

Public Health Protection Against Bioterrorism via Respiratory Pathogenic Viral and Bacterial Agents using Protective Face Masks

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The widespread respiratory transmission of the SARS-COV-2 virus has taught the general public the role that face coverings can play in mitigating the spread of the virus. While vaccines will mitigate widespread viral infection, protective face masks are an important way to prevent respiratory infections from various pathogenic agents. In view of the possibility of respiratory-based bioterrorism or new naturally occurring pathogens in the future, it is possible that the public may have to become comfortable with universal usage of face masks. The Centers for Disease Control recommends that all families have readily available respiratory protection as part of their personal pandemic plan and face masks should be worn by all individuals during a pandemic especially one caused by bioterrorism or an emerging viral or bacterial pathogen. This paper discusses the evolution of protective face masks that capture pathogens, development of face mask filters which enhance the performance of cloth-based protective facemasks for capturing pathogenic respiratory particles, and protective face masks with filters which capture and kill or deactivate pathogens using silver, copper oxide and zinc oxide-based particles.

Keywords: bioterrorism, public health, face mask

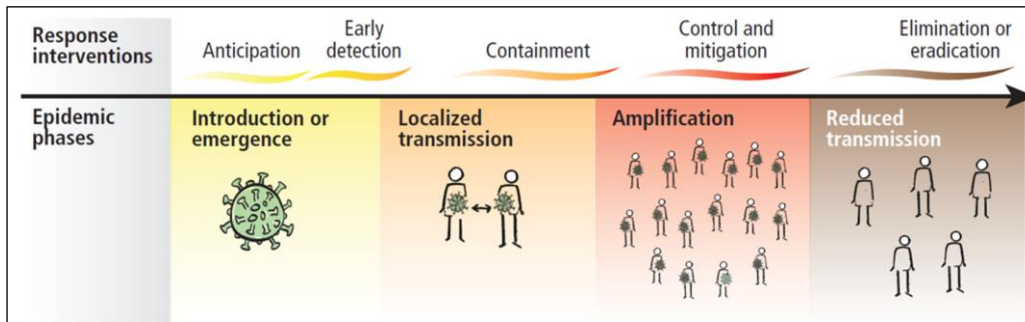
Introduction

Infectious disease disasters are events that involve a biological agent or disease and that can result in mass casualties, such as a bioterrorism attack, a pandemic, or an outbreak of an emerging infectious disease. Infectious disease disasters are different from other types of disasters because they increase the risk of communicable disease spread during and after the incident. Infectious disease disasters include biological terrorism, emerging infectious disease outbreaks, and other pandemics. Common characteristics of this diverse group of biologic agents include the ability to be dispersed in mucosalivary aerosols of 1 to 5 micron-sized particles, which can penetrate the distal bronchioles. Further, once a human is infected by a pathogenic virus it can be transmitted to other humans through respiratory means. There is a high likelihood of such a pandemic occurring in the future and bioterrorism, which is the intentional use of a biological agent or derivative of such an agent to inflict harm or death onto a civilian population, also could occur.¹ Bacterial or viral pathogens can be weaponized and the biologic agents may be dispersed by several techniques including aerosol sprays.²

In 2018, the World Health Organization published a handbook titled “Managing Epidemics”.³ The handbook offered several critical suggestions. Effective and rapid containment of emerging diseases is just as vital as early detection in order to avoid a large-scale epidemic. Rapid containment should start as

soon as the first case is detected regardless of the etiology, which is most likely to be unknown. It requires skilled professionals to safely implement the necessary countermeasures. Pre-training of these professionals is essential to guarantee the safety and efficiency of the operations. Once the infectious disease threat reaches an epidemic or pandemic level, the goal of the response is to mitigate its impact and reduce its incidence, morbidity, and mortality as well as disruptions to economic, political, and social systems.³ (See Figure 1)

Figure 1. Epidemic phases and response interventions



The transmission of pathogenic aerosols can be reduced by wearing face coverings. Different types of coverings offer different degrees of protection. The ultimate goal is to minimize penetration through the porous material of the covering. Penetration usually takes place due to a pressure and concentration gradient across the barrier, respectively. Pathogens, such as the SARS-COV-2 virus, are transmitted most easily through liquids such as mucosalivary aerosols.⁴ These aerosols can be expressed by coughs, sneezes, or just exhaling.⁵ For respiratory pathogens, such as viruses or bacterial, the best way to prevent localized infection and/or mitigate community spread (amplification) are effective protective textile face masks since they can reduce and mitigate airborne transmission. No masking maximizes exposure whereas universal masking results in reducing the exposure via inhalation and transmission via exhalation.

