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Respiratory Protection against Nanoparticle Exposure in Workplaces

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21.1 Introduction

Nanoparticles are produced by natural sources and industrial processes (Biswas and Wu, 2005). A nanoparticle is defined as a nano-material with all three external dimensions ranging in size from approximately 1–100 nm (ISO/TS, 2009). Engineered nanoparticles with unique physical and chemical properties have been utilized for numerous applications. The rapid growth of nanotechnology has increased the production of engineered nanoparticles in industrial workplaces. High concentrations of nanoparticles have been reported in some workplaces (Elihn and Liden, 2011; Gomez et al., 2013; Guerreiro et al., 2014; Johnson et al., 2010; Methner et al., 2010, 2012). Inhalation is the most common route of nanoparticle exposure and is a potential risk during various processes including cleaning engineered nanomaterials from dust collection systems, spills, and disposal. Nanoparticles have been implicated in human health and environmental effects (Cena et al., 2015; O'Shaughnessy, 2013; Sarkar et al., 2014) suggesting that respiratory protection is needed when engineering and administrative controls are not sufficient or feasible.

The Occupational Safety and Health Administration (OSHA) respiratory protection standard requires that National Institute for Occupational Safety and Health (NIOSH) approved respirators be used for protection in industrial workplaces (Federal Register, 1998). For respirators to provide the expected level of protection, employers must implement a complete respiratory protection program including the selection of appropriate respirators for exposed workers. The protection provided by a respirator is estimated based on the OSHA definition of the assigned protection factor (APF) (OSHA, 2006). The APF is the workplace level of respiratory protection that a respirator or class of respirators is expected to provide to employees when the employer implements a continuing, effective respiratory protection program (Federal Register, 1998). The APF accounts for all expected sources of penetration including filter media, face seal, and exhalation valves. To achieve a desired APF value, respirator selection is recommended by the criteria described in the "NIOSH Respirator Selection Logic," which was developed based on toxicological, safety, and other relevant information (NIOSH, 2004).

Workplace protection factor, (WPF) similar to APF, is described as the protection provided in a real workplace, under the conditions of that workplace, by a properly selected, fit tested, and functioning respirator while or when it is correctly worn and used (American Industrial Hygiene Association Respiratory Protection Committee, 2002). The estimates of WPFs for different types of respirators in a variety of workplaces have been described (Bidwell and Janssen, 2004; Cho et al., 2010; Janssen and McCullough, 2010; Zhuang et al., 2003).

Because of the difficulties in measuring WPF for subjects wearing respirators in actual workplaces, a simulated workplace protection factor (SWPF) is measured in a laboratory setting using test exercises simulating normal workplace activities. Several studies have reported the SWPF for N95 filtering facepiece respirators (FFRs) (Coffey et al., 2004; Hauge et al., 2012; Lawrence et al., 2006; Lee et al., 2008). In one study, the SWPF for 18 N95 FFRs was obtained using five different fit testing methods (Coffey et al., 2004). The fifth percentile SWPF values ranged from 1.3 to 48 for the different models. This study also showed that passing the fit test generally resulted in an increase in SWPF. Another study employed a PortaCount® Plus (TSI, Inc. St. Paul, MN) to measure the SWPFs for 15 models of N95 elastomeric half-facepiece respirators (EHRs), 15 models of N95 FFRs, and 6 models of surgical masks (Lawrence et al., 2006). For EHRs and FFRs, the geometric mean (GM) of SWPF values were 35.5 and 20.5, with fifth percentile values of 7.3 and 3.3, respectively. Some studies (Lee et al., 2008; Reponen et al., 2011) have described a protection factor (PF) similar to SWPF except that the test exercises are not believed to represent real workplace activities. There is no prescribed set of exercises for measuring either PF or SWPF.

