Filtering Efficiency of N95- and R95-Type Facepiece Respirators, Dust-Mist Facepiece Respirators, and Surgical Masks Operating in Unipolarly Ionized Indoor Air Environments

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Abstract

The emission of unipolar air ions in the vicinity of a filtering facepiece respirator has been recently shown to considerably enhance its respiratory protection efficiency. The effect is driven by the electric repelling forces that develop between the unipolarly charged mask and the aerosol particles, thus creating a shield for the incoming particles and consequently decreasing the penetration efficiency through the filter. The manikin-based preliminary evaluation of this concept has been performed with a very limited number of variables. In this study, four types of half-mask facepiece filtering devices (N95, R95, and dust-mist respirators, as well as surgical masks), operating at two different breathing flow rates, were tested with unipolar air ion emitters exhibiting different emission rates and polarities. The particle penetration efficiency through the facepiece filter was determined in a room-size indoor test chamber by a real-time particle size selective aerosol monitoring performed inside and outside of the mask, which was face-sealed onto a manikin. Three commercially available ionic air purifiers were utilized as air ion emitters. For the targeted particle size range of ~0.04 – 1.3 μm, a 12- minute air ionization in the vicinity of a manikin enhanced the respiratory mask performance by a factor ranging from 1.61 to 3,250, depending on the respirator type, breathing flow rate, and the ion emission rate. The effect was achieved primarily within the first 3 minutes.

Key words: respirator, mask, ion emission, fine and ultrafine aerosol

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INTRODUCTION

The facepiece filtering respirators has been widely used to reduce human exposure to the aerosol particles. The respirator performance has been extensively studied over the years (Brosseau et al., 1989; Chen et al., 1994; Hinds et al., 1988; Huang et al., 1998; Johnson et al., 1994; Johnston et al., 2001; Lee et al., 2004c; Nicas et al., 2003; Oestenstad et al., 1990; Qian et al., 1997; Qian et al., 1998; Weber et al., 1993; Willeke et al., 1996). A wide variety of the disposable particulate respirators have been characterized with respect to their protection factor. The National Institute for Occupational Safety and Health (NIOSH)-instituted respirator certification program (*Federal Register* 60:110 (1995)) has affected millions of workers that routinely use respirators in their workplaces. Based on the collaboration of NIOSH, the U.S. Army Soldier Biological and Chemical Command (SBCCOM), and the National Institute for Standards and Technology (NIST), appropriate standards and test procedures are being developed for all classes of respirators that should provide respiratory protection from various inhalation hazards, including chemical, biological, radiological, and nuclear aerosol agents.

Although the effort towards the performance evaluation and standardization of conventional disposable particulate respirators and health-care masks have been rather successful, very little progress has been made during the last decade on the improvement of the filtering efficiency of these devices. The outbreaks of emerging respiratory diseases, such as the Severe Acute Respiratory Syndrome (SARS), as well as growing concerns about a deliberate release of the aerosolized biological warfare agents, such as bacteria and viruses, have triggered an urgent demand for improving the performance of existing respiratory protection masks, especially in the fine and ultrafine particle size ranges.

We have recently developed a novel concept, which dramatically enhances the performance of a conventional facepiece filtering respirator/mask against fine and ultrafine particles (Lee et al., 2004a). The concept is based on the charging of aerosol particles by the corona-produced unipolar air ions (Adachi et al., 1985; Hernandez-Sierra et al., 2003; Wiedensohler et al., 1994) in the vicinity of a respirator. The continuously emitted ions impose significant electric charges of the same polarity on the airborne particles and the mask surface. The repelling forces create an "electrostatic shield" against incoming particles, thus decreasing the penetration efficiency through the filter. The newly-developed concept was pilot-tested with two masks, face-sealed on a manikin operated at a fix breathing flow rate of 30 L/min, and one ion emitter (Lee et al., 2004a).

In the present study, we investigated several factors, which affect the ion-emission-driven enhancement of the protection efficiency of a conventional facepiece filtering mask when they are face-sealed to the test manikin. These factors include the type of respirator, the breathing (inhalation) flow rate, as well as the ion emission rate and polarity.