Protective face masks, at the minimum, should provide adequate cover of the wearer’s mouth and nose. Further, they should provide a tight fit while still remaining comfortable. Their function is to minimize or even prevent pathogenic-containing mucosalivary secretions from passing through the mask during exhalation and also minimize or even prevent pathogenic respiratory aerosols or droplets exhaled by others from being inhaled. This is referred to as “capturing ability”. However, capturing ability, while necessary, is not sufficient to prevent infection from a pathogenic agent. To be optimally effective in mitigating spread of respiratory borne diseases, the mask should also deactivate or kill the pathogenic agents. The ideal mask would be able to both capture and deactivate or kill either of these types of pathogenic agents. Further, the protective mask should be reusable for a period of time and be able to be occasionally cleaned using conventional laundering equipment. The protective mask should have an adequate shelf life so it can be held in reserve for immediate deployment in case of a public health threatening bioterrorism event or a transmission of a naturally occurring emerging pathogen. (See Table 1)

Table 1. Mask Mechanisms to Mitigate Airborne Aerosol Spread of Pathogens

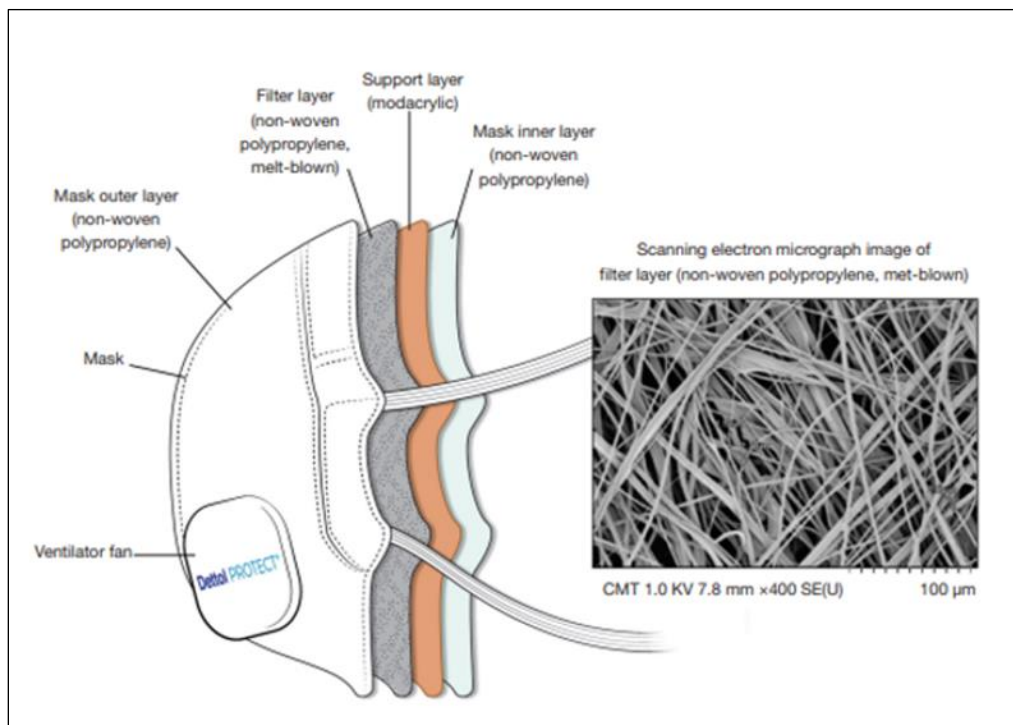
RESPIRATORY FUNCTION	MASK MECHANISM		OPTIMAL MASK MECHANISM
INHALATION	CAPTURE	DEACTIVATE OR KILL	CAPTURE AND DEACTIVATE OR KILL
EXHALATION	CAPTURE	DEACTIVATE OR KILL	CAPTURE AND DEACTIVATE OR KILL

