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Effect of Particle Size on Respiratory Protection Provided by Two Types of N95 Respirators Used in Agricultural Settings

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This study compared size-selective workplace protection factors (WPFs) of an N95 elastomeric respirator (ER) and an N95 filtering facepiece respirator (FFR) in agricultural environments. Twenty-five healthy farm workers ranging in age from 20 to 30 years voluntarily participated in this study. Altogether, eight farms were included representing three different types: two horse farms, three pig barns, and three grain handling sites. Subjects wore the ER and FFR while performing their daily activities, such as spreading hay, feeding livestock, and shoveling. Aerosol concentrations in an optical particle size range of 0.7–10 μm were determined simultaneously inside and outside the respirator during the first and last 15 min of a 60-min experiment. For every subject, size-selective WPFs were calculated in 1-min intervals and averaged over 30 min. For the ER, geometric mean WPFs were 172, 321, 1013, 2097, and 2784 for particle diameters of 0.7–1.0, 1.0–2.0, 2.0–3.0, 3.0–5.0, and 5.0–10.0 μm, respectively. Corresponding values for the FFR were 67, 124, 312, 909, and 2089. The 5th percentiles for the ER and FFR were higher than the assigned protection factor of 10 and varied from 28 to 250 and from 16 to 223, respectively. Results show that the N95 ER and FFR tested in the study provided an expected level of protection for workers on agricultural farms against particles ranging from 0.7 to 10 μm. WPFs for the ER were higher than the FFR for all particle size ranges. WPFs for both respirator types increased with increasing particle size.

Keywords aerosol, agriculture, respirator, workplace protection factor

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INTRODUCTION

Agricultural workers are at risk for exposure to airborne hazards that can cause adverse respiratory effects. Several studies have shown that farmers growing different types of grain and soybeans[1,2] and farmers raising livestock[3] have respiratory symptoms and diseases. This may have considerable impact worldwide considering there are approximately 3 million farm workers in the United States alone.[4] It is difficult to protect farmers from airborne particles by engineering controls due to the diversity of particle generating sources and mobility of farmers.

Although Respiratory Protection Standard (29 CFR Part 1910.134) is not applicable to many agricultural environments,[5] respirators used by agricultural workers should be certified by the National Institute for Occupational Safety and Health (NIOSH) in accordance with 42 CFR Part 84.[6] The efficiency of respirators used in the workplace can be expressed as a workplace protection factor (WPF), defined as a ratio of the concentration of airborne contaminant (e.g., particles) outside the respirator to that inside the respirator, measured under the conditions of the workplace using a properly selected, fit tested, and functioning respirator while it is worn correctly.[7]

Several WPF studies have investigated the efficiency of elastomeric respirators (ERs) and filtering facepiece respirators (FFRs) against airborne particles.[8–12] However, some of the studies were conducted before the issuance of new certification regulations for respirator filters[6] that designate filters based on filter efficiency (95, 99, and 100%) and resistance to solid or liquid aerosols (N, R, and P). These studies reported that 5th percentiles of WPFs were in the range from below 10 to 56 and varied between respirator models. Furthermore, WPFs for ERs were not significantly different from those for FFRs.[12] It was also shown that log-transformed WPFs were negatively correlated with log-transformed inside mass concentrations, whereas there were no correlations between log-transformed WPFs and log-transformed outside mass concentrations.[9,11,12] In addition, some investigators reported that WPFs are not particle size-dependent.[8]

Although these studies provided information on the WPF, the tested occupational environments did not include agricultural settings. Furthermore, most of the previous studies did not aim at quantitatively characterizing the factors, which may cause variation in WPFs, e.g., particle size. In contrast, an earlier investigation by our research group addressed the effect of particle size on WPFs in agricultural environments and demonstrated that WPFs increase with increased size for a typical FFR with average fitting characteristics when challenged by particles of 0.7–10 μm in diameter.[10] The objectives of the current study were to compare the WPF of an N95 FFR with that of an N95 ER and to continue collecting size-selective WPF data in agricultural environments.

