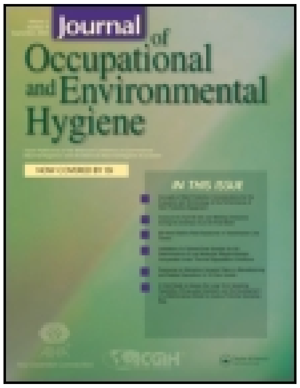

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Nanoparticle Filtration Performance of NIOSH-Certified Particulate Air-Purifying Filtering Facepiece Respirators: Evaluation by Light Scattering Photometric and Particle Number-Based Test Methods

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National Institute for Occupational Safety and Health (NIOSH) certification test methods employ charge neutralized NaCl or dioctyl phthalate (DOP) aerosols to measure filter penetration levels of air-purifying particulate respirators photometrically using a TSI 8130 automated filter tester at 85 L/min. A previous study in our laboratory found that widely different filter penetration levels were measured for nanoparticles depending on whether a particle number (count)-based detector or a photometric detector was used. The purpose of this study was to better understand the influence of key test parameters, including filter media type, challenge aerosol size range, and detector system. Initial penetration levels for 17 models of NIOSH-approved N-, R-, and P-series filtering facepiece respirators were measured using the TSI 8130 photometric method and compared with the particle number-based penetration (obtained using two ultrafine condensation particle counters) for the same challenge aerosols generated by the TSI 8130. In general, the penetration obtained by the photometric method was less than the penetration obtained with the number-based method. Filter penetration was also measured for ambient room aerosols. Penetration measured by the TSI 8130 photometric method was lower than the number-based ambient aerosol penetration values. Number-based monodisperse NaCl aerosol penetration measurements showed that the most penetrating particle size was in the 50 nm range for all respirator models tested, with the exception of one model at ∼200 nm size. Respirator models containing electrostatic filter media also showed lower penetration values with the TSI 8130 photometric method than the number-based penetration obtained for the most penetrating monodisperse particles. Results suggest that to provide a more challenging respirator filter test method than what is currently used for respirators containing electrostatic media, the test method should utilize a sufficient number of particles <100 nm and a count (particle number)-based detector.

Keywords ambient aerosols, filter penetration, filtering facepiece respirator, more challenging test aerosols, NaCl and DOP aerosols, NIOSH certification test

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INTRODUCTION

Particles are generated by a variety of natural and industrial processes. The diameter of inhalable particles ranges from nanometer to micrometer sizes. Recent developments in nanotechnology have introduced engineered nanoparticles (<100 nm) into workplaces. Unlike the bulk material, nanoparticles exhibit unique properties (e.g., chemistry and toxicity) due to the increased surface area. Nanoparticle generation and handling processes in industrial settings can generate aerosolized nanoparticles that may be inhaled, ingested, or absorbed through skin.[1]

Several investigators have studied the adverse effects of known mass concentrations of nanomaterial exposures (in the form of aerosols and solutions) on pulmonary and systemic functions in several systems.[2–4] For example, both inhalation and aspiration of single-walled carbon nanotubes have been shown to produce inflammation, fibrosis, oxidative stress, and mutagenesis in mice.[5] Exposure to nanoparticles also has been shown to increase the incidence of pneumoconiosis among workers.[4] However, the occupational exposure limit for many nanomaterials is not well established.[1] Because of

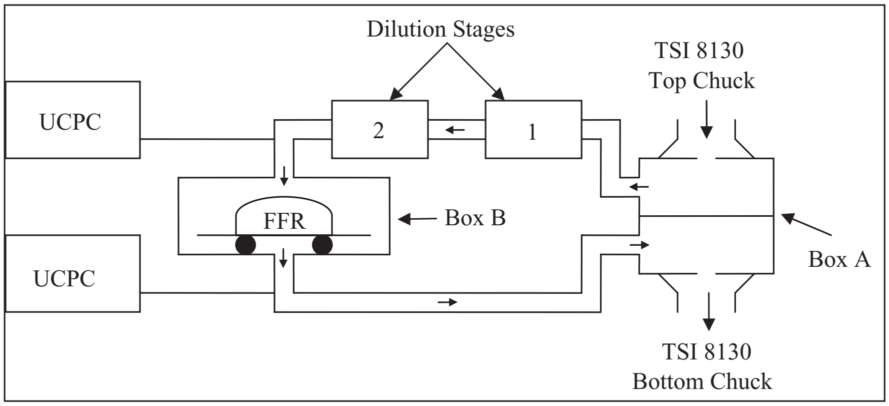

FIGURE 1. Experimental setup used to measure UCPC penetration with TSI 8130 test aerosols (NaCl and DOP) for FFRs.

concerns on nanomaterial exposure to workers in occupational settings, NIOSH and other organizations have recommended further studies on respiratory protection to ensure that currently available respirators provide expected levels of protection.[6–10]

Protection afforded by a particulate respirator is mostly a function of filter efficiency and face seal leakage. NIOSH-approved particulate respirators show polydisperse aerosol penetration values below the allowable values.[11–13] Face seal leakage of particles, however, is a major respiratory concern because the number of particles entering inside the respirator far exceeds the number of particles that penetrate through the filter media. The assigned protection factor (APF) of a respirator takes into account particle penetration through filter media as well as leakage through the face seal area and other components. NIOSH-certified respirators are expected to provide protection consistent with their Occupational Safety and Health Administration (OSHA) assigned protection factor (APF) values.[8] Appropriate respirators should be selected based on the criteria described in the NIOSH respirator decision logic.[8]