Respiratory protection against nanoparticles has been reviewed (Shaffer and Rengasamy, 2009). A limited number of studies have reported the SWPF for nanoparticles (Hauge et al., 2012; Lee et al., 2008; Rengasamy et al., 2014; Vo et al., 2015). Lee et al. (2008) have measured the PF values for nanoparticles as well as larger size particles in a controlled environmental chamber supplemented with NaCl aerosol. Twelve subjects tested four N95 FFR models, and the outside and inside aerosol concentrations were measured using an electrical low-pressure impactor (ELPI), while performing OSHA fit testing exercises. The ELPI measures the particle concentration of different aerodynamic diameter size particles. The results showed that PF values were lower for ~78–130 nm size range particles than for the other size particles and increased with increasing particle sizes up to 1260 nm (Lee et al., 2008). The smaller PFs for nanoparticle sizes in the study indicated lower WPF values in a nanoparticle work environment. Another study described SWPF measurement using a PortaCount® (TSI, Inc.) with a N95 Companion, which measures particles of 30–60 nm sizes (Hauge et al., 2012). The GM SWPF values ranged from 172 to 1073 for all exercises and test subjects.

Recent publications from our laboratory described the protection performance of FFRs and EHRs for nanoparticles at simulated workplace conditions (Rengasamy et al., 2014; Vo et al., 2015). Because of the similarities in measuring respirator performance with these two studies, the PF measured in Study 1 (Rengasamy et al., 2014) is described as a SWPF throughout this chapter. The test protocols in the two studies were different with respect to aerosol characteristics, aerosol exposure, and test equipment. Study 1 (Rengasamy et al., 2014) measured the SWPF values for N95 FFRs worn by test subjects in two different test laboratories with different concentrations of nanoparticles. In Study 2 (Vo et al., 2015), subjects were tested in an environmental chamber supplied with NaCl aerosol continuously. The SWPF values for different size particles in the 10–400 nm range were measured. The results obtained in the two studies are described.

21.2 Methods

The SWPFs for FFRs and EHRs were measured at two different simulated workplace conditions. In Study 1, subjects were exposed to laboratory aerosol supplemented with NaCl aerosol when necessary, in two different laboratories (6 m × 6 m × 2.5 m) (Laboratory 1 and Laboratory 2) for SWPF measurement. Study 2 tested the subjects in an aerosol chamber (2.5 m × 2.5 m × 1.5 m) supplied with polydispersed NaCl aerosol continuously, in a different laboratory. The three laboratories are located in different or separate buildings at the NIOSH facility in Pittsburgh, PA, USA. Further details of the studies are described below.

21.2.1 Study 1

21.2.1.1 Respirators

Five N95 FFR models (Table 21.1) were tested in the study, which included 3M (Model 8000), 3M (9210), Kimberly-Clark (Model 170/174), Sperian-Willson (Model SAF-T-FIT, 10FL), and 3M (8511). The respirators were labeled as A, B, C, D, and E, respectively. Only one model (3M 8511) had an exhalation valve. These models were chosen based on previous use in our laboratory.

21.2.1.2 Subjects

Thirty-five test subjects tested five N95 FFR models in Laboratory 1 and Laboratory 2 as described previously (Rengasamy et al., 2013, 2014). The subjects were not fit tested before SWPF measurement. The facial dimensions of the test subjects were measured and the NIOSH bivariate panel (Zhuang et al., 2008) was used for placement of subjects in specific face length and face width cells. The participants in the study were experienced respirator users, who had previously participated in fit test studies. This study was approved by the NIOSH Institutional Review Board and all subjects gave written consent to participate.

TABLE 21.1

GM, GSD, and Fifth Percentile Values of SWPF for the Five N95 FFR Models Tested in the Two Laboratories

		SWPF			
		Laboratory 1		Laboratory 2	
N95 Model	**Total Number of Tests**	**GM ± GSD**	**Fifth Percentile**	**GM ± GSD**	**Fifth Percentile**
A	105	29.1 ± 1.9	9.9	32.3 ± 2.1	9.8
B*	105	115.1 ± 2.4	28.0	156.4 ± 2.5**	33.7
C	105	44.1 ± 1.8	16.8	43.3 ± 1.6	20.4
D	105	39.1 ± 1.4	21.7	36.4 ± 1.5	18.3
E*	105	92.1 ± 2.1	27.8	111.2 ± 2.2**	30.9

* Significantly different from other models.

** Significantly different from Laboratory 1 for this model.

21.2.1.3 Laboratory (Ambient) Aerosol Measurement

A Scanning Mobility Particle Sizer™ (SMPS, TSI, Inc.) with a long differential mobility analyzer (Model 3081) was used to measure the size distribution of particles in the 10–700 nm size range in both laboratories. The SMPS was programmed to scan the particle size distribution for 135 seconds, three times, every hour from 8:00 a.m. to 4:00 p.m. Monday through Friday (laboratory testing times). From the SMPS scans, the average count median diameter (CMD) of the laboratory aerosol for each day was obtained.

