Current understanding on the Effectiveness of Face Masks and Respirators to Prevent the Spread of Respiratory Viruses

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Abstract

Personal protective equipment (PPE) such as safety foot wares, gloves, face masks and respirators, face shields, and gowns are used both in health care and community settings to contain the spread of infectious diseases during microbial outbreaks. Filtering device including face masks and respirators are important components of PPE to prevent the bio-aerosol and droplet mediated transmission of a disease. In case of respiratory pathogens, droplets originate from an infected person sneezing and coughing and aerosols are formed by exhalation and desiccation of larger droplets. The filtering efficiency of a filtering device depends on nature of the filter, size and nature of particles, user preference, and environmental conditions. The breathability, facial fitness, and contamination from used mask and respirator are important factors to be considered in designing a filtering device. This review discusses on current development in materials used for filtering device, effectiveness of face mask and respirator, emerging technologies for better filtering device, and finally provide a general guideline for proper use and future prospective of face mask and respirator.

Keywords: Personal Protective Equipment, Respiratory Protective Device, Infectious Disease, Respirators, Filtering Efficiency

Background

Several viral outbreaks have occurred in the most recent decades, such as severe acute respiratory syndrome coronavirus–2 (SARS–CoV–2) in 2019[1,2], Ebola virus in 2014[3], Middle East respiratory syndrome coronavirus (MERS–CoV) in 2012[4], influenza pandemic (H1N1) in 2009[5,6] and severe acute respiratory syndrome coronavirus–1 (SARS–CoV–1) in 2002–2003[7,8]. Virus is believed to spread between humans by surface contact, droplet spray , and airborne modes of transmission [9–14], however, relative contribution of each modes is not understood completely for many viruses[15]. In surface contact mode, pathogen transfer to hand upon touching the contaminated surface and subsequently to body by hand to mouth, nose, and eye activities. These various modes of transmission can be partly or fully interrupted by practicing personal hygiene practices such hand washing and by using personal protective equipment (PPE) such as face mask and respirator, and gloves[16]. In droplet spray transmission, larger droplets of aerodynamic radius more than 5μm[17] that originate from the infectious individual (source) during sneezing and coughing transfer virus directly to a healthy individual in close contact. For most viruses, this mode of transmission occurs within a radius of approximately ~1 m (3 feet) feet from the source[1,15,18] and for precautionary measures this distance is recommended to be in the range of 6–10 feet for highly virulent or emerging pathogens[16]. For example, in the most recent SARS–CoV–2 virus social distancing of around 6 feet is recommended to prevent disease transmission. In airborne transmission, the viable and inhalable aerosol nuclei of aerodynamic radius ≤ 5 μm originated directly form source or formed by the evaporation of larger droplets are dispersed to even longer distance by air currents and remain infective[16,19–24]. Based on the most recent research evidences on COVID–19[25,26], China's experience with COVID–19, and SARS and MERS guideline, WHO has concluded that COVID–19 is transmitted between people through contact and droplet transmission, but not by airborne transmission[27]. This conclusion may change as more findings evolve.

Face mask and respirator

Facial protection using PPE, such as goggles, face shield, respirators and surgical face masks is one of the important measures to prevent the droplet and aerosol mediated transmission. Surgical face mask and respirator are important respiratory protective devices (RPDs) used to prevent the infection in health care workers and civilians[28,29]. In most viral outbreaks surgical mask and respirator run out due to high demand[30]. In this case, general public start making their own mask using household cloths and wear them; although the effectiveness of such masks is questionable [31,32]. The surgical face mask (both flat/natural fit and cup shaped/molded) normally has well–defined specifications for fluid resistance and particulate and microbial resistance. It is disposable and does not provide a perfect fit around the face. It may or may not be subject to regulation. For example, in the United States of America, surgical masks regulated under 21 CFR 878.4040. Face masks were designed primarily to prevent the spread of infection from wearers to others by creating a physical barrier to larger droplets and body fluids[33] and are not certified by National Institute for Occupational Safety and Health (NIOSH). In practice, face masks are used by an infected person, health care workers, and general public to reduce the transfer of infectious material from person to person [34].

Respirator, also known as filtering face piece (FFP), is a RPD that provides better filtering efficiency than a face mask and covers at least nose and mouth. The outer rim of respirator is designed to provide better seal/fit around the nose and mouth. Performance of a respirator is regulated and well defined, and designed primarily to use in high risk activities[27,34,35]. A respirator is required to pass seal test before use and training to be provided to the user[36]. Depending on the intended use, respirators of different design are commercially available. A disposable type respirator is designed for one time use and is also called as filtering half face piece. The reusable respirator, also called as elastomeric respirator, can be used multiple times by replacing the filter cartridge. The respirators are available with or without face shield[37]. The respirator may or may not have exhalation valve (EV). The EV helps to minimize excessive dampness and heating and offers decreased breathing resistance thereby making the respirator more user friendly. The EV is designed in such a way that it closes during inhalation and opens during exhalation so that inhaled air comes through the respirator filter[38]. Both EV and non EV respirators are recommended to use for viral protection; for example for COVID–19[39].

