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Respiratory protection against bioaerosols: Literature review and research needs

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Research on respiratory protection against biologic agents is important to address major concerns such as occupational safety and terrorist attack. This review describes the literature on respiratory protection against bioaerosols and identifies research gaps. Respiratory protection is a complex field involving a number of factors, such as the efficiency of respirator filter material; face-piece fitting; and maintenance, storage, and reuse of respirators. Several studies used nonpathogenic microorganisms having physical characteristics similar to that of *Mycobacterium tuberculosis* to analyze microbial penetration through respirators. Some studies showed that high-efficiency particulate air (HEPA) and N95 filters provided a higher level of protection than dust/mist (DM) and dust/mist/fume (DMF) filters. Flow rate and relative humidity appear to alter the level of penetration of microorganisms through respirator filters. The relationship between microbial penetration through respirator filters and the aerodynamic diameter, length, or other physical characteristics of microorganisms remains controversial. Whether reaerosolization of bioaerosol particles should be a concern is unclear, given the fact that one study has demonstrated significant reaerosolization of 1- to 5-μm particles loaded onto respirator filters. Respirator maintenance, storage, and decontamination are important factors to be considered when reusing respirators. The respiratory protection against biologic warfare agents such as anthrax in military and civilian situations is described. (Am J Infect Control 2004;32:345-54.)

In the1980s, there was an increase in the number of reported tuberculosis (TB) cases and mortality rates of persons infected with *Mycobacterium tuberculosis*.[1,2] It was predicted that the number of TB cases would increase in the coming years.[1] The concerns on TB transmission led to the development of the *Guidelines for Prevention of TB Transmission in Hospitals* by the Centers for Disease Control and Prevention (CDC).[3] National Institute for Occupational Safety and Health (NIOSH) recommended guidelines for personal respiratory protection of workers in health care facilities to prevent the transmission of TB.[4] In addition, the Joint Commission on Accreditation of Healthcare Organization, the American National Standards Institute (ANSI), and the American Thoracic Society have developed recommendations for respiratory protection.[5-7] In addition, CDC recommended respiratory protection measures against bioterrorism agents under different situations.[8-13] This review summarizes the available information on efficiency of respirator filters against biologic agents, the importance of face-fitting characteristics, maintenance and storage, and decontamination of respirators. The lessons learned from respirator research on TB prevention may apply to other harmful bioaerosols including biologic warfare agents.

Several deficiencies in the reported data and research gaps were recognized in reviewing the reports and compiling their results. Some of these are listed as follows: First, a large portion of the studies was conducted with respirators approved as dust-mist (DM), dust-fume-mist (DFM), and high-efficiency particulate air (HEPA) respirators under the respirator approval requirements of Title 30 Code of Federal Regulations, Part 11 (30 CFR 11).[14] In 1995, Title 42 CFR 84[15] replaced Title 30 CFR 11,[14] and the DM, DFM, and HEPA filters have not been permitted to be sold and shipped by the approval holders as NIOSH-approved since 1998. New filter materials have been developed

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and the N, P, and R series air-purifying, particulate respirator filters have been recommended as replacements. Confirmation that results from the testing of Title 30 CFR 11[14] filters apply to Title 42 CFR 84[15] technologies is needed. Unlike the filters evaluated under Title 30 CFR 11,[14] all of the filters used with Title 42 CFR 84[15] respirators have been certified to perform at an efficiency level of at least 95% when challenged with a most penetrating size particle. Because the filter efficiency is based on the physical parameters of the particles to be filtered, any biologic particles can be expected to be filtered at no less efficiency than the test aerosol (ie, at least 95% efficient for an N95 filter). The selection of respiratory protection levels to be used against a biologic agent should be based on the infectious dose of that agent more than the filter efficiency. Second, test methodologies and protocols are not fully developed and described in the literature. This limits the amount of cross-comparison of results that can be validly performed. Third, the described test methodologies and protocols are not standardized on test parameters. For example, a number of flow rates were used among the various studies that can greatly influence the penetration through the filters. Finally, the paucity of literature on various aspects of respiratory protection against bioaerosols is a limiting factor in drawing conclusions.