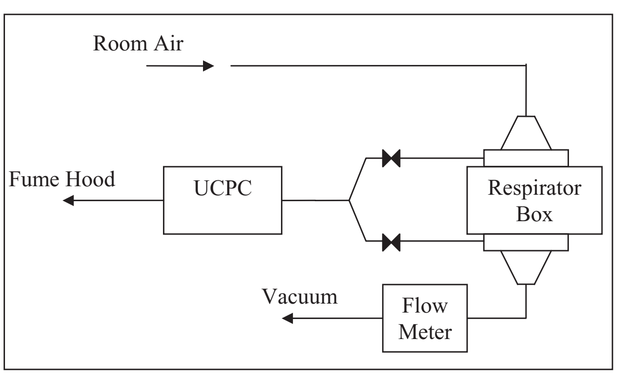

FIGURE 2. Experimental setup used to measure laboratory room air particle penetration for FFRs using an UCPC.

Historically, filter penetration test methods were developed based on a presumed most penetrating particle size (MPPS) of 300 nm for DOP test aerosols. This most penetrating particle size was based on Langmuir's theory of physical capture of small particles by a fibrous filter medium.[14,15] Based on this, an MPPS of 300 nm was applied to the development of filter testers to measure DOP aerosols.[16] Several subsequent studies, however, have reported that the MPPS of high efficiency filters can be smaller than 300 nm.[14,17,18] This was confirmed by research on NIOSH-certified respirators that showed an MPPS in the 30–210 nm (CMD) range.[12,19]

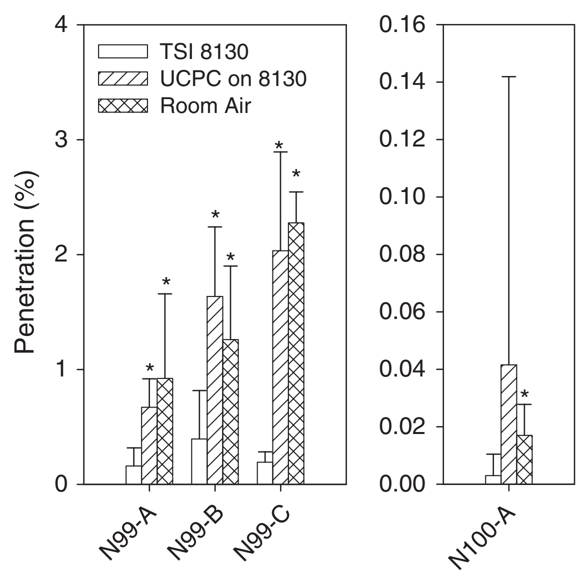

FIGURE 3. Filter penetration measured with a TSI 8130 using NaCl aerosols (open bars) and an UCPC (hatched) for the same TSI 8130 NaCl aerosols for three N99 model FFRs (left) and one N100 (right). Filter penetration for room air particles (cross-hatched) were measured using an UCPC. Error bars represent 95% confidence interval (N = 3). Asterisks indicate results significantly (p = <0.05) higher than TSI 8130 data.

Theoretical as well as experimental studies showed that the MPPS for filters is dependent on several factors, including filter media charge, fiber diameter, fiber packing density, particle diameter, particle charge, and filtration velocity.(15,20) In one study, the filtration efficiency of NIOSH-approved respirators was tested using monodisperse NaCl and DOP aerosols.(21) The authors showed that the MPPS for respirators containing charged fibers was in the near 100 nm size range and for mechanical respirators at ∼300 nm size range. The shift in the MPPS from >100 nm for mechanical filters to <100 nm for electrostatic filter media has been attributed to the electrostatic properties of the filter media.(22–24) Electrostatic filters capture nanoparticles via Coulombic attraction and polarizing forces, in addition to mechanical filtration mechanisms, which causes the shift in the MPPS to smaller particle sizes. Electrostatic filter media containing respirators capture particles efficiently with reduced breathing resistance and weight and are the predominant type of filter media used in respirators on the market today.

NIOSH has developed a new set of regulations in 42 *CFR* 84(25) for testing and certifying nonpowered, air-purifying, particulate-filter respirators. Nine classes of air-purifying particulate respirators are described under 42 *CFR* 84. For certification, N-series respirators are tested against polydisperse NaCl aerosols with a count median diameter (CMD) of 75 ± 20 nm and a geometric standard deviation (GSD) of 1.86 to give a mass median aerodynamic diameter (MMAD) of 347 nm.(26) R- and P-series respirators are tested against polydisperse dioctyl phthalate (DOP) aerosols with a CMD of 185 ± 20 nm and a GSD of 1.60 to give a MMAD of 359 nm.(27) Penetration levels for both aerosol types are measured with charge neutralized particles at 85 L/min flow rate using a TSI 8130 automated filter tester (TSI, Inc., Shoreview, Minn.).

