

Development of a New Method for Measuring the Protection Provided by Respirators against Dust and Microorganisms

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Abstract

The efficiency of respirators is usually determined by the protection factor, which is the ratio of the particle concentration outside the respirator to that inside the respirator. Most studies on workplace protection factors (WPF) of respirators have focused on the measurement of total mass concentrations, ignoring the effect of particle size. Furthermore, there appear to be no previous studies on protection factors against biological particles. In this study, a prototype personal sampling setup was developed for determining the protection provided by respirators against non-biological and biological particles in the size range of 0.7 – 10 µm. The range covers respirable and thoracic dust particles as well as most bacterial and fungal spores. The setup is compatible for field use in workplace environments and was optimized by minimizing particle losses in its aerosol transmission system. Theoretical modeling, laboratory tests, and field tests were performed for design optimization. After accounting for aerosol deposition mechanisms due to gravity, inertia, and turbulence affecting aerosol transmission through the straight and bending sections of specialized tubing, the theoretical data showed best agreement with the laboratory and field data for a tube diameter of ½ inch (~1.27 cm) among the three tested diameters. Tubing of this diameter also had the least amount of particle losses, and can be directed either above the ear or above the shoulder of the person whose respiratory protection is being evaluated. In addition, the ability of the setup to measure the WPF when a human subject donned a respirator was demonstrated successfully during soybean unloading. This study suggests that the new setup is a promising tool for future studies on evaluating respiratory protection against airborne dusts and microorganisms in occupational environments.

Keywords: workplace protection factor, respirator, penetration efficiency, respiratory protection, personal setup.

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1. Introduction

Respirators are commonly used as personal protection equipment in workplaces. Nearly 3.3 million American workers use respirators against contaminants and hazards in the workplace (United States Department of Labor, 2002). However, the degree of comfort provided by respirators is not always acceptable (Akbar-Khanzadeh et al., 1995). Among agricultural workers, disposable respirators are rated best for weight and convenience, whereas powered helmets are rated best for breathing ease, communication ease, skin comfort, and in-mask temperature and humidity. The design of the respirator is usually a trade-off between its comfort and the ability to protect. Reusable half-mask or quarter-mask respirators are most often the best compromise (Popendorf et al., 1995).

Respirators can be classified into two types: air-purifying respirators, which remove contaminants from the ambient air, and atmosphere-supplying respirators, which provide air from a source other than the surrounding atmosphere. Air-purifying respirators are used most frequently in routine work practices because they are small, relatively easy to maintain, and least restrictive of the wearer's movements (Han et al., 1997). The National Institute for Occupational Safety and Health (NIOSH) lists nine categories of respirators (N95, N99, N100, P95, P99, P100, R95, R99, and R100). Among these, N95 respirators have been recommended by the Centers for Disease Control and Prevention (CDC) for health care workers to protect them from infectious diseases potentially spread through the air (such as SARS and tuberculosis). The number 95 in this designation means that the filtration efficiency of the respirator is at least 95% for the most penetrative particle size, which is 0.3 μm . The letter "N" means that this type of respirator is not resistant to oil (NIOSH, 1996).

Penetrations through the filter material and face seal leaks are the two major pathways for particles to enter the respirator cavity. The penetration efficiency of particles through the respirator is defined as a ratio of the particle concentration inside the respirator to that outside the respirator. The NIOSH test method for certifying non-powered particulate respirators is designed for measuring the particle penetration efficiency through the filter material of the respirator at the most penetrative particle size (NIOSH, 1995). This protocol is not intended to account for particle penetration through face seal leaks, although several studies have shown that most of the particles penetrate into the respirator through the leaks (Oestenstad et al., 1990a and 1990b). The NIOSH protocol is also not particle size selective, although the particle size affects the aerosol penetration through both the leaks and the filter material (Holton et al., 1987; Chen et al., 1990 and 1992).

In recent years, an increased effort has been undertaken to evaluate the performance of respirators in the workplace. Respiratory protection is usually evaluated by determining the protection factor, which is the ratio of the concentration outside the respirator to the concentration inside the respirator (inverse penetration efficiency). As the ratio increases, the level of the protection provided by the respirator also increases. Protection factors depend on the conditions under which the aerosol concentration measurements are conducted. The following terms are most commonly used to evaluate

the performance of respirators: fit factor (FF), workplace protection factor (WPF), and assigned protection factor (APF). The fit factor (FF) is a quantitative estimate of the fit of a particular respirator to a specific individual when a respirator is worn under well-defined test conditions (OSHA, 2003). The procedure for determining the FF is referred to as “quantitative fit testing”. The WPF is defined as a measure of the protection provided in the workplace, under the conditions of that workplace, by a properly selected, fit-tested, and functioning respirator while it is correctly worn and used (NIOSH, 1995; AIHARPC, 2002). Thus, the measurement of the WPF is expensive and time consuming (Weber et al., 2000; Nelson et al., 2001; Groves et al., 2003). The APF is an estimate of respirator performance when a respirator is used by a properly fitted and trained user. The Occupational Safety and Health Administration (OSHA) is proposing to revise its existing Respiratory Protection Standard to add the definition of APF. NIOSH (1995) and AIHARPC (2002) have given the definition of the APF, which is the level of the respiratory protection that a properly functioning respirator or class of respirators would be expected to provide to properly fitted and trained users in the workplace. Thus, the proposed APFs would provide employers with important information to use when selecting respirators for employees exposed to contaminants in the workplace.

Only a limited number of data is currently available, which limits OSHA’s ability to regulate the APF for different types of respirators. Thus, there is a need to broaden the WPF database for a variety of occupational environments, personal protection practices, and the particle size ranges of airborne contaminants. Many of the previous studies of the WPF against dust have been performed by collecting the mass of the total dust inside and outside the respirators without investigating the respiratory protection for individual particle size ranges (Myers et al., 1996; Zhuang et al., 1996). Furthermore, there appear to be no prior publications on the WPF against bioaerosols.

