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It is entitled:
Performance of Filtering Facepieces and Powered Air-purifying Respirators Challenged with Different Aerosols

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Performance of Filtering Facepieces and Powered Air-purifying Respirators Challenged with Different Aerosols

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ABSTRACT

The main objective of this research was to evaluate the performance of various respiratory protective devices (RPDs) against different aerosols. The tested devices included surgical masks, N95, R95, P95 and N100 filtering facepiece respirators (FFRs), and powered air-purifying respirators (PAPRs). Challenge aerosols included sodium chloride (NaCl) particles, combustion particles generated by burning of wood, paper and plastic materials, and surgical smoke generated by cutting the animal tissue. Sodium chloride particles were used as the “model” challenge aerosols, and the RPD performance data collected were compared to those obtained with real workplace aerosols. The effects of multiple factors such as challenge aerosol type, breathing flow rates including constant inhalation flow and cyclic flow, particle size, relative humidity of the ambient air, and respirator type on the RPDs’ performance were evaluated.

This dissertation describes four related studies (A-D).

In study A (Chapter 1), the filter samples of N95, R95 and P95 FFRs were challenged against NaCl particles and combustion particles generated by burning of wood, paper and plastic materials. The study revealed that the penetration of combustion particles was significantly higher than that of NaCl particles. However, this result was not observed for R95 and P95 FFR filters. Challenge aerosol type, constant inhalation flow rate, and particle size were significant factors on the filter performance of N95 FFR.
In study B (Chapter 2), two models of N95 FFRs fully sealed on the manikin headform were tested against NaCl particles and plastic combustion particles. The tests were performed under two relative humidities, RH ≈ 20% and ≈ 80%, representing dry and moderately humid air conditions, respectively. Filter penetration decreased significantly with increasing RH. Challenge aerosol type, mean inspiratory flowrate (MIF), RH and respirator model have significant effect on the performance of tested N95 FFRs. The effect of particle size varied depending on the challenge aerosol and respirator model.

In study C (Chapter 3), different RPD types including two surgical masks, two N95 FFRs, and two N100 FFRs were tested on ten human subjects exposed to surgical smoke. Simulated workplace protection factor (SWPF) was measured for each subject wearing an RPD. The study revealed that N95 FFRs and N100 FFRs offer much higher protection level than that of surgical masks while challenging with surgical smoke. Particle size was a significant factor only for the N100 FFRs.

In study D (Chapter 4), improperly sized and stretched-out loose-fitting powered air-purifying respirators (PAPRs) donned on the manikin headform were challenged with NaCl particles. Results showed that the facepiece type and breathing flow rate were significant factors affecting the PAPR performance. Manikin fit factor (mFF) decreased with increasing breathing flows. The protection level of the stretched-out loose-fitting PAPR was significantly lower than the level offered by the other two improperly sized loose-fitting PAPR.

Overall, our results could assist the manufacturers in designing better respirators. Additionally, the work provides database to regulatory agencies and respiratory protection
researchers, which is important for developing guidelines for the selection of appropriate respirators at a workplace.
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Abbreviations

AEH – air exchanges per hour
AORN – periOperative Registered Nurses
BRSS – breathing recording and simulation system
CMD – count median diameter
CPC – condensation particle counter
EVA – ethylene vinyl acetate
FS – face seal
FDA – Food and Drug Administration
FF – fit factor
FFR – filtering facepiece respirator
GM – geometric mean
GSD – geometric standard deviation
HCW – healthcare worker
HEPA – high efficiency particulate air
HPV – human papilloma virus
HVAC – heating, ventilation and air conditioning
IRB – institutional review board
LEV – local exhaust ventilation
MERS – middle east respiratory syndrome
mFF – manikin protection factor
MIF – mean inspiratory flow
MPPS – most penetrating particle size
NIOSH – National Institute for Occupational Safety and Health
OPC – optical particle counter
OR – operating room
OSHA – Occupational Safety and Health Administration
PAPR – powered air-purifying respirator
PIF – peak inspiratory flow
PPE – personal protective equipment
RH – relative humidity
RPD – respiratory protective device
SARS – severe acute respiratory syndrome
SM – surgical mask
SMR – surgical mask respirator
SWPF – simulated workplace protection factor
WPF – workplace protection factor
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The dissertation summarizes the results I obtained on the performance of RPDs and respirator filters, which are presented in peer-reviewed journal articles 1-4 listed below. Additionally, during my doctoral studies, I made a major contribution to article 5 on the performance of stationary HVAC filter and automotive cabin air filter (also listed below). The full manuscripts are presented in Appendices A1 through A5.


The findings described in this dissertation were also presented in the conference presentations listed below.