NIOSH-approved respirators tested for filter penetration using light scattering photometric method have been shown to perform well in many workplaces.(28,29) The photometric filter penetration test method measures larger than 100 nm size aerosol particles with significant mass found in many conventional workplaces. However, the photometric method is not sensitive to measure nanoparticles with no significant mass.(30,31) Recently, significant number concentrations of nanoparticles have been found in some nanotechnology workplaces handling nanomaterials.(32–34) For example, nanoparticle (<100 nm) number concentration was found to increase in the reactor area of carbon black production plants.(35) Similarly, fullerene manufacturing processes showed an increase in nanoparticle number concentrations.(36) This indicates that nanoparticle filter penetration should be measured by a sensitive method.

Filtration performance of respirators has been determined using different methods.(12,13,22,37–39) NIOSH employs the TSI 8130 to measure filter penetration for certification. The photometers in the TSI 8130 measure the light scattering from a cloud of particles that passes through a focused light beam. The light scattering flux has been shown to be proportional to the particle (diameter)^6 or (mass)^2 for small particles where the particle diameter is lower than the wavelength of coincident light.(40) The light scattering signal is approximately proportional to (diameter)^3 or mass for larger size particles with diameters higher than the wavelength of coincident light. The light scattering signal for nanoparticles (<100 nm) is minimum because of their negligible mass. The photometer response decreases drastically for nanoparticles (<100 nm) and hard to measure.(30) The photometer response is mostly due to particles larger than 100 nm size.

Some studies also employed an optical counter (OPC) or a laser spectrometer to measure aerosol penetration through respirators.(38,39,41) OPCs are similar to photometers; however, aerosol flows through a focused light or laser beam as a thin stream surrounded by sheath air, so that only one particle at a time is counted. The sensitivity of conventional OPCs is greatly diminished for particles <100 nm size range. The difficulty in measuring nanoparticles was overcome by further development of condensation particle counters (CPCs) that employ a supersaturated liquid such as alcohol to grow the size of smaller particles for easy detection. CPCs detect individual particles, including nanoparticles, and provide number concentrations. The CPC counts the particles, giving equal importance to individual particles of a wide size range, including nanoparticles. One study tested four different models of CPCs to assess their counting performance for various diameter size ranges of particles.(42) The performance of all four CPC models tested in that study was reasonably good for 24–50 nm particles but decreased dramatically for particles <20 nm size. A wide variation in response to smaller size (<20 nm) particles can also be expected for the different models of modern CPCs. The concentration of nanoparticles in the 3–100 nm range can be measured using an ultrafine condensation particle counter (UCPC 3776, TSI) with a counting efficiency of ∼100%.

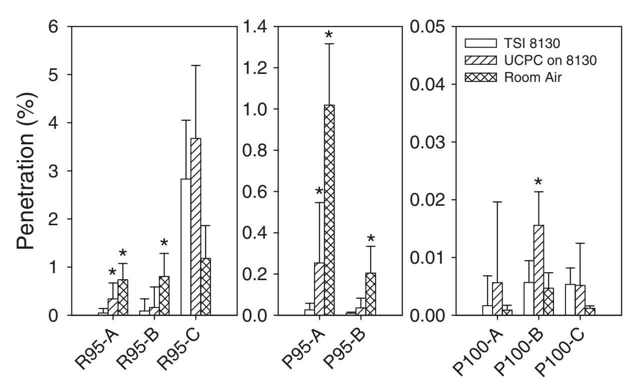

FIGURE 4. Filter penetration measured with a TSI 8130 (open bars) and an UCPC (hatched) for the same TSI 8130 DOP aerosols for three R95 (left), two P95 (center) and three P100 (right) FFR models. Filter penetration for room air particles (cross-hatched) were measured using an UCPC. Error bars represent 95% confidence interval. N = 3 for all tests. Asterisks indicate results significantly (p = <0.05) higher than TSI 8130 data.

TABLE I. Respirators Tested for Filter Penetration

Filtering Facepiece Respirator	Photometric and Particle Number-Based Methods	Particle Number-Based Method	
N-series (N95, N99, and N100)	Polydisperse NaCl (NIOSH)	Ambient room	Monodisperse NaCl
R-series (R95)	Polydisperse DOP (NIOSH)	Ambient room	Monodisperse NaCl
P-series (P95 and P100)	Polydisperse DOP (NIOSH)	Ambient room	Monodisperse NaCl

Several studies compared the filtration performance of filter materials using different test methodologies.[19,43–46] These studies have employed different test aerosols and detection systems for measuring particle penetration levels. For example, the International Atomic Energy Agency (IAEA) report described high efficiency particulate air (HEPA) filter penetration measurements for DOP, NaCl, paraffin oil, and other aerosols using a laser particle counter, flame photometry, and light scattering methods.[44] A consensus finding was that total filter penetration was dependent on filter material, particle size distribution of test aerosols, and velocity. Very few studies have reported comparative performance of filter test methods for larger size particles and nanoparticles. One study compared the penetration levels obtained for HEPA filters using a wide size range of particles, including nanoparticles, by a photometric and a particle counting method.[30] The authors indicated that photometer and particle counter measurements vary widely from no difference to a factor of 10. This variation was attributed to the response function of the photometer, filter penetration, and the size distribution of the test aerosols. Their results showed that photometer response greatly diminished, with a decrease in particle size to nanoparticle size range.[30] Results from the study showed that the difference in penetration measurements between the two methods is due to the detector response as a function of particle size.

