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Review of materials and testing methods for virus filtering performance of face mask and respirator

Bhanu Bhakta Neupane [Corresp., 1] , **Basant Giri** [2]

[1] Central Department of Chemistry, Tribhuvan University, Kathmandu, Nepal

[2] Center for Analytical Sciences, Kathmandu Institute of Applied Sciences, Kathmandu, Nepal

Corresponding Author: Bhanu Bhakta Neupane
Email address: bbneupane@cdctu.edu.np

Respiratory protection device such as face mask and respirator minimize the transmission of infectious diseases by providing physical barrier to respiratory virus particles. The level of protection from a face mask and respirator depends on the nature of filter material, size of infectious particle, breathing and environmental conditions, facial seal, and user compliance. The ongoing COVID−19 pandemics has resulted in the global shortage of surgical face mask and respirator. In such situation, significant global population either have reused the single−use face mask and respirator or used a substandard face mask fabricated from locally available materials. At the same time, researchers are actively exploring filter materials having novel functionalities such as antimicrobial, enhanced charge holding, and heat regulating properties to design potentially better face mask. In this work, we reviewed research papers and guidelines published primarily in last decade focusing on, a) virus filtering efficiency, b) impact of type of filter material on filtering efficiency, c) emerging technologies in mask design, and d) decontamination approaches. Finally, we provide future prospective on the need of novel filter materials and improved design.

1   **Review of materials and testing methods for virus filtering performance of**

2   **face mask and respirator**

3   Bhanu Bhakta Neupane[1*] and Basant Giri[2]

4   *1) Central Department of Chemistry, Tribhuvan University, Kathmandu, Nepal*

5   *2) Center for Analytical Sciences, Kathmandu Institute of Applied Sciences, Kathmandu, Nepal*

10   *Correspondence: bbneupane@cdctu.edu.np

Abstract

Respiratory protection device such as face mask and respirator minimize the transmission of infectious diseases by providing physical barrier to respiratory virus particles. The level of protection from a face mask and respirator depends on the nature of filter material, size of infectious particle, breathing and environmental conditions, facial seal, and user compliance. The ongoing COVID–19 pandemics has resulted in the global shortage of surgical face mask and respirator. In such situation, significant global population either have reused the single–use face mask and respirator or used a substandard face mask fabricated from locally available materials. At the same time, researchers are actively exploring filter materials having novel functionalities such as antimicrobial, enhanced charge holding, and heat regulating properties to design potentially better face mask. In this work, we reviewed research papers and guidelines published primarily in last decade focusing on: a) virus filtering efficiency, b) impact of type of filter material on filtering efficiency, c) emerging technologies in mask design, and d) decontamination approaches. Finally, we provide future prospective on the need of novel filter materials and improved design.

1. Introduction

We have witnessed several viral disease outbreaks in recent decades. Few notable examples of such outbreak include severe acute respiratory syndrome coronavirus–2 (SARS–CoV–2) in 2019(Chen et al., 2020), Ebola virus in 2014(World Health Organization, 2014), Middle East respiratory syndrome coronavirus (MERS–CoV) in 2012(Assiri et al., 2013), influenza pandemic (H1N1) in 2009(Yang et al., 2009) and severe acute respiratory syndrome coronavirus–1 (SARS–CoV–1) in 2002–2003(Donnelly et al., 2003). Respiratory infection spreads through surface contact, droplet spray, and airborne modes of transmission(Atkinson & Wein, 2008; Cowling et al., 2013; Wei & Li, 2016). However, the relative contribution of each mode of transmission is not completely understood for many viruses(Janssen et al., 2013). The recent evidences have shown that COVID–19 is transmitted through contact, respiratory droplets (Huang et al., 2020; Peeri et al., 2020; World Health Organization, 2020), and aerosol routes(Greenhalgh et al., 2021). The various mode of transmission can be partly or fully interrupted by a combination of personal hygiene practices such hand washing, use of personal protective equipment (PPE) such as face mask and respirator, and physical distancing (Siegel et al., 2007).

Virus containing muco–salivary droplets (>5 μm) and aerosol particles (≤5 μm) are exhaled from an infected individual (both symptomatic and asymptomatic) during speaking, breathing, coughing, and sneezing activities. These particles can travel few meters in air depending on their size, gravitational settling, and evaporation rate (Yang et al., 2007a; Prather, Wang & Schooley, 2020). Face masks and respirators significantly minimize and or prevent the spread of infection by creating a physical barrier to the virus particles and droplets(Rengasamy, Zhuang & Berryann, 2004; MacIntyre & Chughtai, 2015). Particle exposure is maximum if physical distance is less than six feet and mask is not worn (Figure 1). Alternatively, maximum protection is achieved if both healthy and infected individuals properly use a recommended mask and physical distancing is maintained (World Health Organization, 2020).

Figure 1: A cartoon showing the importance of face mask in reducing transmission. From Ref.(Prather, Wang & Schooley, 2020). Reprinted with permission from the American Association for the Advancement of Science (AAAS).

86

87 **Surgical face mask**

88 A properly worn surgical mask creates a physical barrier between the immediate environment and
89 respiratory orifices (mouth and nose) thereby blocking or minimizing in and out movement of
90 infectious droplets and particles. (Seale et al., 2009)These masks are labeled as isolation, dental,
91 or medical procedure masks and they are generally known as facemasks. However, all facemasks
92 are not regulated as surgical masks. In USA, the Food and Drug Administration (FDA) regulates
93 surgical masks under 21 CFR 878.4040. The FDA regulation requires that the surgical mask must
94 have recommended filtering efficiency for inert particles and biological particles, fluid barrier
95 protection standards and flammability tests (see section 3) (US Food and Drug Administration,
96 2021). Surgical mask are designed for one time use and generally do not provide good facial seal.
97 The US FDA approved surgical facemasks are recommended for general public and health care
98 professionals at medium to low risk settings(Seale et al., 2009).Three layered flat or cup shaped
99 masks with stretchable ear loops or straps are the most commonly used surgical masks. Each layer
100 in the three-layered surgical mask is designed to have a unique functionality (figure 2a). Details
101 on virus filtering performance and material design of surgical mask is provided in later sections.

