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Evaluation of the Filtration Performance of NIOSH-Approved N95 Filtering Facepiece Respirators by Photometric and Number-Based Test Methods

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N95 particulate filtering facepiece respirators are certified by measuring penetration levels photometrically with a presumed severe case test method using charge neutralized NaCl aerosols at 85 L/min. However, penetration values obtained by photometric methods have not been compared with count-based methods using contemporary respirators composed of electrostatic filter media and challenged with both generated and ambient aerosols. To better understand the effects of key test parameters (e.g., particle charge, detection method), initial penetration levels for five N95 model filtering facepiece respirators were measured using NaCl aerosols with the aerosol challenge and test equipment employed in the NIOSH respirator certification method (photometric) and compared with an ultrafine condensation particle counter method (count based) for the same NaCl aerosols as well as for ambient room air particles. Penetrations using the NIOSH test method were several-fold less than the penetrations obtained by the ultrafine condensation particle counter for NaCl aerosols as well as for room particles indicating that penetration measurement based on particle counting offers a more difficult challenge than the photometric method, which lacks sensitivity for particles <100 nm. All five N95 models showed the most penetrating particle size around 50 nm for room air particles with or without charge neutralization, and at 200 nm for singly charged NaCl monodisperse particles. Room air with fewer charged particles and an overwhelming number of neutral particles contributed to the most penetrating particle size in the 50 nm range, indicating that the charge state for the majority of test particles determines the MPPS. Data suggest that the NIOSH respirator certification protocol employing the photometric method may not be a more challenging aerosol test method. Filter penetrations can vary among workplaces with different particle size distributions, which suggests the need for the development of new or revised "more challenging" aerosol test methods for NIOSH certification of respirators.

Keywords more challenging aerosol, NaCl aerosol, N95 respirator, NIOSH certification test, penetration, room air aerosol

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INTRODUCTION

To reduce the inhalation of harmful particles in occupational settings, respiratory protection is required where engineering and administrative controls are not feasible or not yet implemented. To address respiratory protection issues, the National Institute for Occupational Safety and Health (NIOSH), in cooperation with the Mine Safety and Health Administration (MSHA), developed a standard for the certification of air-purifying respirators (APRs) under 30 CFR Part 11.[1] APRs including dust, fume, mist, and high-efficiency particulate respirators were tested with a set of test criteria to reflect their performance against different harmful particulates in workplaces. For example, filtration performance for APRs was assessed by testing against particles including silica dust, lead oxide fume, aqueous silica mist, lacquer and enamel mists, and dioctyl phthalate (DOP), with limits on penetration and breathing resistance.

However, the NIOSH certification test methods were thought to be deficient in several aspects.[2] Particle penetrations measured were averaged over time instead of measuring instantaneous penetrations. Moreover, test aerosol particle size, flow rate, influence of test conditions, degradation of electrostatic filters, and reproducibility were not considered in measuring more challenging aerosol penetrations. Based on these concerns, 30 CFR Part 11 particulate respirator test methods and requirements were updated in 1995 and replaced with 42 CFR Part 84.[3]

NIOSH approves nine classes of particulate filters in three categories of resistance to filter degradation, each with three filtration efficiency levels under 42 CFR Part 84.[3] The three categories of resistance to oil degradation are the N (non-resistant), R (resistant), and P (proof). Within each series, there are three levels of filters, namely, 95, 99, and 100 with minimum filtration efficiencies of 95%, 99%, and 99.97%, respectively. Both solid (NaCl) and liquid (dioctyl phthalate, DOP) aerosols with ∼350 nm mass median aerodynamic diameter (MMAD) were assumed to be more challenging aerosols to present maximum penetrations.[4,5] Particles in this size range (∼350 nm) were thought to be the most penetrating particle size (MPPS) for respirator filter media.

The rationale for certifying respirators using a more challenging test method was that a subsequent respirator user would be unlikely to encounter a workplace aerosol with conditions more severe that those encountered during the laboratory filtration testing. Thus, the filtration performance of the respirator in use would at least be as good as the more challenging test method results.

N-series respirator testing requires a polydisperse distribution of NaCl particles with a count median diameter (CMD) of 75 ± 20 nm and a geometric standard deviation (GSD) of 1.86.[6] The MMAD for NaCl test aerosols is 347 nm. For R- and P-designated respirators, polydisperse DOP aerosol particles with a CMD of 185 ± 20 nm and a GSD of 1.60 are used to give a MMAD of 359 nm.[7] To obtain maximum penetration levels, NIOSH certification tests are conducted using charge neutralized polydisperse aerosol particles (NaCl and DOP) at an 85 L/min flow rate using a TSI 8130 Automated Filter Tester (TSI 8130, Inc., Shoreview, Minn.). For NIOSH certification of nonpowered air-purifying respirators including filtering facepiece respirators (FFRs), penetrations are measured at 1-min intervals for the entire 200 mg NaCl aerosol loading. The highest penetrations observed throughout the test are recorded as the maximum penetration of the filter. For Class 95 respirator approval, filter penetrations throughout the aerosol loading should be ≤5%.

