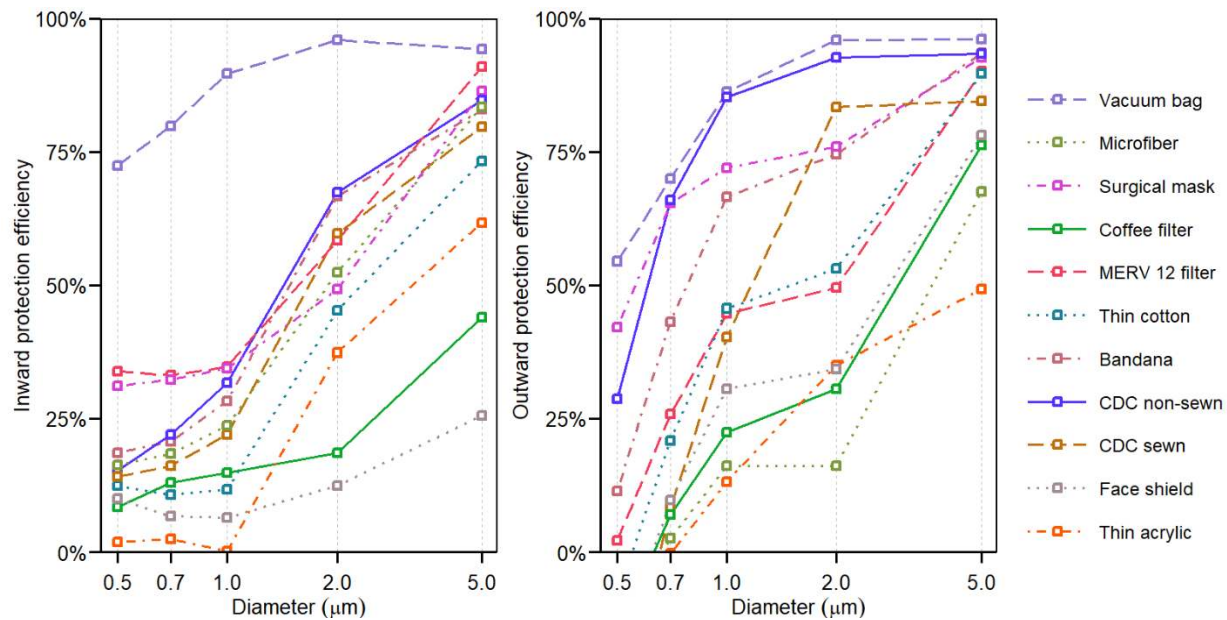
353 at particle sizes ranging from 0.7 to 2  $\mu\text{m}$ , but given the large variability in *OPE*, such differences  
354 were not statistically significant ( $p>0.05$ ). There were no significant differences ( $p>0.05$ ) between  
355 *IPE* and *OPE* for the MERV 12 filter across all sizes.

356 The bandana, CDC non-sewn mask, and the face shield had unique forms. The bandana was folded  
357 in half in a triangle to mimic how people would normally wear it; its *IPE* and *OPE* fell in between  
358 the single-layered and double-layered material filtration efficiency (Figure 5g), with the *OPE*  
359 higher than *IPE* at a particle size of 1  $\mu\text{m}$  ( $p<0.05$ ). The CDC non-sewn mask, whose fit can be  
360 adjusted by tightening or loosening the straps, had an *OPE* that was significantly ( $p<0.05$ ) higher  
361 than the material filtration efficiency at sizes ranging from 1 to 2  $\mu\text{m}$ . It is likely that stretching or  
362 loosening the fabric altered its filtration efficiency. Its average *OPE* was also higher than the *IPE*,  
363 whereas no significant difference was found between its *IPE* and material filtration efficiency. The  
364 face shield did not block almost any aerosols smaller than 0.7  $\mu\text{m}$ , as expected, for it did not fit  
365 closely to the manikin and thus allowed virus-laden aerosols to travel freely around the shield.  
366 However, it exhibited a decent *OPE* for particles at 5  $\mu\text{m}$  (~75%) and an *IPE* of ~25% for such  
367 particles.

368 Figure 7 compares the *IPE* and *OPE* across all masks. The vacuum bag mask had the best  
369 performance in both directions, while the coffee filter mask, thin acrylic mask, and face shield  
370 ranked at the bottom. The CDC non-sewn mask and surgical mask followed the vacuum bag  
371 closely for *OPE* but not *IPE*. Interestingly, the *OPE* values for masks tested spanned a wide range,  
372 whereas their *IPE* values were closer, except for the vacuum bag. In addition, direct comparison  
373 of the two panels in Figure 7 reveals that *OPE* tended to be higher than *IPE*, illustrating that many



374 face coverings work better for source control than protection of the wearer, although the difference  
375 was not significant in most cases.