METHODS

Test Subjects, Sites, and Respirators

Twenty-five healthy farm workers ranging in age from 20 to 30 years voluntarily participated in this study. Among 25 subjects, one Hispanic male and six females were included to reflect the gender and racial makeup of farmers in Ohio and Kentucky (which are very close to the U.S. average). Altogether, eight farms were included representing three different types: two horse/livestock pavilions, three pig barns, and three grain handling sites. Activities on farms of these types were expected to generate high aerosol concentrations with a wide particle size range. The selected farms were typical of those in the south central region of the United States.

The respirators tested in the study were represented by an ER equipped with N95 filters and an N95 FFR. The ER was available in three sizes, whereas FFR was available in two sizes. The respirators used for this study were selected due to their high success rates in passing routine quantitative fit testing, as determined from our clinical experience (i.e., both respirators had good fitting characteristics).

Field Study Design

All subjects signed a consent form approved by the University of Cincinnati's Institutional Review Board and obtained medical clearance prior to field testing using an online questionnaire suggested by the U.S. Occupational Safety and Health Administration (OSHA).[13] All subjects were asked not to smoke for at least 1 hr prior to field testing, and male subjects were clean shaven. Study subjects were trained to wear both respirators according to manufacturer's instructions. All subjects passed user seal checks prior to fit testing. Fit testing was performed using a PortaCount Plus (TSI, Inc., Shoreview, Minn.) with an N95 companion. To minimize systematic errors in results, the type of respirator (ER or FFR) to be worn first was randomly assigned to the first subject each testing day. Respirator type was then alternated for all subsequent subjects.

Voluntary respirator use among this farming population was generally intermittent and varied considerably. Some farmers wore respirators only during activities that they perceived to be dusty operations. During preliminary studies, we observed that some study subjects did not tolerate respirator wear for more than 1 hr at moderate to strenuous work loads. Preliminary studies also confirmed that sufficient particle counts could be obtained for sample times of 30 min. Consequently, our subjects wore the ER and FFR while performing their daily activities, such as spreading hay, feeding livestock, and shoveling. Table I summarizes the activities at each site. Among 25 subjects, two subjects failed fit testing with the FFR (one on Horse Farm 2 and the other in Pig Barn 3). In addition, data were missing on one subject wearing the FFR in Pig Barn 1 due to an instrument malfunction. Thus, data for three subjects were excluded from the FFR dataset.

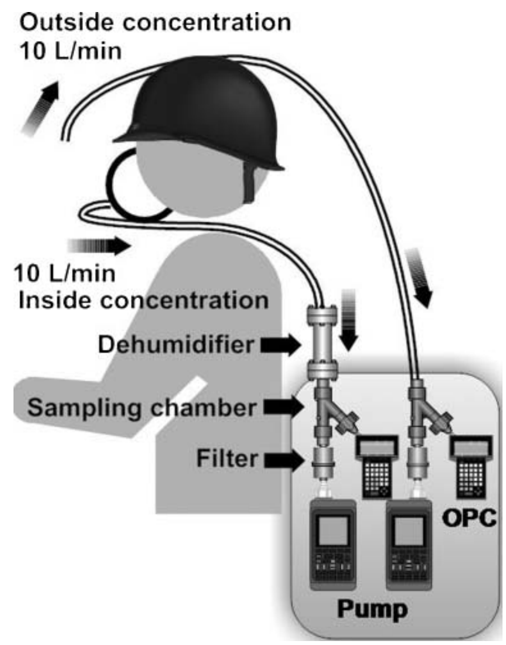

FIGURE 1. Schematic presentation of the personal sampling setup.