In this study, a new personal sampling setup for determining the protection provided by respirators against dust and biological particles in the field or in the laboratory has been developed and evaluated. The setup was designed for particles in the size range of 0.7 – 10 μm , which covers the size of most bacterial and fungal spores (Reponen et al., 1996; Górný et al., 1999). The setup was optimized by minimizing the particle losses in the aerosol transmission system, which may affect the evaluation of the respirator performance. For example, Liu et al. (1984) have shown that particle losses occurring in the sampling probe may underestimate the aerosol concentration inside the respirator, which results in overstating the respiratory protection. We evaluated particle transmission through the aerosol sampling system using theoretical and semi-empirical models (Brockmann, 2001) accounting for gravitational, inertial, and turbulent deposition inside the straight and bending sections of the setup. The theoretical data were compared to experimental data obtained in a walk-in test chamber (laboratory evaluation) and in two horse barns (field evaluation). The results were used to optimize the setup.

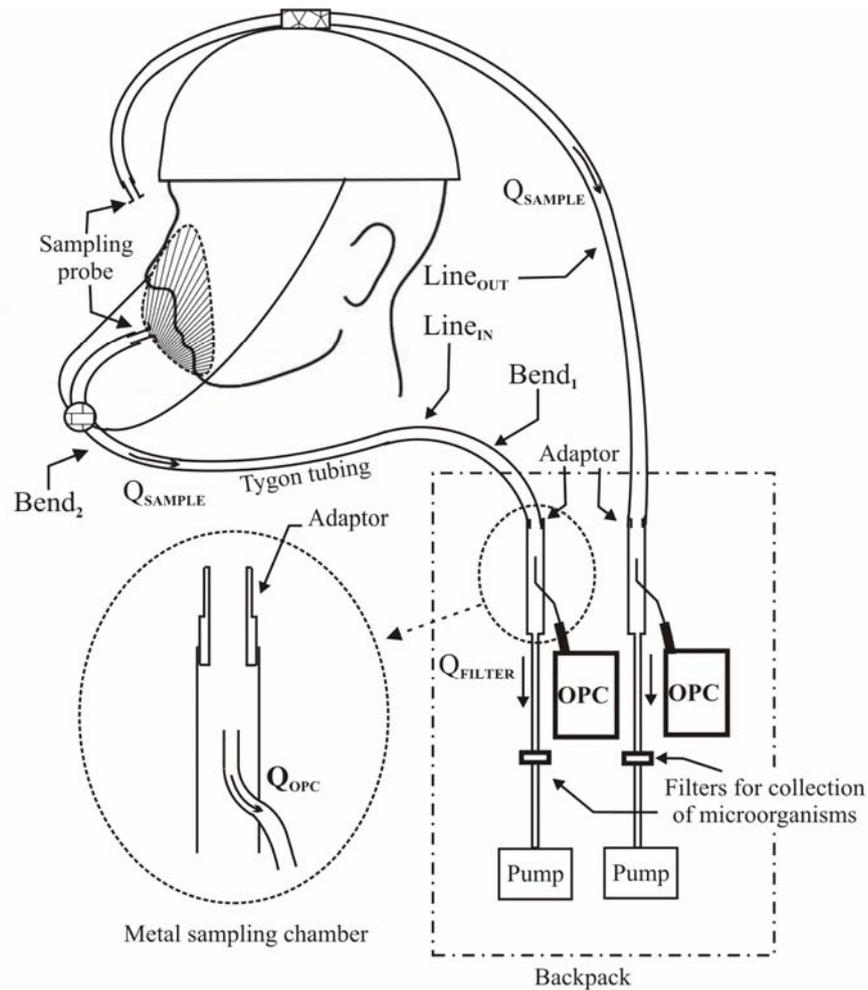


Figure 1. Schematic presentation of the new method for measuring the protection provided by respirators against fungal spores and dust. OPC = Optical Particle Counter; Q = volumetric flow rate.

2. Materials and Methods

2.1. Prototype Personal Sampling Setup

Currently, all Quantitative Fit Tests (QNFTs) performed by aerosol detection are conducted with a sampling probe imbedded in the respirator body in the breathing region between nose and mouth or at the mouth. Disposable sampling probes and ports have been designed for use with different filtering facepiece respirators so that the wearers can choose different brands of filtering facepiece respirators for the fit test (Coffey et al., 2002). The fit factor is defined as the ratio of the concentration outside the respirator to that inside the respirator (OSHA, 2003). Based on the principle of the fit test setup, a portable personal sampling setup has been designed in this study for measuring the concentrations of dust and microorganisms inside and outside a respirator (Figure 1). While conventional quantitative fit testing is performed in a laboratory setting, the new system is compatible for field use in

workplace environments. The setup consists of seven components in each of the two sampling lines: sampling probe (Adaptor Kit 8025-N95, TSI Inc., St. Paul, MN, USA), Tygon tubing (Tygon Tubing, Fisher Scientific, Pittsburgh, PA, USA), adaptor, metal sampling chamber, optical particle counter (OPC, model HHPC-6, ARTI Inc., Grants Pass, OR, USA), 25-mm filter cassette (A.P. Buck Inc., Orlando, FL, USA), and pump (Leland Legacy, SKC Inc., Eighty Four, PA, USA). The total weight of the setup is about 5 kg. The fully charged pump and the OPC can operate continuously for eight hours.