102 There has been a shortage of surgical masks during viral outbreaks including the ongoing
103 COVID–19 due to high demand in the global market(Wu et al., 2020). In such difficult situations,
104 general public wear homemade or locally made cloth face mask (figure 2b) and or face covering.
105 However, homemade masks provide limited protection to the user(Chughtai, Seale & MacIntyre,
106 2013; MacIntyre et al., 2015).

107 **Respirators and their classification**

108 Respirators are recommended for high risk environments; for example for health
109 professionals when providing care to COVID-19 patients (Seale et al., 2009; Phan et al., 2019;
110 World Health Organization, 2020). The outer rim of the respirator provides better seal or fit around
111 the nose and mouth. Since respirators have special design and advanced filter materials (figure 2c),
112 a properly worn respirator provides an expected protection to the user. Details of filtering
113 performance and material design of a respirator is provided in later sections.

114 A proper respirator must be selected for a specific hazards. In the USA, filtering facepiece
115 respirators (FFRs) (disposable half–facepiece respirators), elastomeric half– and full–facepiece

116 respirators, powered air–purifying respirators, supplied air respirators, self-contained breathing
117 apparatus and combination respirators are available. The FFRs are available in N, P and R series
118 having minimum filtering efficiency of 95 (N95, P95 and R95), 99(N99, P99 and R99) and 99.97%
119 (N100, P100 and R100) respectively for particles having aerodynamic mass median diameter of
120 0.3 μm. The letters N, P, and R refer to resistant to oil, partially resistant, and resistant (oil proof);
121 respectively(OSHA, 1996). Other countries have different types of respirators. In UK, FFRs are
122 available as FFP1, FFP2, and FFP3 having minimum filtering efficiency of 80%, 94% and 99.95%;
123 respectively.

124   The N95 FFRs have reasonable cost and are widely used. Surgical N95 respirator are a
125 subset of N95 FFRs which are used in healthcare settings for infectious particles. In USA, surgical
126 N95 respirators are NIOSH certified under 42 CFR Part 84(US FDA, 1995). NIOSH reviews the
127 results for fluid resistance, flammability, pressure difference, and biocompatibility supplied by the
128 manufacturer for certification. The FDA also provides clearance to surgical N95 (under 21 CFR
129 878.4040) for fluid resistance, flammability, and biocompatibility properties. Commercial
130 respirators come with or without exhalation valve (EV). The EV helps to minimize excessive
131 dampness and heating and offers decreased breathing resistance. However, a faulty EV could
132 contaminate the nearby environment with infectious virus particles thereby decreasing the level of
133 protection. The surgical N95 respirator without EV or equivalent is recommend for MERS–CoV,
134 SARS–CoV–1 and SARS–CoV–2 for health care professionals in high risk environments(CDC-
135 NIOSH, 2020).

136   The filtering efficiency of facemask and respirator for neutral NaCl aerosol and other
137 particles are well documented in multiple studies (Rengasamy et al., 2017; Sharma, Mishra &
138 Mudgal, 2020; Palmieri et al., 2021) but the information on virus filtering efficiency is not well
139 described. Also, during the COVID-19 pandemic virus filtering efficiency of facemask and
140 respirator can be of special interest to readers. This review aims to provide in–depth details on the
141 filter media used in face masks and respirators, their virus filtering efficiency, emerging
142 technologies for better performing masks and respirators, and decontamination approaches. We
143 also provide future prospective on the need of novel filter material and improved design.

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2. Survey methodology

We used Google Scholar and PubMed platforms to search relevant documents published before February 2021. The keyword used were "facemask and virus filtering efficiency" OR "facemask and virus" OR "facemask and material". We reviewed abstract of the documents and selected documents that provided new insight on the virus filtering performance of either cloth facemask, surgical facemask, or respirators were considered further. Additionally, documents that reported significant advancement in the material design and or the understanding the facemask filter materials were also included. Patents were excluded in the study.

156

3. Filtering performance of face masks and respirators

Filtering efficiency

A filtering device, here referring to both face mask and respirator, provides a barrier protection to the user by capturing infectious droplets, bio–aerosol, and other particles. Conventional single fiber filtration theory(Raist, 1987) predicts that the particles bigger than 0.3 μm are captured on the filter mainly by interception and inertial impaction and particles smaller than 0.2 μm are captured by diffusion and electrostatic attraction or polarization effects. None of the capture mechanisms are dominant for intermediate sized particles (0.2–0.3 μm), which are known as the most penetrating particles size (MPPS)(Hinds, 1999; Hakobyan, 2015). MPPS depends on the nature of filter material and ranges from 0.03 to 0.1 μm(Shaffer & Rengasamy, 2009).

Filtering efficiency of a device depends on multiple parameters such as property of material used in the device, size of particle, and environmental factors. Filtering efficiency (E) is one the most important parameters to quantify filtering performance of face mask and respirator and is given by equation 1,

$$E = \left(1 - \frac{C_i}{C_o}\right) \times 100 \qquad [1]$$

where, C_i and C_o are the concentration of particles inside (downstream) and outside (upstream) the filtering device. Alternatively, the performance is also measured in terms of the penetration efficiency (P)(Johnston et al., 1992);

176
$$P = 100 - E = \left(\frac{C_i}{C_o}\right) \times 100 \qquad [2]$$

177 The overall filtering performance of a respirator or class of respirators is also measured in terms

178 of assigned protection factor (APF). APF is defined as the level of respiratory protection that a

179 respirator or class of respirators is expected to provide to the user at the workplace when the

180 employer implements an effective respiratory protection program on continuous basis as specified

181 in the 29 CFR 1910.134 standard(OSHA, 2009). AFP of a respirator cannot be measured simply

182 from the known aerosol particles inside (C_i) and outside (C_o) the respirator. Several factors such

183 as nature of filter media, length of exposure, facial seal, nature and concentration of contaminants,

184 duration of exposure are considered while assigning the APF(Janssen et al., 2013). APF of 10 and

185 20 means a respirator reduces the exposure level by a factor of 10 and 20, respectively.