Filtration performance of NIOSH-certified respirators has been evaluated using workplace aerosols. In one study, respirator filters including N95, P95, and R95 were tested for laboratory penetrations using applicable NIOSH certification conditions and then exposed to diesel engine exhaust from a portable air compressor.[8] After exposure to various time points, laboratory penetrations were measured. N95 and R95 filters showed higher than 5% penetrations at different exposure conditions, while P95 filters had penetrations of <5%. At the same time, the highest mean penetration levels for elemental carbon for N95 filters (4.31%) were more than the penetrations for P95 (below detection limit) and R95 (2.09%) filters. Based on the results, the authors suggested that R95 and P95 filters would provide acceptable filtration for workplaces, while N95 filters should not be used.

Another study reported that some electrostatic filters degraded by irradiation with ionizing radiation and isopropanol dip methods showed higher than NIOSH-allowed penetration levels.[9] However, the degraded filters showed no significant difference in the laboratory filtration efficiency before and after exposure to workplace aerosols.[9] The authors also measured the penetration levels for the filters irradiated with ionizing radiation or isopropanol after exposure to a grinding aerosol or an oil mist in a steel foundry. Filters exposed to grinding aerosols showed penetration levels <5% and those exposed to oil mist showed no detectable level for oil mist aerosols.[10] Their results indicated that degraded NIOSH-approved N-, R-, P- series filters may perform well under workplace conditions.[10]

Laboratory filtration performance of particulate respirators against inert and biological aerosols has been reviewed.[11,12] Polydisperse aerosols similar to the NIOSH particulate respirator test aerosols were employed for testing the filtration efficiency of respirators. N95 FFRs from different manufacturers showed penetration levels in the <2% range when tested with polydisperse NaCl aerosol particles similar to the aerosols used for NIOSH particulate respirator certification.[13–15]

One study tested the filtration efficiency of N95 FFRs for *Mycobacterium tuberculosis* using simulant bacteria.[16] The MMAD of the bacterial simulants *Bacillus subtilis* and *Bacillus megatherium* were 800 nm and 1200 nm, respectively, which are larger than the size of *Mycobacterium tuberculosis* (300–600 nm). The authors showed that the filtration efficiency for N95 respirators was 99.5% or higher for both bacterial aerosols.

Several studies employed a wide size range of monodisperse aerosol particles to measure penetration levels with advanced particle analyzing equipment.[13,14,16–18] In one study, a particle spectrometer was employed to measure the penetration levels for N95 respirators using polydisperse NaCl aerosols.[16] Their results showed filtration efficiency for N95 respirators, for all sizes (120 to 700 nm range) of particles tested, higher than dust/mist (DM) and dust/mist/fume (DMF) respirators. The DM and DMF respirators were approved under 30 CFR Part 11 before the promulgation of 42 CFR Part 84 in 1995.

Recent studies have employed modern particle spectrometers capable of sizing and counting particles down to 10 nm size with greater accuracy.[13,18] Many studies have found that the count-based most penetrating particle size (MPPS) for electrostatic filters used in particulate respirators manufactured since 1998 are typically less than 100 nm (electrical mobility diameter).

Higher than 5% penetrations were obtained at the MPPS for a limited number of respirator models with different particle spectrometers.[13,18] Two of the three N95 FFRs models tested with monodisperse DOP aerosols showed ∼5–10% penetrations in the MPPS range.[19] Similarly, penetration value for the MPPS was ∼6% for one of the two N95

FFR models tested in another study with monodisperse NaCl particles.[18] Subsequent studies with five N95 FFR models showed >5% penetrations for two FFR models at the MPPS but were not statistically significant from 5%.[14] Penetration levels up to ~5.9% were also reported for N99 FFRs at the MPPS range at 85 L/min flow rate.[20]

The NIOSH certification test uses a TSI 8130 that employs a forward light scattering photometer to measure the flux of light scattering from particles. Recent studies showed that photometric detection methods are not capable of adequately measuring the light scatter for particles <100 nm in size.[21] This suggests that the NIOSH respirator test protocol may not represent a more challenging aerosol test method for certifying respirators to be used in workplaces containing a wide size range of particles including nanoparticles (<100 nm size). Furthermore, no previous studies have compared the filtration performance of contemporary NIOSH-approved particulate respirators tested by the photometric method with count-based methods using generated and ambient aerosols.

To better understand the effect of key test parameters (e.g., particle charge and detection method), penetration levels for commonly used N95 FFRs were measured with a TSI 8130 employed in the NIOSH certification method and compared with the penetrations measured using an ultrafine condensation particle counter (UCPC) for the same NaCl aerosols employed for the TSI 8130 test. Filtration performance of N95 FFRs was also evaluated for ambient aerosols by measuring penetrations for laboratory room air particles using a UCPC and comparing them with the results obtained using a TSI 8130.

MATERIALS AND METHODS

Respirators

In this study, FFRs from five different N95 manufacturers were selected based on availability from the suppliers. The manufacturers and models of the N95 FFRs are 3M (model 8210; St. Paul, Minn.), Gerson (model 1730; Middleboro, Mass.), Moldex (2600; Culver City, Calif.), North (7130; Cranston, R.I.), and Willson (N1105; Santa Ana, Calif.). None of the five N95 models had exhalation valves. The five FFR models were randomly assigned labels N95-A through N95-E.

