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Respiratory Protection Provided by N95 Filtering Facepiece Respirators Against Airborne Dust and Microorganisms in Agricultural Farms

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A new system was used to determine the workplace protection factors (WPF) for dust and bioaerosols in agricultural environments. The field study was performed with a subject wearing an N95 filtering facepiece respirator while performing animal feeding, grain harvesting and unloading, and routine investigation of facilities. As expected, the geometric means (GM) of the WPFs increased with increasing particle size ranging from 21 for 0.7–1 μm particles to 270 for 5–10 μm particles ($p < 0.001$). The WPF for total culturable fungi ($GM = 35$) was significantly greater than for total culturable bacteria ($GM = 9$) ($p = 0.01$). Among the different microorganism groups, the WPFs of Cladosporium*, culturable fungi, and total fungi were significantly correlated with the WPFs of particles of the same sizes. As compared with the WPFs for dust particles, the WPFs for bioaerosols were found more frequently below 10, which is a recommended assigned protection factor (APF) for N95 filtering facepiece respirators. More than 50% of the WPFs for microorganisms (mean aerodynamic diameter <5 μm) were less than the proposed APF of 10. Even lower WPFs were calculated after correcting for dead space and lung deposition. Thus, the APF of 10 for N95 filtering facepiece respirators seems inadequate against microorganisms (mean aerodynamic size <5 μm). These results provide useful pilot data to establish guidelines for respiratory protection against airborne dust and microorganisms on agricultural farms. The method is a promising tool for further epidemiological and intervention studies in agricultural and other similar occupational and nonoccupational environments.*

Keywords agricultural farms, airborne dust, airborne microorganisms, respirators, workplace protection factor, WPF

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Farmers are at high risk of exposure to airborne dust and microorganisms. These exposures can cause respiratory diseases.[1–4] According to the U.S. Bureau of Labor Statistics,[5] around 13 million people gain some earnings from farming in the United States. Of these, 6 million people are family members living and working on the farms.

The application of engineering controls for preventing farmers and their family members from exposure to airborne particles, including microorganisms, is limited because of the diverse nature of the dust and bioaerosol sources in agricultural settings. Personal protection by respirators is often the only feasible option for farmers to minimize their exposure to airborne dust and microorganisms. However, the Respiratory Protection Standard (29 CFR Part 1910.134) is not applicable to many agricultural environments,[6] and there is limited guidance for respiratory protection against biological particles.

Respirators used by agricultural workers should be certified by NIOSH in accordance with 42 CFR Part 84.[7] Under these certification guidelines, N95 filtering facepiece respirators have the filtration efficiency of at least 95% for the most penetrative particle size of 0.3 μm. These respirators have been recommended by the Centers for Disease Control and Prevention (CDC) for health care workers to protect them from infectious aerosols, which can cause diseases such as SARS (severe acute respiratory syndrome) and tuberculosis. Qian et al.[8] found that the filtration efficiency of some N95 filtering facepiece respirators is 99.5% or higher for the NaCl and PSL particles in the size range of 0.75 to 1 μm as well as for *Bacillus subtilis* (the mean aerodynamic diameter $= 0.8$ μm) and *Bacillus megatherium* (the mean aerodynamic diameter $= 1.2$ μm). The aerodynamic sizes of most bacteria and fungal spores are between 0.7 and 10 μm[9,10] and thus the filtration efficiency by N95 filtering facepiece respirators should be even higher than 99.5%. However, these contaminants enter the respirator cavity not only through the filter material but also through the faceseal leaks, which is the primary pathway for contaminants to penetrate inside negative pressure respirators (especially those that have poor respirator fit). N95 filtering facepiece respirators are relatively comfortable for workers because they are lightweight and do not obstruct vision or hinder communication as much as

elastomeric respirators. Therefore, in the present study, the N95 filtering facepiece respirator was investigated for its field performance in protecting farmers against airborne dust and microorganisms.

The workplace protection factor (WPF) is commonly used to assess respirator performance in the workplace. The WPF, which is defined as a ratio of the particle concentration outside the respirator to that inside the respirator, is a measure of the protection provided in the workplace under the conditions of that workplace, by a properly selected, fit tested, and functioning respirator that is correctly worn and used.[7,11] In our previous study,[12] we developed a new personal sampling system for determining the protection provided by respirators against airborne dust and microorganisms. This personal system was tested for its capability of measuring and reflecting the nearly instant changes in the aerosol concentrations inside and outside the respirator through laboratory and field evaluation.[13] Both laboratory and field studies showed this system to be a promising tool in determining the protection provided by respirators against particles and microorganisms. The objective of the current study was to use the newly developed personal sampling system in agricultural environments to determine the protection provided to farmers by N95 filtering facepiece respirators against airborne dust and microorganisms of different particle size ranges. Our concurrent article[14] will characterize exposures, whereas this article focuses on respiratory protection.