The standard fit testing sampling probe, which can be easily mounted on the respirator body, is used in this setup to take in-facepiece samples from the respirator. In order to minimize the sampling bias between the in-facepiece and ambient sampling lines, the inlets of both sampling lines have been made identical by using standard fit testing sampling probes of the same design. A helmet with a copper tubing frame is used to fix the sampling line in a stable position to minimize face seal leaks due to the movement of the person wearing the sampling setup. The ambient sampling line is located on the top of the helmet while the in-facepiece sampling line can be placed above the ear or above the shoulder. Airborne dust and microorganisms are sampled through the sampling probes and are drawn through Tygon tubing and an adaptor to a metal sampling chamber in each line (copper cylinder with inner diameter [i.d.] = $\frac{1}{2}$ inch [1.27 cm], and length = $4\frac{1}{4}$ inch [10.80 cm]). A portion of each aerosol flow is sampled from the chamber into an OPC, and the rest passes through a filter sampler, where the airborne particles are removed before the airflow is passed through a pump in each line. The OPC inlet, a 3-inch long copper tube (i.d. = $\frac{1}{8}$ inch [0.32 cm]), is imbedded isoaxially in the middle of the sampling chamber. The inner diameters of the sampling chamber and the OPC inlet have been chosen for isokinetic aspiration. The particle concentrations and size distributions are recorded and instantly displayed on the OPC screen each minute. The ARTI-manufactured OPC was chosen because of its portability and built-in data log. The OPC has temperature and relative humidity sensors. It operates at a constant airflow rate of 2.8 L/min. The filter (black polycarbonate, with a pore size of 3.0 μm and an outer diameter of 25 mm; Osmonics Inc., Westborough, MA, USA) in the filter sampler is analyzed for microorganisms by microscopic counting and/or cultivation.

An airflow of 10 L/min (5 times the conventional in-facepiece sampling flow rate used for FF measurements) was chosen for the sampling lines inside and outside the respirator. This higher sampling flow rate decreases the respirator purge time and significantly reduces potential sampling bias for non-homogenous distributions of the particle concentration inside the respirator which have been noted by Myers et al. (1986 and 1988), Beever et al. (1978), and others. 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 respirator performance against low concentrations of airborne microorganisms.

The OPC uses 2.8 L/min of the total airflow of 10 L/min; thus, 7.2 L/min passes through the filter for the collection of microorganisms and other airborne particles. The filter selection is usually a compromise between collection efficiency and pressure drop. A decrease in the filter porosity and

pore size increases the collection efficiency, but at the same time increases the pressure drop, if the flow rate remains the same. The latter is of concern for a portable, field compatible setup because the capacity of the sampling pump is limited. A 3 μm pore size polycarbonate filter has been selected because it has a sufficiently low pressure drop for the high-flow Leland Legacy personal pump, yet provides a high collection efficiency for the particle sizes of interest (95.4% for 3 μm PSL [polystyrene latex] particles at 7.2 L/min). As shown in Figure 1, the two sampling lines simultaneously collect air samples outside and inside the respirator. Therefore, two sampling pumps, two 25-mm filter cassettes, and two OPCs are located in the backpack, which is closer to the breathing zone and more convenient for workers to carry than is possible with the conventional approach of measurement devices placed on a belt. The personal sampling setup can be used for filtering facepiece respirators by imbedding a sampling probe into the respirator surface.

2.2. Theoretical Calculations of Particle Transmission through the Setup

The setup was optimized by minimizing particle transmission losses. The particles are first drawn through the sampling probe into the Tygon tubing, and then transmitted from the Tygon tubing through the adaptor to the metal sampling chamber. Inside the metal sampling chamber, the particles are separately directed to the OPC for the particle measurement and to the filter for subsequent microscopic analysis. Thus, the sampling probe, the Tygon tubing, the adaptor, and the metal sampling chamber are major components where particle losses may occur during aerosol transmission through the setup.

When the aerosol is transmitted through these elements, some of the particles may be lost due to aerosol deposition mechanisms such as gravitational settling, diffusional deposition, turbulent inertial deposition, electrostatic deposition, and thermophoretic deposition. Tygon tubing is chosen to obviate the losses by electrostatic deposition (Liu et al., 1985). Any small temperature gradient in the sampling line is negligible; thus, particle losses due to thermophoretic deposition can also be neglected in the theoretical model. As explained earlier, the particle penetration efficiency is determined for the particle size range of 0.7 – 10 μm . For this particle size range, diffusion deposition is negligible and, therefore, is also ignored in the calculations (Brockmann, 2001).

The particle penetration efficiency of the system was calculated using the computer-based aerosol calculator (Aerosol Calculator Program, TSI Inc., St. Paul, MN, USA). The computer program includes various particle deposition mechanisms (Brockman, 2001), such as gravitation, inertia, and turbulence, which occur in straight lines as well as in bends. The calculations were performed separately for the following sections of the sampling setup: a straight section of Tygon tubing, two bends of the Tygon tubing (Bend₁ and Bend₂ in Figure 1), the sampling probe, the adaptor, and the metal sampling chamber. At the constant sampling flow rate of 10 L/min, the following variables were tested: three tubing diameters: $\frac{1}{8}$ inch (0.32 cm), $\frac{1}{4}$ inch (0.64 cm) and $\frac{1}{2}$ inch (1.27 cm); two tubing lengths: 30 inches (76.2 cm) and 40 inches (101.6 cm); and two bends: Bend₁ and Bend₂.

Sampling pumps, filter samplers, and the metal sampling chamber were vertically positioned inside the backpack. Tygon tubing extending from the metal sampling chamber was directed to the breathing zone, and thus Bend₁ was formed and differed for two tubing placements. Bend₂ was formed by bending Tygon tubing in order to connect with a respirator worn on a subject's face. When the tubing was placed above the ear, the measured angle and radius were 110° and 20.32 cm for Bend₁, and 180° and 5.08 cm for Bend₂ (Figure 1). The respective values were 90° and 10.16 cm for Bend₁, and 180° and 5.08 cm for Bend₂ when the tubing was placed above the shoulder. When the tubing was placed above the ear, its length was 40 inches (101.6 cm). When it was placed above the shoulder, the length was 30 inches (76.2 cm). The theoretical calculations were performed for an air temperature of 20 °C (293.15 °K), pressure of 1 atm (101.3 kPa), and particle density of 1 g/cm³ (1000 kg/m³).

