Effects of Organic Solvents on the Laboratory Filtration Performance of Electret N95 and P100 Filtering Facepiece Respirators

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ABSTRACT

CDC has predicted respirator shortage during a widespread influenza pandemic. To address this issue, research on the reuse of filtering facepiece respirators after simple biological decontamination methods was recommended. Successful reuse of filtering facepiece respirators will require decontamination methods that can inactivate microorganisms without compromising filtration performance. Isopropanol is commonly used for decontaminating many medical devices, but its concentration dependent effect on the filtration performance of filtering facepiece respirators has not been studied in detail. In this study, two models of electret N95 and two models of electret P100 filtering facepiece respirators were treated with varying concentrations of isopropanol and penetration levels for polydisperse and monodisperse NaCl aerosols were measured at 85 L/min flow rate. The results showed that submerging in liquid isopropanol increased the penetration levels of 20-400 nm size monodisperse particles for both N95 and P100 filtering facepiece respirators in a concentration dependent manner. N95 and P100 filtering facepiece respirators exceeded NIOSH allowed 5% and 0.03% penetration levels after treatment with >10% and >50% isopropanol, respectively. In other experiments, penetrations obtained for isopropanol liquid and vapor treated filtering facepiece respirators were compared with those obtained for liquid and vapor forms of xylene, an alternate solvent and cleaning agent. Both 100% isopropanol and 100% xylene treated N95 and P100 filtering facepiece respirators showed a marked increase in penetration levels for polydisperse as well as monodisperse aerosols with an associated shift in the most penetrating particle size from 50 nm to 200-300 nm range. On the contrary, isopropanol and xylene vapors produced different effects on penetrations. Isopropanol vapor exposure dramatically increased the penetration levels for polydisperse and monodisperse aerosols with a simultaneous shift in the most penetrating particle size from 50 nm to 200-300 nm range. However, xylene vapor neither increased the penetration levels for polydisperse and monodisperse aerosols nor shifted the most penetrating particle size. These results can help in the design of future studies on the decontamination of filtering facepiece respirators contaminated with different microorganisms.

Keywords: N95 and P100 filtering facepiece respirators, decontamination, isopropanol, xylene, liquid and vapor, aerosol penetration

INTRODUCTION

The Centers for Disease Control and Prevention (CDC) recommends that healthcare workers use National Institute for Occupational and Safety and Health (NIOSH)-approved filtering facepiece respirators (FFRs) to reduce exposure to infectious aerosols (CDC 2001; CDC 2003; CDC 2004; CDC 2009). The spread of infectious diseases, including the severe acute respiratory syndrome (SARS), avian influenza A (H5N1) and the recent novel influenza virus A (H1N1) pandemic, significantly increased the need for respiratory protection. A survey conducted by the Infectious Diseases Society of America Emerging Infections Network for its members, on hospital planning for SARS indicated that ~25% of their facility had experienced a shortage of FFRs (Srinivasan *et al* 2004). CDC predicted that the need for N95 FFRs could exceed 90 million to protect healthcare workers during a 42 day outbreak of influenza A (H5N1) (Bailar *et al* 2006; CDC 2006). To address the issue of a potential respirator shortage during a widespread influenza pandemic, the Institute of Medicine (IOM) released a report entitled “Reusability of Facemasks during an Influenza Pandemic: Facing the Flu” (Bailar *et al* 2006). The IOM report recommended research on the reuse of disposable FFRs after simple decontamination techniques.

Respirator decontamination issues with different methods have been discussed previously (Rengasamy *et al* 2004; Rengasamy *et al* 2009b). The identification of decontamination agents for critical microorganism categories may facilitate the selection of an effective decontamination agent for a known biological contamination. For unknown and multiple biological contaminations, a multispectrum decontamination agent may be necessary. It is therefore likely that a range of decontamination methods will be needed. Criteria for selecting a given method might include considerations such as the time, equipment, space, personnel training, and overall expense required to conduct the decontamination. To be useful, decontamination procedures for FFRs should successfully kill or inactivate microorganisms without compromising the filtration performance, fit, or pose additional risk to the user (e.g., from off-gassing or dermal irritation). The effects of several decontamination methods have been reported for N95 and P100 FFRs (Fisher *et al* 2009; Viscusi *et al* 2007; Viscusi *et al* 2009; Vo *et al* 2009). FFRs treated with physical processes and chemical agents were assessed for their physical condition and filtration performance. Some decontamination methods including bleach, H_2O_2, ethylene oxide, UV light and microwave showed no significant effect on polydisperse aerosol penetrations of FFRs under the test conditions (Viscusi *et al* 2007). Those methods appear promising for further evaluation of their decontamination efficacy, but additional research is still necessary before decontamination for purposes of respirator reuse will be an accepted practice. On the other hand, methods including submersion in 70% isopropanol (IPA) and autoclave treatments of N95 and P100 FFRs showed marked increase in the penetration levels of polydisperse aerosols (Viscusi *et al* 2007). Those methods warrant further investigation into details of their influence on respirator performance. In designing the current study to expand on the work of Viscusi et al., we have noted that these authors employed limited exposure conditions for testing the efficacy of decontamination methods. For example, these tests used only 70% IPA, while the effects of different concentrations of IPA on the filtration performance of FFRs were not studied in detail. Further studies with different concentrations of IPA are needed to assess their effect on filtration performance of FFRs.