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INTRODUCTION

Objectives

The overall objective of this research was to investigate the performance of different types of respiratory protective devices (RPDs) against various aerosol challenges including NaCl particles, combustion particles aerosolized by burning of wood, paper and plastic materials, as well as surgical smoke. The secondary objective of the study is to evaluate whether NaCl particles can be used as the “model” challenge aerosols for respirator filter testing. The effects of factors such as the challenge aerosol type, breathing flow rate, particle size, relative humidity of the ambient air and respirator type are evaluated. This dissertation presents results of the performance evaluation of face masks, and respirator facepieces obtained through filter performance evaluation, manikin-based study as well as by testing with human subjects. The dissertation consists of four related studies (A-D), which are described in four separate manuscripts.

A. Penetration of combustion aerosol particles through filters of NIOSH-certified filtering facepiece respirators (FFRs).

B. Performance of N95 FFRs against combustion and NaCl aerosols in dry and moderately humid air: manikin-based study.

C. Performance of facepiece respirators and surgical masks against surgical smoke: simulated workplace protection factor study

**Hypotheses**

i. The efficiency of N95 FFRs obtained with NaCl aerosol challenge may not accurately predict the filter efficiency against combustion particles (Studies A and B).

ii. The workplace protection factors (WPF) of the N95 FFRs and N100 FFRs against surgical smoke are significantly higher than that of surgical masks (Study C).

iii. Improperly sized and stretched-out loose-fitting PAPR could not offer adequate protection as expected (Study D).

iv. The performance of the respiratory protective devices depends on aerosol type, breathing flow rate, particle size, relative humidity of the ambient air, and respirator type (Studies A-D).

**Specific Aims**

**Aim 1.** Investigate the penetration of aerosol particles produced by combustion of wood, paper and plastic materials through an N95 FFR filter and compare the data to the penetration of charge-equilibrated NaCl “model” particles (to test hypothesis i).

**Aim 2.** Determine the SWPFs of two surgical masks, two N95 FFRs, and two N100 FFRs worn by human subjects while being exposed to surgical smoke generated by an electrocautery unit applied to an animal tissue in a setting simulating an operating room environment (to test hypothesis ii).

**Aim 3.** Determine the manikin fit factor of the improperly sized and stretched-out loose-fitting PAPR worn by a manikin headform under different workload conditions (to test hypothesis iii).
Aim 4. Evaluate the effects of aerosol type, breathing flow rate, particle size, air relative humidity, and respirator type on the performance of RPDs (to test hypothesis iv).

Executive Summary

When engineering controls are inadequate to reduce the hazards to acceptable levels in the working environment, employees are required to wear personal protective equipment (PPE). Commonly used PPE includes protective clothing, respirators, helmets, goggles, gloves, etc. Respiratory protective devices are widely deployed to protect wearers against airborne particles representing one of the most commonly used PPE.

Research presented in this dissertation was carried out to evaluate the performance of multiple RPDs against different aerosols. The RPD tested included surgical masks, N95 FFRs, R95 FFRs, P95 FFRs, N100 FFRs, and powered air purifying respirators. Challenge aerosols included NaCl particles, combustion particles generated by burning of wood, paper and plastic materials, and surgical smoke generated by cutting the animal tissue. The effects of multiple factors such as challenge aerosol type, breathing flow rate, particle size, relative humidity of the ambient air, and respirator type were evaluated on the RPDs’ performance. Three outcomes were used to evaluate the performance of RPDs including filter penetration, simulated workplace protection factor (SWPF) and manikin fit factor (mFF). This research effort consists of four related studies (A-D).