2.3. Laboratory Evaluation of Particle Transmission through the Setup

For tubing 1/8-inch in diameter, the theory predicts very high losses (about 100%) if the particle size exceeds 3 μm. For the two larger tubing diameters, the losses are lower (depending on the particle size). Therefore, only tubings of 1/4 inch and 1/2 inch were selected for the laboratory and field experiments. A walk-in indoor test chamber (860 ft³ = 24.3 m³), developed in the Center for Health-Related Aerosol Studies (University of Cincinnati) and used in previous studies (Choe et al., 2000), was utilized to conduct the laboratory evaluation of the particle losses in the newly designed personal setup. During the experiments, the test chamber was maintained at a positive pressure of 1 inch w.g. (249 Pa) relative to the ambient air due to a constant oversupply of clean filtered air compared to a stable exhausted air flow. A manikin positioned inside the chamber was equipped with the personal sampling setup simulating the real field situation, except that there was no respirator on the manikin face.

Three challenge aerosols were used in the experiments: the first was generated from a sodium chloride solution (NaCl, 1%, w/v), the second was produced from a suspension of 2.93 μm PSL particles (0.05%, v/v), and the third was prepared through aerosolization of Arizona road dust. A six-hole Collison nebulizer (BGI Inc., Waltham, MA, USA) was utilized to generate NaCl and PSL particles by operating a pump at a pressure of 20 psi (1.38 × 10⁵ Pa) with a flow rate of 12 L/min. Dry air was introduced at a flow rate of 40 L/min. Since the laboratory-generated particles may carry high electrical charges, the entire airflow of 52 L/min was directed through a 10 mCi Kr-85 charge equilibrators (Model 3054, TSI Inc., Minneapolis, MN, USA) to achieve Boltzmann charge equilibrium. The continuous aerosol generation in combination with chamber ventilation allowed constant aerosol concentrations to be achieved and maintained in the chamber. The number concentrations of the larger NaCl particles (5 – 10 μm) generated by the Collison nebulizer were not sufficient. For this reason, Arizona road dust dispersed by a cyclonic vacuum cleaner (Bagless Cyclonic System, Model 4481, Eureka Company, Bloomington, IL, USA) was also used as a test aerosol in selected experiments. An air circulation fan (with a flow rate of about 900 CFM) located in

the outlet of the aerosol generation system distributed the aerosolized particles within the walk-in chamber.

An OPC with an inlet of 0.1 inch (0.25 cm) in diameter was placed next to the manikin breathing zone and measured the aerosol concentration at the inlet of the sampling line (C_{inlet}). The sampling location of this OPC was 2 cm away from the in-facepiece sampling probe. C_{inlet} also represented the aerosol concentrations inside the chamber. The respirator was not actually used in the study, and the sampling probes were placed in the same location relative to the manikin face as they would be in the actual workplace measurements. The ambient aerosols were drawn from the in-facepiece sampling probe to Tygon tubing, and transmitted from Tygon tubing through the adaptor to the metal sampling chamber. The aerosol concentration measured by the other OPC in the metal sampling chamber (i.e., at the outlet of the sampling line [C_{outlet}]), represented the concentration of particles that penetrated through the sampling line. The laboratory experiment began when the aerosol concentration inside the chamber reached steady state. The penetration efficiency of particles (P) through the setup was determined as the ratio of the aerosol concentration measured at the outlet (C_{outlet}) to that at the inlet (C_{inlet}) of the sampling line:

$$P = \frac{C_{outlet}}{C_{inlet}} \quad (1)$$

The particle concentrations C_{outlet} and C_{inlet} were measured continuously during five minutes with the data recorded every minute. The average penetration efficiency was calculated by averaging the data from the middle three minutes of the five-minute interval measurement for each condition. When measured side-by-side, the difference in the aerosol concentrations between the two OPCs was below 10% for each particle size range. In order to further minimize the effect of performance difference between the two OPCs, each experiment was repeated after exchanging the position of the instruments. The average of these six measurements (the sum of three one-minute measurements before and after exchanging the instruments for the same condition) represented the penetration efficiency for each condition. These experimental data sets were compared to the overall penetration efficiency obtained through the theoretical calculations.

Two configurations were tested: the tubing placed above the ear (length = 40 inches) and the tubing placed above the shoulder (length = 30 inches). For each configuration, two tubing diameters were tested: ¼ inch and ½ inch, as described earlier.

2.4. Field Evaluation of Particle Transmission through the Setup

The field study was conducted in two horse barns because this type of environment had sufficient concentrations of aerosol particles, including biological particles, in the size range of interest (0.7 – 10 μm). A manikin equipped with the setup was positioned in a horse stall to simulate how a subject would wear the setup. Similar to the laboratory testing,