Electret FFRs treated with IPA showed several-fold increase in polydisperse aerosol penetrations as measured by a method similar to the penetration test employed for NIOSH particulate respirator certification while showing <5% penetration for workplace aerosols containing iron particles in a steel foundry (Janssen et al 2003a; Janssen *et al* 2003b). The mass median diameter of the iron aerosols was in the 4.6 to 6.0 µm range with a geometric standard deviation of 2.9 to 4.6. In other studies, electret filters dipped in liquid IPA showed increased penetration levels for polydisperse and monodisperse aerosols with a shift in the most penetrating particle size (MPPS) toward a larger size (Chen *et al* 1993; Chen and Huang 1998; Martin and Moyer 2000; Rengasamy *et al* 2009a). Results from these studies indicated that liquid IPA removed the electric charges from the FFRs. Recent studies confirmed the removal of charges from electrostatic filter media treated with liquid IPA using an electron force microscopy technique (Kim *et al* 2007). These authors also showed an increase in polydisperse aerosol penetrations for electret filter media dipped in organic liquid solvents including xylene, toluene and ethyl benzene, while their vapor forms did not show any significant effect (Jasper *et al* 2005; Jasper *et al* 2006; Jasper *et al* 2007). Although, liquid IPA is known to reduce the charges from electret filters with an increase in aerosol penetration, the effect of IPA vapor exposure is not well understood.

To our knowledge, little information is available on the concentration dependent effects of liquid IPA on the filtration performance of disposable FFRs. The goal of this study was to assess the effects of varying concentrations of liquid IPA treatments on polydisperse and monodisperse NaCl aerosol penetrations for electret N95 and P100 FFRs. In addition, the effects of liquid and vapor forms of IPA on the penetration values for N95 and P100 FFRs were compared with the penetration values obtained with those samples treated with xylene liquid and vapor. Xylene, a solvent and a cleaning agent, has been employed to study electret filter degradation (Jasper *et al* 2006). The intent was to provide data to support the intelligent design of future studies on the decontamination efficacy and penetration performance impact of different forms and concentrations of solvents on N95 and P100 FFRs contaminated with different biological agents.

METHODS

FFR Selection

Two commercially available models of NIOSH-approved N95 FFRs and two models of NIOSH-approved P100 FFRs were selected randomly from among those models tested previously in our laboratory (Rengasamy *et al* 2007). Both N95 and P100 FFRs used in the study contained electret filter media. Three samples from each model of N95 and P100 were used for each test.

Liquid Solvent Treatment

Each FFR was dipped into one liter IPA or xylene in a glass beaker, removed, drained and allowed to dry overnight in a fume hood. A dip duration of one minute was used to remove electret charges sufficiently from respirator filter media as shown previously (Rengasamy *et al.*, 2009). Care was taken to ensure that the FFR was completely submerged without any trapped air pockets. In some experiments, FFRs were dipped in IPA at different concentrations (5, 10, 30, 50 and 100 percent) obtained by dilution with deionized water.

Vapor Exposure Treatment

Vapor exposure of the FFRs was accomplished using a treatment system **(Figure 1)** that was designed in this study for both convenience in conducting the current experiment and potential adaptation for routine use in FFR decontamination. The exposure portion of the system consists of a static-free acrylic box (36 x 36 x 36 cm^3) placed inside a fume hood. The box was sufficient to keep 12 FFR samples for vapor exposure at a time. Ultra-pure nitrogen gas was bubbled at a flow rate of 1 L/min through an inlet reaching the bottom of a one liter air tight glass reservoir bottle (kept outside the treatment box) containing 500 ml of IPA (100%) or xylene (100%) . The system was operated at room temperature (22^0 C). Confirmation that vapors were being provided to the treatment box was obtained by measuring the volume of solvent evaporated as a function of time from the reservoir. Approximately 118 ml of IPA and 24 ml of xylene had evaporated at room temperature at a flow rate of 1 L/min nitrogen through the reservoir in 4 hours. This can be expected as the vapor pressures for IPA and xylene are 45 mm and 8 mm Hg, respectively, at 25^0 C at 1 atmosphere pressure. The flow of solvent vapor exiting from the reservoir outlet was passed into another 500 ml air tight glass bottle kept inside the acrylic box to collect any residual droplets and ensure that only vapors were allowed to enter the treatment section of the acrylic box. The vapor exiting from an outlet of the bottle was allowed to mix with the air in the acrylic box. An exit hole (0.64 cm diameter) at the top of the acrylic box allowed the vapor to leave the chamber and be exhausted through ventilation. The interior walls of the box were lined with cardboard to prevent changes in filter charges due to contact with acrylic material. FFRs were attached with only their face sealing area touching the cardboard using a vinyl tape without touching each other. It should be noted that no condensation of the vapor on the wall of the box was observed. Vapor exposed FFRs were left in the hood overnight before testing. FFRs were exposed to vapors for 8 hours to obtain measurable changes in penetration levels as shown for electret filter media previously (Jasper *et al* 2005; Jasper *et al* 2006; Jasper *et al* 2007).