Recently, we compared the penetration of polydisperse NaCl aerosols for five N95 model FFRs using the TSI 8130 and compared with the penetration obtained with an UCPC for the same aerosols.[37] Percentage penetration values by the TSI 8130 method (photometric) were two to six times less than the values obtained by the UCPC method (number-based).[37] The data suggested that a particle number-based test method is more challenging for nanoparticle penetration than the TSI 8130 photometric method.[12,13,22,47,48]

This article is a continuation of our previous work,[37] expanded to include data from five additional classes of FFRs and additional analysis to better understand key test method parameters (e.g., filter media type, challenge aerosol size range, detector). Initial penetration levels for 17 FFR models of NIOSH-approved N-, P-, and R-series were measured using test aerosols (NaCl for N-series and DOP for R- and P-series) employed for NIOSH certification with a TSI 8130 (photometric method), and compared with the penetration measured by a particle number-based test method with two UCPCs for the same TSI 8130 test aerosols (NaCl for N-series and DOP for R- and P-series). To gain additional insight into the parameters that affect filtration performance, penetration obtained with the NIOSH filter test aerosol using the TSI 8130 was also compared with the penetration obtained by the number-based method using ambient room aerosols. Similar to our previous study,[37] we hypothesize that count- or number-based filter test methods will have larger nanoparticle filter penetration for electrostatic FFRs than test methods using a photometric detection method, even when the same aerosol particle size challenge is used.

MATERIALS AND METHODS

Respirators

Of the nine classes of particulate respirators approved by NIOSH, only six classes of FFRs were available during the investigation (Table I). In this study, 12 FFR models including N99 (three models), N100 (one model), R95 (three models), P95 (two models), and P100 (three models) were selected based on availability from the supplier. In addition, penetration data obtained for five N95 model FFRs tested previously[11,37] have been included for analysis (Table I). Manufacturers and models (in parentheses) of the N99 FFRs are Kimberly-Clark (M30), Moldex (2310), and Wilson (N1139); the N100 FFR is 3M (8233); the R95 FFRs are 3M (8240), AO Safety (Pleats Plus), and Gerson (1840); the P95 FFRs are 3M (8271), and Kimberly-Clark (M20); and the P100 FFRs are 3M (8293),

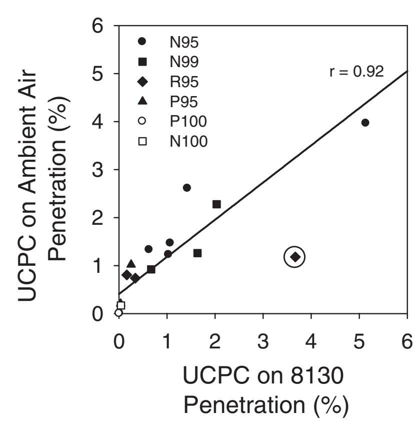

FIGURE 5. Correlation of filter penetration measured by an UCPC for the TSI 8130 test aerosols (NaCl for N-series and DOP for R- and P-series) and ambient room air aerosols for N95 (●, 5 models), N99 (■, 3 models), N100 (□, 1 model), R95 (◇, 3 models), P95 (▲, 2 models), and P100 (○, 3 models). The circled data point represents R95-C model.

Moldex (2360), and Wilson (P1130). FFR models were randomly assigned labels A, B, C, or D for each class FFR models. In some experiments, standard filter materials (Hollingsworth and Vose Company) including N95 (electrostatic) and HF-0031 glass fiber (mechanical) media were tested.

Test Aerosol Size Distribution Analysis

Test aerosols (TSI 8130 NaCl and DOP, and ambient room) were classified based on their electrical mobility diameters by a differential mobility analyzer (DMA, TSI 3081), an integral part of a scanning mobility particle sizer (SMPS, TSI 3080). Concentrations of size classified particles were obtained using an ultrafine condensation particle counter (UCPC, TSI 3776). Test aerosol was passed into the SMPS for analyzing the concentration of different size particles in the 20–1000 nm size range for about 135 sec.

Filter Penetration

Penetration for sealed FFRs was measured using a TSI 8130 light scattering photometer (photometric) and a condensation particle counter (number-based). Table I shows different test aerosols employed for the photometric and number-based methods for measuring filter penetration.

Photometric Method

Three samples from N99 and N100 model FFRs were tested with polydisperse NaCl aerosols, while R95, P95, and P100 FFR samples were tested with polydisperse DOP aerosols using a TSI 8130 automated filter tester (Table I), which measures upstream and downstream particle concentrations using two photometers. The challenge aerosols were those employed for the NIOSH particulate respirator certification.[25] Initial penetration levels were measured for 1 min at 85 L/min flow rate instead of carrying out the entire NIOSH respirator certification test.[11]

Particle Number-Based Method for TSI 8130 Aerosols

Particle number-based penetration levels for another set of three samples from each FFR model were measured employing the same polydisperse aerosols (NaCl for N-series FFRs and DOP for R- and P-series FFRs) generated by the TSI 8130. Number-based penetration was measured using two UCPCs to measure upstream and downstream particle concentrations similar to the TSI 8130 with two photometers. Briefly, a Plexiglas Box A (17.5 × 17.5 × 10 cm^3) with a partition separating 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 Box A and exited through an outlet tube connected to test Box B containing a sealed FFR as described previously.[11] The aerosol from the downstream side of the FFR was passed through an outlet tube into the bottom chamber of 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 UCPCs then recorded the average concentration over a 2-min period. Penetration values were 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 generated particles by the TSI 8130 is several orders of magnitude above the upper limit of the UCPC. To bring the concentration down to usable levels, two dilution stages were used 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. The particle size distribution, however, was not significantly affected by the dilution stages.