CHARACTERISTICS OF BIOAEROSOLS

The characteristics of bioaerosols have been described previously.[16-18] Although the aerosol properties of bioaerosols are generally considered similar to nonbioaerosols, respirator selection and maintenance are complicated by the biologic nature. Bioaerosols include bacteria, viruses, fungi, algae, and dust mites. In addition, biologic products such as pollen, endotoxins, proteins, and animal excreta form aerosols. Both viable and nonviable forms of bioaerosols can be health hazardous. The infectious bioaerosols produce adverse health effects because of their ability to incubate, grow, multiply, and produce toxic substances. The health effects because of inhalation of bioaerosols depend on the number of viable particles, whereas the nonbioaerosols depend mostly on the mass of particles. Bioaerosols are sometimes employed in terrorism events. Some of the naturally occurring microorganisms can survive in the environment for a prolonged time, and they can be weaponized at a low cost. Terrorists utilize the unique features of microorganisms to cause psychologic shock on society and catastrophic effects. This suggests that respirator selection, cleaning, and reuse need to be carefully considered for a better respiratory protection against bioaerosol exposures.

FILTER EFFICIENCY AGAINST BIOLOGIC AGENTS

Several studies have reviewed the role of respiratory protective devices in the control of TB in health care settings.[19-22] Studies on respiratory protection against TB were carried out with nonpathogenic bacteria having physical characteristics similar to that of *M tuberculosis*. Two decades ago, conventional surgical masks were believed to be effective barriers for retaining large droplets expelled from patients as well as from health care workers through speaking, coughing, or sneezing. However, surgical masks were not adequate to remove submicrometer-size bioaerosols.[23,24] The measurement of filtration efficiencies of different respirators against *Mycobacterium chelonae* another surrogate bacteria of *M tuberculosis*, showed that DMF and a HEPA were more effective than the DM and single-use submicron surgical mask under a constant flow of 46 L/min.[25] Mean percentage efficiencies for viable *M chelonae* ranged from 97% for the DM and the surgical mask to more than 99.99% for the HEPA respirator.[25]

Further studies also confirmed that filters such as the HEPA and N95 were more efficient than the DM and DMF filters. A comparison of unloaded N95 particulate respirators with that of DM and DFM respirators against *Bacillus subtilis* and *Bacillus megatherium* and inert test particles were performed.[26] The penetration of both *B subtilis* and *B megatherium* was comparatively more with DM and DFM respirators than with N95 respirators at a flow rate of 85 L/min.[26] In another study, the penetration of *Mycobacterium abscessus* aerosol through 16 respirator filters and 5 surgical masks were determined at 2 different flow rates and at a different relative humidity.[27] The median penetration of *M abscessus* was 2%, 0.4%, and 0.02% for DM, DFM, and HEPA filters, respectively, at 45 L/min. Higher flow rate (85 L/min) resulted in higher penetration, and changes in relative humidity caused minimal effects on bioaerosol collection.[27] Filter performance against biologic agents was consistent with the expectations for nonbiological agents, based on their certified performance.

RESPIRATORY PROTECTION AGAINST BIOAEROSOL EXPOSURE IS DEPENDENT ON SEVERAL FACTORS

Bioaerosol size and filter penetration

Physical properties of different aerosols have been described previously.[16-18] Aerodynamic sizes and shapes of aerosols affect the particle penetration through respirators. The penetration level of polystyrene latex spheres was higher than that of *M chelone*, a rod-shaped bacteria, whereas the 2 types of particles had a similar aerodynamic size.[26] Subsequently, the penetration of microorganisms with

different shapes and aerodynamic sizes through different respirators was investigated.[28] In that study, the penetration of rod-shaped organisms, including *Pseudomonas fluorescens* (similar in size and shape to *M tuberculosis*), *B megatherium, Bacterium alcalophilus,* and a spherical *Streptococcus salivarius* through a surgical mask and a DM respirator, was compared.[28] The penetration of rod-shaped organisms was lower than that of the spherical organism. This study revealed that the microbial penetration through respirators was dependent on the aspect (length to width) ratio of the bacteria.[28]

Subsequently, the measurement of the bacterial aerosol collection by a variety of respirator filters and surgical masks revealed that the penetration of *B subtilis* (a rod) was more than that of *Staphylococcus epidermidis* (a sphere).[29] This suggested that the aerodynamic diameter of the organisms may not be the best parameter for predicting aerosol penetration of nonspherical particles in these filters.[29] A previous study on asbestos aerosols suggested that fiber length rather than aerodynamic diameter was a better predictor of penetration through a respirator.[30] Further research on particles of differing size and shape and their filter penetration properties needs to be conducted to characterize filter performance against the differing shapes and aspect ratios found in bioaerosol particles.