We targeted the particle aerodynamic diameter range of d_a ~ 0.04 – 1.3 μm. Numerous bioaerosol agents that can cause emerging diseases or may be potentially used in the event of bioterrorism belong to this particle size range: e.g., d_a ~0.1 μm for *coronavirus* (the etiological agent of the SARS) and d_a ~1 μm for *Bacillus anthracis* (bacteria causing anthrax).

METHODS

The experiments were conducted in an unventilated indoor test chamber (L × W × H = 3.78 m × 2.44 m × 2.64 m = 24.3 m^3). This facility has been extensively used in our previous studies (Choe et al., 2000; Grinshpun et al., 2002; Lee et al., 2004a; Lee et al., 2004b). Figure 1 demonstrates the schematic diagram of the experimental setup. A breathing manikin with a face-sealed filtering mask was exposed to a polydisperse test aerosol. The leakage tests were conducted prior to the experiments with a detergent-based leakage-detecting liquid (Trubble Bubble, New Jersey Meter Co., Paterson, NJ, USA) to identify possible macro-leaks (> 1 μm) between the mask and the face of the manikin. The manikin was located in the center of the chamber. The particle concentrations inside (C_{in}) and outside (C_{out}) the mask were measured by the electrical low pressure impactor (ELPI, TSI Inc./Dekati Ltd., St. Paul, MN, USA). This cascade impactor has a real-time measurement capability that provides data on the airborne particle number concentration and size distribution in one-minute time increments. The aerosol particles are charged by the corona charger, which is located downstream of the impactor's sampling inlet, and then detected by the electrometers inside the instruments. The data were recorded in 12 ELPI channels, from 0.04 to 8.4 μm. The latter sizes represent the midpoint diameters of the 1st and the 12th impaction stages, respectively (the midpoint = the geometric mean of the stage's boundaries).

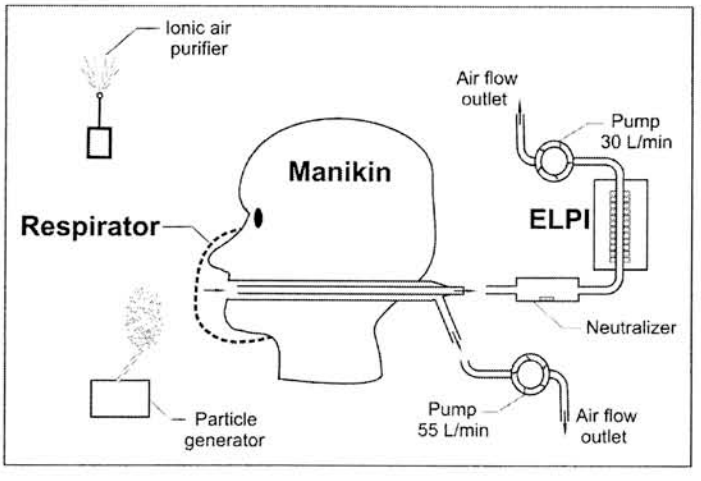

Figure 1. Experimental setup.

The penetration efficiency of the respiratory mask, E_p , was calculated from the measured concentration values by the following equation:

$$E_p = \frac{C_{in}}{C_{out}}, \tag{1}$$

The penetration efficiency was determined as a function of the particle aerodynamic diameter. For each set of condition, the test was conducted, respectively, with no air ionization and with a commercial ionic air purifier continuously operating in the chamber for 12 minutes (since the effect was usually achieved during the first 3-6 minutes, we selected the 12-min interval as sufficient for the testing). When the ELPI was used in the presence of air ion emission, the aerosol sampling inlet of the instrument was equipped with the Kr^{85} charge equilibrator (3M Company, St. Paul, MN, USA), which allowed us to avoid the effect of highly charged aerosol particles on the performance of the ELPI's electrometers. A control experiment was conducted in the chamber (without the manikin and respirator) to demonstrate the satisfactory performance of the charge equilibrator upstream the ELPI. The penetration efficiencies of a face-sealed mask obtained with and without air ion emission were compared at the following time points: t = 3, 6, 9, and 12 min. As the concentration outside the mask decreases with the time due to the particle unipolar charging and their subsequent repelling and migration to indoor surfaces (Lee et al., 2004b), the time dependence C_{out} *(t)* in the chamber was accounted for using the linear interpolation. The ratio of the above efficiencies (calculated at a specific time point) was defined as a respirator performance enhancement factor.