Respirators are named differently in different countries. They are labeled as N95, N99, and N100 in USA[39] and KN90, KN95, and KN100 in China. The numbers 90, 95, 99 and 100 means the respirator can filter *at least* 90%, 95%, 99% and 99.97% of conventional most penetrating particle size of 0.3 µm. In Europe, respirators are named as FFP1 (or P1), FFP2 (or P2) and FFP3 (or P3) having filtering efficiency of 80%, 94% and 99.95%, respectively[40]. The respirators are also rated as N, R, P for not oil resistant, somewhat oil resistant, and strongly resistant to oil (oil proof), respectively[39]. The NIOSH requires manufacturer to have manufacture's name (for examples, 3M), part number (P/N), filter class and filtering efficiency (for examples, N95, P95, R95), and expiry date to be marked on the exterior surface of the respirator[39]. Even though a respiratory virus consist of a lipid (fats and oils) sheath, since the amount of lipid in the tiny virus particle is low, it cannot affect the filtering performance of N–series respirators. Thus, N-series respirators are recommended for protection against the respiratory virus. For example, N95 respirator or equivalent has been recommend for MERS–CoV, SARS–CoV–1 and SARS–CoV–2[39] for health care professions in high risk environments.

Figure 1: Photograph of face mask and respirators: A) Flat or natural surgical face mask, B) Molded surgical face mask, C) N95 respirator without exhalation valve; specifications printed on the outer surface, and D) N95 respirator with an exhalation valve. Source[41]

There have been several discussions regarding efficiency and quality of masks and respirators during the COVID-19 pandemic. Since the performance of masks and protection against viral contamination depends on several factors, this review aims to provide in-depth details about the materials used for fabricating face masks and respirators, their filtering efficiency, emerging technologies for better performing masks and respirators. We also provide a brief guideline on proper use and disposal of masks and respirators. Finally, we discuss on future prospective of these important respiratory protective devices.

Filter media used in face mask and respirator

The filtering performance of a filter membrane depends on morphology (fiber organization and size and pore size), charge and thickness of filter, nature (or charge) of aerosol, size of particle, and environmental conditions such as temperature, relative humidity, and air velocity[42]. A filtering device provides protection by capturing the particles on the filter media. A conventional single fiber filtration theory[43] predicts that the particles bigger than 0.3 µm are captured on the filter mainly by interception and inertial impaction and the 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) and these particles are known as most penetrating particles size (MPPS)[44,45]. The commonly used respirator filter media are electrostatically charged media. The MPPS for such media lies in the range of 0.03–0.1 µm[46]. The performance of a filtering device is measured by using particles having size at or close to MPPS. Surgical masks are not designed to fit tightly on the face, so they cannot provide the same level of protection as the respirators do[39,47].

Non-woven electrostatic type fibrous membrane, also called electret medium, is the major components of surgical mask and respirator. This material can be fabricated from synthetic or natural polymers or composites such as polypropylene and polyethylene by melt blowing technique. The charge is imparted to the medium by corona discharge, induction charging, and triboelectric techniques during fabrication[42,48]. In contrast to conventional filter media, electret media provide better particle capture efficiently by electrostatic interaction. Also, the downstream air pressure drop in such filter is lower resulting in lower resistance to breathing which is referred as better breathability[42,49].

The filtration efficiency of electret filter depends to great extent to the size and arrangement of fiber and hence to fiber manufacturing technique. It is established that filter having smaller fiber leads to higher filtration efficiency than the lager fiber but the pressure drop in the former is higher. Also, fiber having smaller diameter has larger specific surface area and cause smaller pores than large fiber. Filtering efficiency increases with increase of filter thickness at the expanse of breathing resistance. The columbic and di–electrophoretic forces are also known to be stronger in filter media having smaller fibers. Spun bonding and melt blowing are the most commonly adopted techniques for the fabrication of fibrous materials. The melt blowing technique produces filters having smaller fiber diameter. Therefore, this is the method of choice in manufacturing of filtering media for surgical mask and respirators[42].

The charge intensity on the electret media is one of the important parameters to affect the filtering performance. The charge intensity and storage capacity depends on the dielectric property of a fiber material. For same material, charge storage ability is found to vary with the electrostatic charging method. In general, the polymeric materials having high electrical resistance, thermal stability and hydrophobicity (for example; polypropylene, polyethylene) provide better charge storage ability and stability[50]. The most penetrating particle size (MPPS) for electric filter media depends on the charge on the media and also on the fiber diameter. If charge in the electret media is removed, then the filtering efficiency decreases significantly.

The particle penetration efficiency of electret media using NaCl aerosol (0.05–0.5μm) tested at 30% relative humidity and 10 cm/s face velocity did not change in temperature range from $20^{o}C$ to $40^{o}C$[51]. However, the efficiency increased significantly when the relative humidity was increased from 30 to 70%, at a constant temperature of $20^{o}C$ and face velocity of 10 cm/s. The increase in penetration efficiency is believed to be caused by reduction of surface charge due to water molecules. On increasing the face velocity form 0.1 m/s to 1 m/s, keeping RH 30% and temperature at $20^{o}C$, the penetration efficiency for 0.3 μm aerosol increased from 17 to 55% indicating higher face velocity leads to shorter residence time in the filter and to increased penetration.