Effect of flow rate on filtration

Filter efficiency is appropriately described as varying with face velocity. The flow rates generally reported for the various research studies are measured flow rates in the test instruments. The face velocity can vary significantly from the instrument's measured flow rate. The reported flow rate represents the flow through a cross-sectional area of a plane perpendicular to the airflow. The volume of air (flow rate times cross-sectional area) is the air that passes through the cross-sectional area of the respirator filter. Assembled filters are generally not flat. Therefore, when the air volume is distributed over the larger cross-sectional area of the filter, the face velocity is less than the reported flow rate.

Respirator studies mostly use constant flow rates ranging from 20 to 85 L/min to characterize filter penetration based on the airflow rates at normal and heavy working conditions. Previous studies on respiratory measurements have reported a dramatic increase in peak inspiratory air flow rate and minute volume under heavy work conditions, suggesting the need for further investigation on filter penetration of aerosol particles at high airflow velocities.[31-34] Several studies investigated the filter penetration of particles at high airflow rates.[35,36] Hinds and Kraske tested the penetration of different aerodynamic diameter size aerosol particles through half-mask and single-use respirators at flow rates over the range of 2 to 150 L/min using a manikin model.[35] Submicrometer aerosol particles exhibited increased penetration levels with increased flow rates, whereas particles greater than 1 μm showed no significant effect.[35] This result has been subsequently confirmed in a study with a surgical mask, which showed that the penetration of 0.3-μm particles is strongly dependent on airflow.[36] In another study, increasing flow rates from 16 to 85 L/min shifted the most penetrating particle size region toward a smaller particle size.[36a]

Recently, the effects of aerosol penetration at different flow rates have been discussed.[37] This review agreed with previous reports in that large numbers of submicron size particles readily penetrate the filter at higher flow rates while contributing very little to the total mass of the penetrated particles. The number of bioaerosol particles that penetrate through the filter is critical to assess the health problems, whereas nonbiologic aerosols typically depend on the total mass of particles. In the case of bioaerosols, the penetration of a certain number of pathogenic organisms through the filter at higher flow rates may be sufficient to cause serious health problems. This suggests that measuring techniques that count the number of submicron particles reliably may be more appropriate for assessing protection against biologic agents than methods assessing the mass of penetrating particles.

Face-fitting characteristics

Microorganisms can penetrate through respirator filters, sealing surfaces, or other parts of a respirator. Penetration through filters has been studied in detail because filters are the main components involved in aerosol filtration. The performance of the facemask interface, as well as the filter material, can have a significant impact on the respirator's overall protection against aerosols.[38,39] Chen et al studied face seal leakage and filter penetration characteristics during inhalation and suggested that the slope of the aerosol size-dependent penetration curve may differentiate face-seal leakage from filter penetration.[38]

Subsequently, Chen and Willeke investigated the relationship between aerosol penetration and pressure differential across the filter by testing aerosol penetration through DM and HEPA filters using a mannequin model.[39] Leaks of different sizes and shapes were inserted, and aerosol penetration was measured for flow rates ranging from 5 to 100 L/min. They observed that less aerosols passed through a slit-like leak or multiple small circular leaks than a single circular size leak of equal cross-sectional area at a given pressure differential across the filter. Their study suggested that a face-seal leakage at low-breathing rate may cause a HEPA respirator to provide less protection than a DM

respirator. This was due to a higher pressure drop for a HEPA respirator, resulting in more aerosol flow through the leak.[39]

OSHA requires a respiratory protection program in workplaces at which respirators are necessary.[40] The employer shall ensure that employees periodically pass an OSHA-accepted qualitative or quantitative fit test and perform a user seal check each time the respirator is put on. The user seal check is a positive and/or negative pressure check or another manufacturer recommended test to ensure respiratory protection.[40]