186

187 **In vitro measurement of filtering efficiency**

188 The filtering efficiency of a filtering device varies with test parameters used such as

189 particle/aerosol size and distribution, filter media charge and particle charge, face velocity,

190 humidity, and flow rate. For example, the filtering efficiency decreases with increase in relative

191 humidity, face velocity, and flow rate(Yang et al., 2007b; Thakur, Das & Das, 2013).The

192 regulatory recommendations for the use of respirator and surgical mask are made from *in vitro*

193 measurement of filtering efficiency(NIOSH, 1996). To ensure that a device can filter even the most

194 penetrating particles in a workplace, the filtering efficiency is measured at standard testing

195 conditions that mimic the *worst–case scenario* in the workplace.

196 NIOSH uses NaCl aerosol method for testing N95 FFRs(NIOSH, 2019). The test parameters are:

197   a) flow rate of 85 Lmin^{-1} that simulates the breathing volume during a heavy work load,

198   b) poly–dispersed and charge neutralized sodium chloride aerosol particles having count

199   median diameter (CMD) of 75 ± 20 nm and geometric standard deviation (GSD) of <1.86

200   or broad range distribution (log–normal distribution) NaCl aerosol particles having mass

201   median aerodynamic diameter (MMAD) and mass median diameter (MMD) about 300 nm

202   240 nm, respectively(Bollinger, 2004; Shaffer & Rengasamy, 2009),

203   c) aerosol particle concentration of <200mg/m^3,

204   d) pre–conditioning of the filtering device at ~85% relative humidity and ~38° C for 24
205   hours.

206 Different test methods are used for testing the performance of material used in surgical face mask.
207 In the ASTM F2229-03 method, surgical face mask material is challenged with charge neutralized
208 latex spheres having size range of 0.1–5 µm at airflow test velocities (face velocity) of 0.5 to 25
209 cm/s(ASTM, 2003). The recommended aerosol concentration is 10^7–10^8 particles/m^3 and can be
210 diluted if needed. The US FDA recommends slightly different test parameters for testing material
211 (not the entire mask) used in surgical face mask. This method recommends the use 0.1 µm charge
212 un–neutralized polystyrene latex spheres at the air flow velocity of 0.5 to 25 cm/s(US Food and
213 Drug Administration, 2004). The bacterial filtering efficiency (BFE) for the material used in
214 surgical facemask is measured as per FDA guidance and ASTM F2101 method(ASTM, 2001).
215 The mask material (not the whole mask) is challenged with un–neutralized *S. aureus* bacterial
216 aerosol (mean particle size of 3 ± 0.3 µm diameter) at a flow rate of 28.3 L/min. The US FDA
217 provides clearance to surgical mask after reviewing the information provided by the manufactures
218 in the 510(k) premarket application(US Food and Drug Administration, 2004). In the 510(k)
219 application, the manufactures are required to provide the results of fluid resistance, polystyrene
220 latex and *S. aureus* bacterial aerosol filtering efficiency, differential pressure, and flammability
221 tests.

222

223 **Virus filtering efficiency of surgical masks and respirators**

224   Performance of filtering device can also be measured using virus aerosol particles to
225 calculate virus filtering efficiency (VFE). Eninger et al.(Eninger et al., 2008) measured the filtering
226 efficiency of N95 and N99 respirators using three different virus aerosols (enterobacteriophages
227 MS2, T4, and *Bacillus subtilis* bacteriophage) and NaCl aerosol particles at three different
228 inhalation flow rates, 30, 80, and 150 L min^{-1}. The filtering efficiency of both N95 and N99
229 respirator was ≥96% for the 0.02–0.5 µm of aerosol particles. Similar filtering efficiency was
230 reported for virus aerosols suggesting that neutral NaCl aerosols may be appropriate for mimicking
231 the filter penetration of similar size viruses. It is to be noted that the virus efficiency test is not
232 required by FDA or NIOSH for approval process.

233   Balazy et al.(Balazy et al., 2006) measured the VFE of NIOSH certified N95 respirators

234   and surgical masks using MS2 virus. In the study, VFE of not less than 95% was achieved using

235   virus aerosol particles (10–80 nm) and inhalation flow rate of 85 L/min. For the test conditions,

236   VFE of two types of surgical masks was found to be ~80% and ~ 15%, suggesting surgical masks

237   cannot be as effective as N95 respirators for small virus.

238   Shimashaki et al.(Shimasaki et al., 2018) measured the penetration efficiency of two types

239   of nonwoven fabrics [SMS type and S (Spunlace)] that are used in commercial surgical masks

240   using ΦX174 phase and inactivated influenza virus aerosols at a flow rate of 15 Lmin^{-1}. The

241   hydrodynamic diameter of the phase and influenza virus as determined by dynamic light scattering

242   was 28 and 112 nm, respectively. The penetration efficiency for ΦX174 phase and influenza virus

243   was ~6% and 20% for SMS type and ~30% and 80% for S type, respectively. The three layered in

244   SMS type may have provided lower penetration efficiency or higher efficiency. In another study,

245   filtering efficiency of surgical N95 respirator was ≥99.6% for all combinations of experiment

246   configurations using influenza A virus, rhinovirus 14, and bacteriophage ΦX174 at a flow rate of

247   28.3 Lmin^{-1}(Zhou et al., 2018).

248   Even though it is challenging to study the filtering efficiency of masks using *viable* virus

249   aerosol particles, there are few studies reported. Harnish et al.(Harnish et al., 2013) measured the

250   VFE of NIOSH approved N95 respirators using viable H1N1 virus aerosolized in artificial saliva

251   buffer (CMD of 0.83 µm) at a flow rates of 85 and 170 Lmin^{-1}. The respirator was glue sealed in

252   a six inch diameter sample holder. The N95 respirator provided VFR of 99.3% at both flow rates.