Three layered/ply SMS type (Spun bond/Melt blown/Spun bond), having melt blown layer (M) sandwiched between Spun bond (S) layers, masks are the most commonly available surgical face masks. The M layer is fabricated by melt blown and S layers by spun bond techniques. In all layers, fibers are bonded so as to form web like arrangement (Figures 2a and b). The fiber density in middle M layer is higher than in other layers resulting in smaller pores. This arrangement provides gradient filtration capability viz. smaller particles capture in M layer and course particles in S layers. For comparison, we also like to comment on the filter media of cloth face masks. The cloth mask are made from woven or knitted fabrics. Such masks are mostly two layered made by folding same cloth material. Also, in cloth face mask the pores are much bigger (figures 2c and d). This arrangement does not provide gradient filtering and explains why cloth face masks have filtering efficiency than surgical face mask[52–54].

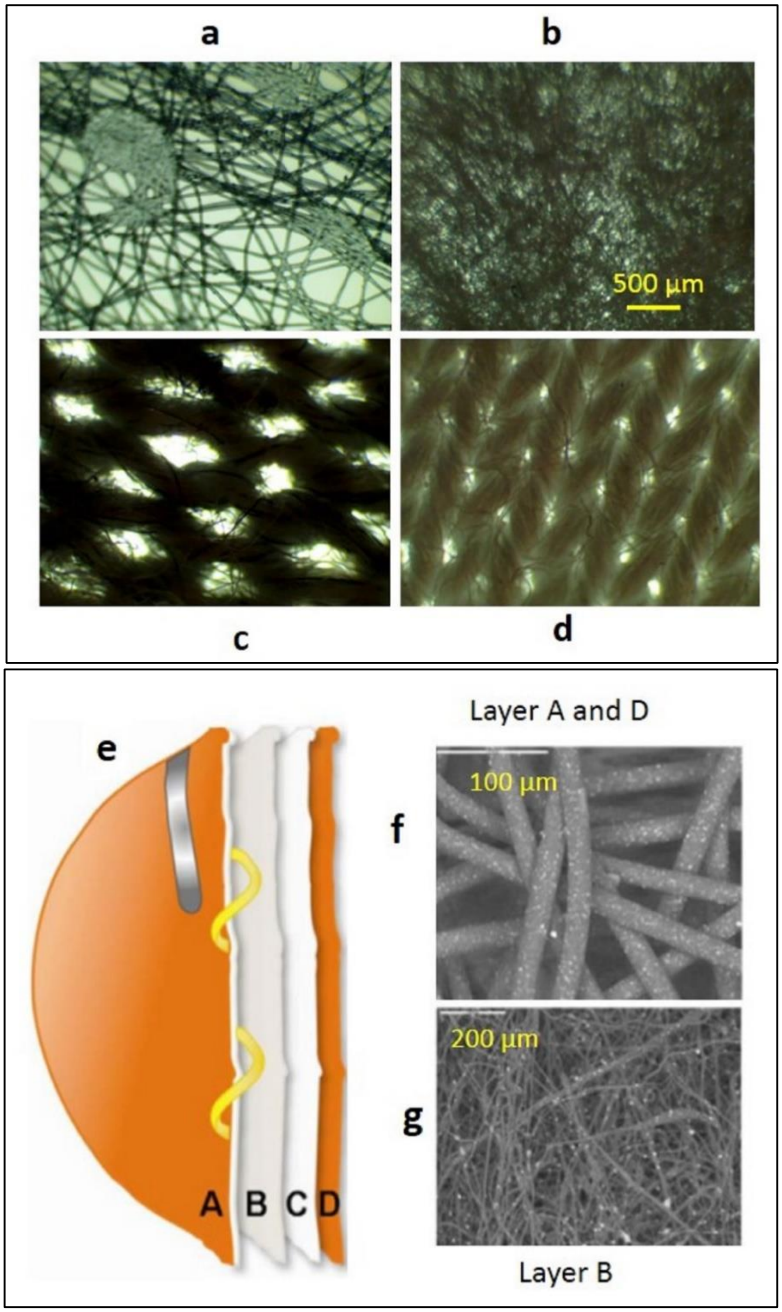

Figure 2: Optical microscopic images of (a) outermost and innermost layers S and (b) middle layer M of SMS type surgical mask (c) and (d) surface of two different cloth face masks. Scale bar shown in (b) is 500 micrometer and applies to the images a, b, c, and d. Reproduced with permission form Ref[52]. e) Multilayered structure of a respirator. Letter A and D represent the spun bonded polypropylene layers, B melt blown layer, and D support layer. f) Scanning electron microscopic (SEM) images of A and D layers. c) SEM image of layer B. Modified form Ref[55].