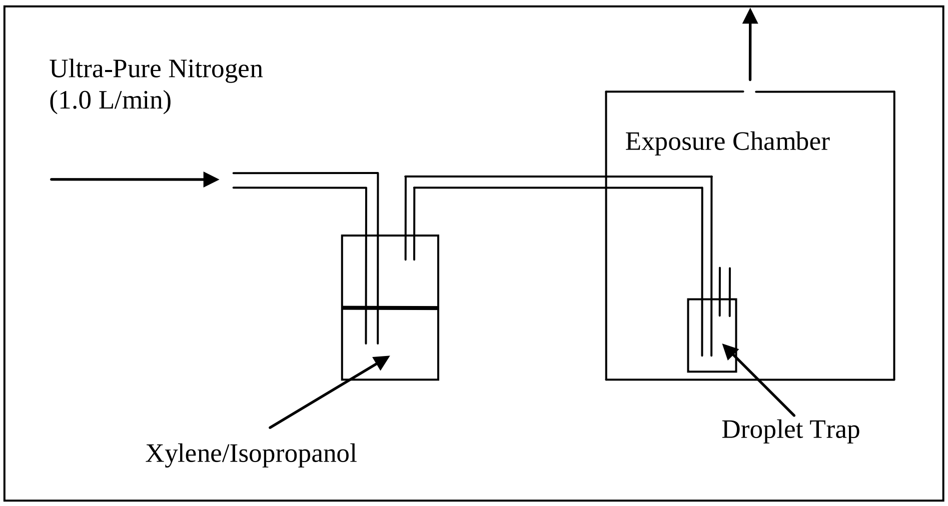

Figure 1. Isopropanol and xylene vapor exposure setup.

Polydisperse NaCl Aerosol Penetration Test

For each type of treatment, three samples from each FFR model were tested for polydisperse NaCl aerosol (count median diameter 75±20 nm and geometric standard deviation 1.86) penetrations with a TSI 8130 Automated Filter Tester (TSI 8130) used for NIOSH particulate respirator certification (Federal Register 1995; NIOSH 2007). Initial penetration levels were measured for one minute at 85 L/min flow rate instead of carrying out the entire NIOSH respirator certification test.

Monodisperse NaCl Aerosol Penetration Test

Monodisperse aerosol penetration test was performed to better understand the effect of liquid and vapor forms of IPA and xylene on the penetration levels of different size particles. For each type of treatment, a set of three samples from each FFR model were tested against monodisperse NaCl particles using a TSI 3160 Fractional Efficiency Tester (TSI 3160) as described previously (Rengasamy *et al* 2007). Initial percentage penetration levels for different size monodisperse aerosols were measured for each sample at 85 L/min flow rate.

Data Analysis

The data were analyzed using the SigmaStat® (Jandel Corporation) computer program. Average penetration values and 95% confidence intervals were calculated for each treatment of each model. A one way analysis of variance (ANOVA) was done to evaluate the significance of penetration levels obtained for the different treatment groups. All pairwise multiple comparisons were performed using the Student-Newman-Keuls test.

RESULTS

Liquid IPA (5%-100%) Dose Response Effects for N95 and P100 FFRs

a. Polydisperse NaCl Aerosol Penetration

Polydisperse aerosol penetrations for two N95 and P100 model FFRs treated with different concentrations of liquid IPA are shown in **Figure 2**. Penetration levels for control samples from two N95 models (first two columns of control group) and two P100 models (third and fourth columns of control group) were within the NIOSH allowed 5% and 0.03%, respectively. For N95 FFRs, penetrations remained less than the allowed 5% for up to 10% IPA solution treatment (first two columns in treatment groups). Penetrations increased significantly (P=<0.05) higher than 5% at IPA concentrations 30% and above. At the same time, P100 FFRs (third and fourth columns in treatment groups) showed no significant change in polydisperse aerosol penetrations up to 50% IPA solution treatment. Both P100 FFRs treated with 100% IPA showed a marked increase in penetration levels to 3.4% and 10%, respectively.