The importance of fit factor in respiratory protection was investigated previously.[41-44] Qian et al. showed that N95 respirators were highly efficient in filtering airborne microbial particles when the respirator was sealed to the head form.[26] However, laboratory studies on N95 respirator performance in human subjects showed that the 95th percentile of the total penetrations for each respirator (95% of wearers of the respirator can expect to have a total penetration value below the 95th percentile penetration value) without fit testing ranged from 6% to 88%, with an average of 33%.[44] When fit-test screening was applied to the data, the 95th percentile of the total penetrations for each respirator decreased to 1% to 16%, with a mean value of 4%, suggesting that fit testing was necessary to achieve the high level of protection. The different aspects of qualitative and quantitative fit testing have been characterized by different research groups.[41,42,44-46] A recent study showed the importance of respirator fit characteristics.[47] Other factors including facial dimensions that influence the level of protection have been described.[48-50] Further research is needed in the following areas: (1) define the facial sizes of the worker population, so manufacturers can better design respirators to fit the broad range of facial dimensions in the workplace; (2) reduce errors in fit-test measurements that result in some poorer fits passing and some better fits being rejected; and (3) reduce variations in fit factors among donnings.

Efficiency degradation of filter material

Although the filtering efficiency of stored electrostatic filters remains very stable for years, their performance can decrease on exposure to industrial aerosols, chemicals, high humidity, and temperature.[51,52] Blackford et al investigated the filter efficiency of electrostatic filters after exposure to fumes such as lead-smelting and foundry-burning fumes and other industrial dusts and then tested for NaCl aerosol penetration.[51] All tested aerosols caused an increase in sodium chloride penetration, suggesting efficiency degradation after exposure to industrial aerosols.

The mechanism of filter degradation was investigated by the removal of electrical forces on filter material as a function of aerosol loading.[53,54] The penetration of corn oil aerosol first increased, which was attributed to a reduction of the electrical force because of fiber coating.[53] Further loading of aerosol decreased penetration or clogged because of the filter's increased packing density, suggesting that filter efficiency is dependent on aerosol loading. Similar conclusions were obtained by Moyer and Bergman, who exposed N95 respirators from different manufacturers to 5 mg sodium chloride aerosol, 1 day a week over a period of several weeks.[54] Whether filters exposed to bioaerosols undergo similar filter-efficiency degradation is unclear. Additionally, there are no indicators to signal the user when the efficiency of the filter has been reduced by exposure to industrial aerosols, chemicals, humidity, or temperature. Future research is needed to understand better the mechanisms of efficiency degradation, its causes, and indicators of exposures that could cause a reduction in efficiency. Further research is also needed to identify, categorize, and quantify various factors that significantly reduce a respirator's filtering efficiency.

RISK ASSESSMENT OF TB AEROSOLS

A risk-assessment model estimated the effectiveness of surgical mask, dust-mist/dust-fume (DM/DF), HEPA, and powered air-purifying respirators (PAPR) against TB in health care settings.[55] Nicas estimated that 42%, 5.7%, 2%, and 0.39% of droplet nuclei penetrate into surgical masks, disposable DM particulate respirators, elastomeric half-mask respirators with HEPA filters, and PAPRs, respectively.[55] In addition, the model estimated the risk of TB infection in health care workers based on a 10-year, cumulative, low and high exposure scenarios. The 10-year, cumulative, low-exposure risks were 15%, 6.7%, 0.94%, 0.33%, and 0.064% for no respirator use, surgical masks, disposable DM, elastomeric half-mask HEPA filter respirators, and HEPA filter PAPRs, respectively. However, the high-exposure, 10-year cumulative risks for no respirator use, surgical masks, disposable DM, elastomeric half-mask HEPA filter respirators, and HEPA filter PAPRs were 48%, 24%, 3.7%, 1.3%, and 0.26%, respectively.

Barnhart et al[56] extended the risk-assessment model described previously[55] to evaluate the risk of TB in health care settings. The estimated respiratory protection by surgical mask, DM/DF, HEPA, and PAPR was 2.4-, 17.5-, 45.5-, and 238-fold compared with the risk with no respirator.[56] Assuming a lifetime exposure of 250 hours, TB infection and TB-related death were estimated to be 0.9% and 0.009%, respectively, which could be substantially reduced by the use of respirators.[56] The above studies suggest that respirators with

HEPA filters provide higher level of protection against bioaerosols compared with DM and DFM respirators, which is consistent with nonbioaerosol particles.