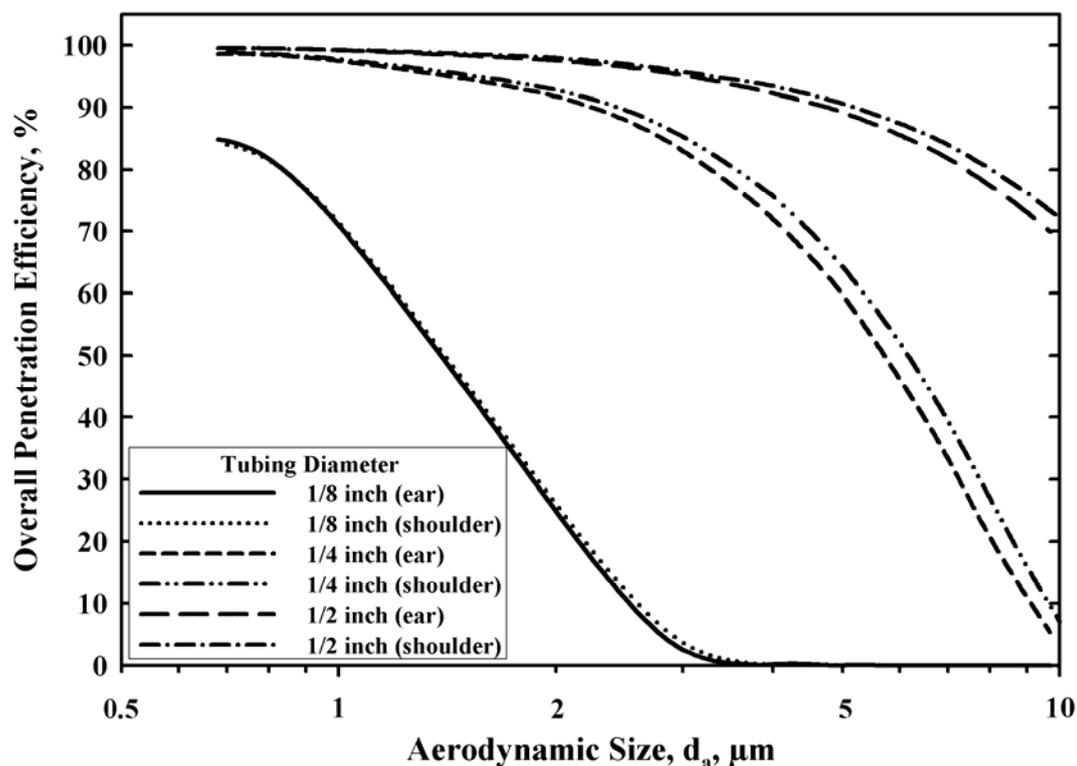


Figure 2. Overall penetration efficiency of particles in the Tygon tubing after accounting for gravitational, turbulent, inertial, and bending losses (theoretical calculation).

two tubing placements (above the ear and above the shoulder), and two tubing diameters ($\frac{1}{2}$ inch and $\frac{1}{4}$ inch) were tested. Two OPCs, which operated at their nominal flow rates, measured particle concentrations at the inlet and at the outlet of the in-facepiece sampling line, respectively, while hay and manure were being moved during a routine cleanup operation. The penetration efficiency was calculated by averaging the data from six measurements (as described in the previous section), and compared to the theoretical data. The results were used to optimize and finalize the design of the newly developed setup.

2.5 Field Evaluation of the Setup

Field evaluation of the setup was performed on an agricultural farm near Clarksville, Ohio, USA. A human subject wearing an N95 respirator (Model 8210, 3M, St. Paul, MN, USA) and the new setup walked around a semi truck during soybean unloading. Fit testing was conducted using a TSI Portacount with an N95 companion (TSI Inc., St. Paul, MN, USA) before the field test. With the quantitative fit test, a fit factor of 100 or above constituted a pass. The field measurements were conducted continuously for 30 minutes with particle concentrations averaged over one-minute periods. The temperature outside the respirator was 18 to 20 °C and the relative humidity was 70 to 75%. The average total concentration of particles measured with the OPC in the size range of 0.7 to 10 μm

outside the respirator was 1.3×10^8 particles/m³.

3. Results and Discussion

Figure 2 shows the theoretical overall penetration efficiency of particles through Tygon tubing as a function of the aerodynamic size after accounting for the combined effect of gravitational, turbulent, inertial, and bending losses for the two tubing placements and the three different tubing diameters. As seen in Figure 2, the overall penetration efficiency decreased with increasing particle size as well as with decreasing tubing diameter. A decrease in overall penetration efficiency was more pronounced in $\frac{1}{8}$ inch tubing compared to the two larger tubing diameters ($\frac{1}{4}$ inch and $\frac{1}{2}$ inch). For particle sizes above 3 μm , the penetration efficiency through the $\frac{1}{8}$ inch tubing was close to zero. In addition, the two different tubing placements (above the ear and above the shoulder) resulted in about the same losses for the same tubing diameter. The overall penetration efficiency decreased with decreasing tubing diameter and increasing particle size. For example, when the tubing was placed above the ear, the overall penetration efficiencies of 10 μm particles were 70% for the $\frac{1}{2}$ inch tubing, 5% for the $\frac{1}{4}$ inch tubing, and 0% for the $\frac{1}{8}$ inch tubing, while the respective values for 0.7 μm particles were 100%, 99%, and 83%.

Based on the results obtained from the theoretical calculations, the $\frac{1}{2}$ inch and $\frac{1}{4}$ inch tubings were selected for further investigation. As indicated earlier, the sampling line included not only the Tygon tubing but also a metal sampling chamber, a sampling probe, and an adaptor. The penetration efficiency of particles through the metal sampling chamber, sampling probe, and the adaptor was calculated by accounting for gravitational, inertial, and turbulent losses (data not shown).

Figure 3 shows the overall particle penetration efficiencies obtained experimentally in the test chamber and calculated theoretically after accounting for various aerosol deposition mechanisms in four elements (sampling probe, Tygon tubing, adaptor, and metal sampling chamber), which direct samples to the OPC and the filter sampler in the sampling line. The data in Figure 3 are presented as a function of particle size. As the experimental values of the penetration efficiency were determined from the particle measurement by the optical particle counter, they were plotted against the optical particle diameter (d_{opt}). The theoretical values were calculated utilizing the aerodynamic particle size (d_a) and are, therefore, plotted against the aerodynamic diameter. The experimentally determined penetration efficiency did not show much dependence on the tubing diameter when it ranged from $\frac{1}{4}$ inch to $\frac{1}{2}$ inch, and was about the same for different types of particles dispersed inside the walk-in chamber. As an example, for the $\frac{1}{4}$ -inch tubing placed above the ear, the experimental penetration efficiencies of the particles ranging from 3 – 5 μm were 77% when tested with NaCl aerosols, 75% when tested with PSL particles, and 61% when tested with Arizona road dust. Correspondingly, these values were 77%, 83%, and 78% for the $\frac{1}{2}$ inch tubing. The experimental data also showed about the same