MATERIALS AND METHODS

Field Study Design

Field samples were collected using a personal sampling system previously described in detail by Lee et al.[12,13] In short, the sampling system consisted of two sampling lines (in-facepiece and ambient sampling lines) that were used to collect particle samples inside and outside the respirator. N95 filtering facepiece respirators (model 8210, 8110S; 3M, St. Paul, Minn.) were used in the field experiments. Airborne dust and microorganisms were sampled through the sampling probes at a flow rate of 10 L/min and drawn through Tygon tubing to a metal sampling chamber at the end of each sampling line. A portion of each aerosol flow (2.8 L/min) was sampled from the chamber into an optical particle counter (OPC, model HHPC-6; ARTI Inc., Grants Pass, Ore.) for dust measurement. The rest of the aerosol flow (7.2 L/min) passed through a filter sampler that collected the airborne microorganisms.

The selected flow rate of 10 L/min is five times the conventional in-facepiece sampling flow rate used for fit testing. As described in Lee et al.,[12] a higher flow rate was selected to decrease the respirator purge time and the potential sampling bias for nonhomogenous distributions of the particle concentration inside the respirator. In addition, the high flow rate decreases the detection limit of particle measurements when measuring for a specific sampling period, which is especially important for evaluating the respirator performance against low concentrations of airborne microorganisms. This high flow rate, however, may lead to the overestimation of particle penetration into the mask particularly at low respiration flow rate.

Our field measurements were conducted in six farms—three types of animal confinements (swine, poultry, and dairy), and three grain farms. Detail information on farming activities and farm characteristics, as well as on the methods for enumeration of airborne dust and microorganisms, are presented in Lee et al.[14]

All subjects recruited in the study had to pass the medical clearance evaluation and fit test before participating in field testing. The medical clearance evaluation was conducted using the questionnaire, specified in OSHA standard 1910.134, Appendix C.[6] The medical clearance was authorized by a licensed physician. Before starting the field test, subjects signed an Institutional Review Board consent form, where the possible risks of the field test were addressed. All study subjects were required not to have beard or stubble on their face and not to smoke 1 hour before the test.

The respirator fit test was performed once for each subject prior to his or her involvement in the field testing. Before fit testing, each subject was trained and instructed to wear the respirator properly. The instructions followed the manufacturer's guidance on the use of the respirator. Fit testing was conducted with a TSI Portacount Plus in connection with N95 companion (TSI, Inc., St. Paul, Minn.) in compliance with the 6-exercise protocol.[15] With the quantitative fit test, a fit factor of 100 or above constituted a pass. The subject then donned the respirator equipped with the personal sampling system. In each farming environment, one to four subjects were involved in the experiment that lasted for 30 to 60 min. The testing time covered the time it took the subject to complete the specific work task under investigation. Subjects were recruited primarily from agricultural farms, while students and staff of the University of Cincinnati also participated.

Correction on WPF Data Based on the Respirator Dead Space and Lung Retention

Several studies have shown that respirator dead space and lung retention decrease the concentration inside the respirator during inhalation, resulting in the overstating of the WPF.[16,17] Hinds and Bellin[16] developed a model to predict the average true concentration inside the respirator after accounting for the effects of lung retention and respirator dead space. In their study, the ratio of an average full breathing cycle concentration to an average inhalation concentration (C_{full}/C_{in}) was related to the ratio of the respirator dead volume to the tidal volume (V_{ds}/V_t). The association was described in detail for five values of fractional particle depositions in the respiratory tract (F_{dep}) in the absence of faceseal leakages. Based on the information obtained for V_{ds}/V_t and F_{dep} in our study, the ratio of C_{full}/C_{in} can be interpolated from a figure presented in Hinds and Bellin's paper.[16] Thus, the corrected WPF (WPF_{corr}) can be

calculated as following:[16]

$$WPF_{corr} = WPF \times \frac{C_{full}}{C_{in}} \quad (1)$$

where the WPF value is measured during the full breathing cycle.