In the first study (Chapter 1, Study A), a NIOSH-certified N95 FFR was examined. This type of respirator is certified based on the performance testing of their filters against charge-equilibrated aerosol challenges such as NaCl particles. However, it is unknown whether the
filtration data obtained with NaCl-challenge could be used to represent the protection level against real aerosol hazards such as combustion particles. A filter sample of the N95 FFR mounted on a specially designed holder was exposed to charge-equilibrated NaCl aerosol as well as to aerosols produced by combustion of three materials (wood, paper and plastic). The study was conducted in a 24.3 m³ exposure test chamber. Testing conditions were chosen to represent four constant inhalation flows of 15, 30, 55, and 85 L/min. The concentrations upstream (C_{up}) and downstream (C_{down}) of the filter were measured with a TSI P-Trak condensation particle counter (CPC) as well as the Mini Wide Range Aerosol Spectrometer. Penetration was determined as (C_{down}/C_{up}) \times 100\%. In addition to N95, the filter samples of R95 and P95 FFRs were tested for data interpretation purposes. The experiments showed that the penetration values of combustion particles were significantly higher than those of the “model” NaCl particles (p < 0.05), raising a concern about applicability of the N95 filters performance obtained with the NaCl aerosol challenge to protection against combustion particles. Aerosol type, inhalation flow rate and particle size were significant (p < 0.05) factors affecting the performance of the N95 FFR filter. In contrast to N95 filters, the penetration of combustion particles through R95 and P95 FFR filters were not significantly higher than that obtained with NaCl particles. The findings were attributed to several effects, including the degradation of an N95 filter by the products released during combustion. The gas-phase compounds (and possibly particles) generated during combustion make the surrounding air environment adopts some properties similar to an oil-based aerosol, which is known for its ability to degrade the N-type filters (N stands for “not resistant to oil”). Overall, the findings of this study suggest that the efficiency of N95 respirator filters obtained with the NaCl aerosol challenge may overestimate the filter efficiency against combustion particles.
In the follow-up study (Chapter 2, Study B), we used the whole respirator facepieces (not the filter samples). Two NIOSH-certified N95 FFRs (A and B) fully sealed on a manikin headform were challenged with particles generated by combustion of plastic as well as NaCl particles. The tests were performed using two cyclic flows with mean inspiratory flow (MIF) rates of 30 L/min and 85 L/min, representing human breathing under low and high workload conditions, and two RH levels of ≈ 20% and ≈ 80%, representing dry and moderately humid air, respectively. The total and size-specific particle concentrations inside (C_in) and outside (C_out) of the respirators were measured with a condensation particle counter and an aerosol spectrometer. The penetration values (C_in/C_out) were calculated after each test. Study results showed that the challenge aerosol, relative humidity, MIF, and respirator model had significant (p < 0.05) effect on the performance of the manikin-sealed FFR. Its efficiency significantly decreased when the FFR was tested with plastic combustion particles compared to NaCl aerosols. For example, at RH ≈ 80% and MIF = 85 L/min, as much as 7.03% and 8.61% of combustion particles penetrated N95 respirators A and B, respectively. The plastic combustion particles and gas-phase products produced during burning likely degraded the electric charges on fibers, which increased the particle penetration. Additionally, the particle penetration was demonstrated to increase with the increasing breathing flow rate for all tested aerosols. The filter efficiency decreased when testing the respirators under high RH condition, this raises a concern about the usage of wet respirators because of the high relative humidity inside the respirator. The RH inside the respirator could reach as high as 100% due to the moisture present in the air exhaled by a wearer. The effect of particle size on penetration varied depending on the challenge aerosol and respirator model. We concluded that N95 FFRs have lower filter efficiency when challenged with contaminant particles generated by combustion, particularly when used under high humidity
conditions compared to NaCl particles.

In the third study (Chapter 3, Study C), ten subjects were recruited to perform a surgical procedure in an exposure chamber using an electrocautery device cutting the animal tissue, which generated surgical smoke. Each subject was fit tested and subsequently exposed to the smoke inside the chamber while wearing an RPD. Each subject was assigned to wear six RPDs including two surgical masks (SMs), two N95 surgical mask respirators (SMRs) as well as conventional and newly-developed N100 FFRs, offer higher protection levels. The newly-developed N100 FFRs were modified with a novel face seal (FS) design, which used ethylene vinyl acetate (EVA) foam as the face seal (FS) materials. The aerosol particle concentrations outside (C_{out}) and inside (C_{in}) of the RPD were measured by an aerosol spectrometer. Simulated workplace protection factor (SWPF) was determined for each RPD-wearing subject as C_{out}/C_{in}.

Study results showed that the geometric means of SWPF_{total} were: 1.49 and 1.76 for the tested SMs, 208 and 263 for the two N95 SMRs, and 1,089 and 2,199 for the two N100 FFRs. Significant difference was observed neither between the two SMs nor between the two SMRs. The SWPF_{total} determined with the newly-developed N100 FFR was significantly higher than the one of the conventional N100 FFR. The SWPF_{total} values of N95 SMRs and N100 FFRs were significantly higher than those measured for SMs. The SWPF was not dependent on the aerosol particle size for the tested SMs and N95 SMRs, but showed size dependency for the N100 FFRs.

We concluded that the SMs do not provide measurable protection against surgical smoke. More efficient N95 SMRs and N100 FFRs are capable of reducing the inhalation exposure to surgical smoke. While we acknowledge that conventional N100 FFRs (equipped with exhalation valves) are not practical for human operating room (OR) use, the results obtained with the newly-developed N100 FFR demonstrate the potential of the new faceseal technology for
implementation on various types of respirators.

