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

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ABSTRACT

The objective of this study was to compare 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 the 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 of the respirator during the first and last 15 minutes of a 60-minute experiment. For every subject, size-selective WPFs were calculated in one-minute intervals and averaged over 30 minutes. For the ER, geometric mean WPFs were 172, 321, 1013, 2097 and 2784 for particles 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 69, 127, 324, 893, and 1994. 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 225, respectively. The results show that the N95 ER and FFR tested in the study provided expected level of protection for workers on agricultural farms against particles ranging from 0.7 to 10 µm. The WPFs for the ER were higher than those for the FFR in all size ranges, and the WPFs for both respirators increased with increasing particle size.

INTRODUCTION

Agricultural workers are at high risk for exposure to airborne hazards that can cause adverse respiratory effects. Several studies have shown that farmers growing different types of grain and soy beans (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 US alone. (4) It is difficult to protect farmers from airborne particles by engineering controls due to the diversity of particle sources and the mobility of farmers. This is one reason why respirators are used on agricultural farms.

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 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 correctly worn.(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 various 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 the study. Among 25 subjects, one Hispanic male and six females were included to reflect the gender and racial make-up of farmers in Ohio and Kentucky (which are very close to US average). Altogether eight farms were included representing three different types: two horse/livestock pavilions, three pig barns, and three grain handling sites. The 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 US.

The respirators tested in the study were represented by one model of ER with N95 filters and one model of N95 FFR. ER was available in three sizes, whereas FFR was available in two sizes. The respirators used for this study were selected because they were known from our clinical experience to have high success rates during routine quantitative fit testing (i.e., good fitting characteristics).

Field Study Design

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 the fit test for the FFR (one on Horse Farm 2 and the other in Pig Barn 3). In addition, the data were missing on one subject (Pig Barn 1) due to an instrument malfunction that took place when this subject was tested with the FFR.

All subjects signed the consent form approved by the University of Cincinnati Institutional Review Board and were medically cleared using an on-line questionnaire prior to the field testing. (13) All subjects were asked not to smoke for at least one hour prior to the field test and male subjects were asked to be clean shaven. In the beginning of the field test, the subjects were trained to wear both respirators according to the manufacturer's instructions. All subjects conducted a user seal check and fit testing. The fit testing was conducted using a TSI PortaCount Plus with an N95 companion (TSI, Inc., St. Paul, MN). In order to minimize systematic errors in results, the type of the test respirator (ER or FFR) to be worn first was randomly assigned to the first subject on each day of the field test and the subsequent subjects were systematically tested so that every other subject had the same order for test respirators. Some farmers wear respirators during the entire time they are working while others only wear respirators during the most critical times, for example approximately 15 minutes in grain bins.

However, our preliminary experiments demonstrated that subjects could not tolerate wearing of respirators more than 1 hour at moderate to strenuous work load. Consequently, each field experiment lasted for 1 hour for each respirator type per subject.

Particle Measurement

The aerosol particle concentrations inside and outside the respirator were measured with the personal sampling system that was 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 with each one including a sampling probe, a sampling chamber, an optical particle counter (HHPC-6, Hach Company, Loveland, CO), and a pump (Leland Legacy, SKC Inc., Eighty Four, PA). The optical particle counter measures the 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 Corporation, Butler, NJ), the flow rate for the pump was adjusted to maintain the total sampling flow of 10 L/min. Particle concentrations were determined simultaneously inside and outside of the respirator during 15 minutes in the beginning and 15 minutes at the end of the 60-minute experiment. The sampling time was shorter than the time of the respirator wear to avoid the build-up of moisture condensation inside sampling tubing. For every subject, size-selective WPFs were calculated in one-minute intervals and then averaged over the 30-minute sampling time. WPF was also calculated for all particles across the tested size range after combining the particle concentrations determined in each of the five channels.

