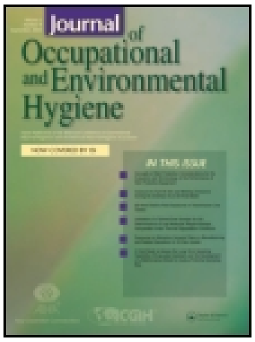

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Filtration Performance of NIOSH-Approved N95 and P100 Filtering Facepiece Respirators Against 4 to 30 Nanometer-Size Nanoparticles

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This study investigated the filtration performance of NIOSH-approved N95 and P100 filtering facepiece respirators (FFR) against six different monodisperse silver aerosol particles in the range of 4–30 nm diameter. A particle test system was developed and standardized for measuring the penetration of monodisperse silver particles. For respirator testing, five models of N95 and two models of P100 filtering facepiece respirators were challenged with monodisperse silver aerosol particles of 4, 8, 12, 16, 20, and 30 nm at 85 L/min flow rate and percentage penetrations were measured. Consistent with single-fiber filtration theory, N95 and P100 respirators challenged with silver monodisperse particles showed a decrease in percentage penetration with a decrease in particle diameter down to 4 nm. Penetrations less than 1 particle/30 min for 4–8 nm particles for one P100 respirator model, and 4–12 nm particles for the other P100 model, were observed. Experiments were also carried out with larger than 20 nm monodisperse NaCl particles using a TSI 3160 Fractional Efficiency Tester. NaCl aerosol penetration levels of 20 nm and 30 nm (overlapping sizes) particles were compared with silver aerosols of the same sizes by a three-way ANOVA analysis. A significant ($p < 0.001$) difference between NaCl and silver aerosol penetration levels was obtained after adjusting for particle sizes and manufacturers. A significant ($p = 0.001$) interaction with manufacturers indicated the difference in NaCl, and silver aerosol penetrations were not the same across manufacturers. The two aerosols had the same effect across 20 nm and 30 nm sizes as shown by the absence of any significant ($p = 0.163$) interaction with particle sizes. In the case of P100 FFRs, a significant ($p < 0.001$) difference between NaCl and silver aerosol (20 nm and 30 nm) penetrations was observed for both respirator models tested. The filtration data for 4–30 nm monodisperse particles supports previous studies that indicate NIOSH-approved air-purifying respirators provide expected levels of filtration protection against nanoparticles.

Keywords monodisperse aerosol, NaCl particles, nanoparticle, particle penetration, respirator, silver particles

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INTRODUCTION

Nanoparticles are particles having at least one dimension that is less 100 nanometers.(1) Sources of nanoparticles from industrial processes include: combustion, welding, laser ablation, milling, grinding, and polishing. With the rapid growth of nanotechnology, exposure to engineered nanoparticles has greatly increased in industrial workplaces. Similarly, cleaning and disposal of engineered nanomaterials from dust collection systems present further potential for inhalation exposure. Nanoparticle inhalation, the most common route of exposure, has been shown to deposit discrete size nanoparticles in the lungs of exposed animals and cause adverse effects on pulmonary functions.(2,3) Recent studies highlighted the potential health impact of nanoparticles.(1−3) This suggests that respiratory protection against a wide range of nanoparticles is important for worker safety and health.

National Institute for Occupational Safety and Health-(NIOSH)-certified, particulate respirators are recommended for protection against airborne inert and biological particles in many workplace settings. NIOSH-approved N, R, and P series particulate respirator types 95, 99, and 100 are certified with minimum filtration efficiencies of 95%, 99%, and 99.97%, respectively. The NIOSH certification test for N- series respirators uses a polydisperse distribution of NaCl particles with a count median diameter (CMD) of 0.075 ± 0.020 μm and a geometric standard deviation (GSD) of less than 1.86. For R- and P- designated respirators, NIOSH tests using a polydisperse distribution of dioctyl phthalate (DOP) particles with a CMD of 0.185 ± 0.020 μm and a GSD of less than 1.60. The filtration performance of respirators against inert and biological aerosols, and related respiratory protection issues have been reviewed previously.[4]

N95 filtering facepiece respirators (FFRs) are commonly used for reasons of economy, comfort, and availability. The laboratory filtration performance of N95 FFRs is well characterized for aerosol size ranges most commonly found in workplaces.[5−12] Filtration performance follows single-fiber filtration theory, with a most penetrating particle size (MPPS) occurring between 40 and 300 nm. The exact MPPS depends on a number of factors, including filter type (e.g., mechanical vs. electret), fiber diameter and charge density, filter geometry/configuration, and face velocity. The factors affecting MPPS and their relevance for respirator filter testing were recently reviewed.[13] The filtration performance of NIOSH-certified N95 FFRs can vary when tested against monodisperse nanoparticles in the MPPS range under "worst-case" conditions (e.g., 85 L/min flow rate, charge neutralized particles, etc.).