Besides the negative pressure RPDs, we also include one positive pressure RPD in the forth study (Chapter 4, Study D). Study D was designed to investigate the protection level offered by a Powered Air-Purifying Respirator (PAPR) equipped with an improperly sized or stretched-out loose-fitting facepiece challenged with NaCl particles. Both constant and cyclic flow conditions were applied. Improperly sized facepieces of two models as well as a stretched-out facepiece were tested. These facepieces were examined in two versions: with and without exhaust holes. Loose-fitting facepieces (size “large”) were donned on a small manikin headform and challenged with NaCl aerosol particles in an exposure chamber. Four cyclic flows with MIFs of 30, 55, 85, and 135 L/min were applied using an electromechanical Breathing Recording and Simulation System (BRSS). The manikin Fit Factor (mFF) was determined as the ratio of aerosol concentrations outside (C_{out}) to inside (C_{in}) of the facepiece, measured with a P-Trak CPC. Results showed that the mFF decreased exponentially with increasing MIF. The mFF values of the stretched-out facepiece were significantly lower than those obtained for the undamaged ones. Facepiece type and MIF were found to significantly affect the performance of the loose-fitting PAPR. The effect of the exhaust holes was less pronounced and depended on the facepiece type. It was concluded that an improperly sized facepiece might potentially offer relatively low protection (mFF < 250) at high to strenuous workloads. A constant inhalation flow was also evaluated to explore the mechanism of the particle-facepiece interaction. Results obtained with cyclic flow pattern were consistent with the data generated when testing the loose-fitting PAPR under constant flow conditions. The time-weighted average values of mFF calculated from the measurements conducted under the constant flow regime were capable of predicting the protection under cyclic flow regime. The findings suggest that program
administrators need to equip employees with properly sized facepieces and remove stretched-out ones from workplace. Manufacturers should emphasize the importance of proper sizing within their user instructions.

Overall, in this dissertation, the performance of six RPD types (SM, N95 FFR, R95 FFR, P95 FFR, N100 FFR, and PAPR) was evaluated using NaCl particles, combustion particles and surgical smoke. Our study result raised a question whether NaCl is the most appropriate surrogate of aerosol particles generated by combustion. It is important because NaCl is used in the NIOSH respirator filter certification. We found the efficiency of FFRs significantly exceeded the efficiency of surgical masks while challenging with surgical smoke. It was found that the improperly sized loose-fitting facepiece PAPR offered relatively low protection at high breathing rates. Multiple factors including the challenge aerosol type, breathing flow rate, particle size, relative humidity of the ambient air and respirator type were shown to be significant factors affecting the RPD performance.
CHAPTER 1

Penetration of Combustion Aerosol Particles through Filters of NIOSH-Certified Filtering Facepiece Respirators (FFRs)

Introduction

First responders and first receivers as well as some other groups of workers are often exposed to airborne particles containing hazardous materials which may cause various respiratory illnesses (Lioy et al., 2002). For example, studies have shown that the first receivers who responded to the collapse of the World Trade Center have substantial loss in pulmonary function and increasing risk for developing a number of cancers (Banauch et al., 2006; Aldrich et al., 2010).

Combustion process can generate a large amount of particles and gases that are known or anticipated to be harmful to both the environment and the health (Morawska and Zhang, 2002). Of particular importance is the combustion of ultrafine/nano-scale particles (<100 nm in size) (He et al., 2014a), which can penetrate deep into the lung; once deposited, some of these particles may cross the air-blood barrier and accumulate in other organs (Kreyling et al., 2010). Workers exposed to the combustion particles may be at risk for developing respiratory and cardiovascular problems (Timonen et al., 2006; Schwartz et al., 1996). Characteristics such as particle size, shape, charge, surface area, chemical properties, and solubility may attribute to the particle toxicity and health effects (Shaffer and Rengasamy, 2009).

The NIOSH-certified filtering facepiece respirators (FFRs), e.g., N95-type devices, are commonly used in the workplace to protect against hazardous aerosols, including those
generated by combustion. The certification is based on the performance testing of the respirator filters against charge-equilibrated aerosol challenges such as NaCl. However, the question is whether the performance data obtained with NaCl particles adequately represent the protection characteristics of these filters against real aerosol hazards.

Numerous studies have been performed to determine the filter efficiency of the FFRs against specific aerosols (Eninger et al., 2008; Martin et al., 2000; Rengasamy et al., 2008). One study conducted with two N99 and one N95 filters challenged with three viral aerosols and NaCl at inhalation flow rates of 30, 85, and 150 L/min, revealed that the filter penetration of the virions did not exceed that of the NaCl particles, suggesting that the NIOSH certification test generated adequate data for modeling the filter penetration of similarly sized virions (Eninger et al., 2008). In another study, which tested the efficiency of N95 FFRs against silver and NaCl particles of 20 – 30 nm at 85 L/min, the investigators found that aerosol type had no significant effect on the penetration values (Rengasamy et al., 2008). The penetration of combustion particles through FFR has been addressed only in a few investigations. He, et al (2013a, 2013b) tested an elastomeric half-mask equipped with P100 filters using particles generated by combustion of wood, paper, and plastic; it was found that the aerosol type significantly affected the filter penetration. To our knowledge, no similar investigation has been conducted with N95, P95, R95, and other filters commonly used in the field.