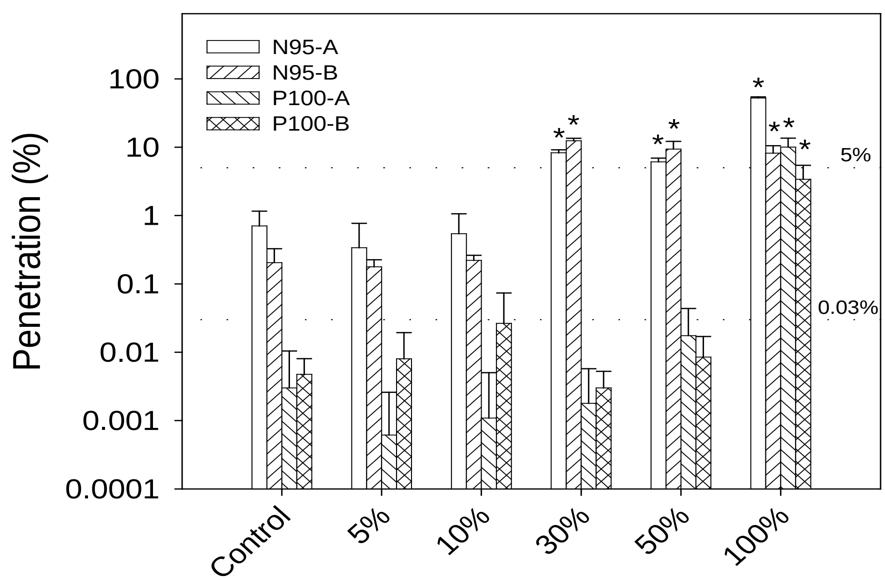

Figure 2: Polydisperse aerosol penetrations of electret FFRs treated with different concentrations of isopropanol. Bar represents an average of three samples. Upper error bar is at the 95% confidence level (n=3). Dashed lines represent NIOSH allowed maximum penetrations for N95 (5%) and P100 (0.03%) FFRs. * Significantly (P<0.05) different from controls.

b. Monodisperse NaCl Aerosol Penetration

N95 and P100 FFRs treated with different concentrations of IPA liquid were tested for monodisperse NaCl aerosol penetrations (**Figure 3**). In general, both N95 and P100 FFRs treated with increasing concentrations of IPA showed an increase in penetration levels for the different size monodisperse particles over the controls. N95 FFRs treated with IPA concentrations 30% to 100% also showed a shift in the MPPS from 40-50 range to 200-300 nm size range particles (**top panels**). With 100% IPA, the penetration levels for the two N95 models at the MPPS were 42% and 32%, respectively. In the case of both P100 model FFRs, the MPPS size remained mostly in the 40-50 nm range for up to 50% IPA treatment (**bottom panels**). Of the two P100 model FFRs tested, one model showed a shift in the MPPS from 50 nm to 200-300 nm range with 100% IPA, while the other model at IPA concentrations 50% and above. The average penetration levels for the two models treated with 100% IPA solution were 18.7% and 4.8%, respectively, at the MPPS (**bottom panels, insets**).