To use this model, information is needed on the respirator dead space volume, tidal volume, and fractional deposition of particles in the respiratory tract. For an N95 filtering facepiece respirator, the respirator dead volume was measured by immersing a human face into an N95 respirator filled with water and measuring the remaining water volume inside the respirator. The average of three repeats was of 123 mL. Tidal volume of 1250 mL was selected to represent an adult male performing light work.[18]

The respiratory deposition of particles was calculated using an existing computer-based deposition model.[18] These calculations were performed separately for each microorganism group/species and for dust particles in the five OPC particle size classes. All of the physiological data, which were required for the respiratory deposition model, were specified for an average height of American adult male (176 cm) under light workload.[18]

Data Analysis

The data analysis was performed by analysis of variance (ANOVA), t-test, and correlation model by Statistical Analysis System (SAS) version 8.0 (SAS Institute Inc., Cary, N.C.). P-values of <0.05 were considered significant. Intra- and intersubject variability in WPFs was investigated by repeated measure analysis using PROC MIXED procedure in SAS. Two different models were considered for both dust and microorganisms. The first model was one-way random effect model used to examine the between-subject and within-subject variability without including the covariate of particle size and microbial type in the model. The second model was a two-factor mixed-effect model, in which one additional covariate (particle size for nonbiological particles, and microbial type for biological particles) was included. Particle size had two levels: 0.7–2 μm and 2–10 μm, and microbial type had two levels: culturable fungi and culturable bacteria.

The between-subject and within-subject variability were estimated by the restricted maximum likelihood (REML) method due to the unbalanced nature of data. In addition, the difference in mean WPFs among five particle sizes as well as among the predominant fungal spores were examined by ANOVA followed by pair-wise comparison using Tukey's studentized range (HSD) test. The t-test was used to examine the difference in the protection factors for biological and nonbiological particles, specifically comparisons between culturable fungi and culturable bacteria and comparisons between two particle size ranges: 0.7–2 μm (bacteria) versus 2–10 μm (fungi). The correlation coefficient was obtained to examine the association between the WPF for airborne microorganisms and the WPF for dust of similar particle sizes. All WPF data used for statistical analyses were log-transformed to achieve normal distribution. When the concentration inside the respirator was undetectable, one-half of the detection limit was used to calculate the WPF.

RESULTS AND DISCUSSION

Figure 1 presents the percentile and mean values of the WPFs, determined as a ratio of the concentration outside the respirator to that inside the respirator. The WPFs provided by N95 filtering facepiece respirators against airborne dust were found to be associated with the particle size. The geometric means (GM) of the WPFs were 24 for the particles in the range of 0.7 to 2 μm and 75 for the particles of 2 to 10 μm. With specific size fractions, GM = 21 for 0.7–1 μm particles, 28 for 1–2 μm particles, 51 for 2–3 μm particles, 115 for 3–5 μm particles, and 270 for 5–10 μm particles. The difference in WPFs for particles in the five size classes was statistically significant ($p < 0.001$). The WPF for the particle size fraction of 2–10 μm, representing the size of most airborne fungi, was significantly higher than that for 0.7–2 μm, representing the size of most bacteria ($p = 0.01$). Correspondingly, the WPF for total culturable fungi (GM = 35) was significantly greater than for total culturable bacteria (GM = 9; $p = 0.01$).

For the most common fungal genera or groups, the geometric means of the WPFs were 5 for *Aspergillus/Penicillium*, 6 for Ascospores, 15 for Basidiospores, 68 for *Cladosporium*, 15 for smut spores, 15 for *Epicoccum*, and 22 for *Alternaria*. Their corresponding calculated mean aerodynamic sizes were 3.7, 5.6, 6.8, 8.1, 9.7, 14.5, and 18.9 μm.[14] Thus, similarly to the situation with nonbiological particles, the WPF increased with an increase in the microorganism size with the exception of *Cladosporium*.

When the individual fungal genera and groups were investigated, *Cladosporium* had a wide range of WPF values compared with other fungi. The large variability in the spore size of *Cladosporium* can explain this phenomenon. The physical size and aerodynamic size of *Cladosporium cladosporioides* are 3.6 ± 0.7 μm and 1.8 ± 0.7 μm, respectively, as reported by Reponen et al.[19] The size of *Cladosporium* spp. measured in our study ranged from 7.8–16.6 μm in length and 4.3–9.2 μm in width, while Ellis[20] reported wider ranges of the spore size (3–40 μm [in length] $\times$ 2–13 μm [in width]) that reflect different species of *Cladosporium*. In addition, the agglomeration of the *Cladosporium* was observed under the microscope for the air samples. The abovementioned factors were attributed to a decrease in the penetration of *Cladosporium* through the faceseal leaks and a greater variation in the WPFs.

Fungal spores as large as *Cladosporium* are not able to remain suspended in the air for a long time. Most of them will settle down on the ground before they reach the sampling probe. The concentration of spores in the air may not rise to considerable levels as long as there is no continuous aerosolization source in the environment. As reported in our concurrent study,[14] most of the concentrations of individual fungal genera and groups outside the respirator were close to

the detection limit in animal confinements. This caused the concentration of these spores inside the respirator to remain below detection limit in several cases. In these cases, the WPFs were calculated by using one-half of the detection limit for the concentration inside the respirator. This might introduce a bias in estimating the respiratory protection against fungal spores as large as *Cladosporium*.