The background aerosol concentration in the test chamber was not sufficient for an accurate measurement inside the mask because the filter removed a considerable number of airborne particles. To increase the background concentration, we used a custom-built smoke generator that aerosolized particles in the submicrometer and micrometer size ranges (Cheng et al., 1995). This was particularly suitable to simulate airborne bacteria and viruses, as well as droplet nuclei that often serve as carriers for the air transmission of infectious agents.

Four types of half-mask filtering facepieces were tested, including the NIOSH-certified N95 and R95 respirators, disposable dust-mist respirators, and surgical masks. All of them are commercially available from a major manufacturer. The tests were conducted at two inhalation flow rates: 30 L/min (breathing under light work load) and 85 L/min (breathing under heavy work load). The lower flow rate was established by the ELPI pump that normally operates at 30 L/min. For the higher flow rate, an additional pump operating at 55 L/min was employed.

Three commercially available ionic air purifiers (Wein Products Inc, Los Angeles, USA) were utilized to produce unipolar air ions in the chamber. These included one stationary unit, VI-2500 (L × W × H =

20 cm × 16.5 cm × 8.5 cm), which emitted negative ions at a rate of ~$2\times10^{14}e^-$/s (e stands for the elementary charge unit), and two wearable units, AS150MM (+) and AS150MM (-) (L × W × H = 6.5 cm × 4 cm × 2.2 cm), which emitted positive and negative ions, respectively, at the same rate of ~$7\times10^{13}e^{\pm}$/s. (Wein Products Inc, Los Angeles, CA. Personal Communication (2002)). To standardize the ion emission rate characteristics of these ionic air purifiers, the ion concentration were measured with the Air Ion Counter (AlphaLab Inc, Salt Lake City, UT, USA) at the same distance from the source during the test. The VI-2500 stationary unit produced an air ion concentration of $(1.34 \pm 0.04) \times 10^6$ $e^- cm^{-3}$ at 1 m from the emission point, while less powerful AS150MM wearable units (positive and neative) produced $(3.62 \pm 0.18) \times 10^5$ $e^+ cm^{-3}$, and $(3.91 \pm 0.22) \times 10^5$ $e^- cm^{-3}$, respectively (Lee et al., 2004b). In each test, a unipolar ion emitter was turned on at a distance of 20 cm from the mask. Once the emitter was turned on in the chamber, the ion concentration rapidly increased to the saturation level (specified above for each device). It occurred in less than 10 seconds, after which the concentration of air ions remained at that level while the device was operating. Once the emitter was turned off, the ion concentration decreased to the initial level in about 3 minutes.

The test chamber was operated at an air temperature of $23 \pm 1C^0$ and a relative humidity of $42 \pm 9\%$, which were monitored during each test by a thermometer/hygrometer (Tandy Co, Fort Worth, TX, USA).

The average value and the standard deviation were calculated for each set of conditions as a result of at least three replicates. The data were statistically analyzed using software package Microsoft Excel (Microsoft Co, Redmond, WA, USA).

RESULTS AND DISCUSSION

Original Characteristics of the Face-Sealed Respiratory Protection Masks (No Air Ion Emission)

First, the respirators tested in this study were characterized with respect to their original penetration efficiency (with no air ionization in the vicinity of the mask). The size-specific (fractional) concentrations of test aerosol particles measured in the chamber by the ELPI (C_{out} at $t = 0$) are presented in Figure 2. The aerosol generator was adjusted to reproduce the initial concentration and size distribution in each test with the coefficient of variation below 50% (determined from 30 replicate tests). It is seen that the aerosol particles were primarily within a range of $d_a \approx 0.04 - 0.5$ μm, with the concentration decreasing by more than an order of magnitude when the particle size exceeded 1 μm.