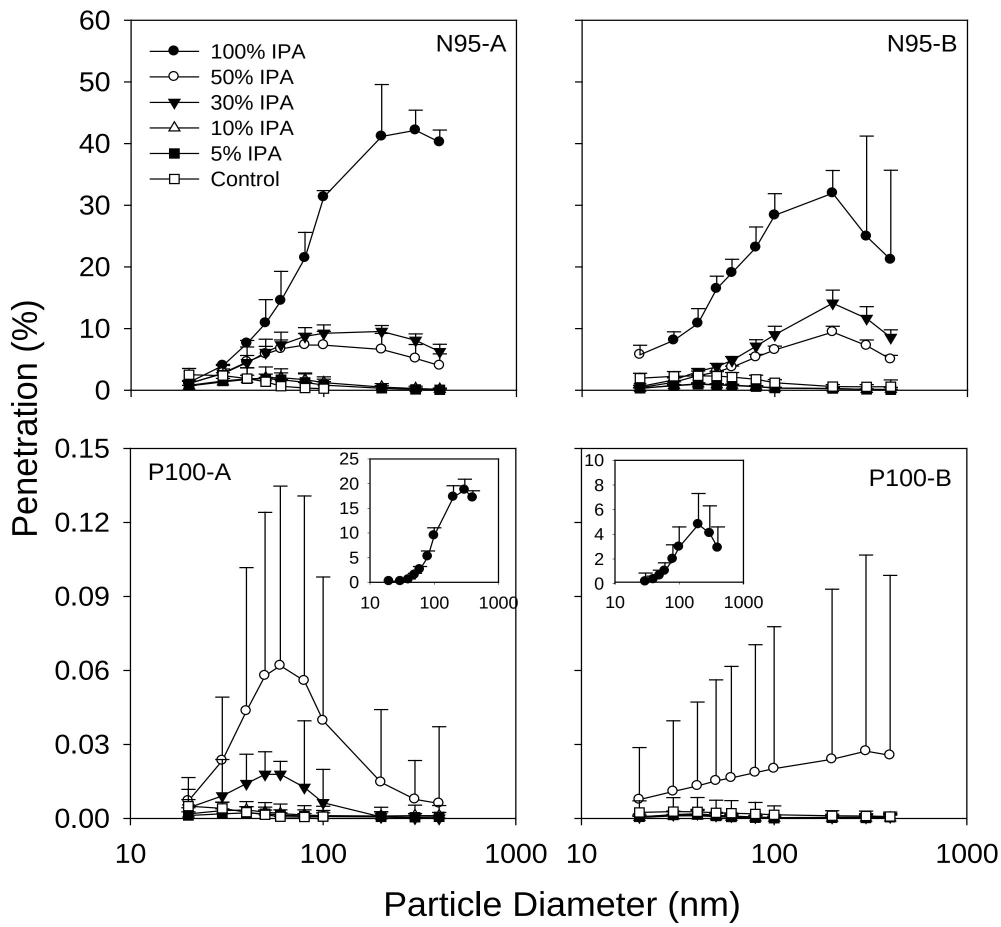

Figure 3: Penetration levels of monodisperse NaCl (20–400 nm) particles for electret N95 (top row) and P100 (bottom row) FFRs from two manufacturers (A and B) at 85 L/min for five concentrations of liquid IPA. Error bar represents the 95% confidence interval (n = 3). Insets in bottom row used to show penetration curves for 100% IPA treatment for the P100 FFR.

Comparison of Polydisperse Aerosol Penetrations for FFRs Exposed to IPA and Xylene

a. Liquid IPA (100%) and Xylene (100%) Treatment

Polydisperse aerosol penetrations for FFRs dipped in liquid IPA and xylene were compared (**Figure 4, top panel**). The penetration levels for the control N95 and P100 FFRs were within the NIOSH allowed limits of 5% and 0.03%, respectively. Both IPA and xylene liquid treatments dramatically increased the penetration values from <1% to 42-52% for the two N95 model FFRs (**left two groups**). Penetration levels for control tests of the two P100 FFR models were around 0.004%, which increased to 10-22% for both IPA and xylene treatments (**right two groups**).

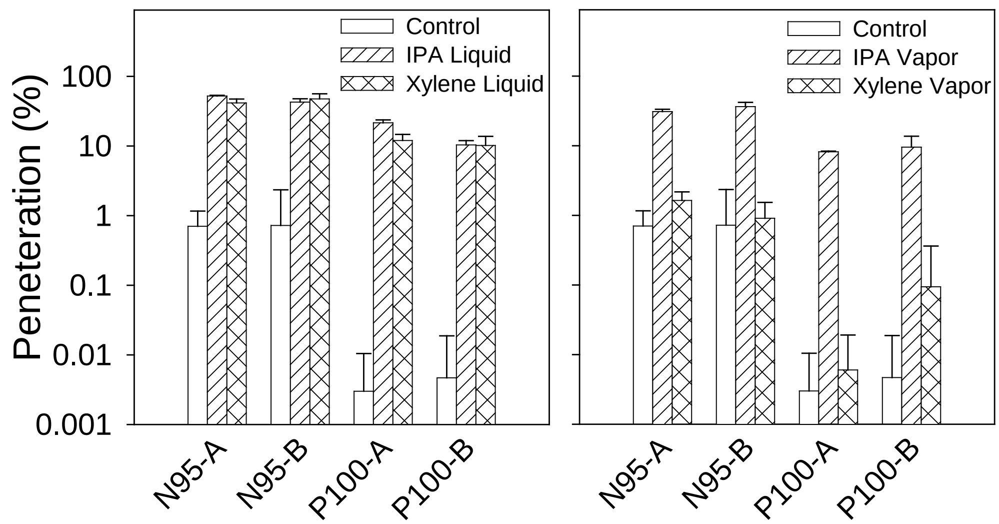

Figure 4: Polydisperse aerosol penetrations for electret N95 and P100 FFRs at 85 L/min after exposure to IPA and xylene liquids (top) and vapor (bottom). Error bar represents the 95% confidence level (n = 3).

b. Vapor IPA and Xylene Exposure

Polydisperse aerosol penetrations for N95 and P100 FFRs exposed to IPA and xylene vapors for 8 hours were compared. N95 FFRs exposed to IPA vapor showed a dramatic increase in penetration levels to 31-37% over the controls, while xylene vapor increased the penetrations to only 0.9-1.6% (**Figure 4, bottom panel, left two groups**). In the case of P100 FFRs, IPA vapor exposure markedly increased the penetrations to 8.2-9.6%, while xylene vapor slightly increased the penetrations to 0.006-0.029% (**Figure 4, bottom panel, right two groups**).