376  
377 Figure 7. Inward and outward protection efficiency for all masks. For improved readability, error bars are not shown  
378 here, but they appear in Figure 5.

379 In response to a study that suggested that neck gaiters offer very little protection (Fischer et al.  
380 2020), we measured the *OPE* of two neck gaiters, one made of thin 100% polyester and another  
381 made of a double layer of microfiber fabric that was 87% polyester and 13% elastane. Their  
382 average *OPEs* were at least 50% at 1 μm and >90% at 5 μm (Figure S5, S7), similar to the results  
383 for the CDC non-sewn mask. When doubled over, the thin polyester neck gaiter achieved an *OPE*  
384 of >90% over the size range of 0.5–5 μm (Figure S6). Due to the late addition of these face  
385 coverings, we were not able to measure their material filtration efficiency or *IPE*.

386 Droplet deposition analysis found no stains in the slides for all face coverings, indicating that all  
387 of them were able to prevent droplets larger than 20 μm from spreading 33 cm away.



## 388 Discussion

389 For most of the face coverings tested, those with a high material filtration efficiency also had a  
390 better *OPE* and *IPE*. One example is the vacuum bag, which achieved outstanding performance  
391 compared to other materials with regards to material filtration efficiency, *IPE*, and *OPE*. It was  
392 able to filter out at least 60% of particles under perfect conditions and had an *OPE* and *IPE* of at  
393 least 50% and 75%, respectively, for particles 0.5  $\mu\text{m}$  and larger. The MERV 12 filter, surgical  
394 mask, thin cotton, and CDC sewn mask also had decent material filtration efficiencies, *OPEs*, and  
395 *IPEs*, whereas the thin acrylic mask performed worst or near-worst on all three metrics. However,  
396 there were some exceptions, such as the microfiber cloth and coffee filter. The material filtration  
397 efficiencies of these two masks was much higher than their *OPEs* and *IPEs* (Figure 5b, d). The  
398 coffee filter and microfiber were thick and stiff, resulting in a poor fit with larger gaps between  
399 the manikin and the mask, through which particles could short circuit the mask. In contrast, the  
400 vacuum bag was thin and soft, which allowed it to conform to the face easily and achieve a high  
401 *IPE* and *OPE*. Hence, we propose that the stiffness of the material impacts the fit of the mask and  
402 can be responsible for large discrepancies between the material filtration efficiency and *OPE* and  
403 *IPE*. Additionally, differences in mask use among individuals will lead to variability in fit and thus  
404 effectiveness.

405 The CDC non-sewn mask was another exception. Generally, the *IPE* or *OPE* should be lower than  
406 the material filtration efficiency because the latter was tested in a filter holder with no opportunity  
407 for leaks. Nonetheless, the CDC non-sewn mask had a higher *OPE* than its material filtration  
408 efficiency. This unexpected result may be due to its unique form, resulting in a different way of it  
409 being stretched. Its two straps can be adjusted to fit it more tightly to the manikin face, especially