The efficacy of respirators against anthrax inhalation by a mathematical modeling was analyzed.[57] Anthrax infection risk with 3 different respirators, namely, a negative-pressure half face piece, a negative-pressure full face piece, and a full face piece PAPR respirator was compared.[57] The cumulative risk of anthrax infection of an individual over 8 respirator-use periods for spore concentrations up to 10^5 per m^3 was determined for different levels of assigned penetration factor. A negative-pressure half face-piece respirator provided very little protection, whereas a negative-pressure full face-piece respirator offered good protection against anthrax spore exposure. However, very little risk of anthrax infection was assigned to a full face-piece PAPR. This analysis suggested that full face-piece PAPR was the best air-purifying device for responding to an anthrax spore attack.

The respirator selection procedure for protection against bioaerosols is relatively difficult compared with that for nonbioaerosols because of insufficient information on airborne concentrations and the occupational exposure limits of bioaerosols. A method for selecting respirators applicable to a variety of settings for a range of infectious organisms has been developed based on previously described procedures for nonbioaerosols.[22] The toxicity of bioaerosol was determined from risk ranking proposed by a variety of organizations. The individual's activity, room volume, and airflow were used to obtain a ranking of airborne concentration of the bioaerosol. From the concentration and toxicity ranks, a minimum assigned protection factor and the corresponding respirator class were determined. This respirator selection procedure was found to be applicable to a range of exposure scenarios with different organisms.[22]

Further research on respiratory protection against bacterial, viral, and their toxic products is important to address the dispersal of bioaerosols in terrorism events. Although respirator selection against bioaerosol should be based on the infectious dose of the microorganism, setting an exposure limit for an individual biologic agent is complicated by several factors. The infectious dose levels of various pathogenic organisms are not fully defined. Second, the airborne concentrations of different types of microorganisms at any given time are unknown. In addition, the survival and viability of the microorganisms vary with time because of the inherent properties of organisms. For example, spores may be alive for several years compared with vegetative bacteria and fungus. Finally, possible reaerosolization (bedding, and others) may cause additional uncertainty (latency periods) in all of the above. For example, anthrax spores used in the Hart Senate Office Building were found to reaerosolize under office working conditions.[58]

MICROORGANISM SURVIVAL ON FILTERS

The survival of infectious microorganisms is dependent on the relative humidity, temperature, oxygen concentration, and other factors.[59] These factors interact with the membrane phospholipids and protein components to cause changes in microbial survival time. For example, *Escherichia coli* strains were most stable at low-humidity conditions and markedly unstable at high-humidity conditions. In the case of *Francisella tularensis,* high levels of survival were exhibited at low- and high-humidity levels but not at intermediate levels. Viruses (polio and foot-and-mouth viruses) without structural lipids were more stable at high-humidity conditions, whereas viruses (influenza and vaccinia) with structural lipids were least stable. Pox viruses have been shown to survive for several months under natural indoor conditions.[60,61]

Several studies investigated concerns of bacterial survival on respirator filters, presenting a potential health problem should respirators be reused. A qualitative evaluation for the presence of viable organisms on 5 types of surgical masks and 18 types of respirator filters challenged with *M abscessus*, *S epidermidis*, and *B subtilis* was performed.[62] The organisms were eluted from filters following exposure, and culturability (percentage of filters with culturable organisms) was determined. The culturability ranged from 35% to 100% for *M abscessus*, 50% to 100% for *S epidermidis*, and 88% to 100% for *B subtilis* at prestorage conditions. After storage for 5 days, the culturability was 1% to 60% for *M abscessus*, 0% to 100% for *S epidermidis*, and 87% to 100% for *B subtilis*, suggesting that respirator reuse should be carefully considered.[62] They also observed that the survival (the ratio of colony forming units measured before and after storage) of *M abscessus* was the least and *B subtilis* the most. In another study, the survival of *M smegmatis* (a surrogate of *M tuberculosis*) on N95 respirators was tested after 1 to 9 days.[63] Bacteria collected on respirator filters were not able to grow and were only able to survive for up to 3 days, even under ideal growth conditions.[62] In a similar study, bacterial survival on NIOSH-certified polypropylene respirator filters has been reported.[64] Although *P fluorescens* and *B subtilis* were unable to grow on polypropylene filters, both bacteria survived. *P fluorescens* on filters lost its viability in less than 3 days, and *B subtilis* remained viable for over 13 days.[64] These studies indicate that spore-forming bacteria may have a greater viability compared with vegetative bacteria. This suggests that the reuse of respirator filters exposed to microorganisms needs careful consideration. Studies