In addition, if the leak size is close to particle size, the shape of the fungal spores, as well as the shape and size of faceseal leaks, might affect the penetration of spores through the faceseal leaks. For example, nonspherical fungal spores, such as *Cladosporium*, penetrate differently when the large end of a spore encounters a small faceseal leak, compared with when it encounters a large faceseal leak. Likewise, penetration is different when the large end of a spore encounters a slit shape faceseal leak compared with a circular faceseal leak. Thus, large variation in the WPF was expected for nonspherical fungal spores.

Figure 1 also shows the proposed assigned protection factor (APF) and the pass/fail criterion for N95 filtering facepiece respirators, which are 10[21] and 100,[6] respectively, for N95 filtering facepiece respirators. Among 19 observations, 68% of the WPFs for particles in the lowest size range of 0.7–1 μm were above 10, whereas for large particles, this percentage was greater. However, more than 50% of the WPFs for microorganisms, such as culturable bacteria (62%), culturable actinomycetes (64%), *Aspergillus/Penicillium* (65%), and Ascospores (64%), were below 10. The mean aerodynamic diameter of these microorganisms was estimated to be below 5 μm. Most of the WPF values for larger fungal spores were higher as discussed above: 59% of smut spores, 78% of *Alternaria*, and 67% of *Epicoccum* in WPF values were