Statistical Analysis

Geometric means (GM) and geometric standard deviations (GSD) were used to describe the outside concentrations and WPFs. Log-transformation was done for each of the continuous variables to induce normality. To compare the average WPF for the first 15 minutes with that for the second 15 minutes, t-test was used (SigmaPlot 11; Systat software Inc., San Jose, CA). Pearson correlation coefficients were calculated to investigate how the WPF was associated with the concentrations measured inside and outside the respirator (SigmaPlot 11; Systat software Inc., San Jose, CA). To identify the factors associated with the outside concentration and WPF, univariate generalized estimating equations (GEE) were used (SAS 9.2; SAS Institute Inc., Cary, NC). (15) Initially, the effect of farm type and particle size was evaluated for each of the two outcomes. For WPF, the effect of respirator type, outside concentration, and gender were also evaluated. Variables that were significant at 5% level under the univariate analysis were considered for the multivariate GEE. Possible interaction effects were also assessed before finalizing the regression model. Variables that were significant at 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 of the respirator at three different types of farms are presented in Figure 2. The multivariate analysis assessed the effect of farm type and particle size on the outside concentrations. Interaction was found between the farm type and particle size and therefore, the model was adjusted for the interaction. On average, horse farms had an 11-fold higher geometric mean outside concentration than grain handling sites ($p \le 0.0001$). There was, however, no significant difference in the concentrations between the grain handling and the pig barns (p=0.101). All the particle size distributions measured in this study appear to be similar to those measured during grain harvesting and unloading by Lee et al.(17) . In contrast to the current study, Lee et al. (17) found that the contribution of large particles (>2 µm) generated 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.,(16) who measured workers' dust exposures in swine confinements using personal photometers, 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.(17) 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.,(17); however, we measured higher concentrations on horse farms.

Before WPF was averaged over the 30-minute sampling time, average of WPFs for the first15 minutes was compared with those for the second15 minutes to obtain insight towards continuing performance of the respirators. Result assessed by t-test showed that there was no statistically significant difference between WPFs for the two periods (ER: p=0.76, FFR: p=0.77). Therefore, an average over the 30-minute sampling time was used in the further data analyses.

Two subjects did not pass the fit test with FFR, and their fit factors were 50 and 80. The effect of not passing the fit test was assessed through analyzing two data sets: including and excluding the WPF values produced by the two subjects who did not pass the fit test with the

FFR from a total of 24 subjects for whom valid FFR data were generated (it is noted that one subject was excluded from the 25-worker cohort because of the malfunction of the optical particle counter while testing with FFR). A multivariate analysis indicated that WPFs and 5th percentiles of WPFs for 24 subjects (including those who passed and failed the fit test) were not statistically significantly different from the 22 subjects who passed the fit test. This is a reasonable result because the failed fit factors were close to 100, which is the passing criteria for the fit test. Therefore, further analyses of the FFR performance included all data obtained for 24 subjects.

Figure 3 presents 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 particles 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 69, 127, 324, 893, and 1994. The 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 difference in WPFs observed in our study and those of Lee et al. are not known with certainty, we believe differences in fitting characteristics between the two FFRs are a plausible explanation. Differences in filter efficiency may be another factor, although likely of smaller magnitude. The WPFs for both respirators in the current study increased as the particle size increased, which is consistent with the results reported by Lee et al.(10) However, it is discrepant to the hypothesis by Janssen and McCullough(8) who measured the WPF of an ER with P100 filters and suggested that WPFs are not particle size-dependent. The 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 was 63.8 in our study and corresponding value for the study conducted by Janssen and McCullough was 51.5. This demonstrates 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(8) calculated WPFs based on mass over all size ranges, WPFs in this study were based on the simultaneous measurements of the number of particles with specific size ranges inside and outside the respirator.

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 upon our fit testing and other experiences with local companies. The selected ER comes in three sizes (versus two for the FFR), consistently achieves high fit factors, and is reported by users to maintain acceptable fit during use. Myers et al.(12) reported that no difference in the performance of ER or FFR was observed 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 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 while another study could select models near the mean.