Polydisperse NaCl Aerosol Penetration Measurement

TSI 8130—Photometric Method (Light Scattering Detection)

Three N95 FFR samples from each N95 model were tested for polydisperse NaCl aerosol penetration using a TSI 8130 used for NIOSH particulate respirator certification.[3,6] Penetration obtained by the TSI 8130 is based on the measurement of the flux of light scattering from particles upstream and downstream of the sample. Initial penetration levels for polydisperse NaCl particles were measured for 1 min instead of conducting the entire NIOSH 42 CFR Part 84 test protocol. Initial penetration levels were measured to avoid any loading effects for better comparison with other testing methods using different concentrations of aerosols. Penetrations were measured at 85 L/min flow rate as described previously.[14] This abbreviated test procedure (e.g., no preconditioning, no loading) provides results similar to that from the longer NIOSH certification test.[22]

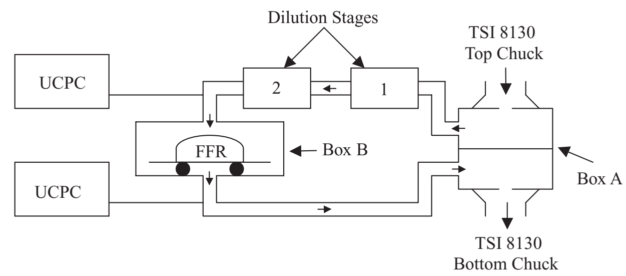

FIGURE 1. Experimental setup for measuring filter penetrations for N95 FFR based on particle number using TSI 8130 NaCl aerosols.

UCPC Method (Count-Based Detection)

Penetration levels for a different set of three samples from each N95 FFR model were measured with a UCPC (TSI 3776), employing the same polydisperse NaCl aerosols used in the TSI 8130. Briefly, a Plexiglas box (Box A; 17.5 × 17.5 × 10 cm^3), partitioned horizontally with no connection between the two halves, was placed between the filter chucks of the TSI 8130 (Figure 1). The top of the upper chamber and the bottom of the lower chamber had a 2.5-cm hole that can be aligned in position with the holes of the TSI 8130 filter chucks. The upstream aerosol from the TSI 8130 was passed into the top chamber of the Box A and exited through an outlet tube connected to a test Box B containing a sealed FFR as described previously.[14] The aerosol from the downstream of the FFR was passed through an outlet tube into the bottom chamber of the Box A and then to the hole in the bottom chuck of the TSI 8130.

Samples upstream and downstream of the respirator test Box B were analyzed for particle concentration using two UCPCs simultaneously. The TSI 8130 was run for 1 min to allow the concentrations to reach equilibrium. The UCPC then recorded the average concentration over a 2-min period. Penetration value was obtained as the ratio of the average particle concentration downstream of the FFR to the average concentration upstream. During normal operation the output concentration of the TSI 8130 is several orders of magnitude above the upper limit of the UCPC. To bring the concentration down to a usable level, two dilution stages were used, each consisting of a HEPA filter and a bypass with adjustable flow resistance. The difference (~3%) in the particle number concentration between the two UCPCs was measured and applied to the data.

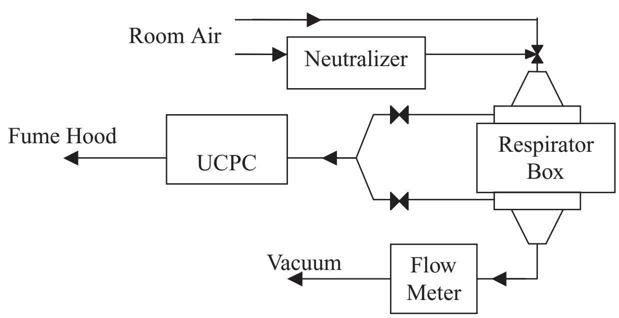

FIGURE 2. Setup used to measure laboratory room air particle penetrations for N95 FFRs.

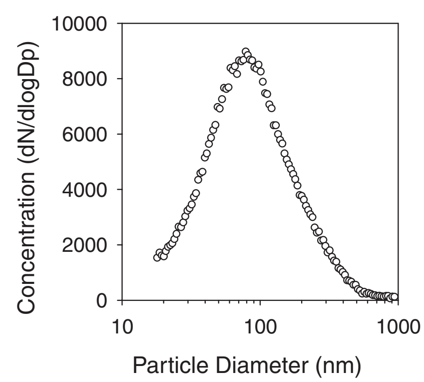

FIGURE 3. Typical size distribution of laboratory room particles analyzed by an SMPS. Particle diameters reported in the measurement are based on electrical mobility.

Room Air Particle Penetration at Measurement

Figure 2 shows the schematic of the room air particle penetration test system. Briefly, laboratory room air particles were passed into a Plexiglas test box (20 cm × 20 cm × 10 cm) mounted with an FFR placed between the upstream and downstream filter chucks as described previously.[14] Room air particles were passed directly into the test box, and upstream and downstream aerosol particles were counted by a UCPC by sampling through ports, off each filter chuck, alternately. Particle numbers upstream and downstream of the FFR samples were measured for 100 sec at 85 L/min flow rate. Penetration value was calculated as a ratio of the number of particles downstream to the number of particles upstream. Four samples from each N95 FFR model were tested for room air particle penetration. The UCPC measured values represent the total penetrations for particles in the 2.5 to ∼3000 nm size range.