253   They also measured the filtering efficiency using 0.8 µm polystyrene latex beads aerosol and got

254   similar filtering efficiency. This study suggested that the dead or live status of aerosol does not

255   affect filtering efficiency. In another study(Harnish et al., 2016), VFE of five different models of

256   NIOSH certified N95 respirators was measured using viable H1N1 influenza aerosol and

257   polystyrene latex bead aerosols having CMD of 0.1 µm representing MPPS for commonly used

258   filter media at a flow rate of 85 Lmin^{-1}. The mean VFE of respirators sealed to the sample holder

259   ranged from 99.23% to 99.997% and particle aerosol filtering efficiency ranged from 99.17% to

260   99.995%. This study suggested that the N95 respirators can be used for protection against H1N1

261   virus in workplace. They also confirmed the earlier conclusion(Harnish et al., 2013) that the dead

262   or live status of aerosol does not affect the filtering efficiency of a respirator.

263 **Virus filtering efficiency of cloth face masks**

264 The particulate matter filtering performance of cloth mask have been found lower than
265 commercially available surgical masks and respirators(Rengasamy, Eimer & Shaffer, 2010;
266 Shakya et al., 2017; Neupane et al., 2019). Davies et al.(Davies et al., 2013) reported the filtering
267 efficiency of two layered cloth mask made from commonly available fabrics using bacteriophase
268 MS2 virus aerosol (~23 nm diameter) at a flow rate of 30 L min^{-1}. The percentage filtering
269 efficiency of cloth masks made of 100% cotton, scarf, tea towel, pillowcase, cotton mix, linen, and
270 silk were 50.85±16.81, 48.87±19.77, 72.46±22.60, 57.13±10.55, 70.24±0.08, 61.67±2.41,
271 54.32±29.49, respectively. The filtering efficiency of three ply surgical mask was better
272 (89.52±2.65%). This study suggested that homemade mask should be considered as the last option.
273 Such masks should be worn only if no better mask is available to prevent the transmission.

274 A cluster randomized trial of cloth masks in healthcare workers in hospital settings reported
275 that influenza like illness was higher in healthcare workers who wore cloth mask than those who
276 wore surgical mask(MacIntyre & Chughtai, 2015). In a recent study(Leung et al., 2020), a
277 significantly lower amount of coronavirus RNA in respiratory droplet and aerosols and influenza
278 virus RNA in respiratory droplets was found in patients who wore surgical masks than in patients
279 who did not wear surgical masks. This study suggested that surgical face masks could be used by
280 COVID–19 patients to reduce onward transmission.

281 A summary of virus filtration efficiency of face masks and respirators along with few major test
282 parameters is summarized in table 1.

283 # 4. Filtering efficiency and material property

284 An important question one can have at this point is: *what makes the filtering efficiency different*?
285 Provided the same test parameters used, the observed difference in filtering efficiency of face
286 masks and respirators is due to: a) inherent property of the filter material, and b) facial fitness i.e.
287 how well the filtering device fits onto the face, and c) breathing condition.

288 A key component of commercially available surgical masks and respirators is a non-woven filter
289 membrane. The membrane consists of 1–20 μm diameter fibers oriented randomly. The material
290 can be fabricated from synthetic or natural polymers or composites such as polypropylene and

291 polyethylene by melt blowing technique. The membrane is mostly electrostatically charged and

292 called as *electret filter*. The charge is imparted onto the membrane by corona discharge, induction

293 charging, and tribo–electric techniques during fabrication(Thakur, Das & Das, 2013; Hutten,

294 2015). In contrast to conventional filter, electret filter provides better particle capture efficiently

295 by electrostatic interaction. Also, the downstream air pressure drop in such filter is lower resulting

296 in lower resistance to breathing which is referred to as better breathability(Thakur, Das & Das,

297 2013; Zhang et al., 2018).

298 The filtering efficiency of electret filter depends on charge density, charge retaining or holding

299 capacity, and size (length and diameter) and arrangement of fiber. These parameters depend on the

300 material type and filter manufacturing technique to a great extent. It known that filter having

301 smaller fiber diameter leads to higher filtration efficiency than the fiber having lager diameter, but

302 the pressure drop in the former is higher making the filtering device less breathable. In addition,

303 shorter fiber form more porous filter than longer fiber. Filtering efficiency increases with increase

304 in filter thickness at the expense of breathing resistance. The columbic and di–electrophoretic

305 forces are also known to be stronger in filter having smaller fiber diameter. This results in stronger

306 capturing of pathogens and better protection. Spun bonding and melt blowing are the most

307 commonly adopted techniques for the fabrication of fibrous filter membrane. The melt blowing

308 technique produces filters having smaller fiber diameter. Therefore, this is the method of choice

309 in manufacturing of filtering media used in surgical mask and respirators(Thakur, Das & Das,

310 2013).

311 The charge density on the electret media affects the filtering performance. The charge intensity

312 and storage capacity depends on the dielectric property of a fiber material. In general, the

313 polymeric materials having high electrical resistance, thermal stability, and hydrophobicity (for

314 example; polypropylene, polyethylene) provide better charge storage ability and stability(Van

315 Turnhout, Adamse & Hoeneveld, 1980). If charge on the electret media is removed, then the

316 filtering efficiency decreases significantly. The *most penetrating particle size* (MPPS) for electret

317 media varies with material properties including charge density and is reported in the range of

318 0.03–0.1 µm(Hinds, 1999; Shaffer & Rengasamy, 2009; Hakobyan, 2015). That is why the

319 filtering performance of a filtering device is measured by using particles having size at or close to

320 MPPS.

321

322

Material design of a surgical mask

323

324 In the mostly commonly used three layered/ply SMS type surgical mask, for example US FDA

325 approved surgical face mask, the middle layer fabricated by melt blown technique (the M layer) is

326 sandwiched between outer and inner layers fabricated by spun bonded technique (the S layers).

327 The three layers are designed to have specific functions. In all layers, fibers are randomly oriented

328 (non-woven) so as to form web like arrangement (Figure 2a and inset). The fiber density in middle

329 layer is higher than in the other two layers resulting low porosity. Since this layer is charged, it

330 can efficiently capture infectious particles above. The outermost layer (typically coded blue) is

331 hydrophobic and limits the penetration of water rich muco–salivary droplets. The innermost layer

332 is hydrophilic and can absorb spit, sweat, and muco–salivary droplets thereby minimizing

333 dampness and increasing user comfort. In recent years, surgical face mask having additional

334 functionality are also being explored (*see* section 5).