Laboratory 1 and Laboratory 2 were located in different buildings separated by ~100 meters. Other laboratories in the buildings were doing experiments not related to the work and particles generated by processes in those laboratories could have contributed to the particle size distributions in the two SWPF test laboratories. A minimum particle concentration of 1000 particles/cm^3 in the test laboratories was used during testing. When needed, a 2% NaCl solution was aerosolized using a particle generator (TSI Model 8026) to supplement particle concentration levels in the laboratories.

21.2.1.4 Subject Testing

SWPF was measured using a PortaCount® Pro+ (Model 8038, TSI, Inc.) with PortaCount mode turned on (N95 mode turned off) by measuring the in-mask particle concentration and ambient concentration during subject testing in each laboratory. The SWPF was defined as a quantitative measurement of the ratio of the particle concentrations in the ambient air (C_{out}) to the in-mask (C_{in}) of the respirator. A "FitPro™ Fit Test software" (TSI) was used to provide a fully automated data processing, recording, and storage during the testing. All SWPF data, including test subject and respirator identifiers were downloaded into a pre-established database and were accessed after the test for analysis. The test data were also recorded manually for immediate review by project personnel.

The test operators were experienced in fit testing subjects. Different test operators administered the SWPF measurement in each of the two laboratories. This study was double-blind in that the test operators in each laboratory did not know the results obtained by the other laboratory. Subjects were trained using the manufacturers' user instructions on the proper donning and user seal check procedures. Prior to SWPF testing, the subjects wore each FFR for a 5 minute period for acclimatization of the respirator on the face. The subjects subsequently connected the PortaCount sample line to the connector on the respirator, donned the FFR, and made any necessary adjustments to the FFR until they felt they had achieved a good fit and could subsequently pass the user seal check without detecting a face seal leak. The test administrators verified that the FFR was being properly donned by the test subject and provided the necessary training to assure conformance to the user instructions. When ready, the subjects gave the test administrator a signal that she or he was ready to start the test. The drag/weight of the sample tubing and its potential effect on the FFR fit were minimized by the test subject holding the sample line with one hand away from the front of their chest. For SWPF measurement, the eight exercises prescribed in the standard OSHA fit test protocol (OSHA, 1998) were used. The exercises were performed in the following order: (1) normal breathing, (2) deep breathing, (3) turn head side to side (4) move head up and down, (5) speak out loud (recitation of the "rainbow" passage), (6) reach for floor and ceiling (7) grimace, and (8) normal breathing. When testing was completed, the subject removed the FFR, redonned the same FFR, and tested two more times consecutively with a 5 minute break between the tests.

21.2.1.5 SWPF Measurement

Subjects were tested in a random order in Laboratory 1 or Laboratory 2 and completed the test in the other laboratory on the same day. A new sample of each respirator model was tested by the subject in each laboratory following the identical donning procedure.

The PortaCount calculated the SWPF for each individual exercise ($\mathrm{SWPF_i}$),

$$\mathrm{SWPF_i} = \frac{\text{Ambient concentration}}{\text{In-mask concentration}}$$

and then obtained the harmonic mean for seven exercises except the grimace as shown below with "n" representing the number of exercises.

$$\mathrm{SWPF} = \mathrm{n}\left(\sum_{\mathrm{i}=1}^{\mathrm{n}} \frac{1}{\mathrm{SWPF_i}}\right)^{-1}$$

Thirty-five subjects tested each FFR model three times (35 subjects × three donnings × five FFR models) to give a total number of 525 SWPF tests in each laboratory. The performance of N95 FFRs was assessed using the fifth percentile SWPF values. The fifth percentile SWPF value was calculated using the formula GM/geometric standard deviation $(\mathrm{GSD})^{1.645}$. The unadjusted GM and GSD estimates do not account for "subject" effects. Statistical significance tests were based on a mixed effects analysis of variance (with "subject" as a random effect) using specific contrasts for hypothesis testing. R software was used for this analysis (R Core Team, 2013) with the "nlme" package (Pinheiro et al., 2013). The CMD values measured in the two laboratories were analyzed by a two-sided t-test (Shapiro–Wilk).