The particle penetration efficiency through the N95 respirator, face-sealed on the manikin inhaling at a flow rate of 30 L/min, was originally ~2%. Although the average efficiency values showed a slight decrease with increasing particle size in the submicrometer range, this effect was rather low. With a flow

rate increased to 85 L/min, we found a higher penetration than at 30 L/min. The primary difference was observed for $d_a < 0.3$ μm (Figure 3). The increase in the flow rate through the respirator filter resulted in the decrease in the residence time, which reduced the efficiency of the diffusional and electrostatic particle deposition inside the filter (the mechanism applies to the respirators equipped with electret filters). Thus, more submicrometer particles were allowed to penetrate through the electret medium of the N95 filter at higher flow rates. Similar results were obtained with the R95-type respirator operated at 30 and 85 L/min, respectively.

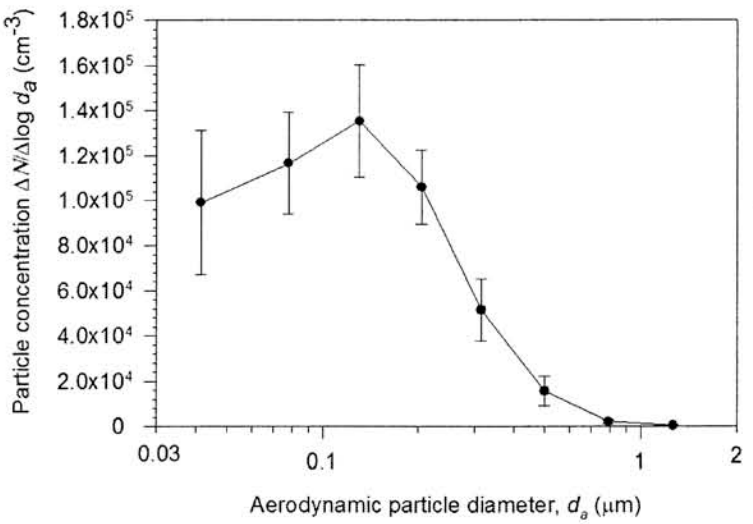

Figure 2. Initial particle size distribution produced by the smoke generator. Each data point represents the average and the standard deviation of 30 replicate tests.

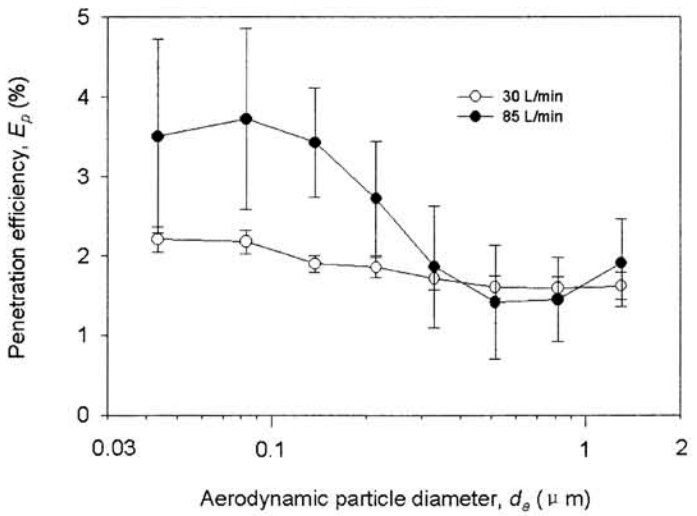

Figure 3. The original penetration efficiency of N95 respirator at inhalation flow rates of 30 and 85 L/min.

For the dust-mist respirators operated at 30 L/min, the original penetration efficiency decreased approximately from 11.0% (d_a = 0.04 μm) to 6.0% (d_a = 1.3 μm). Under the same breathing regime, the surgical masks showed the highest penetration (>20%) for d_a =0.04 μm and the lowest (<15%) for d_a = 1.3 μm. No tests were performed with these two respirators at flow rates exceeding 30 L/min.