In one study, filter penetration levels greater than 5% were observed for 50-nm particles (the MPPS observed in the study) for one N95 FFR model tested.[9] Penetration levels decreased for particles smaller (down to 20 nm) or larger than the MPPS. In another study, the filter penetration levels for five N95 FFRs were studied using monodisperse NaCl particles from 20 nm to 400 nm. Penetration levels at the MPPS (40 nm) ranged from 1.4% to 5.2%.[12]

Respirators equipped with high-efficiency particulate air (HEPA) filters are recommended for some virus particles[14] and asbestos.[15] HEPA filters are at least 99.97% efficiency in removing monodisperse particles of 0.3 μm in diameter.[16] The corresponding NIOSH 42 CFR 84 particulate filters are the N100, R100, P100 and high-efficiency (HE) filters.[15] Of the class-100 respirators, P100 is most common. Unlike the N95 FFRs, the literature on the filtration performance of P100 FFRs and cartridges is very sparse. Martin and Moyer[17] measured the filtration efficiency and the MPPS for P100 filter media in a study that focused on filter degradation. They showed that the MPPS for P100 filter media was in the 50–100 nm range and shifted toward larger sizes in the 250–350 nm range after isopropanol treatment. Recently, another study investigated the penetration of a wide range of monodisperse particles (20 to 1200 nm) through two P100 FFRs and two P100 cartridges.[11] The penetration level for one P100 FFR model was slightly higher than 0.03% (the NIOSH-approved level used for the certification test) at the MPPS (50 nm), whereas the P100 cartridges had expected penetration levels.

The respirator filtration measurements described above used liquid and solid aerosol particles greater than 20 nm size, but none focused on monodisperse aerosol challenges below that size. The need to better characterize the filtration performance of air-purifying respirators (in particular FFRs because of their widespread use) against monodisperse sub-20 nm particles exists due to the possibility that very small particles are not captured by the filter on collision (thermal rebound effect). In this scenario, the mean thermal velocity due to Brownian motion could exceed the capture velocity[18]and thereby cause an increase in particle penetration.

The lack of data on the filtration performance of respirators and filter media against monodisperse particles below 20 nm is due mainly to the technical difficulties in generating a sufficient number of sub-20 nm particles. A deficiency of instrumentation for quantifying those size particles further increases these challenges. Despite these difficulties, limited studies have been done to measure the filtration performance of filter media and air purifying respirators. In one study, glass fiber, composite, and membrane filters were challenged with monodisperse silver (4–10 nm) and dioctyl phthalate (DOP) (32–420 nm) aerosols, and particle penetration was measured at different face velocities.[19] The results were in agreement with the conventional fiber theory showing an increase in filtration efficiency for smaller size particles. No evidence for thermal rebound was observed.

Recently, Kim et al.[20] reported the filtration efficiency of different types of filter media against silver particles in the range of 3–20 nm. Penetration of nanoparticles through glass and electret and nanofiber filter media was measured at different face velocities. Their results showed that particle penetration levels decreased with decreasing particle diameter down to 2.5 nm size, and no evidence for thermal rebound was observed. This suggested that respirators made from similar filter media would be efficient for capturing particles below 20 nm. A recent study investigated the penetration of 4.5 nm to 10 μm NaCl aerosols using one model of NIOSH-approved N95 FFR and one model of European-certified FFP1 FFR.[21] Their results showed that almost all particles below 10 nm were collected by the FFRs.

Other studies have focused primarily on the thermal rebound effect.[22−26] Particles in the region of 10 nm or below were predicted to undergo thermal rebound effects.[22] A subsequent report showed the deviation from the Cheng-Yeh theory occurring at 2 nm diameter and suggested possible involvement of thermal rebound phenomena.[23] However, a preliminary study reported thermal rebound of particles around 20 nm and below that size using polypropylene filters.[24] One study observed thermal rebound effects for particles below 2 nm size.[26] However, the likelihood of monodisperse nanoparticles in that size range ($<$2 nm) appearing in workplaces is negligible because they would agglomerate quickly.[27]

The increased production of engineered nanoparticles in workplaces raises the importance of understanding filtration performance to ensure that NIOSH-approved air-purifying respirators provide expected levels of protection when used in the context of a complete respiratory program. In addition, the knowledge gap on respirator filtration efficiency against nanoparticles smaller than 20 nm requires validation using a wide variety of respirators. To address these issues, this study investigated the filtration performance of five models of NIOSH-approved N95 and two models of P100 FFRs against monodisperse aerosol particles in the 4–30 nm range using a silver particle test system.