Particle Number-Based Method for Ambient Room Aerosols

Figure 2 shows the schematic of the room air particle penetration test system. Briefly, laboratory room aerosols 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.[11] Room aerosol size distribution was analyzed by an SMPS system as described previously.[37] A typical size distribution curve showed a CMD of 65 ± 25 nm. No attempt was made to stabilize the room aerosol size distribution. Room aerosols were passed directly into the test box, and upstream and downstream particles were counted by an ultrafine condensation particle counter (UCPC, TSI 3776) 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 values were calculated as a ratio of the number of particles downstream to the number of particles upstream. Four samples from each FFR model were tested for room air particle penetration.

Monodisperse NaCl Aerosol Penetration Test

A different set of four FFR samples from each respirator model were tested against 10 different size monodisperse NaCl particles in the 20–400 nm range, using a TSI 3160 fractional efficiency tester, which employs two condensation particle counters (CPCs) to measure particle concentrations upstream and downstream of the filter and calculates penetration values. Penetration levels for FFR samples with charge neutralized NaCl aerosols were measured at 85 L/min flow rate as described previously.[11] The penetration level for each FFR model for the MPPS was obtained from the penetration levels for different size monodisperse particles.

Data Analysis

The data were analyzed using the SigmaPlot (version 11.2; Systat Software, Inc.; San Jose, Calif.) computer program. Average penetration values and 95% confidence intervals were calculated for each model. For each respirator model,

TABLE II. Test Aerosols Employed to Measure Filter Penetration

Test Aerosol	CMD (nm)	GSD	Percentage of Nanoparticles (<100nm)
TSI 8130 test aerosols for NIOSH respirator certification			
NaCl	75 ± 20	1.86	~68[A]
DOP	185 ± 20	1.6	~10[A]
TSI 8130 test aerosols employed in the study			
NaCl	59 ± 18	1.82	~79
DOP	190 ± 18	1.46	~5.4
Ambient room aerosols	65 ± 25	2.04	~80

[A]Data from R.M. Eninger, R.M., T. Honda, T. Reponen, R. McKay, and S.A. Grinshpun. What does respirator certification tell us about filtration of ultrafine particles? *J. Occup. Environ. Hyg. 5*:286–296 (2008).

percentage penetration values measured using TSI 8130 aerosols by photometric method were compared with number-based penetration values obtained using TSI 8130 aerosols, ambient room aerosols, or monodisperse NaCl aerosols by one-way analysis of variance (ANOVA).

RESULTS

Test Aerosol Size Classification

Table II shows the size distribution of TSI 8130 NaCl, DOP, and ambient room aerosols employed in the experiments. TSI 8130 generated nanoparticles comprise ~79% of the total number of NaCl and ~5% of the total DOP aerosols by number that are close to their theoretically calculated values.[31] Similar to the TSI 8130 NaCl aerosols, ambient aerosols also showed ~80% of particles in the <100 nm size range. The size range of NaCl aerosol used in the tests is within the required size distribution for NIOSH certification of N-series particulate respirators.

Comparison of Photometric vs. Particle Number-Based Methods for NIOSH Test Aerosols and Ambient Room Aerosols

Figure 3 shows photometric and number-based penetration for N99 and N100 FFR models using TSI 8130-generated NaCl aerosols, and number-based penetration for ambient aerosols. Penetration values for N, R, and P series FFR models are shown in Table III. For the three N99 FFR models, NaCl aerosol penetration measured by number-based method (0.67–2.07%) was significantly ($p<0.05$) higher than the values obtained by the photometric method (0.16–0.39%). The one N100 FFR model tested in the study showed a penetration value of 0.04% by the number-based method and 0.003% by the photometric method, which was not statistically significant. For ambient room aerosols, number-based penetration (0.92–2.28%) for the three N99 FFRs measured were significantly ($p<0.05$) higher than the photometric values for NaCl aerosols. N100 FFR model also showed significantly ($p<0.05$) higher penetration based on particle number (0.017%). Table III also shows significantly ($p<0.05$) higher number-based penetration for all five N95 models than the values obtained by the photometric method.[37] As reported previously, penetration for ambient room aerosols, for all five N95 model FFRs showed significantly ($p < 0.05$) higher number-based values than those obtained by the photometric method.[37]

Figure 4 shows photometric and number-based penetration for R95, P95, and P100 FFR models with TSI 8130-generated DOP aerosols, and number-based penetration for ambient aerosols. Number-based DOP aerosol penetration (0.16–3.67%) for the R95 models was higher than the photometric values (0.05–2.8%) (Figure 4). For room aerosols, number-based penetration for the three R95 FFR models was between 0.74–1.18% and was significantly ($p<0.05$) higher for two of the three models than the photometric penetration values.