335

Material design of a cloth mask

336

337 For comparison, we also like to comment on the material property of cloth or fabric face masks.

338 The cloth mask are made from woven or knitted fabrics and are mostly two layered. In commonly

339 used cloth face mask, the pore size and thread density vary based on the nature of the fabrics(figure

340 2b and inset). The lower performance of cloth facemask(Rengasamy, Eimer & Shaffer, 2010;

341 Shakya et al., 2017; Neupane et al., 2019; Konda et al., 2020) is also due to poor facial fitness and

342 performance of material used. Studies have suggested to use tightly woven fabrics having high

343 thread count and low porosity, such as quilting cotton and cotton sheets, to design relatively better

344 performing cloth face masks(Konda et al., 2020; Neupane, Chaudhary & Sharma, 2020). The

345 efficiency can be further increased by increasing the number of fabric layers. However, more fabric

346 layers increase the breathing resistance making the mask uncomfortable for use(Drewnick et al.,

347 2020; Hancock et al., 2020; Konda et al., 2020; Zangmeister et al., 2020).

348

349 **Figure 2**: Material used in a face mask and respirator. a) SMS type surgical mask and optical

350 microscopic images of the outermost and innermost layers (the S layers) and middle layer (the M

351 layer). (b) A typical cloth face mask and optical microscopic image of the cloth face mask surface.

352 Reproduced with permission from Ref.(Neupane et al., 2019). c) Multilayered structure of a

353 respirator. Letter A and D represent the spun bonded polypropylene layers, B melt blown layer,

354 and D support layer. The scanning electron microscopic (SEM) images layers A and D and B is

355 also shown. Reproduced with permission from Ref. (Borkow et al., 2010).

356

Material design of a N95 respirator

357

358 A typical NIOSH certified N95 respirator consists of four layered structure (labeled A, B, C, D in

359 figure 2c). The outer most layer A (farthest from the face) and D (closest form the face) are made

360 from spun bonded polypropylene(Borkow et al., 2010). These layers contain larger sized fibers

361 and capture course particles and stop moisture entering into the inner layers. The inner layer B is

362 made from melt blown polypropylene. It is charged (electret membrane) and contains highly

363 packed small fibers (i.e., low porosity) and eventually can filter fine particles. The next inner layer

364 C is made from a plain polyester and gives a shape to the respirator. This gradient filtration

365 mechanism in the respirator provides high filtering efficiency. Another important factor for better

366 performance of respirator is its design that provides excellent facial fit. Surgical masks are not

367 designed to fit tightly on the face, so they cannot provide the same level of protection as the

368 respirators(CDC-NIOSH, 2020). It is to be noted that the NIOSH certification does not look at the

369 number of filter media layers and the order of hydrophobic and hydrophilic layers. But the N95

370 respirators should meet the standard test requirements as described in the 42 CFR Part 84.

371

372 **5. Emerging technologies**

373 Several efforts have been reported to make better performing masks and respirators in past. Such

374 efforts involve technologies for making new or modified filter pieces, manufacturing protocols,

375 and disinfecting procedures among others. To contribute to the shortage of standard face mask and

376 respirator in emergency situation, researchers, manufacturers, local hospitals, and even general

377 public have proposed a number of innovative ideas.

378 **3D printing of mask accessories**

379 Additive manufacturing (AM) including 3-dimensional (3D) printing have gained popularity in

380 manufacturing medical devices (Ventola, 2014). 3D printing has been used to make mask

381 components such as mask structure or frame, cover, filter fix, seal etc. A variety of different types

382 of materials including polymax PLA filament, SLS/MJF nylon or flexible SLA resin have been

383 used. Foam or silicone band have been used to print seal with improved airtightness and softer
384 skin touch. Even though the 3D printed masks may look like conventional PPE, they may not
385 provide the same level of barrier protection, fluid resistance, filtration, and infection
386 control(Ventola, 2014; Morrison et al., 2015). The new designs are not approved by any regulatory
387 agencies yet and performance may have been compromised. Since the 3D printed masks and
388 accessories provide low-cost, quick, and decentralized and distributed manufacturing, they can be
389 promising during emergency situation. The US FDA has developed preliminary guidance to
390 devices using AM that involves 3D printing(Morrison et al., 2015; Di Prima et al., 2016).

391

392 **Modified face mask filter media**

393 There are several efforts to modify mask filters with various materials such as antibody
394 and nanomaterials to enhance the antimicrobial activity and filtering efficiency of the masks.
395 Kamiyama et al.(Kamiyama et al., 2011) reported a modified nonwoven fabric–based air filters
396 that were impregnated with antibody for avian influenza H5N1 virus. The filters were found to
397 inactivate the virus trapped in the filter due to antigen–antibody interaction. However, these filters
398 were tested only for birds. All birds housed in antibody filter covered boxes did not die. Similar
399 antibody impregnated filter could be tested for face masks. Such methods may require further
400 research to find out how the antibody impregnated on filters would retain their activity in ambient
401 environmental condition during transportation, storage and use of the filter. The performance of
402 such filters while they are used in mask is not known.

403 Metal oxide and metal nanoparticles display biocidal activities(Vincent, Hartemann &
404 Engels-Deutsch, 2016; Fernando, Gunasekara & Holton, 2018). In particular, copper oxide
405 nanoparticle display potent biocidal properties against a range of microbes including
406 bacteriophages, bronchitis virus, poliovirus, herpes simplex virus, human immunodeficiency virus
407 and influenza viruses(Ingle, Duran & Rai, 2014; Vincent, Hartemann & Engels-Deutsch, 2016;
408 Fernando, Gunasekara & Holton, 2018). Taking the advantage of the biocidal properties,
409 respiratory face masks containing these materials have been tested for anti-microbial activities.
410 The use of biocidal masks may significantly reduce the risk of hand or environmental
411 contamination. They reduce infection due to improper handling and disposal of the masks.