MATERIALS AND METHODS

Generation of Monodisperse Silver Particles in the 4–30 nm Range

Silver nanoparticles were generated by an evaporation and condensation method. This method employs a tube furnace to evaporate silver and form vapor, which is cooled and condensed to an aerosol. Figure 1 shows a schematic diagram of the silver nanoparticle test system. Briefly, a ceramic boat containing pure metallic silver (Alfa Aesar, 99.99%) was placed inside a ceramic tube kept in a furnace (Lindberg/BlueM model TF55035A-1; Thermal Product Solutions, New Columbia, Pa.) and heated at 1050°C. Polydisperse silver nanoparticles generated under these conditions were transported by HEPA-filtered nitrogen gas at 2 L/min flow rate into a scanning mobility particle sizer (SMPS, model 3080; TSI Inc., Shoreview Minn.). A ^{85}Kr neutralizer present in the SMPS charge neutralizes the particles to obtain a well-defined Boltzmann equilibrium charge distribution on the particles. The charge-neutralized particles were subjected to varying voltages by a nano-differential mobility analyzer (Nano-DMA, TSI model 3085). The nano-DMA is an integral part of the SMPS system that classifies particles based on electrical mobility. The selected monodisperse aerosol exiting the nano-DMA were then mixed with HEPA-filtered room air, passed through a ^{85}Kr source (TSI model 3012) for charge neutralization, and then introduced into a Plexiglas respirator test box placed between the upstream and downstream filter chucks. Sampling ports, off each filter chuck, allowed upstream and downstream aerosol particle counting by an ultrafine condensation particle counter (UCPC, TSI model 3025A).

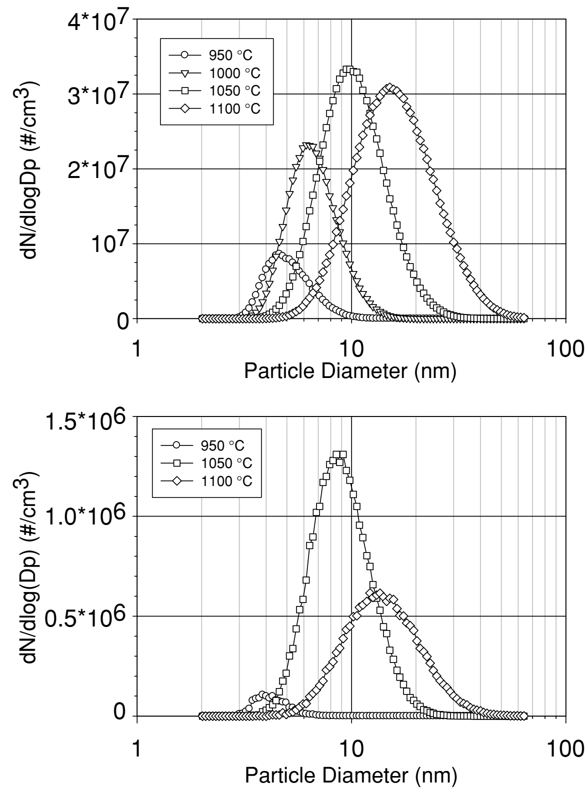

FIGURE 2. Size classification of silver nanoparticles at different furnace temperatures. Analysis of particles bypassing the Plexiglas test box (top panel) and particles passing through the Plexiglas test box at 85 L/min flow rate (bottom panel)

The size distribution and concentration of particles varies with furnace temperature. Figure 2 (top panel) shows the silver nanoparticle size distribution curves at furnace temperatures

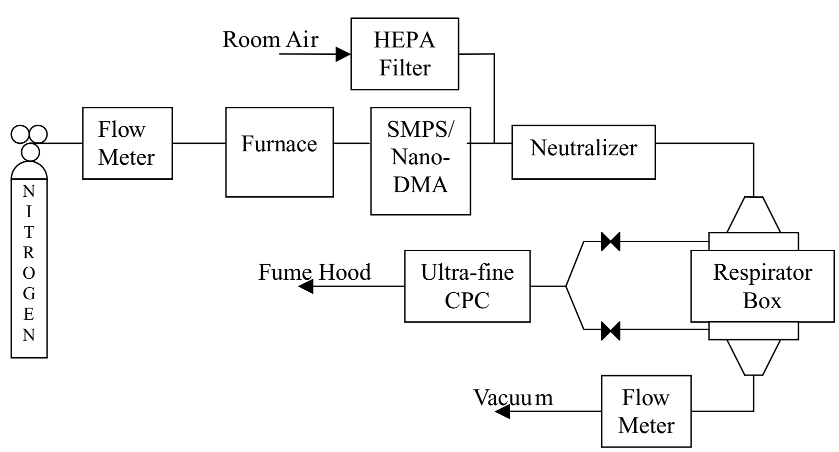

FIGURE 1. Schematic diagram of the silver nanoparticle test system

of 950°C, 1000°C, 1050°C, and 1100°C, when the particles were analyzed after bypassing the Plexiglas respirator test box. An increase in furnace temperature increased particle concentration, reached a maximum at 1050°C, and then decreased. Peak concentrations of particle sizes corresponding to 4.6 nm, 6.2 nm, 9.5 nm, and 15.1 nm were produced at 950°C, 1000°C, 1050°C, and 1100°C, respectively. The concentration of particles decreased approximately one to two orders of magnitude as the particles passed through the Plexiglas box at 85 L/min flow rate (Figure 2, bottom panel).