For the two P95 models, the DOP aerosol penetration values measured by particle number and photometric methods were between 0.03–0.25% and 0.01–0.03, respectively. Particle number-based penetration values were significantly ($p<0.05$) higher for one P95 model (P95-A) (Table III, Figure 4). Ambient room aerosol penetration values for both P95 FFRs were between 0.20–1.02% for room aerosols and were significantly ($p<0.05$) higher than the photometric penetration values. In the case of P100 FFR models, DOP aerosol penetration measured by particle number and photometric methods was between 0.002–0.006% and 0.005–0.016%, respectively. Significantly ($p<0.05$) higher penetration by number-based method was obtained for one P100 model (P100-B). Penetration for the three P100 models obtained with either DOP or ambient room aerosols by the number-based method was not significantly different from the photometric method.

Particle number-based penetration measured using the TSI 8130 aerosols (NaCl or DOP for the respective series respirators) and ambient aerosols for N-, R-, and P-series FFR models tested were correlated (Figure 5). Results obtained for five N95 model FFRs previously[37] were also included in the analysis. A good correlation ($r = 0.92$) for the penetration values was obtained for the 16 FFR models for number-based method for the two different aerosols (Figure 5). The correlation coefficient decreased to 0.82 when the data for model R95-C were included in the analysis (Figure 5).

Comparison of Photometric Penetration for the FFRs with Count-Based Penetration for MPPS

Penetration for different FFR models by photometric method using appropriate test aerosols (NaCl and DOP) with the TSI 8130 are shown in Table III. Number-based penetration for the same FFR models for monodisperse NaCl aerosols in the 20–400 nm range was measured using a TSI 3160. The MPPS was in the 40–50 nm size range for 11 FFR models in this

TABLE III. Summary of Initial Penetration Levels

Filtering Facepiece Respirator	Initial Penetration (%)			
	Photometric Method	Number-Based Method		
		TSI 8130 Aerosols	Ambient Aerosols	Monodisperse NaCl Aerosols
	TSI 8130	UCPC (NaCl or DOP)	UCPC	CPC
N95				
N95-A	0.45 ± 0.03	0.63 ± 0.12[A]	1.33 ± 0.12[A]	4.18 ± 0.72[A]
N95-B	0.86 ± 0.15	4.34 ± 1.70[A]	3.96 ± 0.22[A]	5.01 ± 1.10[A]
N95-C	0.78 ± 0.11	2.10 ± 1.16[A]	2.61 ± 0.05[A]	5.23 ± 1.18[A]
N95-D	0.18 ± 0.04	1.03 ± 0.04[A]	1.23 ± 0.31[A]	1.40 ± 0.26[A]
N95-E	0.17 ± 0.06	1.07 ± 0.08[A]	1.47 ± 0.15[A]	2.33 ± 0.63[A]
N99				
N99-A	0.16 ± 0.10	0.67 ± 0.03[A]	0.92 ± 0.30[A]	0.94 ± 0.05[A]
N99-B	0.39 ± 0.27	2.07 ± 0.76[A]	1.26 ± 0.26[A]	2.37 ± 0.54[A]
N99-C	0.19 ± 0.06	2.03 ± 0.35[A]	2.28 ± 0.11[A]	2.56 ± 0.59[A]
N100				
N100-A	0.0030 ± 0.0030	0.0415 ± 0.0405	0.0170 ± 0.0044	0.0153 ± 0.0103
R95				
R95-A	0.05 ± 0.04	0.34 ± 0.13[A]	0.74 ± 0.14[A]	0.60 ± 0.05[A]
R95-B	0.09 ± 0.10	0.16 ± 0.17	0.80 ± 0.28[A]	0.06 ± 0.02
R95-C	2.83 ± 0.49	3.67 ± 0.61	1.18 ± 0.28	3.90 ± 0.65
P95				
P95-A	0.03 ± 0.01	0.25 ± 0.12[A]	1.02 ± 0.12[A]	0.442 ± 0.059[A]
P95-B	0.01 ± 0.00	0.04 ± 0.02	0.20 ± 0.05[A]	0.011 ± 0.001
P100				
P100-A	0.0017 ± 0.0021	0.0056 ± 0.0056	0.0009 ± 0.0003	0.0047 ± 0.0002
P100-B	0.0057 ± 0.0015	0.0156 ± 0.0024[A]	0.0047 ± 0.0011	0.0098 ± 0.0005
P100-C	0.0053 ± 0.0012	0.0052 ± 0.0029	0.0012 ± 0.0002	0.0052 ± 0.0003

[A]Significantly ($p<0.05$) higher than TSI 8130 photometric penetration value.

study and 5 N95 FFR models from a previous study.[11] This MPPS was similar to a N95 FFR and a standard electrostatic filter media (Figures 6A,B). One FFR model (R95-C) showed a MPPS in the ~200 nm size range similar to a standard mechanical filter media (Figures 6C,D). Number-based penetration values for the MPPS obtained for five N95 models ranged from 1.4–5.2% [11] and were significantly ($p<0.05$) higher than the penetration obtained by the photometric method (Table III). Number-based penetration for all three N99 FFR models at the MPPS ranged from 0.94–2.60%, significantly ($p<0.05$) higher than the photometric penetration values (Table III). Penetration values for the MPPS by the count-based method for one of the three R95 (R95-A) were also significantly ($p<0.05$) higher than the values obtained by the photometric method. Number-based MPPS penetration values were significantly ($p<0.05$) higher than the photometric values for one P95 model (P95-A) tested in the study (Table III).