Comparison of Monodisperse Aerosol Penetrations for FFRs Exposed to IPA and Xylene

a. Liquid IPA (100%) and Xylene (100%) Treatment

Penetration results for monodisperse aerosol particles in the 20-400 nm diameter range are shown in **Figure 5** for FFRs dipped in liquid IPA and xylene. The MPPS for the control N95 as well as P100 FFRs were in the 50 nm range, with penetrations in the range of 2.3-2.5%, and 0.003-0.007% for N95 and P100 FFR samples, respectively. Both IPA and xylene liquid treatments dramatically increased the penetration levels for 20-400 nm size monodisperse particles with a shift in the MPPS to the 200-300 nm range for both N95 and P100 FFRs. Penetration values at the MPPS were between 32-42% and 5-19% for N95 and P100 FFRs, respectively, for the liquid IPA treated samples. Penetrations at the MPPS for liquid xylene treated N95 and P100 FFRs were 47-50% and 14-15%, respectively.

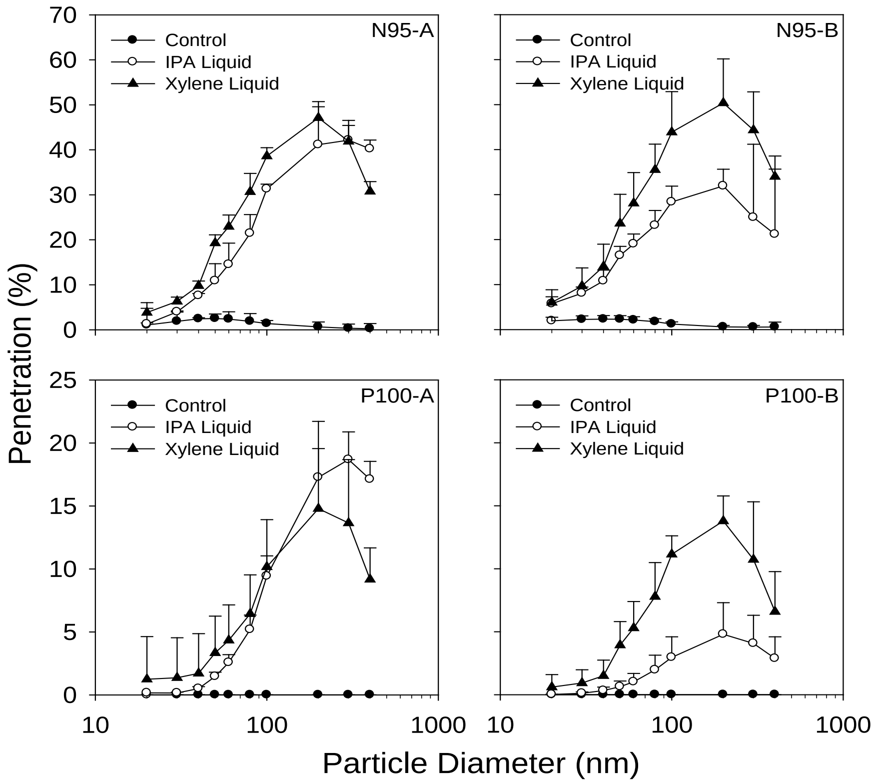

Figure 5: Penetrations of monodisperse NaCl (20–400 nm) particles for electret N95 (top row) and P100 (bottom row) FFRs from two manufacturers (A and B) at 85 L/min for 100% liquid IPA (open circles) and xylene (solid triangles). Error bar represents the 95% confidence interval (n = 3).

b. Vapor IPA and Xylene Exposure

Penetration results for monodisperse NaCl aerosol particles in the 20-400 nm diameter range are shown in **Figure 6** for FFRs exposed to IPA or xylene vapors for 8 hrs. N95 and P100 FFRs showed a large increase in penetration levels with only IPA vapor exposure and not with xylene vapor. The MPPS for IPA vapor treated N95 and P100 FFRs shifted to 200-300 nm range for all test samples. Penetration levels at the MPPS for IPA vapor exposed N95 and P100 FFRs were in the 41-45% and 8-13% ranges, respectively. Unlike IPA vapor, xylene vapor exposure neither increased the penetration levels for N95 and P100 FFRs nor shifted the MPPS toward a larger size. The penetration values at the MPPS between 2.9-3.6% and 0.003-0.006% for N95 and P100 FFRs, respectively, were not significantly different from the controls.