Particle Measurement

Aerosol particle concentrations inside and outside the respirator were measured with a personal sampling system described in an earlier WPF-study conducted in agricultural environments.[14] Briefly, as shown in Figure 1, the personal sampling system consists of two identical sampling lines each with a sampling probe, a sampling chamber, an optical particle counter (HHPC-6, Hach Company, Loveland, Colo.), and a pump (Leland Legacy, SKC Inc., Eighty Four, Pa.). The optical particle counter measures particle number concentration in five size channels: 0.7–1.0, 1.0–2.0, 2.0–3.0, 3.0–5.0, and 5.0–10.0 μm. The corresponding mean sizes of these channels are 0.85, 1.5, 2.5, 4, and 7.5 μm.

Using a DryCal DC-Lite calibrator (Bios International, Butler, N.J.), the pump was adjusted to maintain a total sampling flow of 10 L/min. Particle concentrations were measured simultaneously inside and outside the respirator during the first and last 15 min of a 60-min experiment. Sampling time was intentionally less than respirator wear time to avoid moisture

TABLE I. Summary of Field Testing Sites on Agricultural Farms

	Number of Subjects Tested			
Farm Types	Male	Female	Sampling Time	Activity
Grain Handling 1 (Grain bin)	3		August 2008	Shoveling, sweeping
Grain Handling 2 (Commodities/grain/feed dealer)	2		December 2008	Walking; unloading grain
Grain Handling 3 (Grain bin)	3		October 2009	Shoveling, sweeping
Horse Farm 1 (Horse/livestock pavilion)	1	3	January 2008	Sweeping, spreading hay
Horse Farm 2 (Horse/livestock pavilion)	4[A]		March 2009	Sweeping
Pig Barn 1 (Confinement swine farrowing/nursery barn)		3[B]	March 2008	Sweeping, feeding
Pig Barn 2 (Confinement swine finishing barn)	3		June 2008	Sweeping, scraping
Pig Barn 3 (Confinement swine barn)	3[A]		June 2009	Cleaning with air blowers

[A]One subject on this farm failed fit test with the FFR.
[B]Missing data for one subject with a filtering facepiece respirator due to an instrument malfunction.

condensation inside sample tubing. For every subject, size-selective WPFs were calculated in 1-min intervals and then averaged over the 30-min sampling time. WPFs were also calculated for "all" particle sizes after combining particle concentrations from each of the five particle size channels.

Statistical Analysis

Geometric means (GMs) and geometric standard deviations (GSDs) were used to describe the outside concentrations and WPFs. Log-transformation for each of the continuous variables was conducted to induce normality. To compare average WPFs during the first 15 min with those of the second 15 min, a t-test was used (SigmaPlot 11; Systat Software Inc., San Jose, Calif.). Pearson correlation coefficients were calculated to investigate how WPF was associated with concentrations measured inside and outside the respirator (SigmaPlot 11). To identify factors associated with outside concentration and WPF, univariate generalized estimating equations (GEE) were used (SAS 9.2; SAS Institute Inc., Cary, N.C.).[15]

Initially, the effects of farm type and particle size were evaluated for each of the two outcomes. For WPF, the effects of respirator type, outside concentration, and gender were also evaluated. Variables that were significant at the 5% level with univariate analysis were considered for multivariate GEE. Possible interaction effects were also assessed before finalizing the regression model. Variables that were significant at the 5% level were included in the final multivariate model. Bar and line graphs for outside concentrations and WPFs (GM and GSD) were used to depict important results.

RESULTS AND DISCUSSION

Normalized size-selective number concentrations of particles measured outside the respirator for three different farm types are presented in Figure 2. The multivariate analysis assessed the effects of farm type and particle size on the outside concentrations. Interaction was found between farm type and particle size, and the model was adjusted for this interaction. On average, horse farms had an 11-fold higher geometric mean outside concentration than grain handling sites ($p \leq 0.0001$). There was, however, no significant difference in the concentrations between grain handling and the pig barns ($p = 0.101$).