21.2.2 Study 2

21.2.2.1 Test Subjects and Respirators

Twenty-five subjects (13 females and 12 males) were tested for SWPF measurement under simulated workplace activities (Vo et al., 2015). The age of the panel members ranged from 19 years to 65 years. Placement of subjects in specific cells in the test panel, study approval, and subjects consent for participation are similar to those described in Study 1.

Eight NIOSH-approved respirator models, including two respirator types (FFRs and EHRs) and two classes of filters (N95 and P100) were selected for the test based on their common use in the workplace, and their commercial availability. The respirator models in each series (class of filter) were randomly assigned labels A or B.

21.2.2.2 Preparation of Test Aerosols and Test Equipment

For fit testing, a 2% NaCl solution was aerosolized with a particle generator (Model 8026, TSI, Shoreview, MN, USA) outside of the chamber in the laboratory room. A PortaCount® (Model 8038, TSI) was used for fit testing subjects. For SWPF measurement, an aerosol chamber testing system consisting of an aerosol generation setup, an exposure chamber system, and a particle detector setup was used. The aerosol generation setup included a six-jet atomizer (Model 9306, TSI), a Kr-85 aerosol neutralizer (Model 3054, TSI), and an ultrafine condensation particle counter (UCPC, model 3776, TSI). The exposure chamber system consisted of a chamber (Model 222-6, Dynatech, Albuquerque, NM, USA), a humidity/temperature sensor (Model RHXL3SD, Omega Engineering, Stamford, CT, USA), circulation fans located in each upper corner, and a 14-cm diameter exhaust port. The exposure chamber had sufficient space for a human subject wearing a respirator to perform an SWPF test consisting of several exercises comfortably. The particle detector component consisted of two scanning mobility particle sizers (SMPS, Model 3080 with CPC-3772, TSI), which measured the upstream (outside the respirator) and downstream (inside the respirator) concentrations simultaneously.

21.2.2.3 Fit Test Procedure

Subjects were fit tested using a PortaCount® under laboratory conditions (outside the exposure testing chamber). A particle generator (Model 8026) was used to keep room concentration levels between 3000 and 8000 particles/cm^3 for the fit test. When the laboratory particle concentrations reached the designated level, subjects trained by a test operator donned the FFR or EHR and connected the particle-sample lines to the PortaCount. To ensure the respirator was properly donned, the test operator was required to help test subjects don the respirator, adjust its head straps, reshape its metal nosepiece (if equipped), and perform the standard respirator user seal check. Subjects performed the OSHA standard fit test (OSHA, 1998) exercises as described in Study 1. A fit factor (FF) value $\geq$100 was considered a pass. After passing the fit test, the subject continued to wear the respirator and was escorted to the exposure chamber for the SWPF test.

21.2.2.4 SWPF Test Procedure

A 0.2% NaCl solution was aerosolized using a six-jet atomizer at a dispersion of 30 L/min. The output aerosol was dried with 30% dilution air in an atomizer self-contained dilution system, followed by neutralization with the Kr-85 charging source before entering into the exposure chamber. The aerosol in the chamber was mixed by four internal fans of the chamber. Throughout the experiment, the UCPC monitored the chamber concentration, and a humidity/temperature sensor monitored the relative humidity (RH) and temperature. During particle sampling, NaCl aerosol particles were continuously dispersed into the chamber, while the exhaust port was in the open position to remove excess air and maintain neutral pressure. When the NaCl aerosol concentration in the chamber stabilized at the exposure level of approximately 2×10^5 particles/cm^3, the subject donned with the respirator entered the exposure chamber for the SWPF test. The in-mask sample line was connected to the respirator once inside the chamber.

The SWPF test was performed using six exercises, 3 minutes each in the following order: (1) normal breathing, (2) deep breathing, (3) moving head side to side, (4) moving head up and down, (5) bending at the waist, and (6) a simulated laboratory-vessel cleaning motion. SMPS measured the particle concentrations outside and inside of respirator for 2 minutes during each exercise. The simulated laboratory-vessel cleaning motion involved the subject moving his or her arms forward-down and backward-up in a shovel-scooping-like fashion, with a distance of about 30 cm at a rate of approximately one completed motion every 5 seconds. Test data were recorded and SWPF for the six exercises was calculated as described in Study 1.