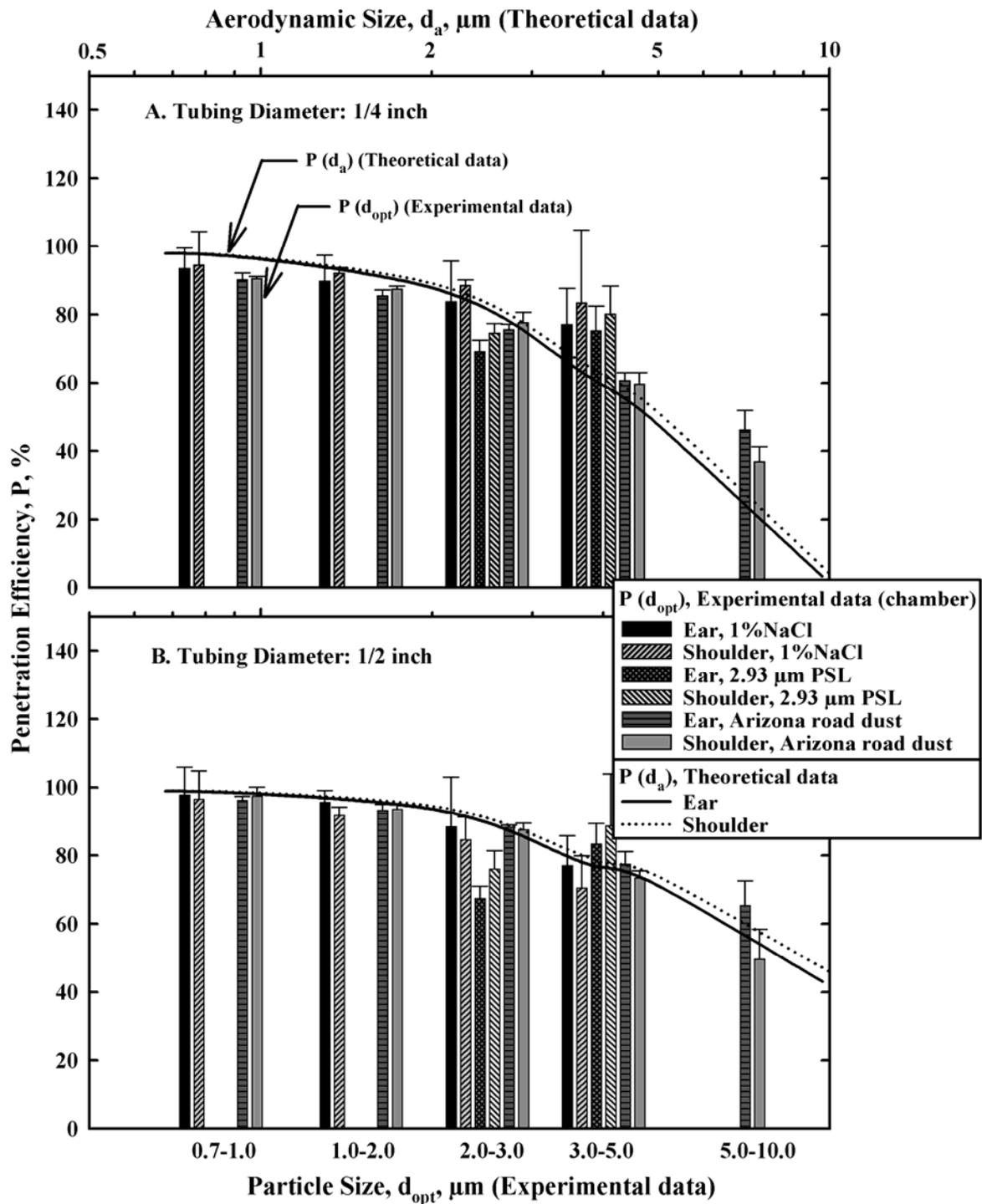


Figure 3. Penetration efficiency of particles through the entire setup with 1/4-inch tubing (A) and 1/2-inch tubing (B): theoretical data vs. experimental data obtained in the walk-in chamber. The top x-axis scale is the aerodynamic diameter for the theoretical data while the bottom x-axis scale is the optical diameter for the experimental data. For the experimental data, each data point is an average of six measurements and the error bar shows the standard deviation.