Table II shows the comparison of the 5th percentiles of the 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 against particles in all five size ranges. Similar trend was seen when WPFs were calculated from the total number concentrations of particles. For the FFR, the 5th percentiles for 24 subjects were not significantly different from those for 22 subjects excluding 2 subjects who failed the fit test. The 5th percentiles of the WPFs for the ER and FFR indicate a similar trend: the WPFs increased as particle sizes increased.

In the univariate analysis, the WPF was found to be significantly associated with respirator type, farm type, particle size, and outside concentration, whereas no association was found with the gender of the respirator wearer. The WPFs measured on horse farms were higher than those measured on the two other farm types. A high co-linearity between outside concentration and farm type was observed. This indicates that the difference in the WPF between farm types was mainly due to the difference in the outside concentration. The possible interaction effects between particle size and respirator type, farm type and particle size, and respirator type and farm type were also explored. The 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 2.2 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 ($p \leq 0.001$) 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 the respirator efficiency may change due to excessive particle load on the respirator filter. The latter increases the pressure drop through the filter, which changes the balance of air flowing through the 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 wearers' faces. 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, it has a limitation associated with a relatively high sampling flow rate. The inside concentration is expected to be affected by high sampling flow rate because increased air flow may affect the faceseal leakage. It is possible that this effect is more pronounced for the ER than the FFR as the open area of the ER filter is 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 which likely caused breathing rates considerable higher than 10 l/min. Although not measured in these experiments, we assume breathing rates were higher than those occurring during the deep breathing exercise conducted in the standard fit testing. The mean inspiratory flow rate during the deep breathing exercise varies from about 20 to 40 L/min according to a recent study involving 25 subjects.(18) 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 more induced 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 non-homogeneous particles.(19-20)

CONCLUSIONS

The N95 ER and FFR tested in the study provided expected 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 225 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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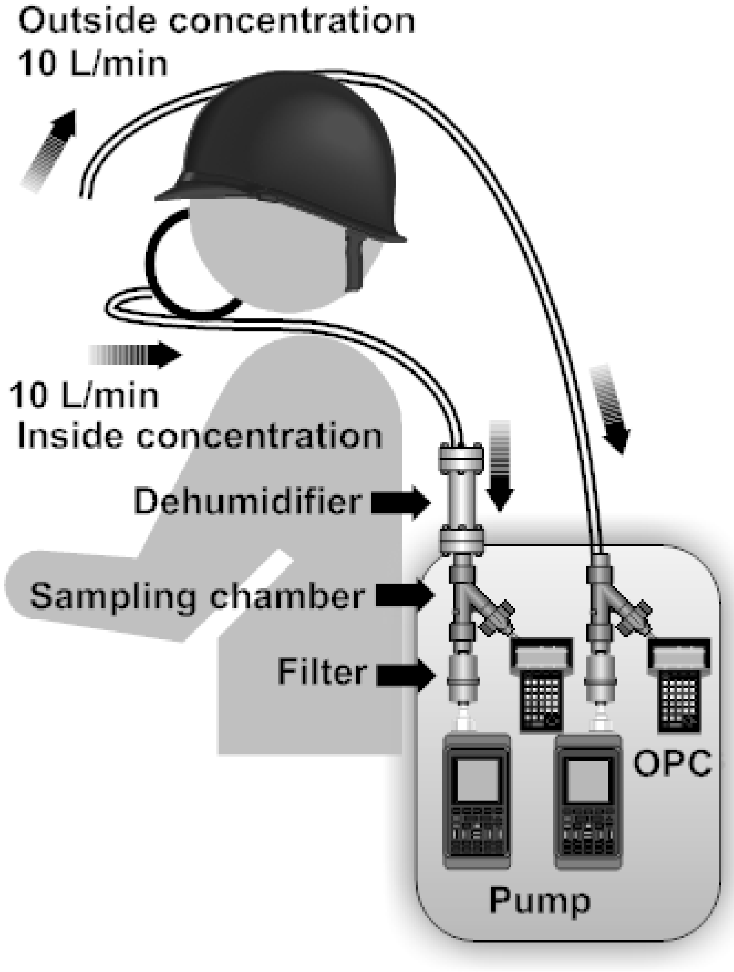

Figure 1. Schematic presentation of the personal sampling setup.