DISCUSSION

Penetration results obtained for both N95 and P100 FFRs showed a concentration-dependent effect of liquid IPA on polydisperse as well as monodisperse aerosol penetrations. Liquid IPA at 30% and higher concentrations increased the penetration values for N95 FFRs above the 5% limit allowed by NIOSH. For P100 FFRs, IPA at 50% and lower concentrations did not increase the penetration values above the 0.03% limit. The results indicate that the filtration performance is less sensitive to liquid IPA for P100 FFRs than for N95 FFRs. The difference in IPA threshold concentrations not compromising the filtration efficiency of N95 and P100 FFRs can be explained partly due to the manufacturing processes of the two different classes of electret FFRs. Unlike the N-type FFR media, P-type FFRs are designed not to be degraded by oils. P-type FFR electret media, therefore, may have a shielding mechanism to prevent electret charge degradation. Such a shielding mechanism is absent or less effective in N95 FFR media. The shielding effect of P100 may be advantageous (or even essential, depending on the type of biological agent and the level of treatment necessary) if biological decontamination methods are employed to enable respirator reuse.

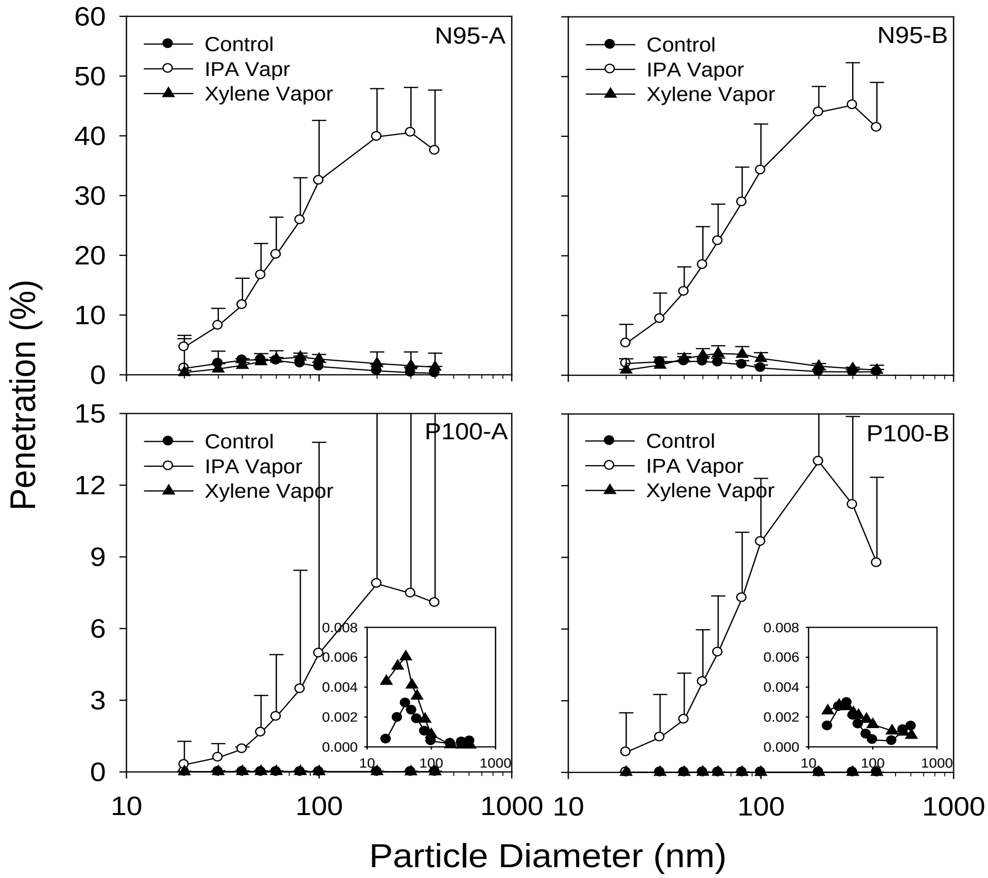

Figure 6: Penetrations of monodisperse NaCl (20–400 nm) particles through electret N95 (top row) and P100 (bottom row) FFRs from two manufacturers (A and B) at 85 L/min after 8 hour exposure to IPA (open circles) and xylene (solid triangles) vapors. Error bar represents the 95% confidence interval (n = 3). Insets in bottom panels show penetration curves for control and 8 hour xylene exposure for the P100 FFRs.