For N95 FFR penetration studies, a furnace temperature of 1050°C was found to be suitable for producing sufficient number of particles for testing the penetration of monodisperse particles in the range of 4–30 nm. The size of the monodisperse test aerosol particles generated by the system was verified by passing the monodisperse aerosol through a second SMPS. In the case of P100 FFRs, which are expected to have less than 0.03% penetration, fewer number of particles are expected to pass through the filter. To increase the chances of particle penetration through P100 FFRs, the number of particles upstream of the FFR was increased by setting the furnace temperatures at 950°C for 4 nm particles, 1050°C for 8 and 12 nm particles, and at 1100°C for 16, 20, and 30 nm size particles.

Penetration of Monodisperse Silver Particles in the 4–30 nm Range

Particle penetration through FFRs and filter media was carried out using a Plexiglas box as described previously.[12] Briefly, an FFR was mounted in a Plexiglas box (approximately 20 cm × 20 cm × 10 cm) placed in between two filter chucks. The Plexiglas box has replaceable top and bottom plates (20 cm × 20 cm × 0.5 cm), each with a circular hole (25 cm^2) in the center. An FFR was placed on the bottom plate with its concave side facing the hole, and its periphery was sealed with melted wax. The bottom plate was placed in the Plexiglas box so that the convex side of the respirator was facing the aerosol upstream filter chuck. The Plexiglas box containing the respirator was placed in between the two filter chucks and aligned to keep the top and bottom plate holes facing the upstream and downstream filter chucks. The upstream (inlet) and downstream (outlet) filter chucks had sampling ports for particle counting and pressure drop measurement. The upstream and downstream aerosols were sampled alternately with a UCPC (TSI model 3025A) at a flow rate of 1.5 L/min. The aerosol particles that pass through the downstream filter chuck exited through outlet tubing connected to a vacuum line. The aerosol flow was monitored by a mass flow meter.

Particle penetration measurements were carried out under airtight conditions. The nano-DMA was operated at zero voltage, and the test system leakage check was conducted by passing HEPA-filtered room air through the setup at 85 L/min flow rate. The absence of any leaks in the test box was ensured by the UCPC measuring zero counts for the upstream and downstream aerosol samples for at least 20 min. Then, monodisperse aerosols were passed through the setup, equilibrated, and particle penetrations were measured. For N95 FFRs, particle counting was maintained for 100 sec or until 40 counts were recorded for the downstream sample. When the particle count was below 40, the counting time was increased up to 20 min. In the case of P100 FFRs, penetration of each size of monodisperse particles was measured for 30 min, irrespective of the number of particles in the downstream sample. When measuring the particle penetration through filter media, the filter was placed in between two Plexiglas plates (20 cm × 20 cm × 0.5 cm) with holes of the same area (25 cm^2) in the center instead of the Plexiglas box used in respirator testing. The percentage of particle penetration was calculated from the ratio of particles downstream to upstream of the respirator or filter media.

Penetration of Monodisperse NaCl Particles in the Range 20–400 nm

Monodisperse NaCl particles were generated using an SMPS (TSI 3160 Fractional Efficiency Tester) equipped with a long differential mobility analyzer (TSI 3080) as described previously.[12] Briefly, the TSI 3160 was programmed for measuring the percentage initial penetration of 11 different size monodisperse particles in the range of 20–400 nm at 85 L/min flow rate. Particle penetration was measured using the same Plexiglas box that was employed for silver aerosol penetration measurements. The Plexiglas box fixed with an FFR was placed between the upstream and downstream filter chucks and NaCl aerosol penetration was measured under air tight conditions.

DATA ANALYSIS

Data analysis was done using the SigmaStat program (version 2). The average penetration levels of silver and NaCl particles and 95% confidence intervals were calculated for each respirator model. Statistical three-way ANOVA compared the penetration levels of silver and NaCl particles for the overlapping size (20 nm and 30 nm) particles after allowing for the effects of differences in factors, including particle size and manufacturers. Multiple comparisons were done by Tukey test.