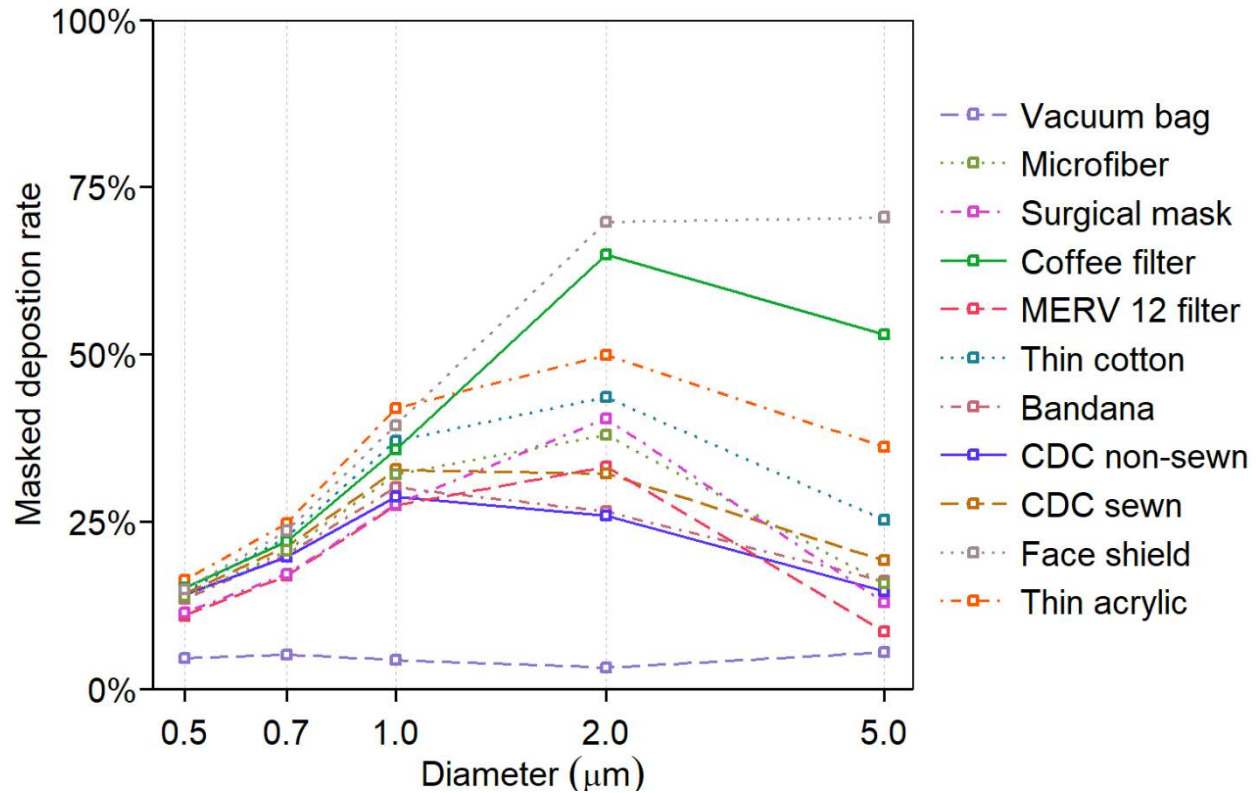
410 to the mouth opening. Hence, the increased pressure caused by the expiratory flow was not able to  
411 push the CDC non-sewn mask outwards to create gaps between masks and the manikin like other  
412 conventional masks do (Lei et al. 2013; Liu et al. 1993; Mittal, Ni and Seo 2020), minimizing air  
413 leakage and bypass through the gaps. The stretching of the fabric may have caused a change in  
414 pore size and woven structure, which further impacted the filtration efficiency. In addition, the  
415 masks themselves also reduced the expired air velocity, which caused the particles to deposit  
416 before they could reach the sampling device, as shown in other studies (Hsiao et al. 2020; Mittal,  
417 Ni and Seo 2020; Tang et al. 2009). The combined effects of reduced gaps and reduced air velocity  
418 resulted in a uniquely high *OPE* for the CDC non-sewn mask. For other masks with a conventional  
419 shape, however, these two effects seemed compensatory during evaluation of *OPE*. While the  
420 masks caused a decrease in the expiratory air velocity, they were also pushed outwards by the  
421 outgoing flow, creating larger gaps between the masks and manikin. The contradiction in part  
422 explained why the differences between *OPE* and *IPE* were not as large as expected for the masks  
423 with conventional shapes, and why the bandana achieved an *OPE* better than expected, because it  
424 created a larger plenum between itself and the manikin that provided additional containment of the  
425 flow to lower the pressure drop and slow the flow jets through the gaps.

426 During the testing of *IPE*, we noticed that the vacuum through the inhaling manikin can suck the  
427 mask tightly against inlet opening, thus reducing the size of any gaps. This can explain the small  
428 differences between the material filtration efficiency and *IPE*, except for the coffee filter and  
429 microfiber as they were stiff and hard to move. However, this phenomenon also illustrates the  
430 tradeoff between breathability and filtration efficiency. Therefore, it is important to select fabrics  
431 that can achieve both high filtration efficiency and low pressure drop for making masks.

432 We also observed variable hydrophobicity of the mask material during the testing of *IPE* and *OPE*.  
433 The fabrics (e.g., thin cotton and thin acrylic) and coffee filter were wetted easily by droplets,  
434 whereas the filter materials, including the vacuum bag and the MERV 12 filter, were hydrophobic  
435 and kept the droplets on the surface of the material. El-Atab et al. developed a reusable  
436 hydrophobic mask and proposed that the hydrophobicity of the mask material might contribute to  
437 repelling the droplets (El-Atab et al. 2020). However, the role of hydrophobicity in filtration  
438 efficiency, *IPE*, and *OPE* remains unclear.