All particle size distributions measured in this study appear to be similar to those measured during grain harvesting and unloading by Lee et al.[16] In contrast to the current study, Lee et al. found that the contribution of large particles

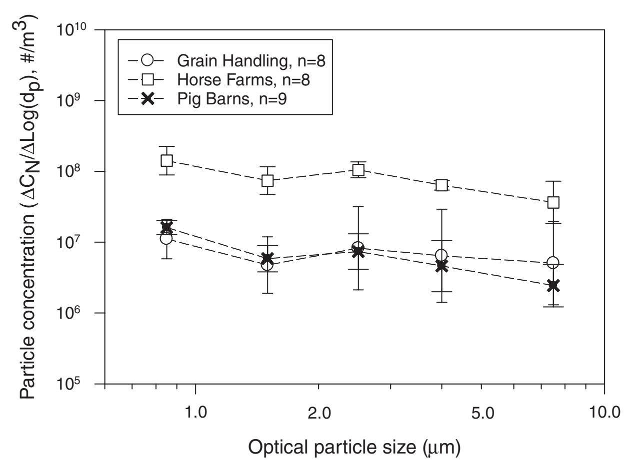

FIGURE 2. Normalized outside particle number concentrations at three different farm types. The symbols present geometric means, and error bars present geometric standard deviations.

(>2 μm) in these workplaces was greater than that measured in animal confinements. The difference may be attributed to the differences in human and animal activities taking place in these two studies. O'Shaughnessy et al.[17] measured dust exposures in swine confinements using personal photometers and showed that work tasks performed near moving animals resulted in the highest exposure.

The total number concentrations of particles (non-normalized) over the entire size range of 0.7–10.0 μm varied from 1.2×10^6 to 3.3×10^7 particles/m^3 at grain handling sites and in pig barns, and from 1×10^7 to 1.7×10^8 particles/m^3 on horse farms. Lee et al.[16] reported that corresponding concentrations ranged from 4.4×10^6 to 5.8×10^7 particles/m^3 at grain harvesting and from 1.7×10^6 to 2.9×10^7 particles/m^3 in animal confinements. Thus, the outside concentrations obtained in our study at grain handling sites and in pig barns were similar to those reported by Lee et al[16]; however, we measured higher concentrations on horse farms.

The average of WPFs during the first 15 min was compared with those from the last 15 min. Results showed no statistically significant difference between WPFs for the two periods (ER: $p = 0.76$, FFR: $p = 0.89$). Therefore, an average over the 30-min sampling time was used for further data analyses.

Figure 3 shows the WPFs provided by the two types of respirators as a function of particle size. For the ER, geometric means (GMs) were 172, 321, 1013, 2097, and 2784 for particle sizes of 0.7–1.0, 1.0–2.0, 2.0–3.0, 3.0–5.0, and 5.0–10.0 μm, respectively. Corresponding values for the FFR were 67, 124, 312, 909, and 2089. Size-selective WPFs for both respirators were higher than those reported for another model of FFR by Lee et al.[10] (21, 28, 51, 115, and 270, respectively).

While the reasons for differences in the WPFs are not known with certainty, we believe differences in fitting characteristics between respirators are a plausible explanation. Differences in filter efficiency may be another factor though less significant. WPFs for both respirators in the current study increased with increasing particle size, which is consistent with the results reported by Lee et al.[10] However, it disagrees with the hypothesis of Janssen and McCullough,[8] who measured the WPF of an ER with P100 filters and suggested that WPFs are not particle size-dependent. Investigators found relatively large particles on the in-facepiece samples and hypothesized that WPFs should not depend on the particle size because both large and small particles enter the respirators during temporary leakage. As indicated in Table II, the 5th percentile of the ER calculated over all particle sizes in our study was 63.8; for the study conducted by Janssen and McCullough the corresponding value was 51.5. Following this finding we concluded that these two types of respirators have similar performance when assessed non-size-selectively. However, the most distinguishable difference between the quoted and the present study is the basis for determining the WPF. While Janssen and McCullough calculated WPFs based on mass over all size ranges, WPFs in this study were based on simultaneous measurement of the number of particles within specific size ranges.