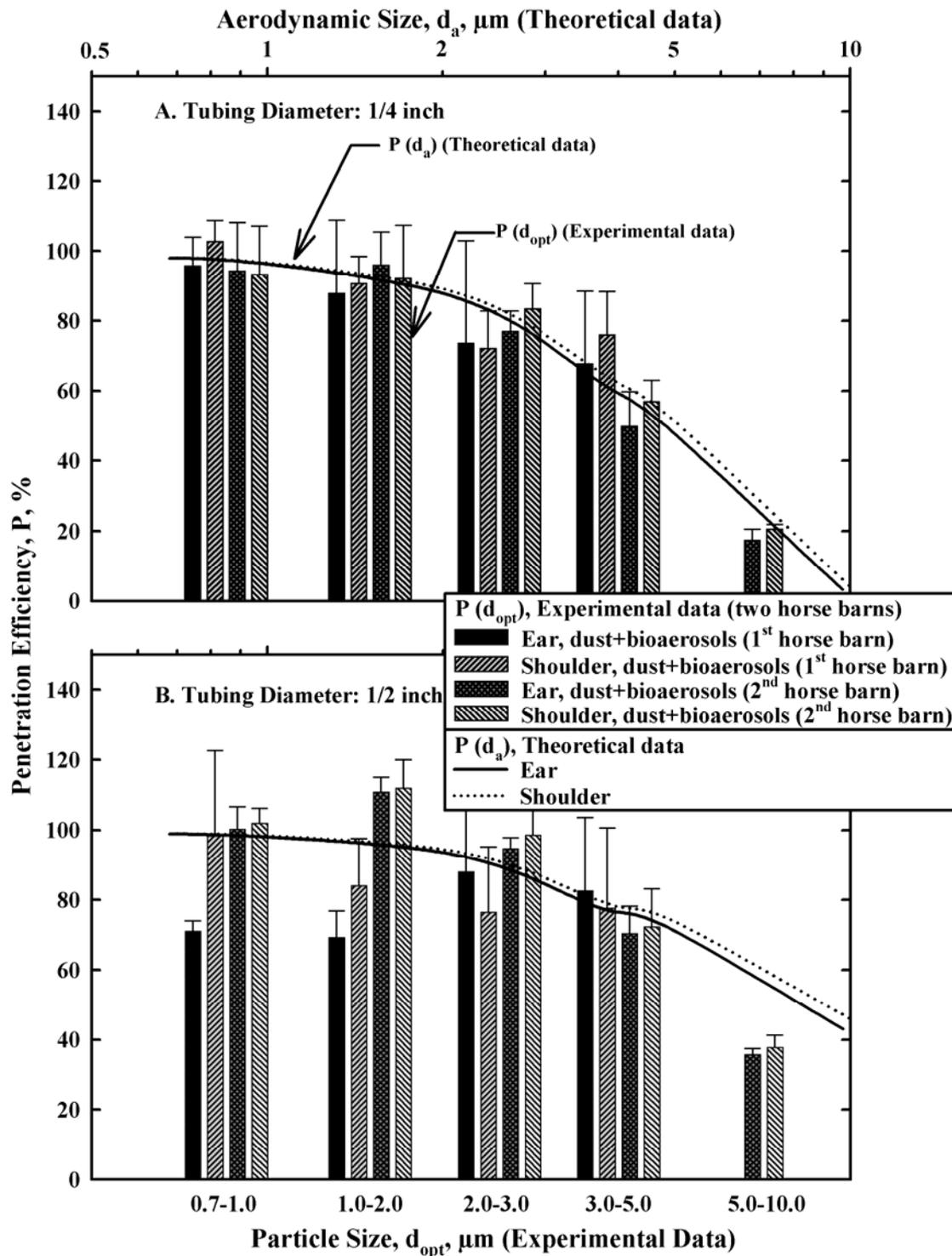


Figure 4. Penetration efficiency of particles through the entire setup with 1/4-inch tubing (A) and 1/2-inch tubing (B): theoretical data vs. experimental data obtained in horse barns. The top x-axis scale is the aerodynamic diameter for the theoretical data while the bottom x-axis scale is the optical diameter for the experimental data. For the experimental data, each data point is an average of six measurements and the error bar shows the standard deviation.

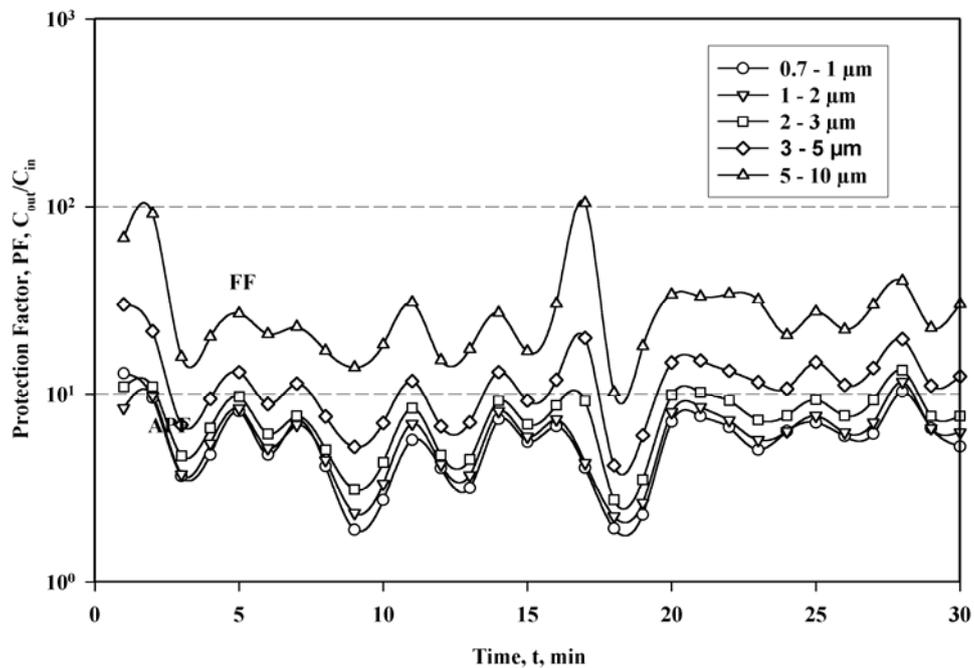


Figure 5. Field-testing on fractional protection factors during soybean unloading. The subject wearing a respirator and the setup breathed normally and walked around semi truck during the entire 30-minute test period. Legend: FF = Fit Factor, APF = Assigned Protection Factor.

results for the two tubing placements (above the ear or above the shoulder). The experimental data for particles in the size range of 5 – 10 μm , which was the broadest size channel of the OPC, was closer to the theoretical data calculated for 5 μm particles than those calculated for 10 μm particles (Figure 3). Particles larger than 5 μm represented only 0.7% of the total number when Arizona road dust was dispersed in the test chamber. In this case, the small particles predominated. Thus, in the size range of 5 – 10 μm , the concentration of 5 μm particles can be expected to be much higher than with the other sizes. Comparing the laboratory-generated data to the theoretical data, the best agreement and highest penetration levels occurred when using the $\frac{1}{2}$ inch tubing. For the $\frac{1}{4}$ inch tubing, the experimental data agreed with the theoretical data for the particle sizes below 5 μm but showed greater values of the penetration efficiency for particles above 5 μm . The difference can be attributed to the effect of particle bounce or reentrainment from the inner wall of the Tygon tubing, which was not accounted for in the theoretical calculations. The effect is more pronounced for the $\frac{1}{4}$ inch tubing because of the higher air velocity in this tubing compared to the $\frac{1}{2}$ inch tubing.

Figure 4 shows the experimental penetration efficiency through the sampling line obtained in two

Table 1. The ratio of the particle concentration measured in the ambient sampling line to that in the in-facepiece sampling line (expressed in percentage). The mean value and the standard deviation are calculated for five measurements.