412 A copper oxide impregnated respiratory face mask was reported by Borkow et al. (Borkow
413 et al., 2010) that demonstrated potent anti-influenza biocidal properties without altering physical

414   barrier properties of the masks. The copper oxide impregnation did not alter the filtering efficiency

415   of N95 masks when tested with aerosolized viruses of human influenza A virus (H1N1) and avian

416   influenza virus (H9N2) under simulated breathing conditions. In these experiments, no infectious

417   H1N1 viral titers were recovered from the copper oxide containing masks within 30 minutes. In

418   case of H9N2 virus, titers were recovered from the copper oxide containing masks but were five-

419   fold lower than the control masks. The copper oxide containing masks successfully passed

420   bacterial filtration efficacy, differential pressure, latex particle challenge, and resistance to

421   penetration(Borkow et al., 2010). The metal oxide or nanoparticle impregnated respirator could

422   have four layers of fabric as reported by Borkow et al.(Borkow et al., 2010). Out of the four layers

423   (Figure 2c), outer two and inner layers were metal oxide impregnated polypropylene fabric and

424   the remaining layer was made of plain polyester to give shape to the mask.

425   A mixture of silver nitrate and titanium dioxide nanoparticles coated facemasks were also

426   tested against infectious agents(Li et al., 2006). The minimum inhibitory concentration of the

427   nanoparticles against *Escherichia coli* and *Staphylococcus aureus* were 1/128 and 1/512,

428   respectively. A 100% reduction in viable *E. coli* and *S. aureus* was observed in the coated mask

429   materials after 48 h of incubation. Skin irritation was not observed in any of the volunteers who

430   wore the facemasks.

431   The efficacy of 4 antimicrobial respirators to decontaminate MS2 virus was

432   evaluated(Rengasamy, Fisher & Shaffer, 2010) using MS2 as a surrogate for pathogenic viruses.

433   The MS2 activity of masks with antimicrobial material was significantly reduced when stored at

434   37 °C and 80% RH for 4 hours than the masks without antimicrobial materials. The antimicrobial

435   materials used in this research included coating of outer layer of mask with silver–copper material,

436   incorporating $EnvizO_3$-Shield on the outer layer of respirator, iodinated resin incorporated on

437   filtering layer, and TiO2 coated filtering layer. This study suggested that MS2 virus

438   decontamination efficacy of antimicrobial respirators were dependent on the antimicrobial agent

439   and storage conditions. One should note that substituting conventional filter media of facemasks

440   with nanofiber may reduce the airflow resistance that could lead to enhanced filtration(Skaria &

441   Smaldone, 2014).

442   A temperature sensitive and reusable and recyclable face mask consisting of

443   graphene–coated nonwoven filter was recently reported by Zhong et al.(Zhong et al., 2020). This

444 mask provided better protection to aqueous respiratory droplets due to its super–hydrophobic
445 surface. Additionally, the mask can be reusable by sterilizing the surface with solar illumination.
446 Although, viruses filtering performance of the mask has not been reported, such mask might be
447 available as next generation face mask.

448 **Virus decontamination methods**

449 Because of increased demand and subsequent shortage during viral outbreaks, surgical
450 mask and respirator are decontaminated and reused. Reuse of these protective gears after proper
451 decontamination may help fulfil supply chain constraints to some extent during the pandemics.
452 However, improper decontamination and reuse of face masks and respirators may pose
453 transmission risk. An ideal decontamination process is expected to inactivate any infectious
454 material without altering the membrane integrity and filtering performance. The decontamination
455 methods can be broadly categorized as self–deactivation and forced de–activation.

456 In the first approach, partly discussed in earlier section, the mask material is functionalized
457 or additional material having novel property is incorporated so as to deactivate the pathogens. One
458 of the strategies is to functionalize fibrous filtration unit of mask by salts such as sodium chloride
459 (Quan et al., 2017). In this experiment, salt coating on the fiber surface dissolved when exposed
460 to virus aerosols. The salt destroyed the pathogens when it recrystallized during drying. The salt-
461 coated filters also showed higher filtration efficiency than conventional mask filtration layer. The
462 virus spiked salt treated filters provided 100% survival rate of mice. Viruses captured on salt-
463 coated filters exhibited rapid infectivity loss compared to gradual decrease on bare filters. Salt-
464 coated filters proved highly effective in deactivating influenza viruses regardless of subtypes and
465 following storage in harsh environmental conditions. This simple pathogen deactivation method
466 can be helpful in obtaining a broad-spectrum, airborne pathogen prevention device in preparation
467 for epidemic and pandemic of respiratory diseases. Similarly, a quaternary ammonium based
468 antimicrobial surfactant was evaluated to examine its efficiency to reduce bacterial burden on FDA
469 cleared surgical face mask surface(Tseng, Pan & Chang, 2016). The antimicrobial surfactant was
470 covalently bound onto mask surface before use. The antimicrobial mask provided >99.3%
471 efficiency for all three bacterial species tested. Interestingly, the antimicrobial agent on the
472 modified mask the antimicrobial agent reduced the average colony rates by 91.8% for bioaerosols
473 that came into contact with the mask (10^3 CFU/m^3). However, the rate decreased with increased
474 bioaerosol concentrations.

475   In a forced de-contamination approach, pathogen is deactivated by using external agents

476   such as vaporized hydrogen peroxide (VGP)(Kenney et al., 2020), ultraviolet germicidal

477   irradiation (UVGI), ethylene oxide (EtO), microwave oven irradiation, autoclaving(Grinshpun,

478   Yermakov & Khodoun, 2020), and bleach(Viscusi et al., 2009). The details of such methods are

479   described in other reviews(Ou et al., 2020; Rodriguez-Martinez, Sossa-Briceño & Cortés-Luna,

480   2020). Therefore, we only briefly mention some of the selected findings.

481   Vaporized Hydrogen peroxide (HP) can penetrate the porous fabric that may harbor virus.

482   The virucidal activity of HP was tested in surgical N95 respirators that were aerosolized with 3

483   bacteriophages: Pseudomonas phage phi-6, T7, and T1(Kenney et al., 2021). It was found that

484   single HP vapor cycle resulted in complete eradication of the bacteriophages from the respirator.