The aim of this study was to investigate the penetration of aerosol particles produced by combustion of wood, paper and plastic through an N95 FFR filter and compare the data to the penetration of charge-equilibrated NaCl “model” particles. In addition to the challenge aerosol type, factors such as inhalation flow rate and particle size were also investigated. The R95 and P95 filters were also tested to help interpret the findings obtained with the N95 filter challenged
Materials and Methods

Tested Filters

Filter samples taken from a widely used N95 FFR model (8110S, 3M Corp., MN) were tested in this study. This filter has an electrically charged layer – a feature which makes it more efficient (He et al., 2013c; He et al., 2014b). To further investigate the interaction between this filter medium and the combustion aerosol particles, R95 (8247, 3M Corp., MN) and P95 FFRs (64420 R20, Jackson safety, GA) filter samples were also tested (in contrast to the N-type, which stands for not resistant to oil degradation), the R- and P-types represent “resistant to oil degradation” and “oil proof”, respectively (Martin and Moyer, 2000).

Challenge Aerosols

Three types of combustion particles, including wood, paper and plastic, were generated in a test chamber by burning a wood stick (24 cm long and 0.4 cm diameter, 1.9 ± 0.5 g), a sheet of paper (23 × 24 cm brown multifold paper towel, 2.1 ± 0.2 g), and a plastic straw (19 cm long and 0.5 cm diameter, 0.6 ± 0.01 g), respectively, using the protocol described elsewhere (He et al., 2014). The burning materials were held by a caliper with a water-filled basin right under it, and were ignited by a lighter. The measurement was started 15 min (= time zero) after the complete burning of each material to allow the particles to reach a uniform concentration inside the test chamber. Based on our previous findings (He et al., 2013a; He et al., 2013b), we expected that the concentration of wood combustion particles would be 160,000 – 200,000 particles/cm³ at time zero; the “initial” particle concentrations for paper and plastic were expected to range from 280,000 to 330,000 particles/cm³. These concentration levels are within the measurement
The sodium chlorite particles were aerosolized using a particle generator (Model 8026, TSI Inc., MN) containing NaCl solution with a concentration of 0.02 g/ml. The generated particles, primarily 20 – 500 nm, were charge-equilibrated before challenging the filters by passing the aerosol through a $^{85}$Kr electrical charge equilibrator (Model 3054, TSI Inc., MN) placed between the generator and the filter sample holder. The generator produced a stable concentration (±17%) of NaCl particles at a level of about 160,000 particles/cm$^3$.

It is acknowledged that in this study design, we charge-equilibrated NaCl particles but not combustion particles. The former was done to follow conventional filter testing protocols (NIOSH,1995), while the combustion particles were not subjected to the same procedure in order to better simulate the field conditions.

Experimental Design

The experiments were conducted in a room-sized test chamber (volume = 24.3 m$^3$). The experimental setup is shown in Figure 1-1. The tested filter sample with a surface area of 45.34 cm$^2$ (about a quarter of the whole respirator area) was mounted on a specially designed holder and challenged with one of the four aerosols. The sampling probes were placed upstream and downstream of the filter sample at the flow centerline. A high speed 2-way electromagnetic valve was placed between the sampling probes and the measurement devices to allow an operator to switch between the upstream and downstream measurements. The holder was connected to an air sampling pump (SP-280, Air Diagnostics and Engineering Inc., ME) producing a constant inhalation air flow (Q). A mass flow meter (4050, TSI Inc., MN) with a range of 0 – 300 L/min was placed between the pump and the holder to monitor the flow rate. Four inhalation flow rates ($Q_{\text{Sample}}$) of 3.75, 7.50, 13.8, and 21.3 L/min were applied on the filter samples. With the sample
areas (A_{Sample}) selected, these allowed matching the air face velocity through the filter sample and the whole respirator at inhalation flows (Q_{Respirator}) of 15, 30, 55 and 85 L/min, respectively (see Table 1-1). The latter simulate low, moderate, high, and strenuous workload, respectively (Sherwood, 2006; Tortora et al., 1990). During the testing, the concentrations of each challenge aerosol were measured upstream (C_{up}) and downstream (C_{down}) of the tested filter with a P-Trak condensation particle counter (8525, TSI Inc., Shoreview, MN) operating within a size range of 20 to >1000 nm and the Mini Wide Range Aerosol Spectrometer (Grimm Technologies, Inc., Ainring, Germany) consisting of a Nanoparticle Aerosol Monitor (Model 1320) and an optical particle counter (OPC) (Model 1.108). We focused primarily on the size range of 20–150 nm since our earlier experiments showed that 90% of combustion particles were in this range (He et al., 2013a). The corresponding mean sizes for the selected channels were 26, 35, 46, 60, 80, 105 and 139 nm. Additionally, larger particles (up to 900 nm) were measured using the Grimm OPC, which allowed comparing the size-integrated (total) concentrations obtained with the aerosol spectrometer and the P-Trak.