on survival of microorganisms with different membrane components at various environmental conditions, including temperature and humidity, are needed to understand the mechanism of microbial survival. Future studies on microbial survival on different parts of the respirator should be conducted to assess better and reduce potential problems associated with the reuse of respirators.

MAINTENANCE AND STORAGE

Proper maintenance and storage of respirators are important steps in preventing spread of diseases by respirator reuse. Storing used respirators in humid environments may result in significant microbial growth as shown in previous studies.[65,66] In another study, the penetration of actinomycete spores through 20 different respirator filters was tested, and penetration ranged from 0.1% to 44%.[67] The effect of microbial contamination and particle penetration through 2 different high-efficiency respirator filters was tested by Pasanen et al.[68] Filters were loaded in environments containing high microbial levels and incubated at 98% relative humidity for 35 days. The bacterial and actinomycete spore concentration in the filters were 1 to 3 orders of magnitude after incubation. One of the 2 filters, which contained more cellulose component, showed considerable penetration of particles and fungal spores at a flow rate of 20 L/min. This suggested that humid environments might facilitate microbial growth and penetration through respirator filters, especially if the filter material is biodegradable.

OSHA requires that work places such as general industry and construction should maintain a respiratory protection program to protect workers from chemical, biologic, and other agents.[40] Whether work places adhere to the national agency's requirements and recommendations on respirator maintenance is unclear. Rosanthal and Paull evaluated the quality of respirator programs using OSHA compliance data from 1976 to 1982.[69] Approximately, 27% of the respirator programs inspected resulted in a citation for a specific program deficiency, of which 30% of the violations were for respirator maintenance and storage. Brosseau and Traubel[70] developed a phone survey based on the recommendations of the American National Standards Institute and OSHA requirements. Of the selected 30 companies that used negative-pressure, air-purifying respirators, more than 90% reported that they were meeting the requirements of the respiratory protection programs. Ninety-three percent reported replacement of inhalation and exhalation valves, and 89% indicated inspection of harness/straps, face piece, and valves. Filters and cartridges were inspected by 75% of the respondents. Eleven percent of the companies reported respirator inspection before and after use, whereas 85% reported daily inspection. Their survey suggested that respirator inspection before and after use, availability of replacement parts, regular cleaning, and hands-on practice in training sessions are important for a good respiratory protection program.

DECONTAMINATION

Traditionally, respirator cleaning and sanitization have been used to prevent the spread of disease during reuse of a respirator face piece by the same or different user. Manufacturers generally provide cleaning and disinfecting recommendations in the respirator's user instructions. Decontamination of respirators and other personal protective equipment prevents contamination and can reduce the cost of equipment. Occupational Safety and Health Administration (OSHA) requires cleaning and disinfecting respirators for reuse.[71] NIOSH recommends that a respirator must be cleaned, sanitized, rinsed, dried, reassembled, and inspected before it can be reused.[72] Decontamination of respirators is an important issue in the wake of growing threats of biologic and chemical weapons. Several decontamination methods against biologic and chemical contaminants have been reported.[73,74] Agents including sodium hypochlorite, calcium hypochlorite, formalin, hydrogen peroxide (H_2O_2), ozone (O_3), chlorine dioxide (ClO_2), ammonia, nanoparticles, L-gel, and aqueous foams decontaminate by mechanisms involving emulsification, neutralization, chemical reaction, disinfection, absorption, and adsorption.