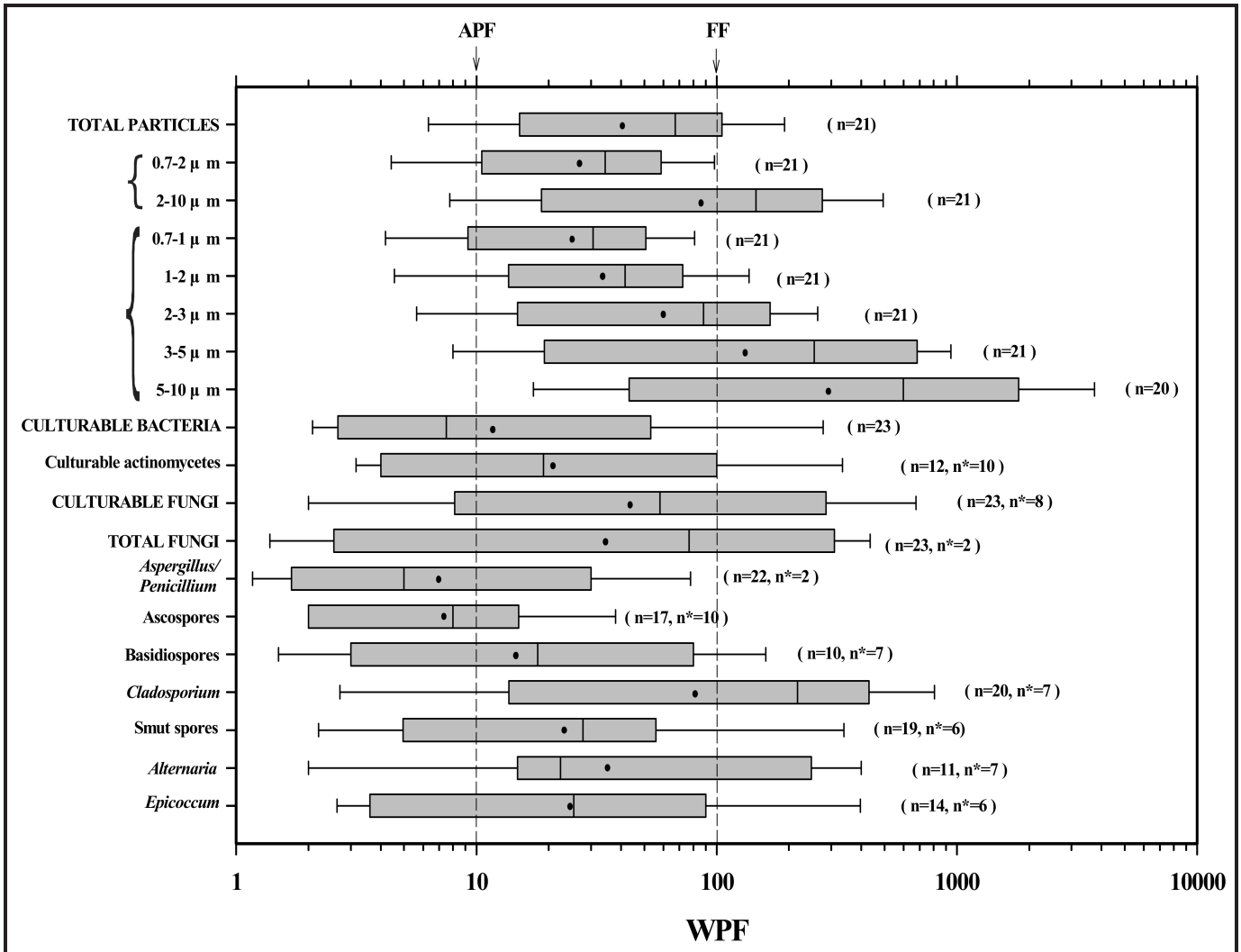

FIGURE 1. Percentile and mean values of workplace protection factor (without correction for respirator dead space and lung retention) against dust and microorganisms. The boxplot shows the following: • geometric mean; vertical lines from left represent 5%, 25%, 50%, 75%, 95% percentiles; n represents the number of observations; n* represents number of those observations, in which the in-facepiece concentrations were below LOD. Legend: FF = fit factor; APF = assigned protection factor.

above 10. Although the WPF for dust and microorganisms showed similar increasing trend with increasing particle size, the WPF for particles were found to be higher than that for microorganisms of the same size range. This might be due to differences in the particle losses occurring in the faceseal leaks due to different shape and density of biological and nonbiological particles.

Another reason could be related to the measurement bias of the OPC in size-selective count of dust particles. The optical particle counter operates by projecting light on particles and detecting light scattering from particles; thus, factors such as shape and color of particles interfering light scattering can affect the instrumental measurement on particles. When the air samples were analyzed under the microscope, dust particles with irregular shape and different colors were observed. Unlike the dust particles, fungal spores have close-to-regular shapes. The difference in reflective index and shape of the dust particles is expected to cause significant variability of the measured particle sizes and number concentrations in a specific environment when using the OPC. Furthermore, the irregular shape of dust particles increases particle losses through the faceseal leaks due to the interception mechanism.

The density of particles may also play a role. The aerodynamic sizes of dust particles and fungal spores were calculated based on the assumption that $\rho = 1$ g/cm^3. However, the density of dust particles, such as sand and clay, can be higher than 1 g/cm^3 whereas for many fungal spores the density is smaller than 1 g/cm^3.[19] This is likely to result in the underestimation of the aerodynamic size of dust particles and the overestimation of the aerodynamic size of fungal spores. Following this logic, the aerodynamic sizes of dust particles may be underestimated whereas those for fungal spores may be overestimated. When the physical sizes of dust particles and fungal spores are about the same and their Stokes numbers are close to 1, even small variation in the density of particles can have a pronounced effect on the dust particle losses in the faceseal leaks due to the impaction mechanism. The concentration of the dust particles inside the respirator was lower than that of the fungal spores, resulting in the higher protection factor. These findings deserve further research. Since there are no OSHA required guidelines for respiratory protection against biaerosols, and OSHA has proposed to change the APF for filtering facepieces,[21] the results obtained in this study provide important preliminary information to consider for respiratory protection against airborne dust and microorganisms in agricultural farms.

Nearly all the WPF studies used to justify the APF = 10 for half-mask respirators have involved particulate contaminants, and many of these studies have been done with large particles. However, large particles, which comprise most of the total mass, were found to be less penetrative than small ones. Thus, by determining the total mass concentration inside and outside respirator, one may lead to underestimate the WPF values for small particles, which would result in the overestimation of the APF values. Our data show that the particle size should be taken into account when assigning APF values.

Since the WPF for both airborne dust and microorganisms was found to be associated with the particle size, we

TABLE I. WPF Correlations

	Dust Particle Size Fractions Within the 0.7–10 μm Range							
	Five Fractions					**Two Fractions**		**Total**
Microorganism	**0.7–1 μm**	**1–2 μm**	**2–3 μm**	**3–5 μm**	**5–10 μm**	**0.7–2 μm**	**2–10 μm**	**0.7–10 μm**
Aspergillius/Penicillium[A] (n = 17)	0.34	0.43	0.46	0.37	0.35[B]	0.37	0.41	0.37
Ascospores[A] (n = 12)	0.05	0.23	0.19	0.03	0.14[B]	0.13	0.17	0.21
Basidiospores[A] (n = 7)	0.36	0.38	0.15	−0.19	−0.08[B]	0.39	0.15	0.44
Cladosporium[A] (n = 15)	**0.58**	**0.58**	**0.57**	**0.52**	**0.61**[B]	**0.59**	**0.57**	**0.61**
	(p = 0.02)	**(p = 0.02)**	**(p = 0.03)**	**(p = 0.05)**	**(p = 0.02)**	**(p = 0.02)**	**(p = 0.03)**	**(p = 0.02)**
Smut spores[A] (n = 14)	0.05	0.06	−0.05	−0.22	−0.22[B]	0.06	−0.07	−0.09
Alternaria[A] (n = 8)	0.13	0.22	0.28	0.28	0.29	0.17	0.32	0.28
Epicoccum[A] (n = 12)	−0.24	−0.28	−0.30	−0.33	−0.34	−0.25	−0.29	−0.22
Total fungal	0.40	**0.47**	**0.50**	0.44	**0.51**[B]	0.44	**0.50**	**0.51**
spores[A] (n = 18)		**(p = 0.05)**	**(p = 0.04)**		**(p = 0.04)**		**(p = 0.03)**	**(p = 0.03)**
Culturable fungal	**0.49**	**0.54**	**0.57**	**0.56**	**0.74**[B]	**0.52**	**0.61**	**0.62**
spores (n = 18)	**(p = 0.04)**	**(p = 0.02)**	**(p = 0.01)**	**(p = 0.02)**	**(p = 0.001)**	**(p = 0.03)**	**(p = 0.01)**	**(p = 0.01)**
Culturable bacteria (n = 18)	0.17	0.23	0.20	0.09	0.11[B]	0.20	0.19	0.25