This procedure was repeated for all eight respirator models. Three replicate tests were conducted for each respirator model for each subject for a total of 600 tests. The SWPF data analysis was performed using an analysis of variance (ANOVA) model provided by the Statistical Analysis System version 9.3 (SAS Institute Inc., Cary, NC). The ANOVA was also used for analyzing statistical computations, including overall SWPF, GM SWPFs, and all pairwise SWPF comparisons. P-values of <0.05 were considered significant. The fifth percentile SWPF was computed from the formula GM/GSD$^{1.645}$.

21.3 Results

21.3.1 Study 1

Thirty-five subjects tested the five N95 model FFRs three times (35 subjects × five FFR models × three donnings) for a total number of 525 SWPF tests in each laboratory. Table 21.1 shows the GM of SWPFs and GSD for the five N95 model FFRs. The GM SWPF ranged from 29.1 to 115.1 in

Laboratory 1 and 32.3 to 156.4 in Laboratory 2. The GM SWPF values for models B and E were significantly ($p \leq 0.05$) larger than the other models in both laboratories. The GM SWPFs for both B and E in Laboratory 1 were significantly ($p \leq 0.05$) smaller than in Laboratory 2. The other three models showed only marginal differences in the GM SWPF values between the two laboratories. The fifth percentile SWPF value was calculated using the formula $GM/GSD^{1.645}$. For both laboratories, the fifth percentile SWPF values for all models were ≥ 10, except for model A. The models B and E showed larger fifth percentile values than the other models, in both laboratories. The fifth percentile SWPFs for respirator models B and E were slightly smaller in Laboratory 1 than in Laboratory 2.

Aerosol size distribution and the CMD were obtained for all test days (27 days in Laboratory 1 and 32 days in Laboratory 2). The mean CMDs were 82 ± 19 nm in Laboratory 1 and 131 ± 23 nm in Laboratory 2. The CMD value represents 50% of particles above and below that size. The CMD in Laboratory 1 was significantly ($p \leq 0.05$) lower than the CMD in Laboratory 2. The CMD values were <100 nm in Laboratory 1 on 93% of SWPF test days compared to 18% of test days in Laboratory 2. The lower CMD values measured in Laboratory 1 indicate the presence of a relatively higher concentration of nanoparticles in Laboratory 1 than in Laboratory 2. Table 21.1 shows the GM, GSD, and fifth percentile SWPF values for the five N95 model FFRs tested in the two laboratories.

21.3.2 Study 2

Based on the particle size range of interest for the respirator performance against nanoparticles, the size distribution range of 10–400 nm was measured. Within this size range, 96% of particles were centered between 28 and 350 nm with a mode of 82 nm, a CMD of 60 nm, and GSD of 2.88.

All subjects passed the fit test with all N95 and P100 EHR models (all FF values ≥ 100). For FFRs, while all subjects passed the fit test with two P100 FFR models, some subjects failed the fit test during the first trial with the two N95 FFR models. Therefore, a test operator helped these test subjects with donning the N95 FFRs and reshaping the metal nosepiece to ensure the subjects passed their fit test with the N95 FFRs before performing an SWPF test.

The respirator performance statistics for the different respirator filter classes (N95 and P100) for both EHR and FFR types as determined by the SWPF testing across the nanoparticle size range (10–100 nm) were determined and compared to the larger size range of 100–400 nm (Table 21.2). The results show that the GM SWPFs for nanoparticles were significantly larger than those of larger particles (100–400 nm) (all P-values <0.05), except N95 EHRs ($P = 0.06$). In general, the GM SWPFs in both ranges had a similar trend order with the highest for the P100 EHRs, followed by P100 FFRs, N95 EHRs, and N95 FFRs (Table 21.2). All P100 class respirators in both ranges provided significantly higher SWPF values compared to class N95 respirators

TABLE 21.2

GM-SWPF and Fifth Percentile Values: Nanoparticles versus Larger Particle Range

		Size Range: 10–100 nm		Size Range: 100–400 nm	
Respirator Type	**Class of Filter**	**GM_SWPF (± GSD)**	**Fifth percentile**	**GM_SWPF (± GSD)**	**Fifth percentile**
FFR	N95	112 ± 2.5	45	83 ± 3.0	14
	P100	6,595 ± 4.2	1,574	3,439 ± 4.5	292
EHRs	N95	196 ± 2.7	72	202 ± 1.9	68
	P100	11,800 ± 3.1	3,777	6,780 ± 2.9	1,199

(all P-values <0.05) for both EHR and FFR types (Table 21.2). The results also show that P100 and N95 EHRs exhibited better performance than P100 and N95 FFRs (all P-values <0.05), respectively.