Evolution of Protective Face Masks That Capture Pathogens

An N95 respirator, which is widely recognized as the “gold standard” face covering by medical professionals, is designed to achieve a very close facial fit and very efficient filtration of airborne particles. The edges of the respirator are designed to form a seal around the nose and mouth. N95 respirators are commonly used in healthcare settings. They are tested for fluid resistance, filtration efficiency (particulate filtration efficiency and bacterial filtration efficiency), flammability and biocompatibility.⁶

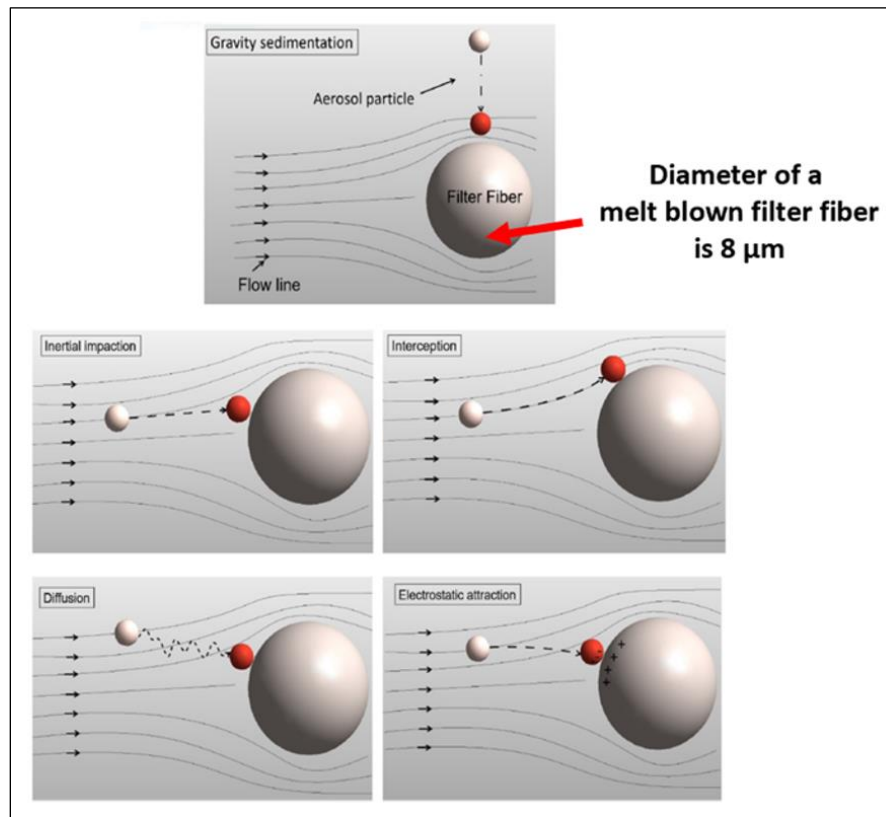
An N95 respirator removes particles from the air that is breathed through it. These respirators filter out at least 95% of very small (<0.3 micron) particles. N95s are capable of filtering out all types of particles, including bacteria and viruses.^{7, 8}(See Figure 2) Melt blowing is a method of producing fibers on the order of 10 µm using high production rates without using spinnerets. A thermoplastic polymer is melted and extruded through relatively large holes. As the polymer leaves the extrusion holes it is hit by a high stream of hot air which breaks up the fiber flow and stretches the filaments until they are relatively fine. At a later stage, cold air mixes with the hot air and the polymer solidifies into a fiber.