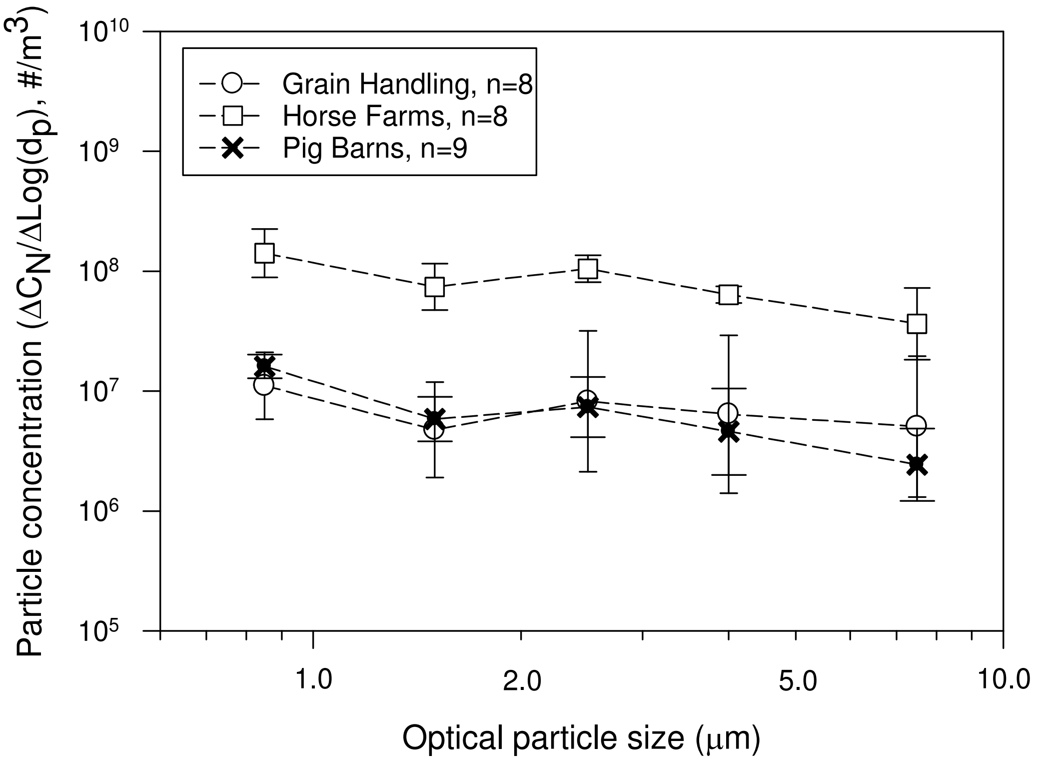

Figure 2. Normalized outside particle number concentrations at three different farm types. The symbols present geometric means, and error bars present geometric standard deviations.