A comparative study on the efficacy of different decontaminating agents against *Bacillus globigii*, a *Bacillus anthracis* simulant, adsorbed to various test materials was performed.[74] The University of Michigan nanoemulsion and the Sandia National Laboratories (SNL; Albuquerque, NM) aqueous foam efficiently decontaminated *B globigii* compared with the other agents tested. The University of Michigan nanoemulsion performed well against *B globigii* adsorbed on ceiling tile, panel fabric, and cement, and the SNL aqueous foam was highly efficient for painted wallboard and carpet material. This study showed that several decontamination agents were effective against *B globigii* on painted wallboard, panel fabric, and painted metal compared with porous surfaces. Recently, Raber and McGuire reported that L-gel was effective against chemical agents and biologic materials.[75] L-gel oxidized *B globigii* spores, nonvirulent strains of *B anthracis* (Sterne), and *Yersinia pestis* (strain D27) on different surface materials. An efficient decontamination of microbial material on smooth surfaces compared with surface materials such as carpet was observed in this study. This suggests that the effectiveness of the decontaminating agent not only depends on its ability

to kill a microorganism, but also on the substrate material to which the organism is adsorbed. Further research on decontamination of pathogenic microorganisms on various respirator materials is necessary to ensure protection to emergency responders and health care and rescue operation workers.

Although it is desirable to have 1 decontaminating agent for all the microorganisms, not all decontaminating agents are effective against every microorganism. The identification of decontaminating agents for critical microorganism categories will facilitate the selection of a decontaminating agent for a known biologic contamination. At the same time, a multispectrum decontaminating agent will be effective against exposures of unknown and multiple biologic materials. Care must be exercised in the use of any decontaminating agents on respirator components. The respirator manufacturer's instructions should be consulted and followed to ensure agents are not used that could damage the respirator components or compromise performance. Respirator damage or compromised performance may not be detectable by the user, thereby reducing protection when reused.

In decontaminating respirator materials, the postdecontamination effect on the environment needs to be considered. Some of the decontaminating agents are known for their toxic, corrosive, and environmentally hazardous effects. Recently, Collins reported the use of tetraamido macrocyclic ligand (TAML)-activated hydrogen peroxide for decontamination of various materials.[76] TAML-activated hydrogen peroxide decontaminated a variety of harmful industrial chemicals and surrogates of chemical and biologic warfare agents. The end products of this decontamination procedure have been shown to be nontoxic. Future research on the design of novel decontaminating agents with no or minimum levels of deteriorating effects on respirators, exposed materials, and the environment are important.

REAEROSOLIZATION OF MICROORGANISMS

Reaerosolization or reentrainment is described as the process by which any aerially deposited material can become resuspended. The size of resuspended aerosol particles may be different from that of the deposited ones because of their association with other dust particles. Reaerosolization of particles from filters is possible when particles previously captured may penetrate and reach the respiratory tract of the wearer at high inhalation rates. Alternately, the captured particles may be released in the air during a violent coughing or sneezing. Coughing and sneezing may allow aerosol particles generated by the wearer to pass through the filter and contaminate the environment.

Reaerosolization of aerosol particles from a previously exposed filter has been reported.[77,78] In one study, bacterial penetration was carried out at 85 L/min, simulating breathing conditions under heavy work, and reaerosolization was measured with airflow opposite to the loading direction. The percentage of reaerosolization was insignificant with N95 respirators when tested with *B subtilis* and *B megatherium* at 22% relative humidity.[77] Reaerosolization of *B subtilis* and *B megatherium* did not exceed 0.025% even at high reentrainment air velocity of 300 cm/sec, which corresponded to 37 times the loading velocity. Under these conditions, the reaerosolization of 5-μm polystyrene (PSL) particles was about 6%. Further studies showed that reaerosolization of 0.6- to 5.1-μm particles increased with the square of particle size and the reaerosolization velocity and decreased with increasing relative humidity.[78] The percentage of particles reentrained from filter was not altered by the thickness of filter media, suggesting deposition of particles on the uppermost fibers of the filter. However, an increase in filter media thickness decreased the percentage of particles when the reentrainment airflow was in the same direction as that of loading.[78]

Reaerosolization of particles was also performed with different filter media and type of aerosol particles.[78] Reaerosolization of 2- to 5-μm PSL particles was observed with fiberglass, HEPA, and polypropylene filters, but not with polypropylene/Modacrylic filters; the reasons for the difference were unclear. The reaerosolization of particles was dependent on the characteristics of aerosol particles as shown by the air cleaner dust particles showing high levels of reaerosolization followed by PSL, NaCl, and corn oil particles.[78] These studies indicate that reaerosolization of particles greater than 1 μm is significantly greater compared with submicrometer particles. The reaerosolization of relatively bigger particles may be important when considering the diameter size (1 to 5 μm) of the infectious droplet nuclei such as TB or *B anthracis* aerosols. This suggests that further research on reaerosolization of different size microorganisms loaded on respirators is needed to assess the significance of reaerosolization.