Figure 2. Schematic of Various Fabric Layers in an N95 respirator



The N95 filter that is included in the N95 respirator is solely designed to capture particles containing pathogens, such as SARS-COV-2, and not deactivate or kill the pathogens. Capturing these particles is a result of 5 different mechanisms: gravity sedimentation, inertial impaction, interception, diffusion, and electrostatic attraction (See Figure 3).⁹

Figure 3. Schematic of the Mechanisms of Aerosol Penetration Through Masks



During the initial stages of the SARS-COV-2 pandemic, the use of cloth masks, many of them homemade, became widely prevalent as commercial masks were not readily available. The efficiency of common fabrics used for cloth face masks made from woven fabrics was recently evaluated.¹⁰ The study presented data of Particulate Filtration Efficiency (PFE) and pressure differential (ΔP) which is an indication of breathability. The PFE is measured using ASTM Standard F2299 “Standard Test Method For Determining The Initial Efficiency Of Materials Used In Medical Face Masks To Penetration By Particulates Using Latex Spheres.”¹¹ For maximizing wearer breathability during exhalation and inhalation, the pressure drop should be as low as possible while maintaining a relatively high particle filtration efficiency. A face mask with relatively high filtration efficiency but physiologically intolerable resistance to airflow is essentially unusable to the wearer. Consequently, both the filter penetration and air resistance should be considered when ranking protective face masks and respirators.

Protective face masks which are purposed to capture aerosolized pathogenic agents should have relatively high-Particulate Filtration Efficiency (PFE). Using the recent data of aerosol filtration efficiency of common fabrics used in respiratory cloth masks from Konda et al. the PFE and pressure drop across the mask material were determined for N95 respirators, surgical masks and a range of woven fabrics for particle sizes $< 0.3 \mu\text{m}$ and $> 0.3 \mu\text{m}$ (See Table 2).¹²

These data indicate that protective face masks made from surgical masks and conventional cloth fabrics have relatively lower filtration rates than N95 respirators. Nonetheless, N95 respirators and surgical masks are superior to the woven fabric cloth masks that were studied. Fit (how tight the seal is between a mask and the wearer) also plays an important role with regard to affecting the PFE (See Table 3).¹²

Table 2. Particle Filtration Efficiencies of Various Test Specimens at a Flow Rate of 1.2 CFM and the Corresponding Differential Pressure (ΔP) across the Specimen



Type of Mask	Particle Filtration Efficiency (PFE), %		Pressure Differential (ΔP), Pa	Comparisons of PFE to N95 melt blown polypropylene filter respirator	
	Particle Size			Particle Size	
	<0.3 μm	>0.3 μm		<0.3 μm	>0.3 μm
N95 Respirator-melt blown polypropylene fiber	85	99.9	2.2		
Surgical Mask -spun bonded polyester	76	99.6	2.2	89.4%	99.7%
Quilter's Cotton – 2 woven layers	38	49	2.5	44.7%	49.0%
Quilter's Cotton – 1 woven layer	9	14	2.2	10.6%	14.0%
Flannel -65% cotton/35%polyester	57	44	2.2	67.1%	44.0%
Chiffon – 90% polyester/10% cotton – 1 woven layer	67	73	2.7	78.8%	73.0%
Chiffon – 90% polyester/10% cotton – 2 woven layers	83	90	3.0	97.6%	90.0%
Silk – 1 woven layer	54	56	2.5	63.5%	56.0%
Silk – 4 woven layers	86	88	2.7	101.2%	88.0%

Table 3. Particle Filtration Efficiencies of Various Test Specimens at a Flow Rate of 1.2 CFM and the Corresponding Differential Pressure (ΔP) across the Specimen (No Gap v. Gap)





Type of Mask	Particle Filtration Efficiency (PFE), %		Pressure Differential (ΔP), Pa	Comparisons of PFE to N95 melt blown polypropylene filter respirator	
	Particle Size			Particle Size	
	<0.3 μm	>0.3 μm		<0.3 μm	>0.3 μm
N95 Respirator-melt blown polypropylene fiber (No Gap)	85	99.9	2.2		
N95 Respirator-melt blown polypropylene fiber (Gap)	34	12	2.2	40.0%	12.0%
Surgical Mask -spun bonded polyester (No Gap)	76	99.6	2.5	89.4%	99.7%
Surgical Mask -spun bonded polyester (Gap)	50	44	2.5	58.8%	44.0%