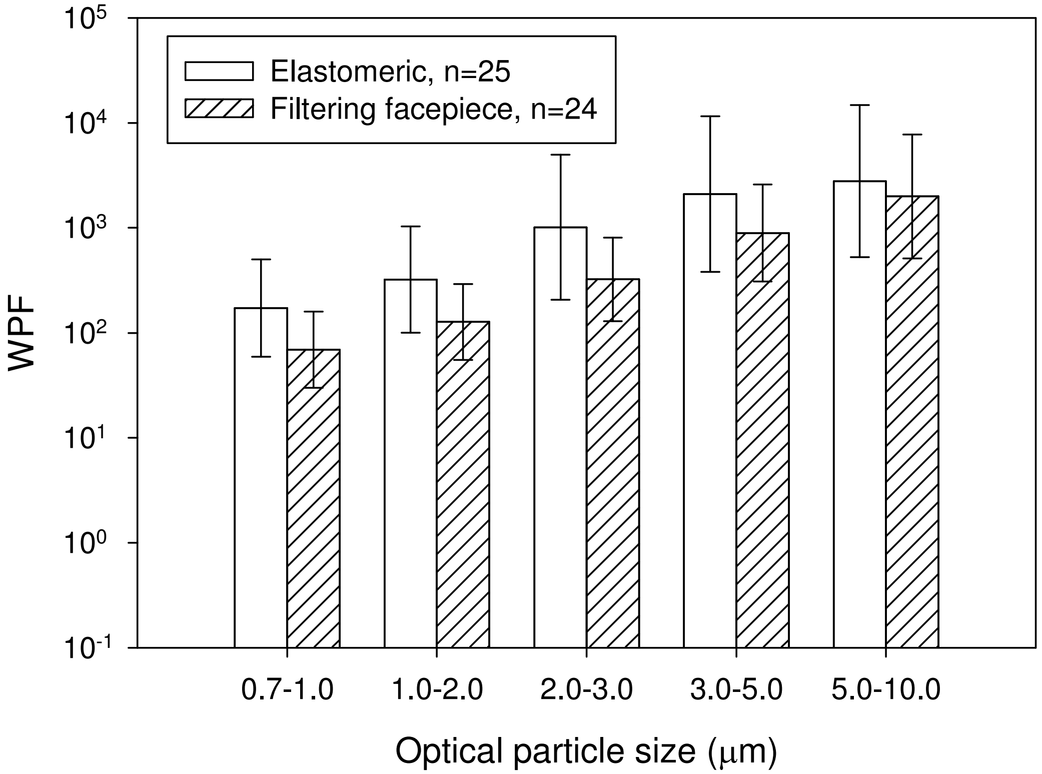

Figure 3. Workplace protection factor (WPF) provided by elastomeric respirator and filtering facepiece respirator for particles of different sizes (n=the number of subjects). The histograms present geometric means, and the error bars present geometric standard deviations.

Table I. Summary of the field testing sites on agricultural farms.

Farm Types	Number of subjects tested		Sampling time	Activity that re-suspended particles
	Male	Female		
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 to the filtering facepiece respirator

[B] Missing data for one subject with a filtering facepiece respirator due to an instrument malfunction

Table II. Comparison of the 5th percentiles of the workplace protection factor (WPF) for the elastomeric respirator and the filtering facepiece respirator.

	5th percentile		
	N95 elastomeric	N95 filtering facepiece	
	N=25	N=24[A]	N=22[B]
0.7 – 1.0 µm	27.8	16.4	16.2
1.0 – 2.0 µm	43.0	33.4	32.2
2.0 – 3.0 µm	61.5	48.0	48.0
3.0 – 5.0 µm	131.5	86.5	86.0
5.0 – 10.0 µm	250.0	224.8	223.4
Total: all particle sizes combined[C]	63.8	47.0	44.0

[A] Including all subjects (22 passed fit-test and 2 failed)

[B] Excluding 2 subjects that did not pass fit-test

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

Table III. Multivariate analysis results for log-transformed workplace protection factors assessed by the generalized estimating equation.

Variables	Regression Estimates (95% Confidence Interval)	p-value
Group	Regression coefficient[A]	
Filtering facepiece	Reference	
Elastomeric	0.81 (0.48, 1.14)	≤ 0.0001
Size		
0.7 – 1.0 µm	Reference	
1.0 – 2.0 µm	0.61 (0.52, 0.71)	≤ 0.0001
2.0 – 3.0 µm	1.66 (1.38, 1.94)	≤ 0.0001
3.0 – 5.0 µm	2.53 (2.13, 2.93)	≤ 0.0001
5.0 – 10.0 µm	3.27 (2.65, 3.88)	≤ 0.0001

[A] The regression estimates are log-transformed. For example, the elastomeric respirator had $e^{0.81}$ = 2.2 times higher geometric mean than the filtering facepiece respirator.