Room Air Particle Penetration as a Function of Particle Size

Percentage penetrations for three samples from each N95 FFR model were also measured as a function of particle size from 20–1000 nm using a Scanning Mobility Particle Sizer (SMPS; TSI 3080) in the scan mode. Particle concentration upstream and downstream of the FFR was measured using the Plexiglas box set up at 85 L/min. Room air particle concentrations for the 20–1000 nm size range particles were measured for 135 sec for upstream and downstream samples, alternately. Particles are classified based on their electrical mobility diameters by a TSI differential mobility analyzer (DMA), an integral part of the SMPS. Penetration for each size bin was calculated as a ratio of particle concentration downstream to particle concentration upstream.

Net Charge Measurements

An electrometer (TSI 3068B) was employed to measure the current (fA) as a measure of net charge for room air particles with or without charge neutralization (charge neutralized and un-neutralized, respectively) using a charge neutralizer (TSI 3077). In the case of monodisperse NaCl aerosols generated by the TSI 3160 Fractional Efficiency Tester (TSI 3160), charge neutralized particles were obtained by passing the aerosols through a charge neutralizer (TSI 3077). To obtain unipolar (singly) charged monodisperse NaCl aerosols, the charge neutralizer downstream of the DMA was removed from the TSI 3160. Current measurement data were reported as an average of over 10 min to minimize the impact of any noise in the data. A set of four FFR samples from each of the five N95 models were tested at 85 L/min.

Particle Penetration as a Function of Particle Size and Charge with the TSI 3160

Penetrations for the charge neutralized and unipolar monodispersed (10 different sizes) NaCl aerosols were measured using the TSI 3160. A set of four FFR samples from each of the five N95 models was tested at 85 L/min.

RESULTS

Comparison of TSI 8130 Photometric Method with UCPC Method

A typical distribution of 20–1000 nm aerosol particles in the laboratory room air is shown in Figure 3. Room air particles showed a CMD of 60 ± 25 nm and a GSD of 2.04. Particles above 400 nm sizes showed about one order of magnitude less particle concentrations than the MPPS peak values. Figure 4 shows a comparison of the penetration levels obtained for polydisperse NaCl aerosols using the TSI 8130 and the UCPC, and room air particle penetrations with a UCPC for the five N95 FFR models. Polydisperse NaCl aerosol penetrations for N95 FFRs measured by the UCPC had penetrations between 0.63 to 4.3% and were 2 to 6 times the penetrations obtained with the TSI 8130 at 85 L/min flow rate. Similarly, N95 FFRs had room air particle penetrations between 1.2–4.0% that were 3 to 8 times the penetrations recorded by the TSI 8130.

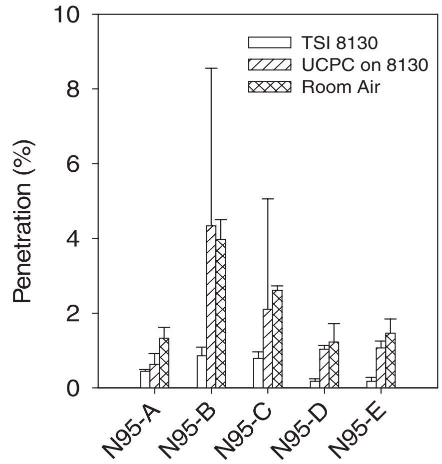

FIGURE 4. Laboratory room aerosol penetration data for five N95 FFR at 85 L/min. Comparison of penetration values from the TSI 8130 (open bars) with values obtained by the UCPC for the TSI 8130 NaCl aerosols (hatched bars). Laboratory room air penetrations represent the values for particles in the 2.5–1000 nm range (cross hatched bars). Error bars are at the 95% confidence level (n = 3).

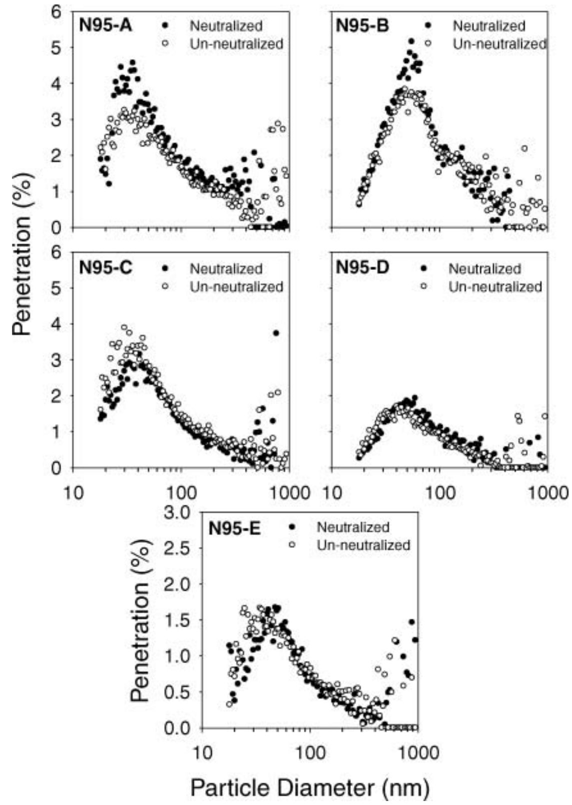

FIGURE 5. Laboratory room air particle penetrations measured as a function of particle size using a SMPS for N95 FFRs at 85 L/min with and without a charge neutralizer. Data averaged from four samples.