The average SWPF value as a function of particle diameter for the four combinations of filter classes and respirator types (N95 FFRs, P100 FFRs, N95 EHRs, and P100 EHRs) was evaluated. The SWPFs decreased with increasing particle diameter from 10 to 400 nm size range for all respirator types. The SWPFs values were larger for different size particles for the P100 EHRs, followed by P100 FFRs, N95 EHRs, and N95 FFRs. All P100 class respirators provided significantly higher SWPF values compared to N95 class respirators (all P-values <0.05) for both FFR and EHR types.

21.4 Discussion

The data from Study 1 (Rengasamy et al., 2014) showed a relationship between SWPF and particle size distribution. Two N95 FFR models (B and E) showed that the GM SWPFs in Laboratory 1 were significantly ($p \leq 0.05$) smaller than the values in Laboratory 2, while the other three models showed only marginal or no effect. The particle size distribution showed that the average CMD value for each day was <100 nm in Laboratory 1 on 93% of test days compared to 18% in Laboratory 2. The mean CMD (for all SWPF test days) of 82 nm in Laboratory 1 was significantly ($p \leq 0.05$) smaller than 131 nm in Laboratory 2, indicating the presence of a relatively higher concentration of nanoparticles in Laboratory 1. The SWPF measurement with test subjects showed that the GM SWPFs and the fifth percentile values for models B and E increased with an increase in the CMD of ambient aerosols. The data obtained in the study show the impact of particle distribution on SWPF of N95 FFRs.

The results obtained in the study are corroborated by the findings reported in the literature (Holton and Willeke, 1987; Lee et al., 2008; Reponen et al., 2011). Particle size-dependent leakage was measured for particle sizes between 0.07

and 4.4 μm through a negative pressure half-mask respirator worn by a human subject (Holton and Willeke, 1987). From the data obtained in the study, the authors showed that the ratio of percentage leakage for exposure aerosols with CMDs of 0.28 and 2.2 μm could be as large as 5:1 (Holton and Willeke, 1987), indicating lower PFs for exposure aerosols with smaller CMD values. Recent studies investigated the particle size dependency of PFs using different technologies. In one study, the PF values were measured for four N95 model FFRs worn by human subjects for eight different particle size ranges between 40 and 1260 nm using an ELPI (Lee et al. 2008). The ELPI measurement is based on particle numbers of different aerodynamic diameter size particles. Their results showed that the PF values were lowest for 78–130 nm aerodynamic diameter particles and increased with increasing particle sizes up to 1260 nm. Similarly, the fifth percentile WPFs for 0.7–10 μm diameter particles showed an increase from 16 to 223 for N95 FFRs using an optical particle counter (OPC) (HHPC-6, Hach Company, Loveland, Co) (Cho et al. 2010). The SWPFs obtained with a PortaCount® Pro+ in Study 1, the PFs measured using the ELPI (Lee et al., 2008), and the WPFs obtained by the OPC method (Cho et al., 2010) consistently showed the particle size dependency of PF or WPF.

On the other hand, the data obtained in Study 2 showed decreasing SWPF values with increasing particle sizes from 10 to 400 nm range for all N95 and P100 class FFR models and EHR models (Vo et al. 2015). The SWPF values were relatively larger for 10–30 nm particles compared to ~50 nm size particles, which is consistent with the PF data from previous studies (Lee et al., 2008; Reponen et al., 2011). The reference studies (Lee et al., 2008; Reponen et al., 2011) showed higher PF values for smaller and larger than the most penetrating particles, which were attributed to the total inward leakage (TIL) for different size particles. On the other hand, the SWPF results of Study 2 showed a decreasing trend for particles in the 10–400 nm size range for all respirators. The authors explained that higher RH conditions inside the breathing area of respirators contribute to the growth of different size particles, which increases the concentration of larger size particles with a concomitant decrease in the concentration of smaller size particles. The results from the study showed lower SWPF for larger size particles than for smaller size particles, which contradict the current understanding of respiratory protection for different particle sizes, and the results described in the literature (Holton and Willeke, 1987; Lee et al., 2008; Rengasamy et al., 2014; Reponen et al., 2011).