Table 4. Comparison of surgical masks to 100% cotton T-Shirts for *B atrophaeus* and Bacteriophage MS2 bacterial agents

<i>B atrophaeus</i> bacterial agent			
Mask Material	Bacterial Filtration Efficiency (BFE), %	Pressure Differential, ΔP (Pa)	Comparisons of BFE to spun bonded surgical mask
Surgical Mask -spun bonded polyester	96.4	5.23	
100% Knitted Cotton T-Shirt fabric – 1 layer	69.4	4.29	72.0%
100% Knitted Cotton T-Shirt fabric – 2 layers	70.7	5.13	73.3%
Bacteriophage MS2 bacterial agent			
Mask Material	Bacterial Filtration Efficiency (BFE), %	Pressure Differential, ΔP (Pa)	Comparisons of BFE to spun bonded surgical mask
Surgical Mask -spun bonded polyester	89.5	5.23	
100% Knitted Cotton T-Shirt fabric – 1 layer	50.9	4.29	56.9%

The efficacy of homemade cloth masks made from knitted cotton fabric, compared to surgical masks, was assessed to determine if they would be effective in an influenza epidemic (H1N1). The results of the study, which compared the bacterial filter efficiency (BFE) and pressure drop, are seen in Table 4.¹³ The efficacy of homemade cloth masks made from knitted cotton fabric, compared to surgical masks, was assessed to determine if they would be effective in an influenza epidemic (H1N1).¹³ The results of the study, which compared the bacterial filter efficiency (BFE) and pressure drop, are seen in Table 4. Bacterial agents were used as proxies for the H1N1 virus, and the data indicate that homemade masks made from knitted cotton fabric should not be used for the reduction of transmission from diseases which can be transmitted via mucosalivary secretions.

Tables 2, 3, and 4 suggest the relative ineffectiveness of masks made from cloth fabrics without filters. Further, the importance of a tight fit between the wearer and the mask is apparent.

Development of Face Mask Filters to Enhance the Performance of Cloth-Based Protective Face Masks for Capturing Pathogenic Mucosalivary Particles

The particle filtration efficiencies of protective masks made from common woven or knitted fabrics have been shown to have a minimal effect in the filtration of mucosalivary secretions such as those from persons infected with viral and bacterial pathogens. Hence, there is a need to enhance the filtration capability of cloth masks. This can be accomplished with the incorporation of textile materials specifically designed to filter particles such as those expressed by either wearer exhalation or inhalation. Since protective face masks made from conventional woven or knitted fabrics are minimally effective in containing droplets and aerosols when compared to the N95 respirator which has a middle layer comprising a melt blown fibrous filter face mask developers are now recognizing the importance of fibrous filters to substantially reduce the transmission of respiratory induced particles.

Particulate filters have been used in a wide range of other applications. For example, in 1976 a patent was issued for the production of fibrous filters, which was directed at spinning solutions which are electrostatically sprayed and deposited continuously onto a gas permeable band-form support.¹⁴ In 2006, a study determined the filtration efficiency of the most penetrating aerosol particles in melt blown fibrous

filters and nano-electro spun fibrous filters.¹⁵ Nano-electrospinning is a fiber production method which uses electric force to draw charged threads of polymer solutions or polymer melts up to fiber diameters in the order of less than 1 μm . Electrospinning uses an electrical charge to draw very fine (typically on the micro or nano scale) fibers from a liquid or polymer solution. Using the procedure for determining the particle filtration efficiencies, four different filters were studied with fiber diameters of 10 μm , 2 μm , 0.7 μm , and 0.1 μm . The researchers found “*that utilization of nanofibers to manufacture air filters seems to be an excellent solution from the standpoint of the filter efficiency improvement, especially if the process target is removal of sub micrometer-sized aerosol particles, usually being the hardest (sic) to filter out.*”¹⁵