RESULTS

Standardization of the Silver Aerosol Test System

The silver nanoparticle test system employed in this study was standardized for measuring the penetration of monodisperse particles in the 4–30 nm range. The size of the monodisperse aerosol particles generated by the test system was size classified and verified by a second SMPS. The sizes of the monodisperse aerosols measured by the two SMPS systems agreed with each other. The GSD of different size monodisperse particles used in this study was in the range of 1.03 to 1.09 (Table I). For further standardization, two different fiberglass filter media (Hollingsworth & Vose Co., East Walpole, Mass.) were challenged with 4–20 nm silver

TABLE I. Silver Nanoparticle Size Classification

Parameter	Particle Diameter (nm)					
Median	4	8	12	16	20	30
GSD	1.03	1.08	1.08	1.08	1.09	1.08

Note: Monodisperse particles of the diameters listed were generated at 1050°C, and the sizes were verified by a second SMPS.

particles and percentage penetrations were compared with the results from a previous study.[20] Particle penetrations of three samples of each fiberglass filter media were measured at a face velocity of 15 cm/sec. Penetration levels decreased with decreasing diameter of particles (Figure 3). Average percentage penetrations for 4 nm, 8 nm, and 20 nm particles were 0.02, 0.28, and 5.8, respectively, for HE1021media and 0.034, 0.86, and 18.1, respectively, for HF0031 media. The data was compared with the results from the study conducted by Kim et al.[20] Their results showed average percentage penetrations of approximately 0.003, 0.22, and 5.5 for 4 nm, 8 nm, and 20 nm particles, respectively, for HE1021 and 0.014, 0.65, and 10.1, respectively, for HF0031 media.

Penetration of Nanoparticles Through N95 FFRs

Five models of N95 FFRs were challenged with monodisperse silver nanoparticles in the range of 4–30 nm diameter. Five samples from each model were tested at 85 L/min flow rate, and the mean percentage penetration level and 95% confidence interval were calculated. Figure 4 shows the penetrations of different size monodisperse particles in the 4–30 nm range for the five different N95 FFR models tested. The mean penetration levels of 30 nm particles were between 1.1% and 4.0% for the five models. Particle penetration levels for all five N95 models decreased with decreasing particle diameter down to 4 nm. The average percentage penetration levels of 4 nm particles were between 0.000018 and 0.03 for the five models.

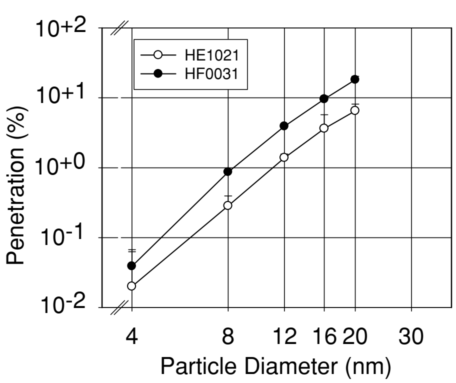

FIGURE 3. Penetration of monodisperse silver particles (4–20 nm) through fiberglass filter media at a face velocity of 15 cm/sec. Error bar indicates the 95% confidence interval.

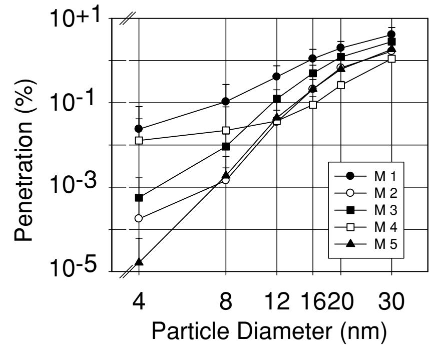

FIGURE 4. Penetration of monodisperse silver particles (4–30 nm) through N95 respirators from five manufacturers (M1, M2, M3, M4, and M5) at 85 L/min flow rate. Error bar indicates the 95% confidence interval.

A different set of five samples from each of the N95 FFR models (that were used for silver nanoparticles) were challenged in a previous study with monodisperse NaCl particles in the range of 20–400 nm at 85 L/min, and penetration levels were measured. The percentage penetration levels of the two overlapping sizes, namely, 20 nm and 30 nm, for silver and NaCl particles were compared (Figure 5). The penetration levels of 20 nm and 30 nm NaCl particles were slightly higher than the penetration levels of 20 nm and 30 nm silver particles for all five N95 FFR models. Statistical analysis by a three-way ANOVA showed a significant difference between NaCl and silver aerosol penetration levels ($p < 0.001$) after adjusting for particle size and manufacturer. There was no significant interaction with particle size ($p = 0.163$), indicating that aerosol had the same effect (or at least not significantly different effects) across both particle sizes. Aerosol did however have a significant interaction with manufacturer, indicating that the differences in penetration levels between NaCl and silver particles were not the same across manufacturers. The MPPS for all five models was in the 40 nm range.

Penetration of Nanoparticles Through P100 FFRs

In the case of P100 FFRs, five samples from each of the two manufacturers were challenged with monodisperse silver particles, and the penetration levels were measured for 30 min. Figure 6 (top panel) shows the mean percentage penetration levels for different size monodisperse silver particles for the two P100 FFR models. Percentage penetrations decreased with decreasing particle diameter size. Penetrations of 12–30 nm particles for one model and 16–30 nm particles for the other model were measured, while no particle penetration was observed for 4 nm and 8 nm size particles for either P100 FFR models.