The size specific particle penetration values (P_{dp}) were determined for these sizes as

\[ P_{dp} = \left( \frac{C_{down_{dp}}}{C_{up_{dp}}} \right) \times 100\% \]  

(1-1)

The total particle penetration (P_{total}) was determined from the P-Trak data as

\[ P_{total} = \left( \frac{C_{down_{total}}}{C_{up_{total}}} \right) \times 100\% \]  

(1-2)

The P-Trak was chosen for the total count because it has the same operating principle as a PortaCount respirator fit testing apparatus (8038, TSI Inc., Shoreview, MN) which is utilized for evaluating the fit factor of FFRs.

**Data Analysis**

Statistical data analysis was performed using SAS version 9.3 (SAS Institute Inc., Cary,
NC). Two-way analysis of variance (ANOVA) was conducted to study the effects of inhalation flow rate, challenge aerosol type, and their interaction on the $P_{\text{total}}$. T-test was used to evaluate the differences between NaCl and three combustion particles. One-way ANOVA was performed to study the effect of particle size. P-values less than 0.05 were considered significant.

**Results and Discussion**

**Total Particle Penetration ($P_{\text{total}}$)**

The total particle penetration ($P_{\text{total}}$) obtained for the N95 FFR filter samples challenged with four tested aerosols is presented in Figure 1-2. Combustion particles penetrated more readily, with the penetration values significantly higher than those of “model” NaCl particles ($p < 0.05$) regardless of the inhalation flow rates. At $Q_{\text{Respirator}} = 85$ L/min, the flow rate condition under which the respirators are tested for NIOSH certification, the $P_{\text{total}}$ of NaCl was at least 50% lower than that of combustion particles. One possible explanation could be the difference in shape, density, charge, surface properties and possibly other characteristics between the combustion particles and NaCl particles. Further investigation was undertaken to understand how these differences may affect the outcome (described below). It is noted, however, that although the N95 filters did not provide the same filtration efficiency against combustion particles as they did for NaCl, their collection efficiency was still above 95% (none of $P_{\text{total}}$ exceeded 5%), which is acceptable for the N95 filters.

For the three combustion materials, the penetration of plastic particles was the highest, followed by paper and wood. This finding is consistent with our previous studies, which were conducted using elastomeric half-mask with P100 filters (He et al., 2013b; He et al., 2014a).

The results obtained with the P-Trak were in agreement with the size-integrated data
generated by the Grimm spectrometer in a range of 25 to 900 nm. No significant difference (p >0.05) was observed between the total particle penetration obtained with the two aerosol measurement devices.

1. **ANOVA Results on the Effect of Challenge Aerosol**

A two-way ANOVA with interaction showed that the type of the challenge aerosol has a strong significant effect on the performance of the N95 filter (p < 0.0001) (see Table 1-2). Further analysis was undertaken using a pair-wise multiple comparison to assess the significance of the penetration difference when each challenge aerosol was compared with the other three challenge aerosols. As seen from Table 1-3, all the differences were significant (p < 0.05).

2. **ANOVA Results on the Effect of Inhalation Flow Rate**

The total particle penetration increased with increasing constant flow rate. This could be explained by particle capture mechanisms, which are primarily diffusion and electrical charge interaction. These mechanisms are affected by the face velocity of the air flow, with higher face velocity resulting in a shorter residence time and, consequently, higher penetration level.

As shown in Table 1-2, inhalation flow rate was a significant factor affecting $P_{\text{total}}$ (p < 0.0001). The interaction between the challenge aerosol and the inhalation flow rate had also a strong significance (p < 0.0001). Pair-wise comparison (Table 1-4) revealed that the differences among the data series of four flow rates were significant except the data series obtained at 15 and 30 L/min. One possible reason is that the flow rate increment (the interval between 15 and 30 L/min is only 15 L/min) is not large enough to significantly reduce the penetration levels.

**Size-Selective Particle Penetration ($P_{dp}$)**

The size-selective particle penetration values determined by Grimm Nanoparticle Aerosol Monitor are presented in Figure 1-3. While retrieving the particle size distribution data across
the entire operational size range of this spectrometer, we found that, based on the aerosol type, 97-99% (by number) of combustion particles generated were within the selected range of 20 to about 150 nm. The figures represent four challenge aerosols and four inhalation flow rates.

Increasing the inhalation flow resulted in an increase in $P_{dp}$ values for all the tested combustion particles as well as NaCl particles, which is consistent with the results of previous studies conducted with N95 FFRs (Balazy et al., 2006a; Rengasamy et al., 2008). The results of paired t-test showed that the difference between each paired flow rate was also significant ($p < 0.05$).