Room Air Particle Penetration as a Function of Particle Size

Penetrations for un-neutralized and charge neutralized room air particles in the 20–1000 nm size range were measured as a function of particle size using an SMPS. Particle concentrations for upstream and downstream samples were measured alternately for four samples of each of the five N95 model FFRs at 85 L/min. Figure 5 shows the average penetration curves for the un-neutralized (open circles) and the charge neutralized (solid circles) room air particles. The MPPS was in the 35–55 nm range for un-neutralized as well as for the charge neutralized aerosols for all five N95 model FFRs. N95-A, N95-B, and N95-C FFRs showed higher penetration levels (4.6%, 5.2%, and 3.2%) at the MPPS size range for charge neutralized aerosols than the un-neutralized aerosols (3.3%, 3.8%, and 3.9%), respectively. The penetration levels for the un-neutralized and charge neutralized aerosol particles were similar for N95-D and N95-E model FFRs.

Net Charge Data for Room Air Aerosols

The currents measured for un-neutralized and charge neutralized room air particles and charge neutralized TSI 3160 generated monodispersed NaCl aerosols were within the ±5 fA instrument error of zero. No significant difference in the current levels for un-neutralized and neutralized room air particles was obtained. However, for the unipolar charged monodisperse particles (from the TSI 3160 without the neutralizer), the electrometer recorded a consistent one sign current indicating a strong bias of positive charge.

Penetrations for Charge Neutralized and Unipolar Monodisperse NaCl Particles with the TSI 3160

Penetrations for five N95 model FFRs were measured using the TSI 3160 generated charge neutralized and unipolar charged NaCl particles (Figure 6). For the charge neutralized particles, the MPPS occurred at 40 nm for all N95 FFRs (left panel) with maximum penetrations between 1.4–5.2%. Unipolar charged particles caused a shift in the MPPS to 200 nm with penetrations between 0.30–2.1% among the FFR models (right panel).

DISCUSSION

Penetration results obtained for the five N95 model FFRs by photometric and particle counting methods were significantly different. Percentage penetration levels by the UCPC method for NIOSH certification test NaCl aerosols were 2 to 6 times the penetration levels obtained with the TSI 8130. This can be explained by the difference in the methodology employed in the two penetration measurements. The UCPC method measures penetrations based on particle count for polydisperse NaCl test aerosols with a size distribution in the 22–258 nm range (CMD 75 ± 20 nm).

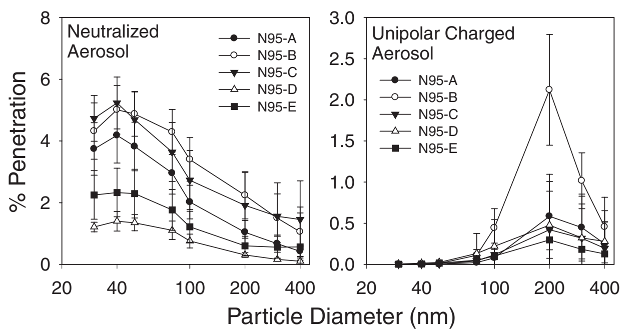

FIGURE 6. Penetrations of charged neutralized (left) and unipolar charged (right) monodisperse aerosols using the TSI 3160 at a flow rate of 85 L/min. Error bars are at the 95% confidence level for the average of three samples.

However, the TSI 8130-obtained penetrations are based on the flux of light scattering from particles. The scattering light flux has been shown to be proportional to the particle $(mass)^2$ or $(diameter)^6$ when particle diameter is lower than the wavelength of coincident light.[23] The scattering light flux is dependent on the diameter or mass of test aerosols. Nanoparticles' contribution to the scattering light flux is insignificant because of their lack of significant mass. On the other hand, the UCPC counts particles giving equal importance to all size test aerosols including nanoparticles. Thus, penetration level obtained using a particle counter exceed the TSI 8130 values.

The higher penetration levels obtained with the UCPC method are consistent with a previous study that compared the penetration levels for HEPA filters by a photometer and a condensation nuclei counter (CNC).[24] Penetration values for HEPA filter medium were measured using dioctyl sebacate aerosols with a CMD of 200 nm and a GSD of 2.0. The penetration values by the CNC were 8 to15 times the penetration values obtained with a photometer. The photometric method was found to be associated with the particle volume or mass distribution of the test aerosol. The authors showed that, for aerosols below 100 nm, the photometer response decreased drastically. This is consistent with the calculated photometer response for the NIOSH certification test NaCl aerosols with a CMD of 75 nm and a GSD of 1.86.[21] The photometric method showed no significant response (0.6% of the total light scattering signal) for particles below 100 nm sizes, which accounts for 68% (by count) of the total number of particles. Similarly, a high correlation was reported between filter penetration results measured using a photometric method (TSI 8130) and a count-based method (TSI 3160), with penetration levels typically ∼4 times for monodisperse aerosols at the MPPS measured using the count-based method compared with the corresponding TSI 8130 measured results.[25] Taken together, these studies suggest that a particle number-based test method would be more applicable to reasonably ensure a certain level of filtration performance for a wide size range of particles including nanoparticles.