A typical NIOSH certified N95 respirator consists of four layered structure (labeled A, B, C, D in figure 2e[55]). The outer most layer A (furthest from the face) and D (closest form the face) are made from spun bond polypropylene. These layers contain larger fibers and capture course particles and stop moisture entering the inner layers. The inner layer B is made from melt blown polypropylene and contains small fibers and filter fine particles. The next inner layer C is made from a plain polyester and is designed to give shape to the respirator. This gradient filtration mechanism provides high filtering efficiency to the respirator.

Filtering performance of a face mask and respirator

Filtering efficiency

Performance of a filtering device is measured in terms of filtering efficiency (E) or assigned protection factor (APF) which are defined as[56,57]:

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

$$APF = \left(\frac{C_o}{C_i}\right) \qquad [2]$$

where, C_i and C_o are the concentration of particles inside (downstream) and outside (upstream) the filtering device. The E and APF are related to each other as follows:

$$E = \left(1 - \frac{1}{APF}\right) \times 100 \qquad [3]$$

APF is considered as the expected ability of a device to reduce exposure measured under the conditions that best reflects the workplace conditions [47]. It means, APF of 10 and 20, means that a device may reduce the exposure level by a factor of 10 (or filters 90%) and 20 (or filters 95%), respectively. Alternatively, performance is also measured in terms of the penetration efficiency (P)[57].

$$P = 100 - E = \left(\frac{C_i}{C_o}\right) \times 100 \qquad [4]$$

In a workplace, the protection factor of a filtering device depends on additional factors, such as duration of exposure and the filtering device worn time. To account these additional factors, effective protection factor (EPF) has been introduced as[15]:

$$EPF = t_e\left(\frac{WPF}{t_w + t_{nw}WPF}\right) \qquad [5]$$

where, t_e is the exposure duration, t_w is the time the filtering device is worn, t_{nw} ($=t_e-t_w$) is the not worn time, and *WPF* is the workplace protection factor and can be same or different from the *APF*. According to equation 5 the *EPF* decreases quickly if the not wear time increases. The significance of the equation is better understood from figure 3 in which plot of effective protection factor (EPF) is platted against not wear time for exposure duration of 300 minutes for two different WPF scenarios of 20 (filtering efficiency of 95%) and 100 (filtering efficiency of 99%). If not worn time is 10 minute (i.e. the filtering device is not worn only for 10 minutes out of total exposure duration of 300 minutes), the protection factor drops from 20 to 12 and 100 to 23.

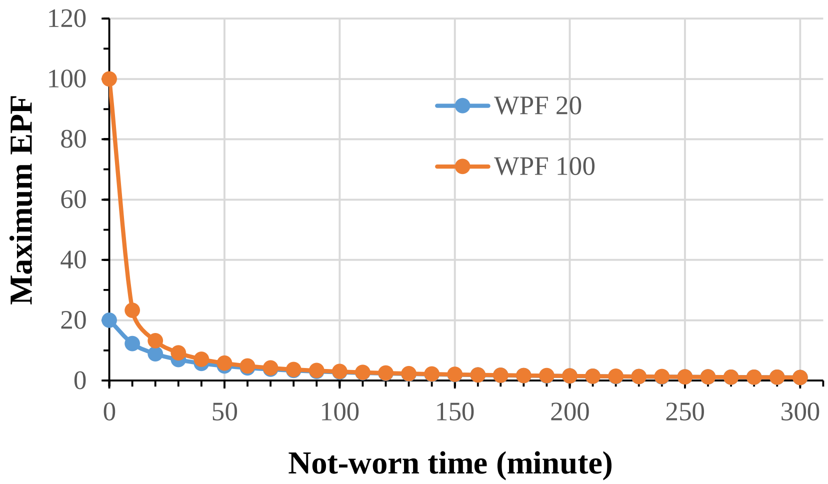

Figure 3: A plot of Effective protection factor and not-worn time of a filtering device.

Measurement of filtering efficiency

The regulatory recommendations for the use of respirator and surgical mask are made from *in vitro* measurement of filtering efficiency[58–60]. A user can use a filtering device in a wide range of particle size and concentration distribution situations. To ensure that the device can filter even the highly penetrating bio-aerosol particles in workplace, the filtering efficiency is measured at standard testing conditions that mimic the *worst case* scenario in workplace. Commonly used test conditions for lab based measurement are: 1) face velocity of 0.5 to 25 cm/sec, 2) flow rate of 80 $\mathrm{Lmin^{-1}}$, and 3a) poly–dispersed sodium chloride aerosol particles having count median diameter (CMD) of 75 ± 20 nm and geometric standard deviation (GSD) of <1.86 (NIOSH NaCl method), or 3b) poly–dispersed dioctyl phthalate (DOP) aerosol particles having CMD and GSD of 185 ±20 nm and <1.60, respectively, or 3c) broad range distribution (log–normal distribution) NaCl aerosol particles having mass median aerodynamic diameter (MMAD) and mass median diameter (MMD) about 300 nm 240 nm, respectively[46,61]. The other technical details for NIOSH NaCl aerosol method are: a) pre–conditioning of the filtering device at ~85% relative humidity and ~38 °C for 24 hours, b) 2% (wt/vol) aerosolized NaCl solution should be charge neutralized and then passed through the convex side of filtering device. The filtering device should be properly sealed on the sample holder or mannequin[56]. The flow rate of 80 $Lmin^{-1}$ simulates the breathing volume during a heavy work load.