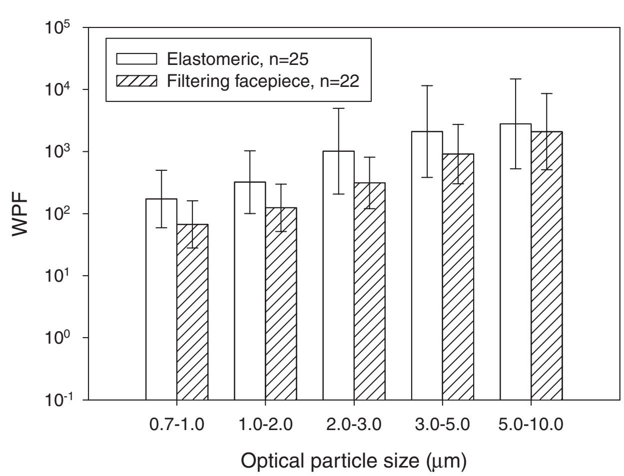

FIGURE 3. Workplace protection factor (WPF) provided by elastomeric respirator and filtering facepiece respirator for particles of different sizes (n = the number of subjects). The histograms present geometric means, and the error bars present geometric standard deviations.

TABLE II. Comparison of the 5th Percentiles of the WPF for the ER and the FFR

	5th Percentile	
	N95 Elastomeric n = 25	N95 Filtering Facepiece n = 22
0.7–1.0 μm	27.8	16.2
1.0–2.0 μm	43.0	32.2
2.0–3.0 μm	61.5	48.0
3.0–5.0 μm	131.5	86.0
5.0–10.0 μm	250.0	223.4
Total: all particle sizes combined[A]	63.8	44.0

[A]WPF values were calculated from the total number concentrations (by adding up all the number concentrations for each size range).

Another observation from Figure 3 is that the WPFs were higher for the ER than the FFR in all size ranges. Thus, for the respirator models tested in this study, the ER provided a higher level of performance than the FFR. This finding was not surprising, since the ER selected for this study was based on our fit testing experience with local companies. The selected ER comes in three sizes (FFR is available in two sizes), consistently achieves high fit factors, and is reported by users to maintain acceptable fit during use. Myers et al.[12] reported no difference in the performance of ER or FFR at different workplaces. However, the filter materials used in their study may not be directly comparable with N95 filters used in our study, as their study was conducted before the issuance of new certification regulations.[6] Performance characteristics and the selection of respirators (within the same category) may

TABLE III. Multivariate Analysis Results for Log-Transformed WPFs Assessed by the Generalized Estimating Equation

Variables	Regression Estimates (95% Confidence Interval)	p-value
Group	Regression Coefficient[A]	
Filtering facepiece	Reference	
Elastomeric	0.88 (0.55, 1.22)	≤ 0.0001
Size		
0.7–1.0 μm	Reference	
1.0–2.0 μm	0.63 (0.53, 0.73)	≤ 0.0001
2.0–3.0 μm	1.71 (1.41, 2.01)	≤ 0.0001
3.0–5.0 μm	2.62 (2.21, 3.03)	≤ 0.0001
5.0–10.0 μm	3.42 (2.79, 4.05)	≤ 0.0001

[A]Regression estimates are log-transformed. For example, the elastomeric respirator had $e^{0.88} = 2.4$ times higher geometric mean than the filtering facepiece respirator.

also be a consideration whenever a small number of models are compared. WPF performance ranges are expected, and the actual performance of any two models is not known until they are evaluated. Consequently, two models could be selected from the two tails of WPF studies, while another study could select models near the mean.