DISCUSSION

As expected, the data from this study showed that the percentage penetration obtained for many electrostatic FFR models with the number-based method was significantly ($p<0.05$) higher than the penetration obtained by photometric method for the same test aerosols employed for NIOSH particulate respirator certification. Similarly, number-based penetration for several FFR models for ambient room air particles was significantly ($p<0.05$) higher than the penetration measured by the photometric method. Count-based penetration for the MPPS was also higher than the photometric

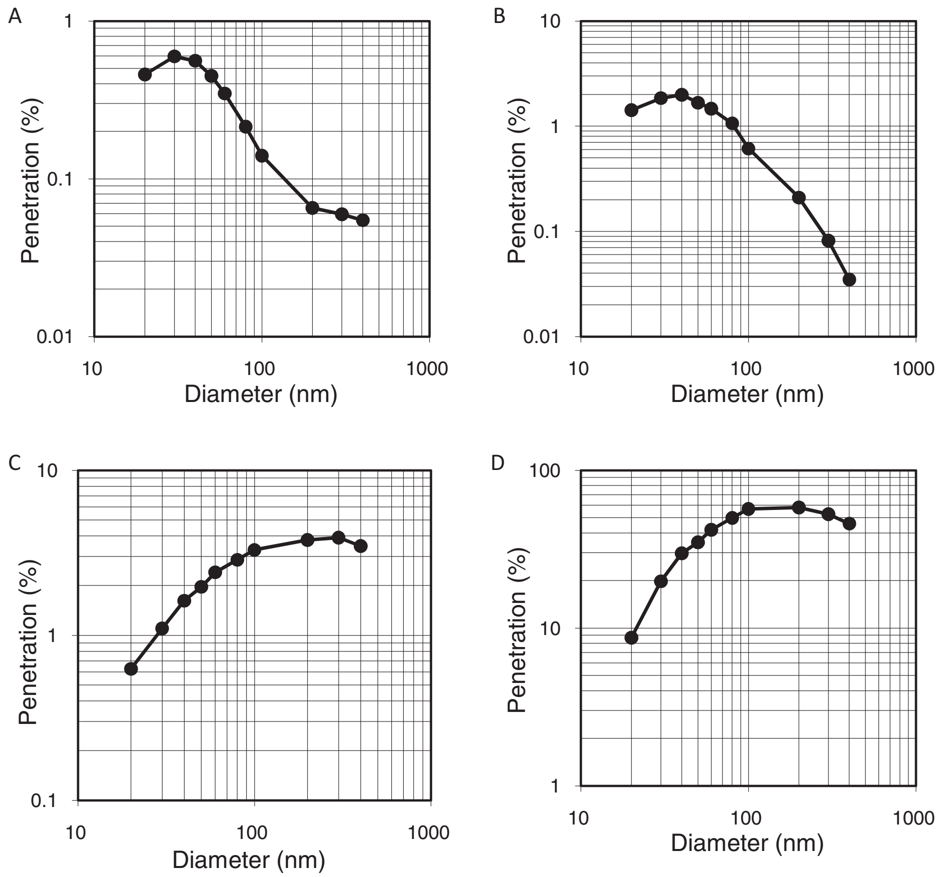

FIGURE 6. Typical filter penetration for a N95 FFR (A), an electret N95 filter media (B), a R95-C FFR (C), and a mechanical filter media HF-0031 (D) tested for different size monodisperse NaCl aerosols using a TSI 3160.

penetration value. Overall, the data suggest that the penetration values obtained by a number-based method may be larger than the values obtained by the mass-based photometric method employed for NIOSH certification of particulate air-purifying respirators.

The higher penetration levels for FFRs obtained by the count-based method over the photometric method can be explained by the difference in the test methodologies employed in the two methods. The count-based method gives equal importance to each particle in the test aerosol.[30] Unlike the count-based method, the photometric method is based on light scattering. The photometer light scatter signal is not linear to the entire size range of particles used in the tests. For example, the photometer response has been shown to decrease dramatically with decreasing particle size.[30] In that study, the light scatter signal for particles <100 nm size decreased drastically and was difficult to measure. The major reason for the difference in the penetration levels obtained by the two methods is due to the detector response as a function of particle size. The poor performance of the photometric method to measure nanoparticles is corroborated for NaCl aerosols employed in the TSI 8130 contributing negligible light scatter signal for particles <100 nm size that are ~68% of the total particles by number.[31]

The presence of a large portion of nanoparticles in the TSI 8130 NaCl aerosol agrees with our results showing ~79% of particles by number in the <100 nm size range (Table II). The photometric light scatter signal is disproportionately higher for larger size particles in spite of their fewer numbers.[31] For example, the TSI 8130 NaCl aerosols >200 nm sizes make up only ~5% of the total number of test particles but account for ~90% of the total light scatter signal. Thus, for nanoparticles, penetration measured by counting will be higher than penetration measured by mass (i.e., using a photometer).