Aerosol size is a critical parameter in filter efficiency measurement but the dead and live status of aerosol is shown to have no effect on the filtering performance[62]. The diameter of aerosol particles used in the test method is comparable to the size of most virus particles; for example SARS–CoV and MERS–CoV viruses have size of around 0.125 µm[63]. The measurement is carried out in a specially designed chamber with a filtering device worn on the mannequin face. Aerosol is generated by air compressor and nebulizer. Particle concentration and distribution is measured with a particle spectrometer or equivalent[64].

Performance of filtering device can also be measured using virus aerosol particles to calculate virus filtering efficiency (VFE). Eninger et al.[65] measured the filtering efficiency of N95 and N99 respirator using three different virus aerosol (enterobacteriophages MS2 and T4 and *Bacillus subtilis* phage) and NaCl aerosol particles at three different inhalation flow rates, 30, 80, and 150 L min^{-1}. The performance of both N95 and N99 respirators was very close in the size range 0.02–0.5 µm of aerosol tested with filtering efficiency of ≥96%. The filtering efficiency for both NaCl and virus aerosols was similar suggesting that neutral NaCl aerosols may be appropriate for mimicking the filter penetration of similar size viruses. Balazy et al.[59] measured the VPF of N95 respirators and surgical masks using MS2 virus. In the study, virus aerosol particles in size range of 10–80 nm and inhalation flow rate of 85 L/min was used. It was found that the NIOSH certified N95 mask provided, as expected, VFE of 95%. However, two types of surgical masks provided VFE of only 80 and 85% suggesting surgical masks are not as effective as N95 respirators for small virus.

Shimashaki et al.[66] measured the penetration efficiency of nonwoven surgical masks of SMS type (Spunbond/Meltblown/Spunbond) and S (Spunlace) types using ΦX174 phase and inactivated influenza virus aerosols at the flow rate of 15 $Lmin^{-1}$. The hydrodynamic diameter of phase and influenza virus as determined by dynamic light scattering was 28 and 112 nm, respectively. The penetration efficiency for ΦX174 phase and influenza virus was ~6% and 20% for SMS mask and ~30% and 80% form S type mask, respectively. In was concluded that the lower penetration efficiency (higher efficiency) in SMS surgical mask was due to its three layered structure (3 ply mask). In another study, Zhau et al.[67] studied the filtering efficiency of N95 respirator. The respirator was challenged with aerosols of influenza A virus, rhinovirus 14, and bacteriophage ΦX174 at a flow rate of 28.3 $Lmin^{-1}$. The filtering efficiency was ≥99.6% for all combinations of experiment configurations and types of viruses.

Although challenging, there are also few studies reported on the *viable* virus aerosol particles. Harnish et al.[62] measured the VFE of N95 respirators viable H1N1 virus aerosolized in artificial saliva buffer (CMD of 0.83 µm) at the flow rates of 85 and 170 $Lmin^{-1}$. The respirator was glue sealed in a six inch diameter sample holder. It was found that the N95 respirator at both flow rates provided VFR of 99.3%. They also measured the filtering efficiency using 0.8 µm polystyrene latex beads aerosol and got similar filtering efficiency. This study suggested that the dead or live status of aerosol does not affect filtering efficiency. In another study[68], VFE of five different models of NIOSH certified N95 respirators was measured using viable H1N1 influenza aerosol and polystyrene latex bead aerosols having CMD of 0.1 µm, representing MPPS for commonly used filter media, and at flow rate of 85 $Lmin^{-1}$. The mean VFE for the respirators, which were sealed to the sample holder, ranged from 99.23% to 99.997% and particle aerosol filtering efficiency ranged from 99.17% to 99.995%. This study suggested that the N95 respirators studied can be used for protection of H1N1 virus in workplace, and confirmed that the earlier conclusion[62] that the dead or live status of aerosol does not affect the filtering efficiency of a respirator.

To better mimic the workplace scenario, protection factor of a filtering device is also measured using two mannequin; one acting as source that mimics infected individual and the other as receiver that mimics healthy individual[69,70]. In a ventilated design and tidal breathing condition, keeping 3 feet separation between source and receiver, it was found that applying respirator only on the source without a seal provided protection factor of 250. However, putting a N95 respirator sealed on receiver PF of only 100 was achieved[69].

Next study was carried in a negative pressure chamber with exhaust fan above the source and inhale fan above the receiver[70]. It was found that placing the natural fit surgical mask on source during coughing, PF of 1587 was obtained in the receiver. Interestingly, by putting a vaseline sealed N95 respirator on receiver, PF of only 17 was obtained[70]. This finding suggested that putting exhaust fan behind patient wall can minimize the contamination then putting on ceiling in hospital setting.