The impaction-, interception-, and diffusion-based filtration models predict that the peak penetration is reached at d_a between 0.1 and 0.3 μm, and the particles below 0.1 μm should be collected more efficiently as their size decreases (diffusion regime) (Halvorsen, 1998; Hinds, 1999; Lee and Mukund, 2001). This tendency is not clearly seen from our experimental data. The discrepancy can be partially attributed to additional mechanisms, not considered by the above models. For example, image forces, associated with the initially charged fibers (e.g., the N95 filtering facepieces are usually pre-treated), may shift the penetration efficiency curve toward smaller particles. In addition, the penetration of ultrafine particles may occur through undetected facial micro-leaks, as well as submicrometer leaks between the core filter material and the elastic peripheral support (Lee et al., 2004a). Another factor could be associated with the spatial variations in fiber diameter, orientation, packing density, as well as initial fiber electrostatic charge level (Huang et al., 1998). The influence of the above factors on the original respirator penetration efficiency was considered to be beyond the scope of this study, as the study focused on the effect of unipolar air ion emission. Further experiments are needed to address the limitations of the manikin-based respirator evaluation protocol for ultrafine particles.

Penetration Efficiency of Different Masks Affected by the Continuous Unipolar Air Ion Emission

Figure 4a demonstrates the effect of continuous negative ion emission produced by a powerful VI-2500 ionic air purifier on the filtering efficiency of a face-sealed dust-mist respirator. The latter operated at 30 L/min. It is seen that the penetration efficiency decreased from 6-11% to almost 0% for the entire test particle size range. Figure 4b shows that the penetration efficiency of the face-sealed N95 respirator at the same inhalation flow rate also dramatically decreased due to the ion emission (the data were originally reported in our earlier paper (Lee et al., 2004a) and are presented here for comparison). Continuous operation of the VI-2500 emitter for 12 minutes resulted in about a 50-fold enhancement the N95 respirator protection.

The enhancement factors achieved after 12-minute air ionization were calculated for the N95, R95 and dust-mist respirators, as well as the surgical mask, using the penetration efficiency values integrated over the entire tested particle size range (weighted by the number of particles at each size fraction):

$$Enhancement\ factor = \frac{\overline{E_{p\,(t=0)}}}{\overline{E_{p\,(t=12\,min)}}} \tag{2}$$

The data are presented in Table 1. All the facepiece filtering masks demonstrate a considerable enhancement effect, from about 20-fold to over 3000-fold. The dust-mist respirator exhibited almost no penetration as a result of the air ion emission. The difference in the enhancement factors observed for different masks exposed to the same air ion concentration can be attributed to their filter materials. As very little information on the properties of the filter materials used for commercial respirators is available from the manufacturer, no further discussion can be offered at this point.