The influence of RH on aerosol particle size for respirators has been reported (Mahdavi et al., 2014). The data from the study showed an increase of larger size particles with a decrease in smaller size particles at higher than 50% RH. The most penetrating particle size showed a shift of ~20 nm toward larger sizes at higher RH. The SWPF results obtained in Study 2 decreased with particle sizes from 10 to 400 nm size range and showed no particle size dependency for all types of respirators. This indicates that the growth of particles to larger sizes at higher RH may not explain the SWPF results obtained in the study.

Some studies on WPF showed no particle size dependency (Bidwell and Janssen, 2004; Janssen et al., 2007; Janssen and McCullough, 2010). This can be explained by a closer look at the particle size distribution in those workplaces. The workplaces above showed a particle size distribution of approximately ~5 μm mass median aerodynamic diameter (MMAD). In these studies, the distribution of relatively larger size range particles contributed to the TIL (inverse function of respiratory protection) measured for respirators. One study measured TIL for N95 FFRs worn by human subjects as well as a manikin head form (Grinshpun et al., 2009). Their results showed that both filter media penetration and face seal leakage were higher at ~100 nm (aerodynamic diameter) and decreased with increasing particle sizes. The results are supported by the decrease in the TIL measured with increasing particle sizes from 50 nm up to 800 nm size particles using a breathing manikin head form (Rengasamy and Eimer, 2012). The above results suggest that TIL values would be much smaller for particles in the larger size range (~3–10 μm). Smaller TIL or larger SWPF values are expected to show only a weak or no relationship between particle size and WPF described in some studies (Bidwell and Janssen, 2004; Janssen et al., 2007; Janssen and McCullough, 2010). Moreover, measuring the concentration of larger size particles inside the respirator has potential problems as reported in previous studies (Janssen and Bidwell, 2007; Janssen et al., 2007).

Despite the difference between Study 1 and Study 2 results, the two studies showed some similarities. Both studies showed the influence of filter efficiency of respirators on SWPF values. Study 1 showed relatively higher filter efficiency for one of four N95 FFR models tested for filtration performance (Rengasamy et al., 2013). The higher efficiency model was found to produce larger GM SWPF and fifth percentile values in the two test laboratories. The three less efficient models showed relatively lower GM SWPF and fifth percentile values (Rengasamy et al., 2014). Interestingly, the data from Study 2 also showed filter efficiency dependency of SWPF values. The relatively higher efficiency P100 FFR models tested in the study showed larger GM SWPF and fifth percentile values than the two lower efficiency N95 FFR models. Similarly, higher efficiency P100 filters of EHRs showed larger GM SWPF and fifth percentile values than the two N95 filters of EHRs. The larger SWPFs for higher efficiency respirators obtained in our studies can be explained by the smaller TIL obtained using test subjects (Frost et al., 2014; Rengasamy et al., 2013) and a manikin (Rengasamy and Eimer 2012).

21.5 Conclusions

Study 1 results showed that the SWPFs and fifth percentile SWPFs for two N95 FFR models were smaller in Laboratory 1 for aerosol with a mean CMD of 82 nm than in Laboratory 2 with a CMD of 131 nm showing a relationship between particle size distribution and SWPF values. The results indicate that smaller SWPFs and fifth percentile values can be expected for particle size distributions within the nanoparticle size range (<100 nm). Results from Study 2 showed that the SWPF and fifth percentile values decreased with increasing particle sizes from 10 to 400 nm for FFRs and EHRs. Filter efficiency appears to influence the SWPF and fifth percentile values. The SWPF results obtained in our studies indicate that NIOSH-approved respirators would provide expected levels of protection for nanoparticles. Further studies on the relationship between particle size distribution and SWPS, and particle size growth during human breathing conditions are needed to understand respiratory protection from nanoparticles.

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