In resource limited settings and during viral and bacterial outbreaks, commercial surgical mask and respirators are not easily available. In such emergency situations, locally made cloth mask are widely used due to low cost and added advantage of decontamination and washing between uses[31]. The particulate matter filtering performance of cloth mask have been found lower than commercially available surgical masks and respirators[52–54]. Davies et al.[71] reported the filtering efficiency of two layered cloth mask made from commonly available fabrics using bacteriophase MS2 virus aerosol (~23 nm diameter) at flow rate of 30 L min^{-1}. The filtering efficiency of two layered cloth masks made of 100% cotton, scarf, tea towel, pillowcase, cotton mix, linen, silk, and cotton mix was 50.85±16.81, 48.87±19.77, 72.46±22.60, 57.13±10.55, 70.24±0.08, 61.67±2.41, 54.32±29.49, and 70±29.49, respectively, whereas the filtering efficiency of three ply surgical mask was 89.52±2.65.

A cluster randomized trial of cloth masks in healthcare workers in hospital settings reported that influenza like illness was higher in health care workers who wore cloth mask than those who wore surgical mask[28]. In a most recent study[72], a significantly lower amount coronavirus RNA in respiratory droplet and aerosols and influenza virus RNA in respiratory droplets was found in patients who wore surgical masks than in patients who did not wear surgical masks. This study suggested that surgical face masks could be used by COVID–19 patients to reduce onward transmission.

The regulatory recommendation of mask and respirators are made based on *in vitro* studies. A summary of filtration efficiency of different face masks and respirators along with few test parameters is summarized in table 1.

Table 1: Comparison of virus filtration efficiencies

Filtering device	Filtration efficiency	Test parameters
N95	≥95%	MS2 virus aerosol, flow rate 85 L min^{-1}, and perfect sealing[59]
	≥99.2%	H1N1 viable virus, flow rate 85 L min^{-1} and perfect sealing [68]
	97.1-97.8%	bacteriophage phiX174, 28.3 L min^{-1} and perfect sealing[56]
Surgical mask (3 ply/SMS type)	~85%	MS2 virus aerosol, flow rate 85 L min^{-1}, and perfect sealing[59]
	~94%	bacteriophage phiX174, flow rate 15 $Lmin^{-1}$ and perfect sealing[66]
	~80%	Influenza virus, flow rate 15 $Lmin^{-1}$ and perfect sealing[66]
	~90%	bacteriophase MS2, flow rate 30 $Lmin^{-1}$ and perfect sealing[71]
Cloth mask (two layered)	50-70%	bacteriophase MS2, flow rate 30 $Lmin^{-1}$ and perfect sealing[71]

Guidelines for proper use of mask and respirator

Respiratory protection is effective if appropriate device is worn properly and the used device properly decontaminated and disposed[27].Prolonged use of face mask and respirator along with frequent hand to face contact can lead to the increased risk of infection[35,73,74]. Facemasks and respirators pose potential risk of primary and secondary infection and transmission due to improper handling and disposing them. In workplace, an employer is required to give training to each employee regarding: a) importance of facemask and respirator and other PPEs, b) what type of facemask and respirator is necessary, b) when such device is necessary, c) limitations of the device, d) proper care, maintenance, and disposal of the device, e) how to put on and remove and check the seals of the device[75]. Respirators are used in high risk environments and designed to fit perfectly on the face. So, fit test is necessary to check if any leakage exists before use. The fit test can be done by Saccharin or Bitrex qualitative fit test method or any of the quantitative fit test methods, such as PortaCount Plus, companion, generated aerosol, and simulated workplace protection factor testing[76].

Respiratory protection by a face mask and respirator is effective when used in combination with proper hand washing. WHO recommends using face mask if someone is coughing or sneezing or needs to take care of suspects. Recent preliminary studies have suggested to use face mask when going to public during epidemics[77]. In case of emergency when surgical masks are in shortage, wearing even cloth masks may provide limited degree of protection and minimize the spread of virus[77]. Mask should not be touched with dirty hand. Hand should be washed with soap and water or rubbed with alcohol based sanitizer that contains at least 60% alcohol before putting on the mask. The mask should be put on the face such that it covers the face properly and no gap exists between face and mask. Mask should be discarded if it is damp and single use mask should not be re-used. Special care should be taken while removing and disposing the mask. Mask should be removed from behind and dump it in a closed bin, and hands should be cleaned again with soap and water or sanitize with sanitizer.

Emerging technologies

Several efforts have been reported to make better performing masks and respirators. Such efforts involve new technologies for making new or modified filter pieces, manufacturing protocols, and disinfecting procedures among others. Recent coronavirus pandemic created shortage of PPE posing challenges to providing care of patient and safety of health care workers around the world. To contribute to the emergency situation, many independent manufacturers, individuals, local hospitals have proposed a number of innovative ideas including design of PPE using 3D technology and decontaminating PPE for reuse[78–80].