Another set of five P100 FFR samples from two manufacturers (that were employed for silver particles) were also challenged with monodisperse NaCl particles. Figure 6 (two bottom panels) shows penetration curves for particles in the 20–400 nm range for the two models in combination

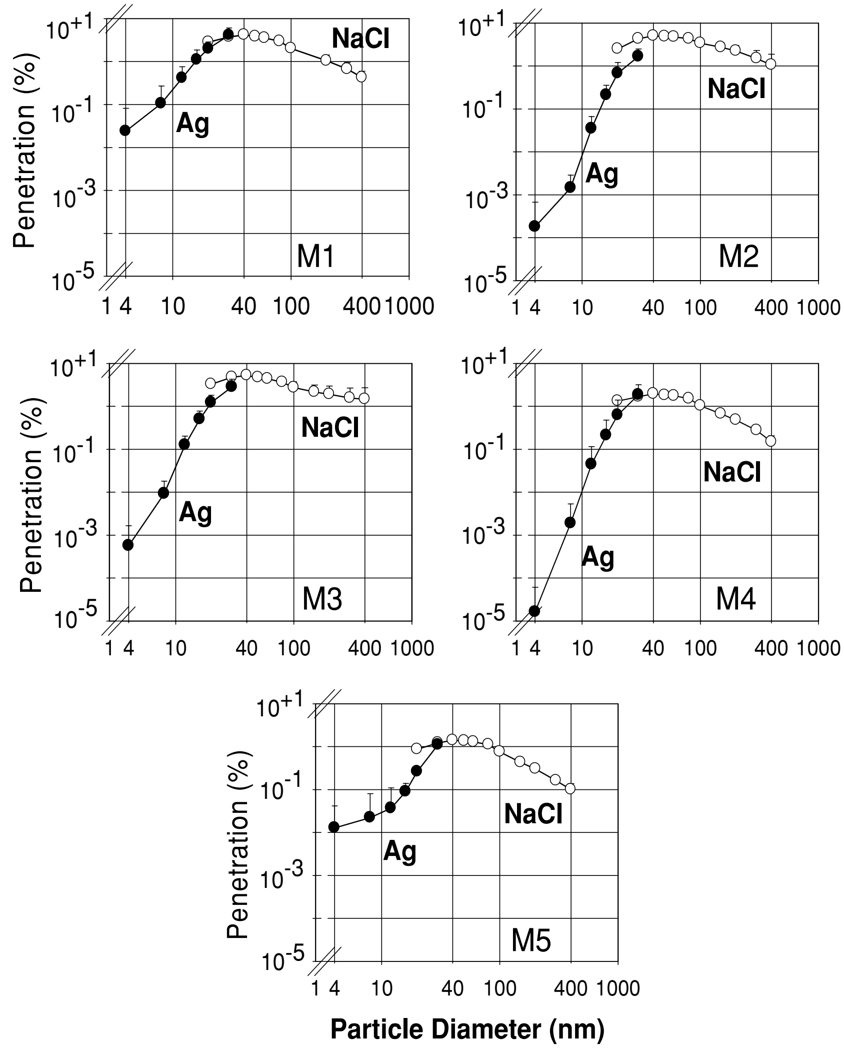

FIGURE 5. Penetration of monodisperse silver (Ag, 4–30 nm) and NaCl (20–400 nm) particles through N95 respirators from five manufacturers (M1, M2, M3, M4, and M5) at 85 L/min. Error bar represents the 95% confidence interval.

with 4–30 nm silver particles. Statistical analysis by a three-way ANOVA showed a significant difference between the penetration levels of NaCl and silver aerosols ($p < 0.001$) after adjusting for particle size and manufacturer. There were no significant interactions with either particle size ($p = 0.740$) or manufacturer ($p = 0.07$), indicating that aerosol had the same effect (or at least not significantly different effects) across both particle sizes and all manufacturers. The MPPS was found to be in the 40–50 nm range for the two P100 models tested.

DISCUSSION

The increased occurrence of unbound aerosolized nanoparticles in the workplace has caused renewed scrutiny in the filtration performance of NIOSH-approved particulate respirators. This is partly due to scant experimental data on respirator filtration of particles smaller than 20 nm diameter. To address this issue, the filtration efficiency of NIOSH-approved N95 and P100 FFRs against 4 to 30 nm silver monodisperse particles was investigated. Silver aerosol was selected for particle penetration measurements because silver aerosol has been successfully used in previous studies on particle filtration.[19,20] Typically, filtration studies use control inert aerosols as surrogates for aerosol challenges found in workplaces.