Notes: Values denote Pearson correlation coefficients (R) for log-transformed WPFs. Significant correlations in **bold**; an entry in the parentheses indicates the p values; n = number of observations.

[A] Based on the microscopic analysis.

[B] For some microorganism, one observation was lost.

investigated whether the WPF of airborne microorganisms and the WPF of dust of the same size range correlate with each other. Table I shows the correlation between the WPF of dust and the WPF of fungal spores for predominant groups and genera. The WPF for *Cladosporium*, total fungi, and culturable fungi showed a significant association with the WPF for total dust (0.7–10 μm) as well as with the WPF of dust in the corresponding size range: 5–10 μm for *Cladosporium* ($r = 0.61$, $p = 0.02$), 2–10 μm for total fungal spores ($r = 0.50$, $p = 0.03$) and culturable fungal spores ($r = 0.61$, $p = 0.01$). Although the WPF of *Aspergillus/Penicillium* did not significantly correlate with the WPF of dust, the best correlation between the WPF for *Aspergillus/Penicillium* and dust was observed with the particles in the size range of 2–3 and 3–5 μm, which coincides with the size of *Aspergillus/Penicillium* spores. The WPFs obtained for other microorganisms were found to have much lower correlation with those obtained for the particles.

As mentioned above, the variation in the shape and reflection index of nonbiological particles may play a role in the measurement of their size and may explain the poor correlation between the WPF of airborne microorganisms and the WPF of dust. In addition, the mean aerodynamic size of *Alternaria* (14.5 μm) and *Epicoccum* (18.9 μm) were greater than 10 μm, which exceeded the upper limit of the particle sizes that the OPC can measure at about 10% efficiency. Thus, for further study involving these two large fungi or similar ones, the OPC should be customized to measure particle sizes up to 20 μm. Moreover, the sampling losses through the sampling line should be carefully addressed for these large particles.

Figure 2 presents the regression plots for the associations that were found to be significant: WPF of *Cladosporium*, total fungi, and culturable fungi vs. the WPF of dust particles for the corresponding size range. The equations provided in Figure 2 can be used to estimate the WPF of these microorganisms when only dust measurement is performed. It means the WPFs of microbes can be obtained by importing the WPFs of particles of the same aerodynamic size in the equation. Considerable time and expense could be saved for the microbiological analysis. However, as we found significant correlations for only a few microbial types, our data indicate that the WPFs for most of the microorganism genus/groups cannot be estimated utilizing WPFs measured for particles.

Several subjects recruited among students and staff at the University of Cincinnati repeated the experiment in different farming environments. This allowed us to investigate the difference in WPFs between and within subjects. Table II shows the variability of the WPFs between subjects and within subjects for airborne dust and microorganisms. The Appendix shows the raw data used in these calculations. The first model (without covariates) shows that the between-subject variability was 1.08 for dust and 0.13 for microorganisms, while the within-subject variability was 1.43 and 3.9, respectively. This demonstrates that the within-subject variability in WPFs was