All three combustion particles featured significantly higher penetration values than NaCl regardless of the particle size and flow rate ($p < 0.05$). One-way ANOVA revealed that the particle size had a significant effect on the penetration of combustion particles ($p < 0.05$) while not being a significant factor ($p > 0.05$) for NaCl. In contrast, our earlier study on the efficiency of an N95 FFR against NaCl particles under cyclic flows with mean inspiratory flows (MIFs) of 15, 30, 55 and 85 L/min [conducted using a Nano-ID (NPS500, Naneum, Canterbury, UK)] showed that the effect of particle size was significant (He et al., 2013c). An important difference between these investigations is an instrument deployed for aerosol measurement. The sensitivity of the Grimm spectrometer (used in the present study) is not as high as that of the Nano-ID (used in the quoted study) at low penetration levels observed with NaCl. This may be, at least partially, a reason for ANOVA not yielding the penetration dependency on size. The disagreement can also be attributed to differences in the experimental design and flow regime used in these two studies. E.g., in the quoted investigation, cyclic flow regime was applied on a manikin headform wearing the N95 FFRs while in the present effort a constant flow regime was applied on the N95 FFR filters. In the cyclic regime, the returned clean air (exhalation) dilutes the aerosol inside the
respirator. This “cleaning” effect is different for different particle sizes. Furthermore, some particles present inside the respirator cavity may deposit on the inner surface of the filter or move out through the filter and faceseal leakage during exhalation. These effects are also anticipated to be particle size dependent.

The most penetrating particle size (MPPS) varied depending on the aerosol type. For example, the curves obtained for NaCl were almost flat with a barely visible peak at about 70 nm; the penetration of wood steadily increased until the particle size reached 46 nm, then the \( P_{dp} \) started to decrease; the curves for paper were relatively flat reaching a small peak at 35 nm; the MPPS values for plastic particles were in the range of 46-80 nm. Overall, the MPPS for the tested N95 FFR filter against combustion particles was observed in the size range of 35 – 105 nm, which is consistent with the results of earlier studies reporting the MPPS values below 100 nm for the N95 FFRs (Balazy et al., 2006a; Huang et al., 2007; Rengasamy et al., 2009). The MPPS is also dependent on the tested filter type. In one study that included a half-mask respirator with P100 filters, the MPPS for plastic particles fell in the range of 120 –140 nm, while the MPPS for wood and paper was difficult to identify since the penetration curves were close-to-flat (He et al., 2013a).

**Interpretation of Data Obtained for an N95 Filter. Testing of R95 and P95 Filters**

Generally, combustion particles, which are electrically charged, should be collected more efficiently by the N95 filter fibers than the charge-equilibrated (quasi-neutralized) NaCl particles. Thus, it was surprising to observe that the combustion particles penetrated through an N95 FFR filter significantly more readily than the “model” NaCl. We hypothesized that the “reverse” trend seen in our experiments can be, at least partially, attributed to the following. The combustion particles (as well as vapors originated when burning different materials) contain
hydrophobic molecules (or hydrophobic portions of molecules). E.g., the plastic combustion has been shown to emit hydrophobic organic compounds (Teuten et al., 2007). In this regard, having properties similar to oil particles (and in presence of “oily” vapors), the combustion particles may degrade an “electret” filter (media used for FFRs not resistant to oil, e.g. N95), if deposited on its fibers (Biermann et al., 1982; Tennal et al., 1991), thus increasing the aerosol penetration. This may be associated with the charge neutralization during the filter collection (Biermann et al., 1982), dielectric shielding of fibers and ionic conduction (Tennal et al., 1991).

An additional experiment was conducted to examine the above interpretation. In contrast to the N95 filter type, the filters of R95 and P95 FFRs are designed to protect against oily particles; therefore, we repeated the particle penetration experiments using these two types of filters. We anticipated that since R95 and P95 filters are resistant to degradation associated with oil aerosols, we should observe no significant difference in penetration of combustion particles and NaCl particles, which would support our hypothesis.

As shown in Figure 1-4, the penetration values through R95 and P95 were extremely low as compared to N95, with the total particle penetration being below 0.15% for all the tested materials at $Q_{\text{Respirator}} = 85$ L/min. This finding is consistent with other studies (He et al., 2013a; Lee et al., 2005; Martin and Moyer, 2000; Tennal et al., 1991). Remarkably, for R95 and P95 filters, the penetration levels of combustion particles were not higher than that of NaCl. We believe it is because, unlike an N95, these two filters were “non-degradable” or “less degradable” which supports our above interpretation of the effect of particle type. Furthermore, opposite to the test results obtained with an N95 filter, the R- and P-type filters allowed penetrating fewer combustion particles than NaCl particles in most experimental conditions (with an exception of plastic particles penetrating through a P95 filter) ($p < 0.05$). Unlike NaCl aerosol that passed the
electrical charge equilibrator, combustion particles carried some electric charges, which
enhanced their deposition on fibers. The net charge is not expected to be substantial though
because the freshly-generated particles were allowed to interact with air ions for 15 minutes
before the measurement began, which should have led to their partial neutralization. The charge
neutralization rate of combustion particles is unknown, which is a limiting factor for our data
interpretation involving the particle charge. In any case, because of their design, the R- and P-
type filters were not subjected to substantial degradation due to exposure to combustion aerosols
– the phenomenon caused the “reverse” trend for the N95 filter.