Nano-electrospinning has emerged as an effective technique for the fabrication of micro and nanoscale objects, and it is particularly useful in the fabrication of fibrous filters. In the fabrication of filters, nano-electrospinning has an advantage over traditional technologies, such as melt-blowing, of operating at room temperature. Another significant advantage, and one that is unique to electrospinning, is its ability of producing fibers in the submicron scale. As such, due to their submicron diameter they have a substantially higher surface area to volume ratio than fibers that are produced using the melt blowing process and, as such, are considered more efficient filters.¹⁶

Researchers in Singapore recently reported that a key factor that affects the function of air filter is fiber diameter and when it is reduced to nanoscale ($<1\mu\text{m}$) the surface area to volume ratio is relatively high and results in a more effective filter. Nanoscale fibers are commonly produced by nano-electrospinning of electrically charged polymer solutions.¹⁷ There are now many protective face mask manufacturers supplying products with insertable nanoscale fiber filters. For example, HaloMask™, offers one with an insertable nanofiber filter.¹⁸ The nanofiber filters were tested for Bacterial Filtration Efficiency (BFE), Differential Pressure (ΔP) and Particle Filtration Efficiency (PFE). Below are the data for BFE and ΔP obtained by the manufacturer of HaloMask™ using ASTM standards.^{19,20}

Table 5. Bacterial Filtration Efficiency and Particle Filtration Efficiency of HaloMask™

Bacterial Filtration Efficiency (BFE)	Pressure Differential, ΔP (mm H₂O/cm²)	Test Method
~98%	~2.0	ASTM F2101-19
Particle Size	Particle Filtration Efficiency	Test Method
0.1 μm	~ 99.0%	ASTM F2299/F2299M – 03
0.3 μm	98.8%	ASTM F2299/F2299M – 03
0.5 μm	97.8%	ASTM F2299/F2299M – 03
1.0 μm	98.0%	ASTM F2299/F2299M – 03

Masks with Filters Which Capture and Kill or Deactivate Pathogens

While filtration of pathogenic respiratory agents is necessary to minimize airborne transmission, when filtration is also coupled with pathogenic deactivation a protective face mask will significantly minimize infection of the wearer and thus also minimize transmission to others. Pathogenic deactivation can be affected by various metal-based elements and compounds which can be incorporated into masks or mask filters.

Silver Particle-Based Deactivation of Pathogens

A study in the early 2000's was directed at the antimicrobial effect of surgical masks coated with nanoparticles.²¹ The study assessed the antimicrobial activity of nanoparticles (consisting of a mixture of silver nitrate and titanium dioxide) and nanoparticle-coated facemasks to protect against infectious agents. *Escherichia coli* and *Staphylococcus aureus* were used for this study as both are reference strains used for antimicrobial susceptibility testing. The researchers found that masks coated with nanoparticles at low concentrations were effective against *E. coli* and *S. aureus*, and that bacteria attached to the surface of nanoparticle-treated masks were killed completely. An earlier study showed that impregnation, instead of coating the medical device with nanoparticulate silver metal, improved the antimicrobial activity of the device. This is probably due to the slow and continual release of silver that prolonged the antimicrobial effect.²² As such, silver-based antimicrobial formulations and nanoparticles have been identified as effective antibacterial agents.^{23,24} In 2011 it was reported that silver nanoparticles have mainly been studied for their antimicrobial potential against bacteria, but have also proven to be active against several types of viruses including human immunodeficiency virus, hepatitis B virus, herpes simplex virus, respiratory syncytial virus, and monkey pox virus.²⁵

Silver-based nanoparticles have been incorporated and functionalized in polyester/cotton fabrics using pad-dry-cure method (a common textile fabric coating process).²⁶ This composite proved to be effective for inhibiting the SARS-COV-2 virus, decreasing the number of replicates in 99.99% after an incubation period of 2 minutes. In addition, it caused 99.99% inhibition of the bacterial pathogens *S. aureus*, *E. coli* and *C. albicans*, preventing cross-infections and does not cause allergies or photo irritation processes, demonstrating the safety of its use.²⁵