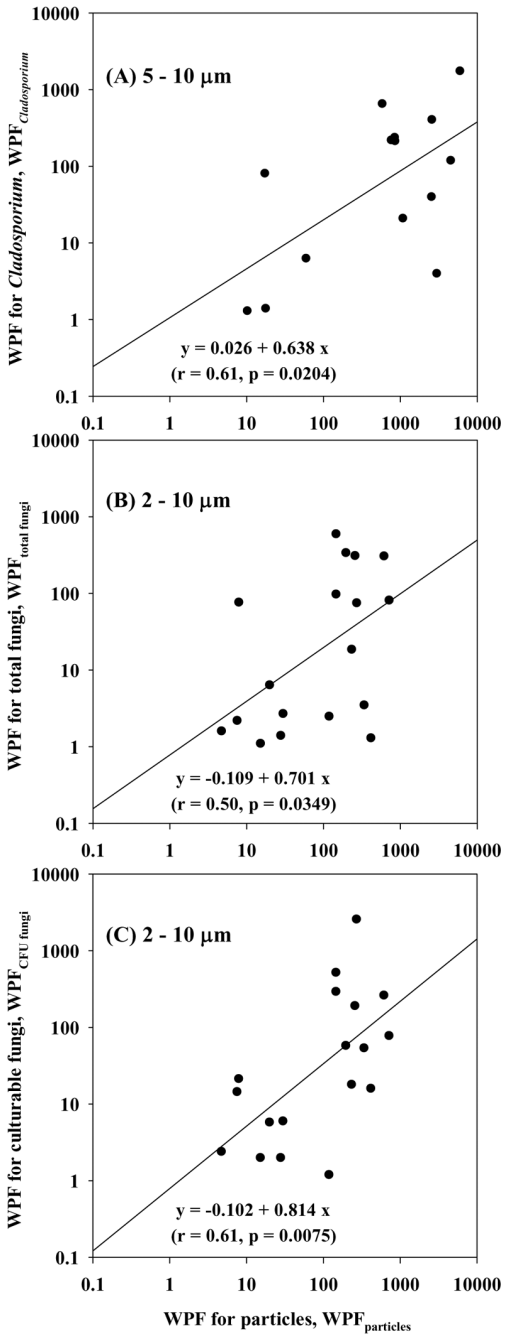

FIGURE 2. Correlation between the WPF for microorganisms and the WPF for particles of corresponding particle size: (A) *Cladosporium* vs. 5–10 μm particles, (B) total fungi vs. 2–10 μm particles, and (C) culturable fungi vs. 2–10 μm particles. $y = \log$ (the WPF for microorganisms); $x = \log$ (the WPF for particles).

greater than the between-subject variability for half-mask respirators when there were no other covariates included in the model. The findings support the results presented by Nicas and Neuhaus.[22]

However, when the covariate, such as particle size or microbial type, was included in the model, the within-subject variability decreased as seen in Table II. This may result

TABLE II. Variability of WPFs Between Subjects (σ_B^2) and Within Subjects (σ_w^2) for Dust and Microorganisms

	σ_B^2	σ_w^2	$\frac{\sigma_B^2}{\sigma_B^2+\sigma_w^2}$	GSD_B^A	GSD_W^B	Reduction for Within-Subject Variation Compared with Model with No Covariates (%)
Particles						
No covariates	1.08	1.43	0.43	2.83	3.31	
Size only	1.18	1.07	0.52	2.96	2.81	25
Microorganisms						
No covariates	0.13	3.9	0.03	1.43	7.21	
Type only	0.18	3.49	0.05	1.53	6.48	11

[A] GSD_B = between-subject geometric standard deviation.
[B] GSD_W = within-subject geometric standard deviation.

in the within-subject variability being equal to or smaller than the between-subject variability at least for nonbiological particles. Table II also shows that the fraction of the between-subject variability versus the total variability for dust increased from 43% to 52% when the particle size was accounted for in the model. Note that the between-subject variability in microorganisms was much smaller than the within-subject variability. Also, the latter for biological particles was two to three times larger than that for nonbiological ones. It is likely that different farming activities involved different particle size distributions, different microbial composition, and different faceseal leakage.

When comparing the within-subject and between-subject variability in WPFs for airborne dust and microorganisms, other covariates such as particle size, microbial types, and farming activities should be carefully addressed, and the effect of these factors on WPF measurements in agricultural environments should be further investigated. From our small-scale study results, it appears that the WPF distributions between biological and nonbiological particles are very different from each other. Therefore, more detailed research will help to better characterize WPFs.

Previous studies showed that respirator dead space and lung retention decrease the concentration inside the respirator

TABLE III. Differences in WPF Data Before and After Accounting for Lung Deposition and Respirator Dead Volume

	Mean Aerodynamic Size (μm)[A]	F_{dep}^B (%)	C_{full}/C_{in}^C	WPF	WPF_{corr}^D	Bias *E* (%)
Dust						
0.7–1 μm	0.9	39	0.82	92	76	22
1–2 μm	1.5	70	0.68	146	99	47
2–3 μm	2.5	92	0.59	343	202	69
3–5 μm	4.0	96	0.57	932	531	75
5–10 μm	7.5	89	0.60	2563	1538	67
Fungal spores						
Aspergillius/Penicillium	3.7	95	0.57	3	2	75
Ascospores	5.6	93	0.58	5	3	72
Basidiospores	6.8	92	0.59	240	142	69
Cladosporium	8.1	87	0.61	406	248	64
Smut spores	9.7	84	0.62	60	37	61
Alternaria	14.5	72	0.67	256	172	49
Epicoccum	18.9	63	0.71	90	64	41