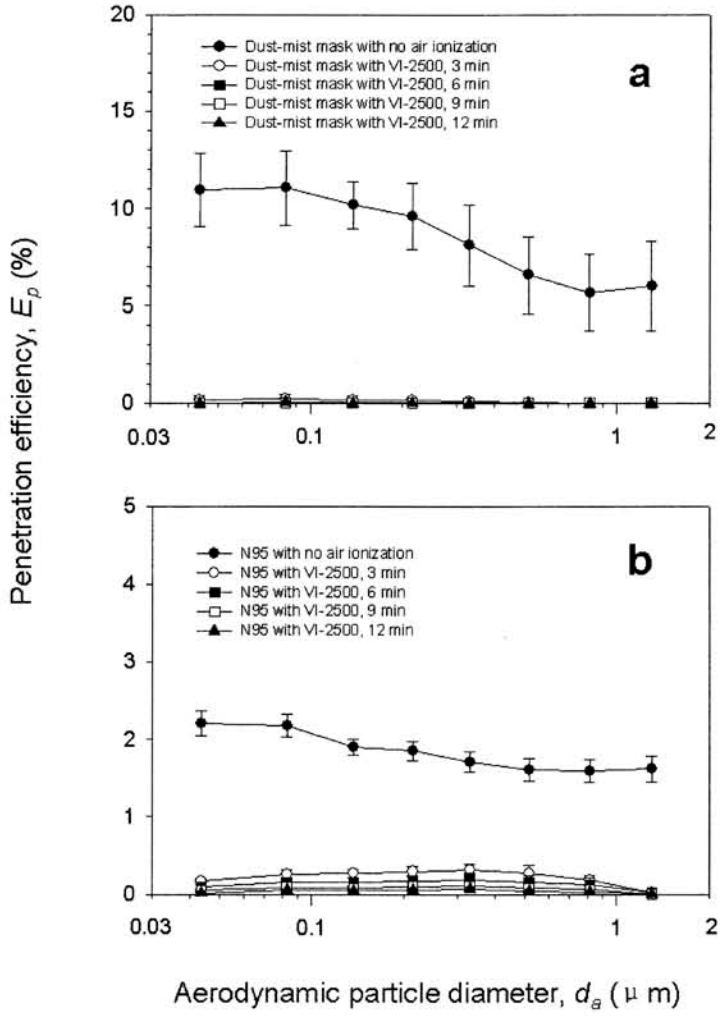

Figure 4. Penetration efficiencies of the dust-mist (a) and N95 (b) respirators operating at 30 L/min. Continuous air ion emission is produced by VI-2500.

Table 1. Enhancement factors due to the ion emission for four facepiece filtering masks.

Half-mask respirator	N95	R95	Dust-mist respirator	Surgical mask
Enhancement factor	48.4	22.3	3250	194

Note: Ion emitter = VI-2500; inhalation flow rate = 30 L/min; emission time = 12 min.