3D printing of mask accessories

Additive manufacturing (AM) including 3-dimensional (3D) printing have gained popularity in manufacturing of medical devices[81]. Advantages of AM technology includes ease in fabricating complex geometric structures, allowing the creation of engineered porous structures, tortuous internal channels, and internal support structures that would not be easily possible using traditional (non-additive) manufacturing approaches[81–83].

3D printing has been used to make mask components such as mask structure or frame, cover, filter fix, seal etc. A variety of different types of materials including polymax PLA filament, FDM ABS, SLS/MJF nylon or flexible SLA resin have been used. Foam or silicone band have been used to print seal with improved airtightness and softer skin touch. 3D-printed masks may look like conventional PPE. However, they may not provide the same level of barrier protection, fluid resistance, filtration, and infection control. The new designs are not approved by any regulatory agencies yet and performance may have been compromised. But since they provide low-cost, quick, and decentralized and distributed manufacturing, 3D printed masks are seen as help during emergency situation. The federal drug agency of United States of America (USFDA) has recently developed preliminary guidance to devices using additive manufacturing (AM) that involves 3-dimensional (3D) printing[83,84].

Modified filter material

There are several efforts to modify filters with various materials such as antibody and nanomaterials to enhance the antimicrobial activity and filtering efficiency of the masks. Kamiyama et al.[85] reported a modified nonwoven fabric–based air filters that were impregnated with antibody for avian influenza H5N1 virus. The filters were found to inactivate the virus trapped in the filter due to antigen–antibody interaction. However, these filters were tested for birds only. All birds housed in antibody filter covered boxes did not die. Similar antibody impregnated filter could be tested for face masks. Such methods may require further research to find out how the antibody impregnated on filters would retain their activity in ambient environmental condition during transportation, storage and use of the filter. It is also not clear the performance of such filters while they are used in mask.

Metal oxide and metal nanoparticles display biocidal activities. Taking the advantage of the biocidal properties, respiratory face masks containing these materials have been tested for anti-microbial activities. The use of biocidal masks may significantly reduce the risk of hand or environmental contamination, and thereby subsequent infection due to improper handling and disposal of the masks. A copper oxide impregnated respiratory face mask was reported by Borkow et al. [55] that demonstrated potent anti-influenza biocidal properties without altering physical barrier properties of the masks. Copper oxide displays potent biocidal properties against a range of microbes including bacteriophages, bronchitis virus, poliovirus, herpes simplex virus, human immunodeficiency virus and influenza viruses[86–88]. The copper oxide impregnation did not alter the filtering efficiency of N95 masks when tested with aerosolized viruses of human influenza A virus (H1N1) and avian influenza virus (H9N2) under simulated breathing conditions. In these experiments, no infectious H1N1 viral titers were recovered from the copper oxide containing masks within 30 minutes. In case of H9N2 virus, titers were recovered from the copper oxide containing masks but were five-fold lower than the control masks. The copper oxide containing masks successfully passed bacterial filtration efficacy, differential pressure, latex particle challenge, and resistance to penetration[55].

The metal oxide or nanoparticle impregnated respirator could have four layers of fabric as reported by Borkow et al.[55]. Out of the four layers outer two and inner layers were metal oxide impregnated polypropylene fabric and the remaining layer was made of plain polyester to give shape to the mask (Figure 2e).

Another study investigated the biocidal activity of silver nitrate and titanium dioxide coated facemasks[89]. A mixture of silver nitrate and titanium dioxide nanoparticles coated facemasks were tested against infectious agents. The minimum inhibitory concentrations of the nanoparticles against Escherichia coli and Staphylococcus aureus were 1/128 and 1/512, respectively. A 100% reduction in viable *E. coli* and *S. aureus* was observed in the coated mask materials after 48 h of incubation. Skin irritation was not observed in any of the volunteers who wore the facemasks. Nanoparticles showed promise when applied as a coating to the surface of protective clothing in reducing the risk of transmission of infectious agents.

The efficacy of 4 antimicrobial respirators to decontaminate MS2 virus was evaluated[90]. MS2 is used as a surrogate for pathogenic viruses. The MS2 activity of masks with antimicrobial material was significantly reduced when stored at 37 °C and 80% RH for 4 hours than the masks without antimicrobial materials. The antimicrobial materials used in this research included coating of outer layer of mask with silver–copper material, incorporating EnvizO_3-Shield on the outer layer of respirator, iodinated resin incorporated on filtering layer, and TiO2 coated filtering layer. This study suggested that MS2 virus decontamination efficacy of antimicrobial respirators were dependent on the antimicrobial agent and storage conditions. One should note that substituting conventional filter media of facemasks with nanofiber may reduce the airflow resistance that could lead to enhanced filtration[91].

Virus deactivation methods

Improper decontamination and reuse of used masks and N95 respirators may pose the transmission risk. However, reuse of these protective gears after proper decontamination may help fulfil supply chain constraints to some extent during the pandemics such as current COVID-19 pandemic. The decontamination process must inactivate any infectious material on the filtering face piece respirators without clogging the filtering device[51,92]. Clogged respirators apparently show higher filtering efficiency but resistance to breathing increases significantly making the fiber unfit to use. There are several strategies to deactivate the viruses on masks such as functionalization of fibrous filtration unit by sodium chloride salt[93], ammonium salt[94], vaporized hydrogen peroxide (VGP)[95], ultraviolet germicidal irradiation (UVGI), ethylene oxide (EtO), microwave oven irradiation, and bleach[96].