NIOSH-certified respirators tested under stringent laboratory test conditions were believed to reasonably ensure that the filtration performance would not be significantly worse in any given workplace. Interestingly, the five N95 model FFRs challenged with room air particles showed initial penetration levels 3 to 8 times the penetration levels obtained with polydisperse NaCl aerosols employed in the NIOSH certification test method using the TSI 8130. The data indicate that a particle number-based test method may measure higher penetrations than the NIOSH particulate respirator certification test method using polydisperse NaCl aerosols and may not be a challenging aerosol test method for N-series FFRs as previously thought. Penetration levels can vary with the size distribution of the particles in the work environment. The particle size distribution will vary widely among workplaces based on factors including the presence/absence of engineering controls, materials being handled, and work processes (e.g., grinding, milling, combustion). Recent studies have shown that some workers may be exposed to aerosolized nanoparticles resulting from their generation, handling, and cleaning. [26–28] Particles in this size range fall within MPPS range observed for respirators containing electrostatic filter media.

Penetration levels for charge neutralized and un-neutralized room air particles increased with particle size, reached a maximum at 35–55 nm range, and then decreased for larger size particles. The MPPS 35–55 nm range obtained for the five different N95 model FFRs at 85 L/min flow rate were similar to the values obtained for charge neutralized monodisperse NaCl particles for the same five N95 model respirators.[14] Two models of N95 FFRs (D and E) with relatively low penetration values in this study showed no significant difference in the penetration levels for the charge neutralized and un-neutralized room air particles. Similar results were obtained for some models of FDA-cleared surgical masks in a previous study,[29] suggesting that room air particles are charge neutralized. The results obtained for charge neutralized and un-neutralized room air particles in this study and previously[30] are consistent with the finding that comparatively aged aerosol particles in many workplaces are charge neutralized to Boltzmann equilibrium.[30,31]

On the other hand, charge neutralized room air particle penetration levels for some N95 respirator models (A, B, and C) were slightly higher than the levels obtained for un-neutralized room air particles in the MPPS range. One possible reason for this discrepancy is that room air particles are not completely charge neutralized. This may be the reason that charge neutralized room air particles showed higher penetration levels at the MPPS than those penetrations for the un-neutralized room air particles. Room air particles may carry net electric charge due to ongoing particle generation processes at the time of penetration measurements. These experiments were conducted in an active, open laboratory environment with no special particle containment controls in place.

This raises a question why room air particles carrying net electric charges did not shift the MPPS toward a larger size as shown for the DMA classified singly charged monodisperse particles. Results obtained in the study showed that the DMA classified singly charged (not passed though a charge neutralizer) monodisperse 50 nm size particles had negligible penetration levels (Figure 6, right panel). Penetrations for the singly charged particles showed a MPPS at 200 nm, unlike the charged neutralized particles (passed though a charge neutralizer) with a MPPS at 40 nm (Figure 6, left panel). This can be explained by the electrostatic filtration mechanisms for particles with different charge levels.[32,33] The authors showed that the MPPS for both charge neutralized and uncharged particles were in the sizes <100 nm, while at sizes >100 nm for the DMA classified singly charged particles. For the five N95 FFRs tested in the study, the current measured for un-neutralized and charge neutralized room air particles was within the ±5 fA instrument error of zero with no significant difference between them. The MPPS for the un-neutralized and charge neutralized room air particles was in the 35–55 nm range for all five N95 model FFRs (Figure 5). This indicates that room air containing an overwhelming number of charge neutralized particles retained the MPPS in the 35–55 nm size range, while relatively fewer numbers of singly charged particles were unable to shift the MPPS toward a larger size.

The results obtained in the study have potential applications for development of more challenging NIOSH particulate respirator certification protocols. With the recent advances in particle science, many industrial workplaces employ nanoparticles for various applications. Exposure to high levels of nanoparticles has been implicated in human health.[34–36] Many NIOSH-approved FFRs are electrostatic filters with MPPS in the 50 nm range.[14,15,17–19] However, the photometric method employed for NIOSH respirator certification does not account for penetrations for particles <100 nm size, which are most likely to penetrate through the respirators.[20] The polydisperse NaCl particles employed in the NIOSH certification protocol contain 68% (by count) particles below 100 nm size, which account for only 0.6% of the total light scattering signal by photometry. For testing the filtration efficiency of respirators, a more challenging penetration test method based on particle count may be more appropriate than a photometric method.[12,21,25] Considering these factors, a respirator certification test capable of measuring the penetration levels for a wide size range of particles including nanoparticles found in contemporary workplaces should be considered.