[A] Mean aerodynamic size is the same as that presented in authors' concurrent paper.[14]
[B] F_{dep}: fractional deposition of particles in the respiratory tract.[18]
[C] C_{full}/C_{in}: ratio of an average concentration measured during the full breathing cycle to that measured during inhalation.[16]
[D] WPF_{corr}: WPF corrected after accounting for lung deposition and respirator dead volume ($WPF_{corr} = WPF \times C_{full}/C_{in}$).
[E] Bias: $[WPF\text{-}WPF_{corr}]/[WPF_{corr}] \times 100\%$, calculated with nonrounded numbers.

during inhalation, resulting in overestimation of the WPF.[16,17] So far, only a few WPF studies have investigated the effects of respirator dead space and lung retention because the information on the distribution of the particle size inside the respirator was not readily available. In this study, the OPC provided the size distribution of particles inside the respirator for five different size fractions in the particle size range of 0.7 to 10 μm. In addition, the size information for fungal spores was obtained from the data presented by Lee et al.[14]

Table III presents the differences in the WPF data before and after accounting for the lung deposition and respirator dead volume. As seen from the table, the total deposition in human respiratory tract (F_{dep}) ranged from 39 to 96% for particles in the size range of 0.7 to 10 μm, and from 63% to 95% for fungal spores, which cover the particle size range from 3.7 to 18.9 μm in mean aerodynamic size. The measured WPF values were corrected by accounting for respirator dead space and lung retention using Hind and Bellin's approach.[16] The bias was calculated by dividing the difference between the protection factors before (WPF) and after correction (WPF_{corr}) by the protection factor after correction. For particles in the size range of 0.7 to 10 μm, the WPFs before correction were overestimated by 22% to 75%. For fungal spores in the mean aerodynamic size of 3.7 to 18.9 μm, the protection factors before correction resulted in the overestimation ranging from 41% to 75%. This information provided the possible bias caused by respirator dead space and lung retention when we evaluated the respiratory protection against airborne dust and microorganisms in agricultural farms. As compared with the WPF values presented in Figure 1, the percentage of WPF values less than 10 would be increased after correction for dead respirator space and lung retention. For example, the percentage of WPF values less than 10 for *Aspergillus/Penicillium* was increased from 65% to 71% resulting from the correction.

CONCLUSIONS

The protection provided by N95 filtering facepiece respirators against dust and airborne microorganisms varied with particle size, shape, and density. The WPFs for microorganisms were smaller than those for nonbiological (dust) particles of the same size range measured by OPCs. This may be due to pronouncedly irregular shape and higher density of dust particles as compared to biological particles. More than 50% of the measured WPFs for microorganisms (mean aerodynamic size <5 μm) were less than the proposed APF of 10. Even lower WPFs were calculated after correcting for respirator dead space and lung deposition. As a consequence, the APF of 10 for N95 filtering facepiece respirators against microorganisms (mean aerodynamic size <5 μm) seems to be inadequate for more than 50% of wearings. Our data shows that particle size and the nature of particles (nonbiological/biological) should be taken into account when computing APF values for particulate respirators. In order to establish respiratory protection guidelines against airborne microorganisms in agricultural farms, more field data must be obtained. The present results provide preliminary data toward developing such guidelines, and the method developed can be used for further epidemiological and intervention studies in agricultural and other environments with considerable bioaerosol contamination.

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APPENDIX I. Relicated WPF Values of Airborne Dust and Microorganisms

	0.7–2 μm	2–10 μm	Culturable Fungi	Culturable Bacteria
Subject 1	17.6	117.8	1.2	1.5
	45.3	337.7	54.0	3.1
Subject 2	27.0	194.9	58.0	9.0
	34.3	269.2	400.0	2.2
	35.3	145.7	2575.0	1.6
	55.1	414.1	520.6	116.7
	28.7	29.7	16.0	13.8
			6.0	2.2
Subject 3	74.3	258.8	192.0	709.5
	2.9	4.7	74.4	12.5
	4.5	7.5	2.4	3.3
	8.6	19.8	14.5	5.6
	11.1	27.7	5.8	3.6
	31.3	15.1	2.0	14.0
			2.0	2.5
Subject 4	40.3	232.3	70.0	25.3
	8.8	12.5	18.0	4.3
Subject 5	160.7	712.5	78.1	2.5
	39.4	145.8	293.5	7.5
	115.3	612.6	262.5	169.2
Subject 6	4.3	7.9	21.4	62.4