N95 and P100 FFRs treated with liquid IPA as well as xylene when challenged with polydisperse and monodisperse aerosols (20-400 nm sizes) showed dramatic increase in penetration levels. The increase in penetration levels for electret filters treated with organic solvents was believed to be due to filter discharging as a consequence of the increased chemical reactivity of solvents with the surface charge present as free radicals or ions (Biermann *et al* 1982). Subsequent studies attributed the removal of electric charges from the filter media fibers to the increased aerosol penetration levels and the shift in the MPPS to larger particle size range (Chen *et al* 1993; Chen and Huang 1998; Martin and Moyer 2000; Rengasamy *et al* 2009a). However, one study indicated that the increase in penetration was due to swelling and dissolution of low molecular weight polymers from electret filters treated with liquid IPA

(Myers and Arnold 2003). On the other hand, a recent study showed that particle release from IPA treated electret FFRs was not contributing to the increased penetration levels (Rengasamy *et al* 2009a). Removal of filter charges with liquid IPA was substantiated from the results obtained with electrostatic force microscopy technique (Kim *et al* 2007). The authors measured the electrostatic charge levels of polypropylene electret filters with and without IPA treatment. Without IPA treatment, the filters exhibited attractive or repulsive responses depending on the sign of the bias voltage applied, whereas IPA treated filters exhibited only attractive responses for either sign of tip bias voltage indicating IPA-induced charge degradation.

Although both IPA and xylene liquid treatments consistently increased the penetration levels for N95 and P100 FFRs, their vapor forms showed differential effects. FFRs exposed to xylene vapor for 8 hrs showed no significant increase in monodisperse or polydisperse NaCl aerosol penetrations. The data agree with previously published results for electret filter media exposed to solvent vapors including xylene, toluene, and ethyl benzene for up to 8 hrs (Jasper *et al* 2005; Jasper *et al* 2006; Jasper *et al* 2007). The authors distinguished the effects of solvent vapor from liquid by explaining that the increased penetrations with liquid solvent treatment was due to a reduction in electric field caused by the creation of a thin layer of solvent over the surface of the electret filter fibers. However, for solvent vapors, sorption and diffusion processes occur at different time scales with diffusion being a rate-limiting step. Interestingly, results obtained in the study for IPA vapor exposure showed effects similar to those obtained for liquid IPA immersion with a marked increase in polydisperse as well monodisperse aerosol penetrations for electret FFRs with a shift in the MPPS from 50 nm to 200-300 nm range. Thus, IPA vapor effects on electret filtration are in contrast with the results obtained for vapor forms of toluene, xylene and ethyl benzene (Jasper *et al* 2005; Jasper *et al* 2006; Jasper *et al* 2007). This may suggest that IPA vapor diffuses rapidly and interacts with the charges on electret FFRs. Further studies are needed to delineate the mechanism of IPA vapor on charge removal from electret FFRs.

Limitations of the Study

The purpose of this study was to address issues associated with degradation of electret filter performance, rather than to assess the decontamination efficacy of different concentrations of IPA for the inactivation of microorganisms trapped on FFRs. The selected decontamination treatment conditions were selected mainly to be consistent with conditions that have been shown to be relevant. For example, for hand hygiene purposes, alcohols at 60-95% concentrations were found to be effective against several enveloped viruses, and gram-negative and gram-positive bacteria (Boyce and Pittet 2002). However, as shown previously (Viscusi *et al* 2007) and confirmed in the current study, IPA concentrations >50% can produce adverse effects on respirator filtration. The authors showed that N95 and P100 FFR samples dipped in 70% IPA for 1 min showed increased NaCl aerosol penetrations exceeding NIOSH allowed levels. The data obtained for different concentrations of IPA represent performance of the two N95 and the two P100 FFR models tested in the study. The IPA concentration effects for other models may be different. This study did not evaluate the biological decontamination efficacy of IPA concentrations not detrimental to filtration performance of FFRs. Moreover, the decontamination effect of IPA is likely to vary between biological agents. Nevertheless, the findings from the study are of scientific interest to better understand the mechanism of electret charge removal by IPA vapor.

CONCLUSIONS

Results obtained in the study showed that liquid IPA effects on the filtration performance of electret N95 and P100 FFRs are concentration-dependent. Penetration levels exceeded NIOSH allowed limits for N95 and P100 FFRs at >10% and >50% isopropanol concentrations, respectively, indicating that P100 FFRs are more resistant to electret charge degradation. A marked increase in penetration levels for polydisperse as well as monodisperse aerosols with a simultaneous shift in the MPPS from 50 nm to 200-300 nm range was obtained for both N95 and P100 FFRs dipped in IPA and xylene liquids. At the same time, both types of FFRs exposed to IPA and xylene vapors for 8 hrs showed different effects on penetration values. N95 and P100 FFRs exposed to IPA vapor showed a dramatic increase in penetration levels for polydisperse and monodisperse aerosols with a simultaneous shift in the MPPS from 50 nm to 200-300 nm range. However, xylene vapor exposure neither increased the penetration levels for polydisperse and monodisperse aerosols, nor shifted the MPPS to larger particle sizes. Future studies on electret FFRs exposure to solvent liquids and vapors may unravel the mechanisms of charge removal from electret filters. Such understanding can help in the design of future studies on the decontamination efficacy and penetration performance impact of different forms and concentrations of solvents on electret N95 and P100 FFRs contaminated with different microorganisms.

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