A silver nanoparticle test system for the 4 to 30 nm diameter particles was established and characterized. Particle size classification by the SMPS of the test system was verified by a second SMPS. Particle size measurements by this equipment agreed with each other showing consistency of the test particle sizes. The silver particles used in this study were monodisperse as shown by the geometric standard deviation (GSD) between 1.03 and 1.09 for the different diameter size particles employed in the study. The filtration characteristics of the monodisperse silver particles were confirmed by comparison with the Kim et al.[20] study that measured the penetration of silver particles through fiberglass and other types of filter media. The average

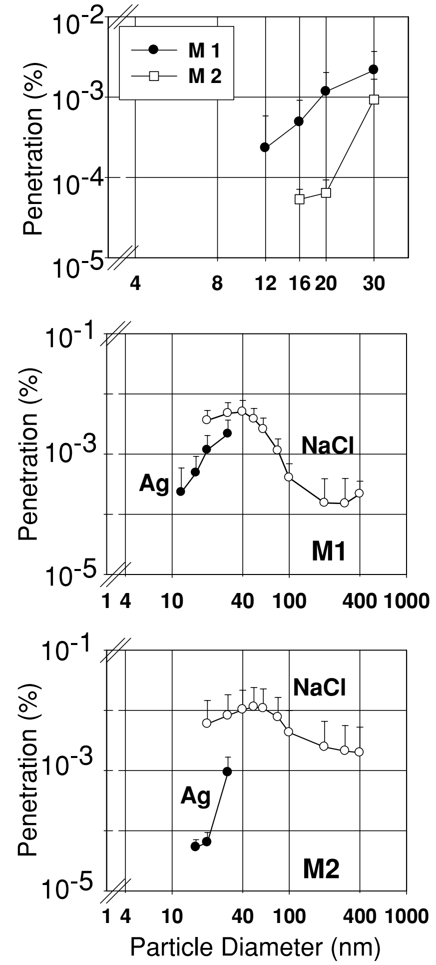

FIGURE 6. Penetration of monodisperse silver (Ag, 4–30 nm, top and bottom two panels) and NaCl (20–400 nm, bottom two panels) particles through P100 respirators from two manufacturers (M1 and M2) at 85 L/min. Error bar represents the 95% confidence interval.

percentage penetrations for 4 nm, 8 nm, and 20 nm particles, 0.02, 0.28, and 5.8, respectively, for HE1021 media and 0.034, 0.86, and 18.1, respectively, for HF0031 media obtained in the present study correlated ($r = 0.99$) well with the average percentage penetrations of 0.003, 0.22, and 5.5 for 4 nm, 8 nm, and 20 nm particles, respectively, for HE1021 and 0.014, 0.65, and 10.1, respectively, for HF0031 media. The penetration data obtained in this study was consistent as shown by a decrease in particle penetration with decreasing particle diameter down to 4 nm as predicted by single-fiber theory. This suggested that the silver nanoparticle test system developed in the authors' laboratory is reliable and can be employed for measuring respirator filtration of nanoparticles below 30 nm size.

The efficiency of NIOSH-approved N95 and P100 FFRs against 4–30 nm particles at a flow rate of 85 L/min was investigated. These two types of FFRs were selected because of their availability and wide use against various particulates in workplaces.[4,14,15] Results from this study showed that 4–30 nm size particle penetration levels were less than 5% and 0.03% for the N95 and P100 FFRs, respectively. The penetration levels decreased with decreasing particle size down to 4 nm and 12 nm for N95 and P100 FFR types, respectively. This demonstrates that the filtration efficiency of N95 and P100 FFRs increased with a decrease in particle size as expected by the single-fiber filtration theory.

The MPPS for all five N95 respirator models employed in this study was consistently in the 40 nm range and confirms the previous results obtained for N95 respirator filters.[9,11,12] Richardson et al.[11] employed a test system similar to the one in this study, measured the penetrations of NaCl particles using limited numbers of monodisperse particle sizes (20, 50, 100 nm and larger size particles) and observed that the MPPS was 50 nm. Furthermore, Balazy et al.[9] used more than 20 different monodisperse NaCl particle sizes between 20 and 100 nm range in a manikin model and showed that the MPPS for two N95 respirator filters was 50 nm.

Similar to N95 FFRs, the MPPS for the P100 FFRs was in the 40–50 nm range at 85 L/min flow rate. This finding was somewhat surprising due to the assumption that P100 FFRs are mechanical type and the MPPS would be in the 300 nm range. The MPPS observed in this study agrees with a previous study that measured the penetration of DOP aerosol at 85 L/min instead of NaCl employed in the present study.[11] Although a recent study predicted that the MPPS for mechanical filters would be 300 nm (at a face velocity of 12.9 cm/sec) based on theoretical calculations,[9] the P100 FFRs used in this study are not the purely mechanical type as expected. The results from this study suggest that both P100 FFRs studied here share filtration characteristics of electret N95 filters.