BIOLOGIC WARFARE AGENTS

Several nations have massive quantities of biologic weapons, including pathogenic bacteria, bacterial toxins, and viral agents.[79] Strategies to defend against a bioaerosol attack on military personnel, emergency responders, and civilian population have been discussed.[80-83] For example, the use of M17/M40A1 or MCU-2/P respirators was suggested to be suitable for the military, based on their ability to protect against biologic warfare agents such as smallpox, brucellosis, pneumonic plague, and other viral agents.[80,84]

CDC recommendations on respiratory protection to personnel in different workplaces are based on the assessment of biologic hazard and exposure potential.[10,11,13] According to CDC Interim Recommendations, the use of half-mask or full face-piece air-purifying respirators with particulate filter efficiencies ranging from N95 (for hazard such as pulmonary TB) to P100 (for hazards such as hantavirus) is required as a minimum level of protection.[10] A self-contained breathing apparatus (SCBA) is needed for emergency responders to a suspected bioaerosol attack, whereas a PAPR with HEPA filter is recommended for response to dissemination of biologic agents by a letter or a package.[10]

ADVANCES IN FILTER TECHNOLOGY

Recent developments in nanofiber technology are being advocated for their potential in filtration applications.[85,86] Nanofibers of 10- to 200-nm diameter provide high surface area, small pore size, and dramatic increases in filtration efficiency. The electrostatic charge on nanofibers can be manipulated to capture environmental contaminants in various workplaces. In addition, biocidal compounds have been incorporated into personal protective equipment to prevent microbial infection. For example, halamine, a biocidal compound, covalently linked to protective clothing was found to be effective against bacteria such as *Escherichia coli* and *Staphylococcus aureus*.[87] Similar modification of respirator filter fibers with biocidal compounds may yield filters capable of protecting respirator wearers from microorganisms. The more recent developments in filter technology will greatly improve respiratory protection in workplaces.

CONCLUSIONS

The use of anthrax spores in the 2001 terrorism incidents and the recent Severe Acute Respiratory Syndrome (SARS) outbreak highlighted the importance and relevance of further research on the selection and performance of respiratory protection against bioaerosols. Filter penetration of bioaerosols has been studied mostly on respirators that were certified under the requirements of Title 30 CFR 11,[14] which were replaced by the current Title 42 CFR 84[15] requirements. Studies need to be conducted to define better the physical characteristics of microorganisms likely to pose significant respiratory threats to workers as well as the general population. Reports of previous research in filter performance against particles of various sizes, shapes, and aspect ratios (such as rod shaped) do not contain sufficient detail to resolve apparent contradictory results. Reports of future research efforts detailing the penetration behavior through various respirator filters must contain more complete protocol documentation to facilitate the appropriate comparison of results. Improved design of filters as well as selection and use guidance will be facilitated by better understanding and determination of whether long-held beliefs of similar filter performance against biologic and nonbiologic particles based on effective aerodynamic diameters are confirmed.

Research on infectious dose range of microorganisms and exposure concentrations are needed for a better respiratory protection against bioaerosols. The selection of respiratory protection can also be achieved by developing risk models for various categories of bioaerosols and further verification of the models. Research on more universal decontamination agents that are suitable for respirator components and environment is needed. Further research on nanofibers and biocidal fibers is likely to improve respiratory protection in workplaces.

Rigorous implementation of fit test and user seal check according to OSHA regulations in workplace will ensure adequate respiratory protection. Further research in defining the facial dimensions of various worker populations is needed for designing respirators. Inconsistencies associated with fit-test measurements and variations among donnings need to be investigated to ensure high levels of respiratory protection.

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