Among the three series of NIOSH-approved respirators, all N-series models are known to contain electrostatic filter media with a MPPS in the ~50 nm size range. In these experiments, all N-series respirators tested with NaCl aerosols (CMD ~59 nm), as well as with ambient room air particles (CMD ~65 nm), showed higher penetration values by the number-based test methods, indicating that the filter penetration measured were mostly due to nanoparticles. Moreover, the photometer is less sensitive to measure nanoparticles than larger size particles. As reported previously,[37] this suggests that a number-based test method is likely to be a more challenging test for N-series respirators with a MPPS in the ~50 nm range.

In the case of R- and P-series FFRs, TSI 8130-generated DOP aerosols were used for measuring penetration levels by photometric and number-based methods. Seven out of eight R- and P-series FFR models were found to be electrostatic respirators. Six of the seven electrostatic respirator models showed higher penetration with the count-based method than the values obtained by the photometric method (Figure 4). Penetration results obtained for electrostatic R- and P-series FFRs (∼50 nm MPPS) raised a question on how the number-based method showed higher penetration for DOP aerosols with CMD in the ∼190 nm range. It appears that the ∼5% portion of the test aerosols in the <100 nm range (Table II) was sufficient to produce higher penetration values by the number-based test method (Table III). Number-based penetration obtained for ambient room aerosols was also higher for four of the seven electrostatic FFR models. Taken together, the higher number-based penetration values obtained for NaCl, DOP, and ambient room aerosols for the electrostatic N-, R-, and P-series FFR models indicate that a particle size distribution of the test aerosol near 50 nm (MPPS) is critical for obtaining the most challenging set of conditions for respirator filter testing.

Number-based penetration measured for ambient aerosols and TSI 8130 aerosols showed a good correlation coefficient (r = 0.92) for the 16 electrostatic respirator models. The correlation coefficient value decreased to 0.82 by including the data for the mechanical respirator model R95-C. This can be explained by the differences in the MPPS for electrostatic and mechanical respirators and the size distribution of the test aerosols. Monodisperse aerosol penetration showed that the MPPS was at 50 nm range for 16 electrostatic type respirator models, while the one mechanical respirator model (R95-C) was at ∼200 nm size ranges. As expected, particle number-based penetration values for R95-C model FFRs was higher for DOP aerosols with a CMD of 185 nm (size distribution 73–464 nm) than for ambient aerosols with a CMD of 65 nm (22–359 nm). The data suggest that filter media charge status as well as test aerosol size distribution are important factors to be considered in measuring more challenging filter penetration.

The good correlation obtained for particle number-based penetration with the TSI 8130 aerosols and ambient aerosols suggests that ambient aerosols could also be employed for testing respirator filters. A previous study used ambient and DOP aerosols to evaluate the penetration levels for different size particles at a flow rate of 30.3 L/min using a particle counter.[18] Penetration results for ambient and DOP aerosols were similar for Whatman GF/A and Oshitari SO filters in that study.

In another study, ambient aerosols were employed for testing high efficiency air filters.[49] A LASX particle counter (Particle Measuring Systems, Boulder, Colo.) was utilized for the measurement of ambient aerosol penetration in the 135–550 nm size range. Results from that study showed consistent penetration values for the high efficiency filters between tests indicating that ambient aerosols can be used for testing filter efficiency instead of DOP aerosols.[49] Because filter penetration is dependent on the size distribution of the test aerosols, the use of ambient aerosol particles for filter penetration tests can produce undesirable results if not controlled properly. Ambient aerosol size distribution is likely to vary at different times of a day and among seasons and influence penetration levels for test filters.

Limitations of the study are that only a few models for six of the nine classes of respirators were tested for filter penetration, and only one mechanical respirator model was included. Further research with additional models for all classes of respirators available is needed. The UCPCs employed in the study showed higher penetration values by the number-based method than by the photometric method. A wide variation in the counting efficiency of CPCs available in the market is likely to produce variable filter penetration values. Poor-performing CPC models may show penetration levels closer to the photometric values. In this study, electrostatic R- and P-series FFR models were tested with DOP aerosols with a CMD of ∼190 nm to measure filter penetration. To provide the most stringent set of conditions for respirator filter testing of respirators containing electrostatic filter media, the aerosol challenge should contain a sufficient number of particles in the <100 nm size range. Filter penetration test methods for nanoparticles should also consider factors including filter media charge (e.g., electrostatic vs. mechanical), particle charge, aerosol size distribution, resistance to oil degradation, and face velocity. Other aspects of respirator filter testing such as aerosol loading need to be explored as well.

CONCLUSIONS

As expected, initial penetration levels for 17 models of NIOSH-approved N-, R-, and P-series FFRs using the TSI 8130 photometric method were less than the penetration obtained using a number-based method for the same challenge aerosols. Similarly, penetration values obtained with the TSI 8130 were less than the number-based penetration obtained for ambient aerosols. The smaller penetration values obtained by the photometric method can partly be attributed to the limitation of the photometer to measure nanoparticles (<100 nm size) that have no significant mass. Monodisperse aerosol penetration measurements showed that the MPPS was ∼50 nm for 16 electrostatic respirator models and ∼200 nm for one mechanical respirator. Many electrostatic respirator models also showed lower penetration values by the photometric method than by the number-based method using monodisperse aerosols. The results in this study suggest that to provide a more challenging respirator filter test method than what is currently used for respirators containing electrostatic media, the test method should utilize a sufficient number of particles <100 nm and a count (particle number)-based detector.

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