For both N95 and P100 FFRs, the penetration levels of 20 nm and 30 nm silver particles were generally less than those for NaCl particles of the same sizes (Figures 5 and 6). This may partly be due to the difference in the GSD of monodisperse NaCl and silver particles used in the experiments. The GSD of 20 and 30 nm silver particles were in the 1.03–1.09 range, while it was in the 1.41–1.52 range for NaCl particles. The higher GSD suggest that TSI 3160 generated 20 and 30 nm monodisperse particles contain particles closer to the MPPS (40 nm) resulting in higher penetration levels for 20 and 30 nm particles. Some studies reported similar penetration levels for different types of aerosols.[28] The difference in penetration levels observed for silver and NaCl particles of the same sizes (20 nm and 30 nm) may also be due to the number of particles measured in the downstream sample.

For N95 FFRs, penetrations of 20 nm NaCl particles were more than 10,000 (using the Fractional Efficiency Tester, TSI 3160) compared with 100–250 for silver particles. The decrease in the particle number in the downstream sample may underestimate the penetration level. This is very evident in the case of high-efficiency P100 FFRs, where the number of downstream particles was fewer compared with N95 FFRs. In the case of P100 FFRs, 20 nm NaCl particles in the downstream of filters were 1020–2050 for both models. On the other hand, silver particles in the downstream were 15–100 for one P100 FFR model and one particle for the second model. This suggests that penetration measurements with very few particles in the downstream sample should be cautiously interpreted. Furthermore, the practical significance of the statistical differences in filter penetrations between the two aerosol test systems for both 20 and 30 nm particles is minimal. The penetration levels of both 20 and 30 nm particles of these two aerosol systems were all within the NIOSH allowed levels for certification of N95 and P100 FFRs, and the magnitudes of differences in average penetration levels were generally small (e.g., for three of the five N95 FFR models at 30 nm the differences were less than 0.1%).

A preliminary report showed high penetration levels for particles around 20 nm diameter and below compared with larger size particles.[24] In that study, polypropylene filters were challenged with 10 to 500 nm sebacic acid-bis (2-ethylhexyl) ester aerosol particles. The efficiency of filters increased with decreasing particle diameter down to 20 nm and then decreased for particles below that size indicating a thermal rebound phenomenon. Subsequent findings by Heim et al.[25] demonstrated that nickel mesh, stainless steel filter, and polypropylene mesh effectively filtered charged and uncharged monodisperse NaCl particles down to 2.5 nm diameter, showing no thermal rebound for particles in this size range. These investigators also explained the technical problems in the preliminary study that observed thermal rebound even for particles of 20 nm diameter.

Subsequent filtration studies using particles as small as 2.5 nm, and fibrous filter media showed no deviation from single-fiber theory and thermal rebound occurring for particles of 2 nm and below.[20,26] This finding was confirmed in this study, which showed an increase in respirator filtration efficiency with decreasing particle sizes. The data from this study also showed no evidence for thermal rebound effect for particles in the size range of 4–30 nm, which agrees with previous findings.[20,21,25,26] The results provide further validation that NIOSH-approved N95 and P100 particulate FFRs should provide expected levels of filtration performance against nanoparticles between 4 and 30 nm diameter.

In addition to filtration, particle leakage around face/mask interface is an important component of respiratory protection. Occupational Safety and Health Administration (OSHA) has set the assigned protection factor (APF) at 10 for disposable FFRs regardless of filter designation when used in the context of a complete respiratory program, including proper FFR selection and fit testing.[29] This suggests that up to 10% of airborne particles, including particles in the 4–400 nm range, could still reach the breathing zone of a respirator wearer even after properly sized, fitted, and worn in a workplace. Research on whether nanoparticles are more or less likely than larger particles to penetrate through the face/mask interface is lacking.

CONCLUSION

A silver nanoparticle test system was characterized for particle generation at different furnace temperatures. The test system was found to be reliable for measuring the filtration efficiency of fibrous filter materials, including filter media and filtering facepieces. Penetration levels of monodisperse silver nanoparticles below 30 nm decreased with decreasing particle size down to 4 nm for the five N95 and two P100 FFR models tested in this study. In the case of N95 FFRs, the penetration levels of 4 nm particles were a few orders of magnitude less than that of 30 nm particles. The P100 FFRs tested showed 4–8 nm particle penetrations less than one particle/30 min. The MPPS values for the N95 and P100 FFRs in this study were in the 40–50 nm range, suggesting that the two P100 FFR models contain electret filter media similar to that of the N95 FFRs. The increase in filtration efficiency of FFRs for particles below 30 nm with decreasing particle size agrees with models based on single-fiber theory. The data from this study confirms that NIOSH-approved N95 and P100 FFRs provide filtration performance of greater than 95% and 99.97%, respectively, against particulates between 4 and 30 nm sizes. An APF of 10 for N95 and P100 FFRs suggests that up to 10% of airborne particles, including those in the 4–30 nm range, could still penetrate the face seal even after properly sized, fitted, and worn in a workplace and should be taken into account when selecting a respirator for protection against nanoparticles.

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