Table II compares the 5th percentiles of WPFs for the ER and FFR. For both respirator types, all particle size-selective WPFs were higher than the assigned protection factor (APF) of 10 for half facepiece respirators.[7] The 5th percentiles for the ER were higher than those for the FFR for all five particle size ranges. A similar trend was seen when WPFs were calculated from the total number concentration of particles. The 5th percentiles of the WPFs for the ER and FFR indicate a similar trend: WPFs increased as particle size increased.

In the univariate analysis, the WPF was significantly associated with respirator type, farm type, particle size, and outside concentration, whereas no association was found with gender of the respirator wearer. WPFs measured on horse farms were higher than those measured on the other farm types. A high co-linearity between outside concentration and farm type was observed, which indicates that the difference in WPFs between farm types was mainly due to differences in outside concentration. Possible interaction effects between particle size and respirator type, farm type and particle size, and respirator type and farm type were also explored. Results on the multivariate analysis assessing factors that affect the WPF are summarized in Table III. In the final multivariate model, only respirator type and particle size remained significant. The WPFs were 2.4 times higher for the ER than for the FFR ($p \leq 0.0001$). Furthermore, the size-selective WPFs increased significantly with the increase in particle size.

The association between WPFs and total outside/inside concentrations was further investigated by a correlation analysis. The correlation coefficient was –0.41 ($p = 0.005$) for the inside concentration and 0.31 ($p = 0.03$) for the outside concentration (data not shown). This is consistent with several WPF studies demonstrating that log-transformed WPFs were significantly, negatively correlated with log-transformed inside concentrations rather than outside concentrations.[9,11,12] No clear explanation, however, was previously offered for this correlation. The outside concentration could theoretically affect the WPF under high loading conditions, as respirator efficiency may change due to excessive particle load on the respirator filter. The latter increases pressure drop through the filter, which changes the balance of air flowing through filter and faceseal leaks. Mathematically, WPFs have correlations with both outside and inside concentrations because WPF is the ratio of the concentration of particles outside the respirator to the concentration of particles inside the respirator. Negative correlation between the WPF and inside concentration could occur when outside concentration does not vary much, but the WPF varies due to different fitting of the respirator on the wearer's face. Thus, the presence or lack of correlation appears to be a reflection of the variation in the outside concentration and in the respirator's ability to form a good seal on the wearer's face.

While this study provides valuable information about particle size-selective WPFs, the measurements are obtained with a relatively high sampling flow rate. The inside concentration is expected to be affected by high sampling flow rate because increased airflow may affect faceseal leakage. It is possible that this effect is more pronounced for the ER than the FFR, as the surface area of the ER filter used in this study was smaller. The sampling flow of 10 L/min adds to the constantly changing subject's inhalation flow rate. Test subjects in this field study performed relatively strenuous tasks that likely caused breathing rates to be considerably higher than 10 L/min. We assume breathing rates were higher than those occurring during the deep breathing exercise conducted in the standard fit testing, although breathing rates were not measured in these experiments.

According to a recent study involving 25 subjects,[18] mean inspiratory flow rate during the deep breathing exercise varies from about 20 to 40 L/min. Moreover, especially during inhalation, as the direction of the sampling flow is opposite to the direction of the inhalation, sampling bias of large particles would be induced more at smaller sampling rates. In this study, high sampling flow rate was selected because it decreases the particle detection limit for a specific sampling period. The latter is important especially when measuring bioaerosols at low concentration. Higher sampling rate also reduces respirator purge time and significantly declines potential sampling bias especially for nonhomogeneous particles.[19,20]

CONCLUSIONS

The N95 elastomeric and filtering facepiece respirators tested in the study provided expected level of respiratory protection for workers in agricultural farms. The 5th percentiles for the ER and FFR were higher than the APF of 10 and varied from 28 to 250 for ER, and from 16 to 223 for FFR. The WPFs for the ER were higher than those for the FFR in all size ranges, and the WPFs for both respirators increased with an increase in particle size.

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