A limitation of the study was that only three or four samples of five N95 models were tested for room air particle penetrations using the UCPC. Further research with additional N95 and other class FFRs is needed to confirm the results obtained in the study. Penetration measurement by the UCPC must also be verified using other particle counters. To evaluate the filtration performance of NIOSH-approved respirators for ambient aerosols, penetration levels for N95 FFRs were tested for penetration of laboratory ambient room air particles. Further studies on the penetration levels for NIOSH-approved respirators in different workplace settings are needed.

CONCLUSIONS

N95 FFR penetrations measured by the particle number-based method (UCPC) were 2 to 6 times greater than the levels measured by the photometric method (TSI 8130), when tested with the same NaCl aerosols employed in the NIOSH respirator certification method. Room air particle penetrations for N95 FFRs measured using a UCPC was 3 to 8 times the penetration levels obtained for polydisperse NaCl aerosols employed in the NIOSH certification test method. These results indicate that penetration values obtained using the UCPC based on particle number are more challenging than the photometric method, which lacks sensitivity for particles <100 nm size range.

All five N95 FFR models showed that the MPPS was in the 50 nm range for room air particles with or without charge neutralization, and at 200 nm range for singly charged NaCl monodisperse particles. Room air with fewer charged particles and an overwhelming number of neutral particles may have contributed to the most penetrating particle size at 50 nm, indicating that charge state for the majority of particles determines the MPPS. The data suggest that the NIOSH particulate respirator certification test employing the photometric method is not a more challenging aerosol test method. This suggests the need for the development of “more challenging” aerosol test methods based on particle counting for possible NIOSH certification of respirators. Further research is needed to develop methods to test all of the existing classes of particulate respirators with particle counting and to address the need to test filters with particle loading conditions.

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REFERENCES

1. “Mineral Resources. Respiratory Protective Devices; Tests for Permissibility; Fees." *Code of Federal Regulations* Title 30, Part 11. 1984. pp. 7–71.
2. **Moyer, E.S.:** *Respirator Filtration Efficiency Testing*. Philadelphia: ASTM, 1986.
3. “Respiratory Protection Devices. Final Rules and Notice." *Federal Register 60*:110 (June 8, 1995). pp. 30335–30398.
4. **Stevens, G.A., and E.S. Moyer:** “Worst case” aerosol testing parameters: I. Sodium chloride and dioctyl phthalate aerosol filter efficiency as a function of particle size and flow rate. *Am. Ind. Hyg. Assoc. J. 50*:257–264 (1989).
5. **Reed, L.D., D.L. Smith, and E. Moyer:** Comparison of respirator particulate filter test methods. *J. Int. Soc. Res. Prot. 4*:43–60 (1986).
6. “Procedure No. TEB-APR-STP-0059, Revision 2.0. Determination of Particulate Filter Efficiency Level for N95 Series Filters Against Solid Particulates for Non-Powered, Air-Purifying Respirators Standard Testing Procedure (STP).” [Online] Available at

http://www.cdc.gov/niosh/npptl/stps/pdfs/TEB-APR-STP-0059.pdf (Accessed Oct. 27, 2010).