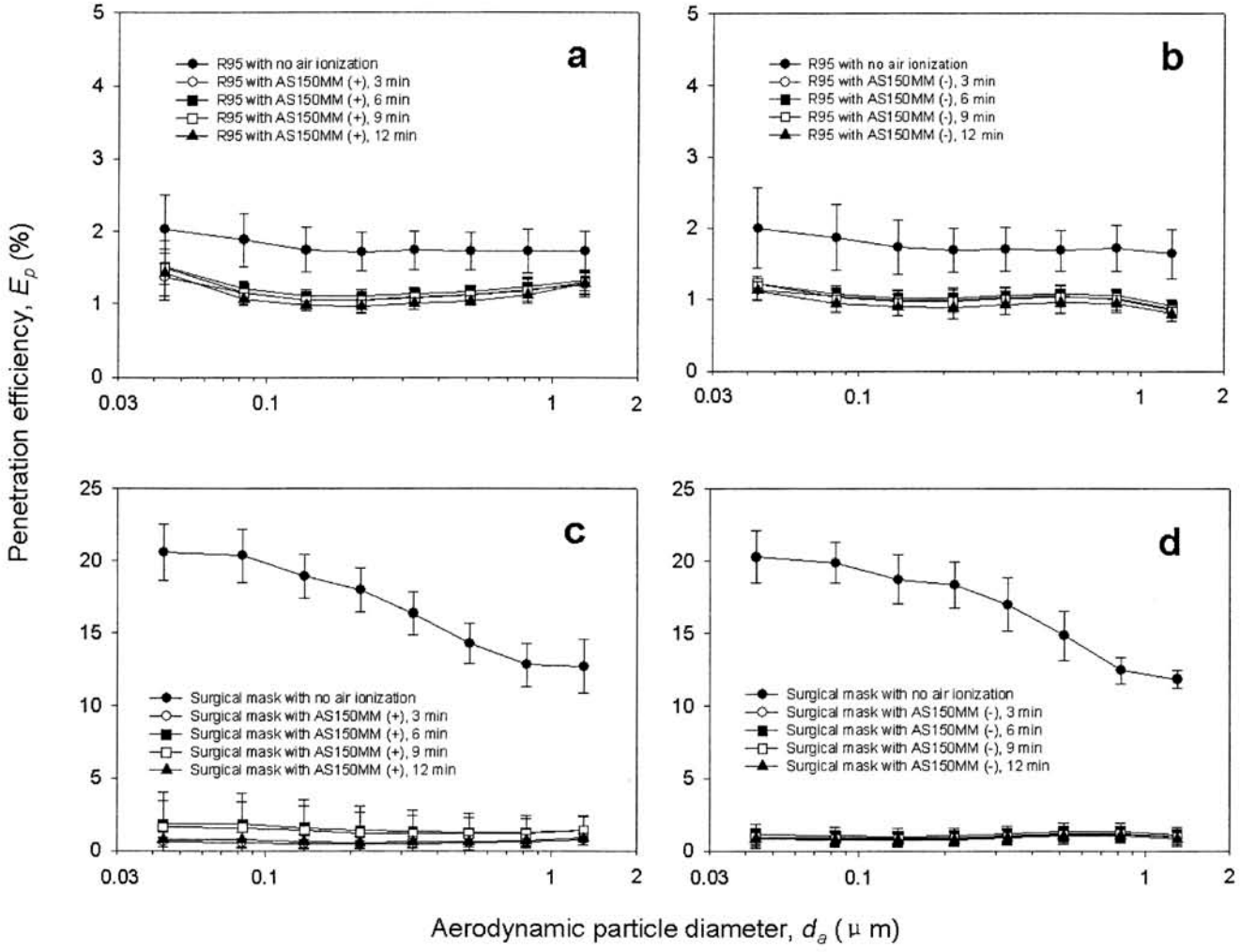

Figure 5. Penetration efficiencies of the R95 respirator (a and b) and surgical mask (c and d) operated at 30 L/min. Continuous air ion emission is produced by AS150MM (+) (a and c) and AS150MM (-) (b and d).

Table 2. Enhancement factors of the R95 respirator and surgical mask due to ion emission provided by three ionic air purifiers.

Ionic air purifier	Enhancement factor	
	R95	Surgical mask
VI-2500	22.3	194
AS150MM (+)	1.61	23.4
AS150MM (-)	1.89	18.7

Note: Inhalation flow rate = 30 L/min; emission time = 12 min.

Effect of the Air Ion Polarity and Emission Rate

The continuous emission of unipolar ions at the same rate caused approximately the same enhancement effect, irrespective whether the emitted ions were positive [AS150MM (+)] or negative [AS150MM (-)]. The effect of the polarity of air ions is shown in Figure 5 for the R95 respirator (a and b) and surgical mask (c and d) operated at 30 L/min.

Table 2 shows the enhancement factors provided by the VI-2500 ionic air purifier (higher emission rate) and the AS150MM purifiers (lower rate). The data show that the higher concentration of air ions in the vicinity of the respirator resulted in a stronger enhancement of the respirator performance.

Effect of the Inhalation Flow Rate

The penetration efficiency curves, obtained for the N95-type respirator operated at a flow rate of 85 L/min, are shown in Figure 6. Continuous emission of negative ions by the VI-2500 ionic air purifier during 12 minutes decreased the penetration efficiency of ultrafine particles through the respirator filter from about 3.5% to <0.1%. For larger particles (d_a ~1 μm), the penetration efficiency decreased from approximately 1.9% to 0.3%. Table 3 compares the enhancement factors determined for N95 and R95 respirators face-sealed on the manikin and operated at two inhalation flow rates (the values are particle size integrated within the test range of d_a = 0.04 – 1.3 μm). The change in the flow rate seems to have no significant effect on the particle penetration through the N95 respirator. The role of the inhalation rate appeared to be more prominent for the R95 respirator as the enhancement factor increased almost 3-fold with the flow rate increasing from 30 to 85 L/min. The difference between the data obtained for the R95 and N95 respirators, with respect to the flow rate effect on their performance enhancement, is likely caused by different properties of the filter materials (electret media of N95 versus carbon-based media of R95).