The main fibrous filtration unit of a surgical mask can be functionalized with sodium chloride salt to destroy the pathogens[93]. The salt coating on the fiber surface dissolved upon exposure to virus aerosols. The salt destroyed the pathogens when it recrystallized during drying. The salt-coated filters also showed higher filtration efficiency than conventional mask filtration layer. The virus spiked salt treated filters provided 100% survival rate of mice. Viruses captured on salt-coated filters exhibited rapid infectivity loss compared to gradual decrease on bare filters. Salt-coated filters proved highly effective in deactivating influenza viruses regardless of subtypes and following storage in harsh environmental conditions. This simple pathogen deactivation method can be helpful in obtaining a broad-spectrum, airborne pathogen prevention device in preparation for epidemic and pandemic of respiratory diseases. Similarly, a quaternary ammonium based antimicrobial surfactant was evaluated to see its efficiency to reduce bacterial burden on mask surface[94]. The antimicrobial surfactant was covalently bound onto mask surface before use. The antimicrobial mask provided >99.3% efficiency for all three bacterial species tested. In addition, the antimicrobial ability of the coated mask maintained efficacy at least one week after coating. For bioaerosols that came into contact with the mask (103 CFU/m^3), the antimicrobial agent reduced the average colony rates by 91.8%, but the rates decreased with increased bioaerosol concentrations. Moreover, the filtration performance of the surgical mask was not significantly altered.

Vaporized Hydrogen peroxide (HP) has also been used for bio-decontamination of various protective equipment. The peroxide vapor can penetrate the porous fabric that may harbor virus. The virucidal activity of HP was tested after inoculating respirators with aerosolized bacteriophage as a proxy for SARS–CoV–2[95]. Respirators were then vaporized with a long aeration phase HP vapors. A single HP vapor cycle resulted in complete eradication of phage from masks. After 5 cycles, the respirators appeared similar to new with no deformity.

Viscusi et al[96] compared five different decontamination methods for nine different models of NIOSH-certified respirators (three models each of N95 FFRs, surgical N95 respirators, and P100 FFRs). Each mask was treated with each decontamination method and were evaluated for changes in physical appearance, odor, filter aerosol penetration, filter airflow resistance, dry heat laboratory oven exposures, off-gassing, and FFR hydrophobicity to better understand material properties and possible health risks to the respirator user following decontamination. Microwave oven irradiation melted samples from two FFR models. The remainder of the FFR samples that had been decontaminated had expected levels of filter aerosol penetration and filter airflow resistance. The scent of bleach remained noticeable following overnight drying and low levels of chlorine gas were found to off-gas from bleach-decontaminated FFRs when rehydrated with deionized water. UVGI, ethylene oxide (EtO), and VHP were found to be the most promising decontamination methods.

Conclusions and future perspectives

The filtering efficiency of a face mask and respirator depends on number of parameters such as nature of filter media, size of particle, and environmental parameters. The level of protection also depends on the user compliance. Literature studies show that the N95 respirator or equivalent or higher, if worn properly, can effectively provide protection to virus. In vitro studies have suggested that the filtering efficiency of surgical mask is lower than the N95 respirators, and cloth face mask perform even poorer (please refer to table 1). A cluster randomized trial study on the use of cloth masks in hospital settings suggested that home–made cloth/fabric mask cannot be effective to prevent viral infection [28]. The most recent cluster randomized study suggested that the surgical mask, if worn by infected patients, could prevent the droplet mediated transmission of influenza virus and SARS-CoV-2 virus and aerosol mediated transmission of SARS–CoV–2 virus [72].

One of the issues regarding the use of respirator is discomfort to the user in prolonged wearing partly due to imperfect facial fitness and increased breathing resistance. In worst cases, this could even lead to psychological impact[97,98] and reduced adherence and loss of workplace protection factor[99]. The emerging 3D printing technology along with development of smart materials could help to solve this issue.

Currently used respiratory protection device pose potential risk of primary and secondary infection and transmission due to improper handling and disposing them. In viral outbreaks, because of increased demand and subsequent shortage, surgical mask and respirator are decontaminated and reused. There is still a chance of infection during decontamination process or by ineffective decontamination. Also, device interiority and performance may deteriorate and level of protection could decrease. So, there is need of better decontamination method other than explored in Ref[95,96]. Solution to this issue could the incorporation of filter media that can self-decontaminate, partly explored in Refs.[55,94,100], or design of a device that incorporate resistive heating element.

Another issue during viral outbreak, including COVID-19, is inevitable use of cloth face mask especially in low income countries; although such masks only provide reduced protection. Lower efficiency of such mask is partly due to loosen facial fitting and the material used. So there is a need of research that can provide cheap and effective home–made alternative to the cloth face mask.

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