485   Viscusi et al(Viscusi et al., 2009) compared the effectiveness five different decontamination

486   methods [ethylene oxide, bleach, microwave oven irradiation, germicidal irradiation (UVGI), and

487   vaporized hydrogen peroxide (VHP)] in nine different models of NIOSH-certified respirators

488   (surgical N95 respirators, N95 FFRs, and P100 FFRs). Each respirator was tested for five

489   decontamination methods and the change in ordor, physical appearance, airflow resistance and

490   aerosol penetration was studied. Also, change in material properties of the respirator and possible

491   health risks to the user were evaluated. They found that microwave oven irradiation melted some

492   of the samples. The scent of bleach low levels of chlorine gas were found in the decontaminated

493   respirators. The VHP, ethylene oxide (EtO), and UVGI, were found to be better decontamination

494   methods.

6. Conclusions and future perspectives

496   The filtering efficiency of a face mask and respirator depends on number of parameters such as

497   nature of filter media, size of particle, and environmental parameters. The level of protection also

498   depends on facial seal and user compliance. Several studies have shown that the N95 respirator or

499   equivalent or higher, if worn properly, can provide expected protection to the user in high risk

500   environments. The filtering efficiency of surgical mask is lower than the N95 respirators, and cloth

501   face mask perform even poorer.

502   A few issues regarding the use of respirator and face mask are the discomfort to the user in

503   prolonged wearing due to imperfect facial fitness, poor heat management inside the filtering

504 device, filter clogging, and increased breathing resistance. In worst cases, this could even lead to

505 psychological impact(Roberge et al., 2010; Roberge, Kim & Coca, 2012) and reduced adherence

506 and loss of workplace protection factor. So, there is need of next generation facemask and

507 respirator having improved functionalities. The emerging 3D printing technology along with the

508 development of novel materials such as metal organic framework (MOF)based filters (Li et al.,

509 2019), nano-fibrous membrane containing charge enhancer(Liu et al., 2015), and use of material

510 having high infrared transparency or reflectance for heat management during summer and winter

511 seasons(Yang et al., 2017) will be very useful. In recent years, due to significant advancement in

512 electrospinning technology, fabrication of filter membranes having desired fiber size, surface area,

513 porosity, and functionality is possible. It is expected that novel facemask and respirators, which

514 incorporate electrospun membranes, will be available commercially in future(Cheng et al., 2017;

515 Tebyetekerwa et al., 2020; Zhang et al., 2021).

516   Currently used respiratory protection device pose potential risk of primary and secondary

517 infection and transmission due to improper handling and disposing them. In viral outbreaks,

518 because of increased demand and subsequent shortage, surgical mask and respirator are

519 decontaminated and reused. There is still a chance of infection during decontamination process or

520 by ineffective decontamination. Also, device interiority and performance may deteriorate, and

521 level of protection could decrease. So, there is need for better decontamination methods other than

522 explored in Ref(Viscusi et al., 2009; Kenney et al., 2020). Solution to this issue could the

523 incorporation of filter media that can self-decontaminate, partly explored in Refs.(Borkow et al.,

524 2010; Fujimori et al., 2012; Tseng, Pan & Chang, 2016), or design of a device that could

525 incorporate resistive heating element.

526   Another issue during viral outbreak, including COVID–19, is inevitable use of cloth face

527 mask, especially in low income countries. Lower efficiency of such mask is partly due to loosen

528 facial fitting and the material used. There is a need of low-cost and effective home–made

529 alternative fabric material to the cloth face mask. One of the possibility for better performing cloth

530 facemask (Zhao et al., 2020) could be the use of fabrics that can be charged electrostatically so

531 that the filtering efficiency can be increased.

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Figure 1

A cartoon showing the importance of face mask in reducing transmission.

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Particle size (μm)