Table 3. Enhancement factors of N95 and R95 respirators due to ion emission at two inhalation flow rates.

Half-mask respirator	Enhancement factor	
	30 L/min	85 L/min
N95	48.4	46.4
R95	22.3	66.4

Note: Ion emitter = VI-2500; emission time = 12 min.

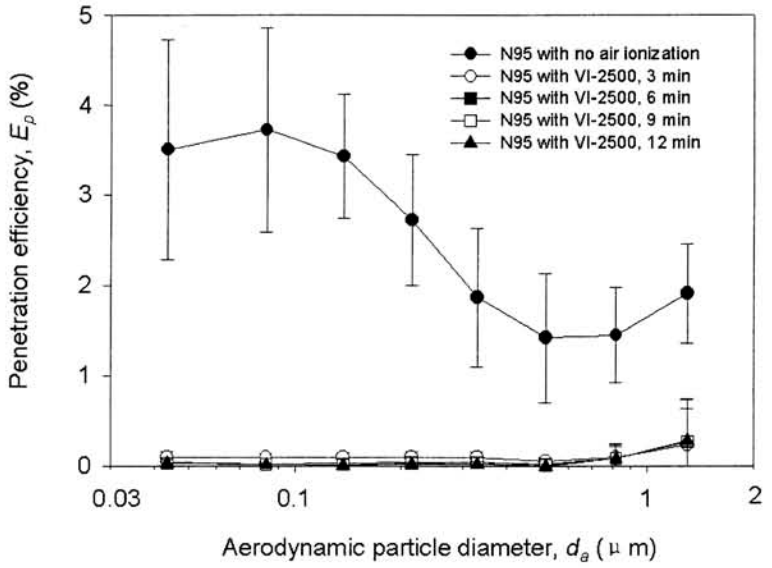

Figure 6. Penetration efficiencies of the N95 respirator operated at 85 L/min. Continuous air ion emission is produced by VI-2500.

Effect of the Ion Emission Time

Resulting from the tests conducted for 3-, 6-, 9-, and 12-minute time intervals, the penetration efficiency values integrated over the tested particle size range showed some decrease with the time. Although observed for all masks, this trend was not statistically significant (p-values of all t-tests were greater than 0.05). The findings suggest that the major enhancement of the respirator performance is achieved within the first 3 minutes of ion emission. The actual "characteristic" time of the enhancement effect is likely to be shorter than 3 minutes since the air ion concentration reaches its saturation level during the time interval as short as 10 seconds after the emitter is turned on. However, the study design limitations and the measurement precision criteria did not allow us to conduct tests at t<<3 min.

CONCLUSIONS

Continuous emission of unipolar air ions by corona-ionizing air purifiers in the vicinity of a disposable half-mask respirator enhanced its protection characteristics against fine and ultrafine particles of bacterial and viral size ranges. In this study, the effect was proven for four types of face-sealed respiratory protection devices, including N95, R95, and dust-mist respirators, as well as surgical masks, with the particle penetration efficiency reduction up to about 3000-fold. The enhancement of the respirator filtering efficiency does not appear to depend on the particle size (within the size range tested in this study). While a higher ion emission rate is strongly associated with greater respirator performance, the ion polarity (negative versus positive) was found to have no effect on the performance enhancement factor. The findings hold true for two inhalation flow rates tested in this study: 30 and 85 L/min. It was concluded that the major enhancement effect occurred in the first 3 minutes of the ion emission. Overall, a dramatic improvement of the aerosol filtering efficiency of a disposable respirator due to continuous unipolar ion emission is achievable under various conditions. It should be noted that our experiments presented in this paper utilized a manikin-based protocol with a respirator/mask, which was face-sealed on the manikin, so that we addressed primarily the aerosol penetration through a filter material; the respirator fit remains beyond the scope of this study and should perhaps be investigated more appropriately through tests involving human subjects and a fit-testing protocol.

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DISCLAIMER

Reference to any companies or specific commercial products does not constitute or imply their endorsement, recommendation, or favoring by the University of Cincinnati or by the investigators conducting this study.

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