7. "Procedure No. TEB-APR-STP-0051, Revision 2.0. Determination of Particulate Filter Efficiency Level for P100 Series Filters Against Liquid Particulates for Non-Powered, Air-Purifying Respirators Standard Testing Procedure (STP)." [Online] Available at http://www.cdc.gov/niosh/npptl/stps/pdfs/TEB-APR-STP-0051.pdf (Accessed Oct. 27, 2010).
8. **Janssen, L., and J. Bidwell:** Performance of four class 95 electret filters against diesel particulate matter. *J. Int. Soc. Respir. Prot. 23*:21–29 (2006).
9. **Janssen, L.L., J.O. Bidwell, H.E. Mullins, et al.:** Efficiency of degraded electret filters: Part I. Laboratory testing against NaCl and DOP before and after exposure to workplace aerosols. *J. Int. Soc. Respir. Prot. 20*:71–80 (2003).
10. **Janssen, L.L., J.O. Bidwell, H.E. Mullins, et al.:** Efficiency of degraded electret filters: Part II. Field testing against workplace aerosols. *J. Int. Soc. Respir. Prot. 20*:81–90 (2003).
11. **Rengasamy, A., Z. Zhuang, and R. BerryAnn:** Respiratory protection against bioaerosols: Literature review and research needs. *Am. J. Infect. Control 32*:345–354 (2004).
12. **Rengasamy, S., Z. Zhuang, R. Roberge, et al.:** Particulate respiratory protection —Overview, emerging issues and research needs. In *Protective Devices: Types, Uses and Safety*, V.E. Argosyan (ed.). Hauppauge, N.Y.: Nova Science Publishers, Inc., 2010. pp. 131–160.
13. **Moyer, E.S., and M.S. Bergman:** Electrostatic N-95 respirator filter media efficiency degradation resulting from intermittent sodium chloride aerosol exposure. *Appl. Occup. Environ. Hyg. 15*:600–608 (2000).
14. **Rengasamy, A., R. Verbofsky, W.P. King, et al.:** Nanoparticle penetration through NIOSH-approved N95 filtering-facepiece respirators. *J. Int. Soc. Respir. Prot. 24*:49–59 (2007).
15. **Rengasamy, S., W.P. King, B. Eimer, et al.:** Filtration performance of NIOSH-approved N95 and P100 filtering-facepiece respirators against 4-30 nanometer size nanoparticles. *J. Occup. Environ. Hyg. 5*:556–564 (2008).
16. **Qian, Y., K. Willeke, S.A. Grinshpun, et al.:** Performance of N95 respirators: Filtration efficiency for airborne microbial and inert particles. *Am. Ind. Hyg. Assoc. J. 59*:128–132 (1998).
17. **Eshbaugh, J.P., P.D. Gardner, and A.W. Richardson:** N95 and P100 respirator filter efficiency under high constant and cyclic flow. *J. Occup. Environ. Hyg. 6*:52–61 (2009).
18. **Balazy, A., M. Toivola, T. Reponen, et al.:** Manikin-based performance evaluation of N95 filtering-facepiece respirators challenged with nanoparticles. *Ann. Occup. Hyg. 50*:259–269 (2006).
19. **Martin, S.B. Jr., and E.S. Moyer:** Electrostatic respirator filter media: Filter efficiency and most penetrating particle size effects. *Appl. Occup. Environ. Hyg. 15*:609–617 (2000).
20. **Eninger, R.M., T. Honda, A. Adhikari, et al.:** Filter performance of N99 and N95 facepiece respirators against viruses and ultrafine particles. *Ann. Occup. Hyg. 52*:385–396 (2008).
21. **Eninger, R.M., T. Honda, T. Reponen, et al.:** What does respirator certification tell us about filtration of ultrafine particles? *J. Occup. Environ. Hyg. 5*:286–295 (2008).
22. **Viscusi, D.J., M.S. Bergman, E. Sinkule, et al.:** Evaluation of the filtration performance of 21 N95 filtering facepiece respirators after prolonged storage. *Am. J. Infect. Control 37*:381–386 (2009).
23. **Johnson, T., and S. Smith:** Correlation of penetration results between filter testers that use different particle generators and detection methods. Technical paper #A104. In *Proceedings of the 1998 Nonwoven Conference, TAPPI.* St. Petersburg, Florida, March 9–11, 1998. pp. 161–174.
24. **Biermann, A.H., and W. Bergman:** Filter penetration measurements using a condensation nuclei counter and an aerosol photometer. *J. Aerosol Sci. 19*:471–483 (1988).
25. **Shaffer, R.E., and S. Rengasamy:** Respiratory protection against nanoparticles: A review. *J. Nanopart. Res. 11*:1661–1672 (2009).
26. **Bello, D., B.L. Wardle, N. Yamamoto, et al.:** Exposure to nanoscale particles and fibers during machining of hybrid advanced composites containing carbon nanotubes. *J. Nanopart. Res. 11*:231–249 (2009).
27. **Johnson, D.R., M.M. Methner, A.J. Kennedy, et al.:** Potential for occupational exposure to engineered carbon-based nanomaterials in environmental laboratory studies. *Environ. Health Perspect. 118*:49–54 (2010).
28. **Methner, M.M., L. Hodson, A. Dames, et al.:** Nanoparticle emission assessment technique (NEAT) for the identification and measurement of potential inhalation exposure to engineered nanomaterials—Part B: Results from 12 field studies. *J. Occup. Environ. Hyg. 7*:163–176 (2010).
29. **Rengasamy, S., A.K. Miller, B. Eimer, et al.:** Filtration performance of FDA-cleared surgical masks. *J. Int. Soc. Respir. Prot. 26*:54–70 (2009).
30. **John, W.:** Particle charge effects. In *Generation of Aerosols,* K. Willeke (ed.). Ann Arbor, Mich: Ann Arbor Science, 1980.
31. **Johnston, A.M., J.H. Vincent, and A.D. Jones:** Measurements of electric charge for workplace aerosols. *Ann. Occup. Hyg. 29*:271–284 (1985).
32. **Kanaoka, C., H. Emi, Y. Otani, et al.:** Effect of charging state of particles on electret filtration. *Aerosol Sci. Tech. 7*:1–13 (1987).
33. **Yang, S., Y.-M.G. Lee, H.-L. Huang, et al.:** Aerosol penetration properties of an electret filter with submicron aerosols with various operating factors. *J. Environ. Sci. Health Part A 42*:51–57 (2007).
34. **Hoet, P.H., I. Bruske-Hohlfeld, and O.V. Salata:** Nanoparticles — Known and unknown health risks. *J. Nanobiotechnol. 2*:12–27 (2004).
35. **Schulte, P.A., C. Geraci, R. Zumwalde, et al.:** Occupational risk management of engineered nanoparticles. *J. Occup. Environ. Hyg. 5*:239–249 (2008).
36. **Department of Health and Human Services (DHHS), Centers for Disease Control and Prevention (CDC), National Institute for Occupational Safety and Health (NIOSH):** *Approaches to Safe Nanotechnology: Managing the Health and Safety Concerns Associated with Engineered Nanomaterials*. NIOSH Pub. No. 2009-125. Cincinnati, Ohio: DHHS, CDC, NIOSH, 2009.