439 Whether particles actually deposit along the respiratory tract, potentially delivering an inhaled  
440 pathogen to a receptor, depends on two factors: (1) their ability to be inhaled into the respiratory  
441 tract and (2) their likelihood of depositing. The first can be reduced by a mask, and the second can  
442 be predicted as a function of particle size. Accounting for these two factors, we calculated the  
443 masked deposition rate (*MD*) by combining the inward protection effectiveness (*IPE*) and the  
444 International Commission and Radiological Protection (ICRP) model (Hinds 1999), as shown in  
445 equation (3):

$$MD(D_p) = (1 - IPE(D_p)) \left( 1 - 0.5 \times \frac{1}{1 + 0.00076 D_p^{2.8}} \right) \left( 0.0587 + \frac{0.911}{1 + e^{4.77 + 1.485 \ln(D_p)}} \right) + \frac{0.943}{1 + e^{0.508 - 2.58 \ln(D_p)}} \quad (3)$$



446

447 Figure 8. Masked deposition rate of 10 masks and a face shield as a function of the aerodynamic diameter.

448 Figure 8 shows the masked deposition rate as a function of particle size. Here, lower values are  
449 better. The vacuum bag performed best, with a deposition rate of <10% across all sizes. The thin  
450 acrylic mask, the coffee filter mask, and the face shield were the worst, with a 50% or higher  
451 deposition rate at a particle size of 2 μm. Although there is considerable concern about exposure  
452 to virus in the smaller particles, the particles with the highest deposition rate were those around 2  
453 μm. For example, SARS-CoV-2 RNA has been detected in particles in the size range of 1–4 μm  
454 (Chia et al. 2020). The smallest particle size considered in this analysis was 0.5 μm, but the  
455 deposition efficiency of 0.3 μm particles in the respiratory tract is even lower, so it is possible that  
456 concerns about mask efficiency at this size are overstated.

457 This study was designed to test masks under tightly controlled conditions, which necessitate the  
458 use of mechanical particle generation and manikins instead of humans. However, this approach  
459 presents several limitations. The manikins are much more rigid than human skin, so masks may  
460 not fit as tightly. A study involving a head form with pliable, elastomeric skin found that fit factors  
461 of respirators were comparable to those measured on humans (Bergman et al. 2015), whereas in  
462 prior studies with head forms made of more rigid material, the fit factors were not as good  
463 (Bergman et al. 2014). In addition, our manikins did not perfectly mimic human respiratory  
464 activities because the aerosol flow traveled in only one direction in the inhaling manikin and the  
465 exhaling manikin. As discussed above, inhalation and exhalation will alter the plenum between the  
466 mask and the manikin, thus resulting in changes of the pressure drop and expiratory jets. We  
467 investigated only one flow rate out of the possible spectrum from gentle breathing to vigorous  
468 sneezing. Additionally, masks fit differently on different head shapes. Therefore, the performance  
469 of the masks on a human face under real-world conditions will certainly vary from the  
470 experimental results in this study. We did not test masks constructed of multiple layers of fabric,  
471 as prior work has shown that overall filtration efficiency is readily predicted by combining  
472 individual layers in series (Drewnick et al. 2020).

473 Based on these results and other studies (Drewnick et al. 2020), we recommend a three-layer mask  
474 consisting of two outer layers of a very flexible, tightly woven fabric and an inner layer consisting  
475 of a material designed to filter out particles. The inner layer could be a high efficiency particulate  
476 air (HEPA) filter, a MERV 14 or better filter (Azimi, Zhao and Stephens 2014), a good surgical  
477 mask, or a vacuum bag. This approach produces a good fitting mask with high performance in  
478 both directions. If the filter material is 60% efficient at the most penetrating particle size and the  
479 outer layers are 20% efficient (Figure 1), the mask would have a minimum efficiency of 74%. At

480 a particle size of 1  $\mu\text{m}$ , where filter materials can easily have an efficiency of 75% and common  
481 fabrics 40%, the overall efficiency would be greater than 90%.

## 482 **Conclusion**

483 In this study, we evaluated the material filtration efficiency, inward protection efficiency, and  
484 outward protection efficiency of 10 masks and a face shield on a manikin, using NaCl aerosols  
485 over the size range of 0.04  $\mu\text{m}$  to >100  $\mu\text{m}$ . The vacuum bag performed best on all three metrics;  
486 it was capable of filtering out 60–96% of particles, and achieved an outward protection efficiency  
487 of 50%–95%% and an inward protection efficiency of 75%–96%% for particles of aerodynamic  
488 diameter 0.5  $\mu\text{m}$  and greater. The thin acrylic performed worst, with a material filtration efficiency  
489 of <25% for particles at 0.1  $\mu\text{m}$  and larger, and inward and outward protection efficiencies of  
490 <50%. The material filtration efficiency was generally positively correlated with either inward or  
491 outward protection effectiveness, but stiffer materials were an exception to this relationship as they  
492 did not fit as closely to the manikin. Factors including stiffness of the material, the way of wearing  
493 the mask (e.g., earloops vs. tied around the head), and material hydrophobicity affected the fit of  
494 the mask and thus its performance. Future studies may focus on the influence of material properties  
495 on the fit of the mask, and how the transmission of real viruses, including SARS-CoV-2, is altered  
496 by wearing the masks.

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