Copper Oxide-Based Deactivation of Pathogens

Impregnation of copper oxide into respiratory protective face masks endows them with potent anti-influenza biocidal properties without altering their physical barrier properties such as breathability. Further, 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. The masks were challenged with virus (H1N1) or an aerosolized avian influenza virus (H9N2). The mean (5 masks were tested) Bacterial Filter Efficiency (BFE) was 98.2 %.²⁷

Zinc Oxide Particle-Based Deactivation of Pathogens

Zinc oxide nanoparticles are antibacterial and inhibit the growth of microorganisms by permeating into the cell membrane. The oxidative stress damages lipids, carbohydrates, proteins, and DNA.²⁸ With regard to the antiviral effect of zinc oxide nanoparticles a study was done on the inhibition of H1N1 virus infection.²⁹ Zinc oxide nanoparticles and polyethylene glycated zinc oxide nanoparticles were studied. The study showed that polyethylene glycated zinc oxide nanoparticles had a stronger antiviral effect than just zinc oxide nanoparticles.

A patent was recently issued which discloses how zinc oxide nanoparticles can be applied using ultra sonics to coat fabrics.³⁰ The patent is being used by Sonovia Ltd. in Israel to produce the SonoMask.³¹ The SonoMask has been tested to be 99.35% effective against SARS-COV-2, an ability to filter 91% of 3µm and 95% of 5µm particles and be able to withstand at least 55 laundering cycles. As such, the SonoMask both captures and deactivates viral pathogens. Further, since the SonoMask can be reused many times it does not significantly contribute to environmental waste.

Another possibility for creating mask filters which both capture and deactivate viral and bacterial borne pathogens involves nano-electro spinning nanofibers (which have a relatively high surface area to volume ratio), such as polyvinylidene difluoride (PVDF) or polyacrylonitrile (PAN), and including in them nanoparticles such as zinc oxide or silver which deactivate viral pathogens and kills bacterial pathogens

Conclusions

The potential for bioterrorism events that are a result of aerosolized viral and bacterial pathogens exists. We have learned from the SARS-COV-2 pandemic how dangerous aerosolized viral pathogens are and while eventually vaccines may be developed to mitigate the spread of new pathogens, effective protective face masks are an important element that can mitigate the immediate continuous spread and containment of the pathogen. While at first the only widely available masks were cloth-based they proved to be substantially ineffective when compared to the “gold standard” N95 respirator. As the pandemic continued many researchers and companies developed masks that, at first, were only effective in capturing the pathogenic aerosol. Capturing the aerosols with face masks, while useful for protecting the public health, are not as effective until they can also deactivate or kill the pathogen. The CDC recommends that all families have readily available respiratory protection as part of their personal pandemic plan because face masks should be worn by infected individuals when in public places during a pandemic.³² This would especially true during a bioterrorism induced pathogenic pandemic or the emergence of new naturally occurring pathogens including SARS-COV-2 variants.

The United States has seen approximately 1500 deaths per million (1.5 in a 1000) of its population as of late February 2021 while Canada has only seen about 580 deaths per million of its population.³³ American failures have remained dramatic as such questions as wearing masks and how to relax lockdowns have been bitterly politicized.³⁴ As such, if the U.S. public is ever threatened by respiratory aerosol pathogen-based bioterrorism attack or another pandemic from an emerging virus, the public will have no choice but to adopt universal mask usage or face the consequences of wide spread infection and death.

Finally, speaking during an online briefing by the WHO in late December 2020, Dr. Mark Ryan, Head of the WHO Emergencies Programme, said that other emerging diseases could be more dangerous than SARS-COV-2. Dr. Ryan said:

This pandemic [SARS-COV-2] has been very severe, it has spread around the world extremely quickly and has affected every corner of this planet - **but this is not necessarily the big one**. This virus is very transmissible and it kills people and it has deprived so many people of loved ones but its current case fatality is reasonably low compared to other emerging diseases. This is a wakeup call, we are learning now how to do things better. How to do science better, how to do logistics better, how to do training better, how to do governance better, how to communicate better.³⁵

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