0.7 – 1.0 μm			1.0 – 2.0 μm			2.0 – 3.0 μm			3.0 – 5.0 μm			5.0 – 10.0 μm		
Mean	\pm	SD	Mean	\pm	SD									
124.5	\pm	2.5	116.0	\pm	2.8	100.5	\pm	2.3	94.8	\pm	5.0	76.5	\pm	6.9

horse barns. In the first horse barn, only 0.2% of the ambient total particle concentration was composed of particles larger than 5 μm . Thus, the C_{outlet} of large particles was not sufficiently high to determine penetration efficiency. Generally, the field data in the first horse barn were in good agreement with the laboratory-generated data and the theoretical data for particles $<5 \mu\text{m}$. In the second horse barn, however, more large particles were present. The penetration efficiencies obtained in the second barn for 5 – 10 μm particles were close to the theoretical values determined for 10 μm particles. For example, the field-measured average penetration efficiencies of particles through the $\frac{1}{2}$ inch tubing were 36% (ear) and 38% (shoulder), while the theoretical overall penetration efficiencies of particles in the size range of 5 – 10 μm varied from 43 to 72% (ear) and from 46 to 74% (shoulder). Both the experimental and theoretical data sets showed that there was no significant difference in the two different tubing placements. In the second barn, particles larger than 5 μm comprised 36% of the total particle number. Particles larger than 10 μm represented about 13% of the total number. The particle size distribution with greater percentage of large particles, which was encountered in the second horse barn, caused greater losses inside the sampling line. This explains why the field data for particles in the size range of 5 – 10 μm were close to the theoretical data obtained for 10 μm particles. The channel of the OPC that provides the concentration of the particles in the size range of 5 – 10 μm is the broadest size range compared to other channels of this instrument (particles larger than 10 μm are not classified further by size). If the small particles represented the major contribution to the particle concentration in the environments, the penetration efficiency of particles in the size range of 5 – 10 μm can be expected to be close to the theoretical data for 5 μm particles (72%, tubing above the ear). Otherwise, it is closer to the theoretical data obtained for 10 μm particles (43%, tubing above the ear). Thus, the size distribution of the particles in the environment can be a cause of the variability of the penetration efficiency for the size range of 5 – 10 μm , which potentially explains some discrepancy between the theoretical and experimental data that occurred in the size range of 5 – 10 μm (Figures 3 and 4). In addition, the effect of bounce or reentrainment was considerably larger in the $\frac{1}{4}$ inch tubing than in the $\frac{1}{2}$ -inch tubing, as described above. Thus, the experimental data in the $\frac{1}{4}$ inch tubing were expected to be much higher than the theoretical data, which is true if the experimental data in the size range of 5 – 10 μm is compared to the theoretical data obtained for 10 μm . For example, the experimental penetration efficiencies of 10 μm particles were 38% for the

½-inch tubing and 21% for the ¼-inch tubing when the tubing was placed above the shoulder, while the respective theoretical values were 45.9% and 4.1%.

Because the particle size distribution and the tubing placements affect the particle penetration efficiency of the sampling line, especially for particles of 5 – 10 µm, the respirator protection factors should be calibrated based on the sampling bias between the in-facepiece sampling line and the ambient sampling line. Table 1 shows the ratios of the particle concentrations measured in the ambient sampling line to that in the in-facepiece sampling line (expressed in percentage). The results represent the experiments performed with NaCl particles. The standard deviations (representing precision) of the ratios (expressed in percentage) obtained for the five particle size fractions within the size range of 0.7 to 10 µm varied from 2.3 to 6.9 for five repeats. The bias can be estimated by subtracting the ideal 100% from the individual number for each particle size range. This bias varied from 0.5 to 24.5% and includes the difference in the penetration efficiencies through the in-facepiece and the ambient sampling lines, as well as the difference in the counting efficiencies of the two OPCs. The results show that precision and bias can be controlled within 25% or better, which is generally considered acceptable for personal samples collected in a process of industrial hygiene evaluations (Johnston et al., 2001). These data can also be used as a quality control for trials performed in field environments.

The newly developed personal setup for assessing the efficiency of respirators against particles was finalized after evaluating the penetration efficiency of sampling lines using the theoretical model, laboratory experiments, and field experiments. The results suggest that the tubing diameter of ½ inch is the most suitable for a particle size range of 0.7 to 10 µm. Since there was no considerable difference in penetration efficiency resulted from two tubing placements (above the ear and above the shoulder), both can be used for sampling. Figure 5 shows an example of a WPF measurement conducted on a soybean farm. As seen in Figure 5, the protection factor increased with increasing particle size, as expected. The protection factor ranged from 2 to 12 for $d_{opt} = 0.7 - 1 \mu\text{m}$, from 2 to 12 for $d_{opt} = 1 - 2 \mu\text{m}$, from 3 to 13 for $d_{opt} = 2 - 3 \mu\text{m}$, from 4 to 30 for $d_{opt} = 3 - 5 \mu\text{m}$, and from 4 to 30 for $d_{opt} = 5 - 10 \mu\text{m}$. It is worth noting that all the WPF-values were below the fit factor (100) and most of them even below the assigned protection factor (10 for filtering facepiece respirators). The further application of the personal setup in measuring the respiratory protection against airborne dust and microorganisms will be investigated in future field studies.

4. Conclusions

A new personal sampling setup was developed for measuring the protection provided by respirators against dust and microorganisms in the size range of 0.7 – 10 µm. The setup was optimized by minimizing particle losses in the aerosol transmission system through theoretical modeling, laboratory tests, and field tests. After accounting for aerosol deposition mechanisms due to gravity,

inertia, and turbulence in the straight and bending sections, the theoretical data showed best agreement with the laboratory and field data for a tubing diameter of ½ inch (~1.27) cm among the three tested tubing diameters. The selected tubing also exhibited the least particle losses, and can be directed either above the ear or above the shoulder of a person wearing the setup. In addition, the setup demonstrated its capability for measuring the protection factor in real field conditions on a soybean farm. The theoretical, laboratory, and field tests have demonstrated that the new personal setup is a promising tool for future studies on evaluating respiratory protection against airborne dusts and microorganisms in occupational environments.

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