100 10 1 0.1

Infected, asymptomatic

Healthy

Maximum
exposure

Minimum
exposure

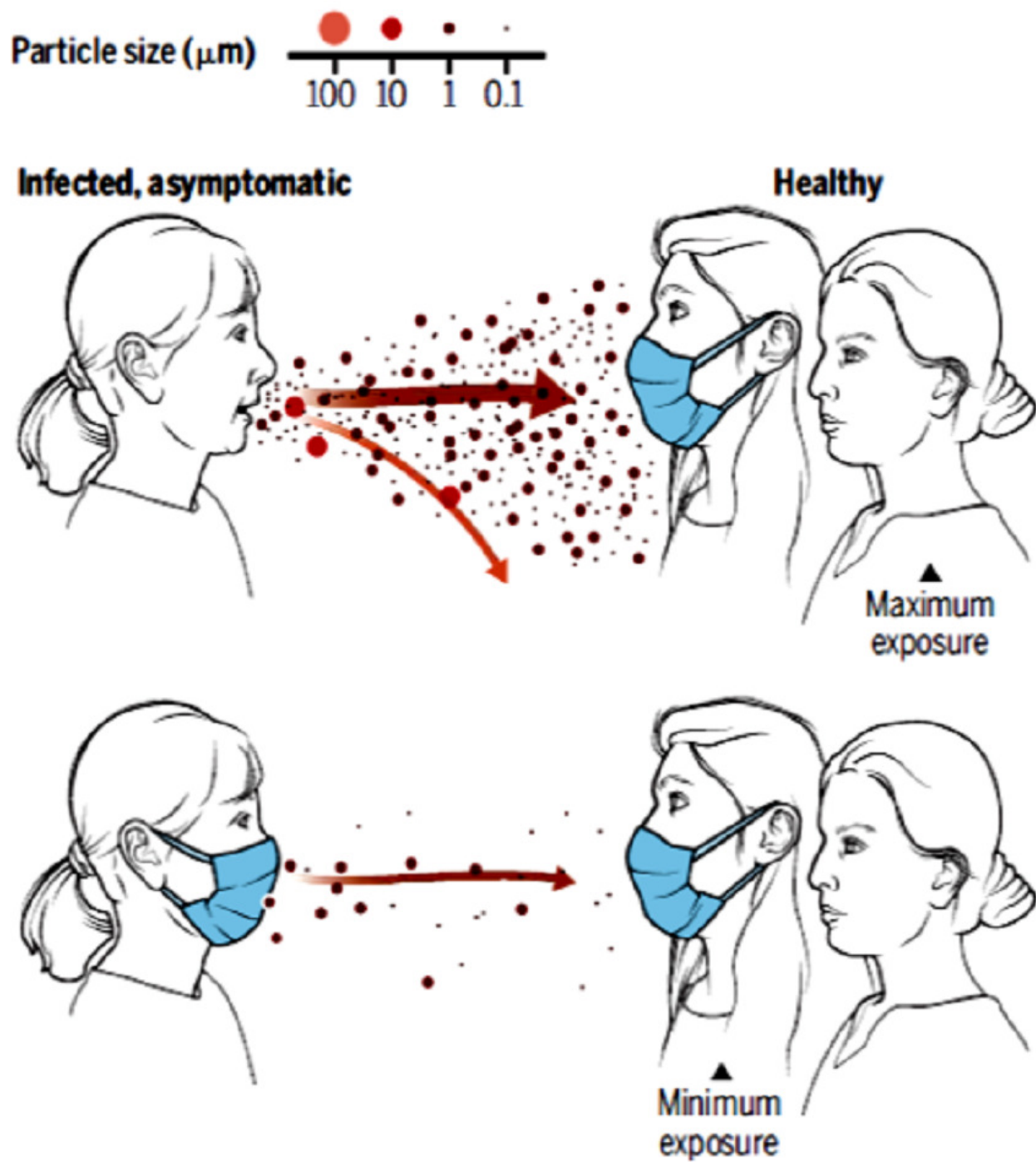
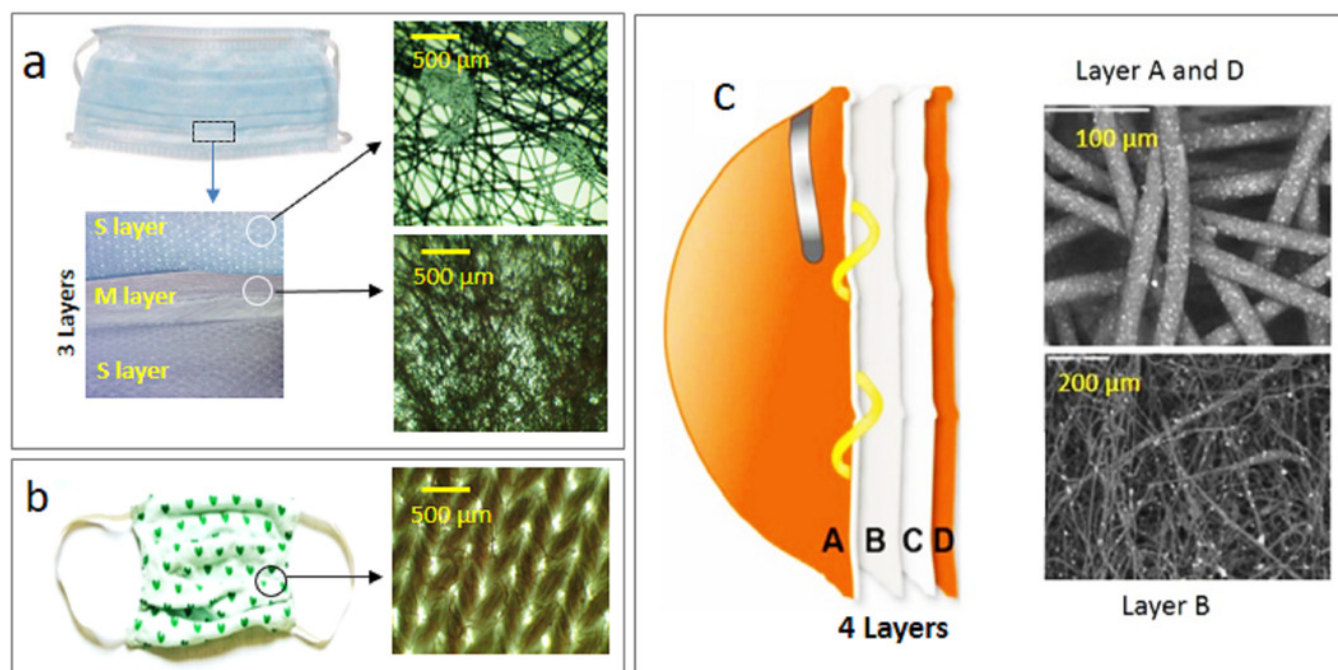



Figure 2

Material used in face mask and respirator

a) SMS type surgical mask and optical microscopic images of the outermost and innermost layers (the S layers) and middle layer (the M layer). (b) A typical cloth face mask and optical microscopic image of the cloth face mask surface. Reproduced with permission from Ref. (Neupane et al., 2019) . c) Multilayered structure of a respirator. Letter A and D represent the spun bonded polypropylene layers, B melt blown layer, and D support layer. The scanning electron microscopic (SEM) images layers A and D and B is also shown. Reproduced with permission from Ref. (Borkow et al., 2010) .

Filtering efficiency

A comparison of virus filtration efficiencies.

2 **Table 1**: Comparison of virus filtration efficiencies

Filtering device	Filtration efficiency	Major test parameters
N95	≥95%	MS2 virus aerosol, flow rate 85 L min^{-1} (Balazy et al., 2006)
	≥99.2%	H1N1 viable virus, flow rate 85 L min^{-1} (Harnish et al., 2016)
	97.1-97.8%	bacteriophage phiX174, 28.3 L min^{-1} (Rengasamy et al., 2017)
Three layered surgical mask	~85%	MS2 virus aerosol, flow rate 85 L min^{-1} (Balazy et al., 2006)
	~94%	bacteriophage *phiX174, flow rate 15 Lmin^{-1}* (Shimasaki et al., 2018)
	~80%	Influenza virus*, flow rate 15 Lmin^{-1}* (Shimasaki et al., 2018)
	~90%	bacteriophase MS2, flow rate 30 *Lmin^{-1}*
Two layered cloth mask	50-70%	bacteriophase MS2, flow rate 30 *Lmin^{-1}*