Other possible mechanisms that may explain the differences in penetration of combustion
and NaCl particles through an N95 filter include the formation of loose agglomerates on the
fibers, neutralization or reduction of charge occurring on fiber due to deposition of oppositely
charged particles, as well as chemical reaction (Barrett and Rousseau, 1998).

Conclusions

Performance of the N95 FFR filter was significantly affected by the aerosol type and
inhalation flow rate. The penetration of combustion particles through an N95 respirator filter was
significantly higher than that of the “model” NaCl particles (p < 0.05), raising a concern about
applicability of the N95 filters performance obtained with the NaCl aerosol challenge to
protection against combustion particles. The findings were attributed to several effects,
including the degradation of an N95 filter due to hydrophobic organic components originated in
the air during combustion. Their interaction with fibers is anticipated to be similar to those
involving “oily” particles. Additional experiments with oil-resistant and oil-proof FFR filters
supported our explanation. The total penetration increased with an increasing flow rate regardless
of particle types. Particle size was also found to be a significant factor on the penetration of combustion particles. The findings of this study suggest that the efficiency of N95 respirator filters obtained with the NaCl aerosol challenge may not accurately predict (and rather overestimate) the filter efficiency against combustion particles.
CHAPTER 2

Performance of N95 FFRs against Combustion and NaCl Aerosols in Dry and Moderately Humid Air: Manikin-based Study

Introduction

Air-purifying respirators are commonly used in the U.S. for protection against job hazards. According to a voluntary survey conducted on U.S. employers regarding the use of respiratory protective devices, 95% of the workers used air-purifying devices (BLS/NIOSH, 2003). The N95 filtering facepiece respirators (FFRs) are the most popular air-purifying respirators. They are expected to filter out at least 95% of airborne particles ("N" stands for non-oil-resistant). The National Institute for Occupational Safety and Health (NIOSH) estimates that 20 million American workers, including healthcare providers, firefighters, first-responders, and construction workers use respirators every day for reducing exposure to airborne hazards (NIOSH, 2013). First responders such as emergency medical personnel and police – the first people who arrive at the scene of emergency and possibly exposed to elevated levels of hazardous materials present in flame and smoke – are often equipped with N95 FFRs (as evident from the response to the 9/11 terrorist attacks in New York and Washington). In various working environments, airborne combustion particles may be generated by burning plastic, wood, paper, cotton, and other construction materials, of which, open burning of plastic is particularly dangerous to the workers’ health.

Burning of plastic generates black smoke containing decomposition compounds, which contaminate the ambient air and cause harmful exposures (Karasek and Tong, 1985; Simoneit et
The chemical compounds generated by plastic burning include carbon monoxide, hydrogen cyanide, dioxin, acrolein, formaldehyde, etc. (Guidotti and Clough, 1992). These compounds may be present at the levels substantially exceeding their recommended exposure limits (RELs), which can cause health impairments and death (Milkovits, 2006). Some hazardous compounds have been shown to adhere to or stick to particles, which results in a deeper penetration into the respiratory tract, causing toxicological effects (Genovesi, 1980; Karasek and Tong, 1985; Kulkarni et al., 2011). The health effects of exposure to smoke and fumes from plastic burning have been associated with various occupational diseases, including heart disease, lung cancer, asthma and emphysema, nausea, headaches, and damages in the nervous system (Timonen et al., 2006; Schulte et al., 2008).

NIOSH generates charge neutralized sodium chloride (NaCl) particles of approximately 300 nm mass median aerodynamic diameter as the challenge aerosols to test the filtration efficiency of N95 FFRs (42 CFR Part 84), by using automated filter tester (TSI 8130, TSI Inc., Shoreview, MN, USA). The referred size was originally assumed to be near the most penetrating particle size for N95 FFRs, which has been questioned in several studies (Lee et al., 2008; Martin et al., 2000). It has not been demonstrated that NaCl particles can be used as a model aerosol that can accurately simulate aerosols produced by combustion for the filter/respirator testing purposes. Particles aerosolized from different sources feature different properties such as size distribution, charge distribution, and chemical composition, which can influence the filter performance (Balazy et al., 2006b; Eninger et al., 2008; He et al., 2013a; Lathrache and Fissan, 1986; Lathrache et al., 1986; Martin and Moyer, 2000). For example, Balazy et al. (2006b) who challenged two N95 FFRs with MS2 virus concluded that some N95 FFRs may not provide 95% filter efficiency against airborne virions that are smaller than the
conventionally used 300-nm NaCl particles. Walsh and Stenhouse (1996) reported that factors such as size, charge and composition of aerosol particles had significant effects on the filter performance; furthermore, these investigators stated that the charge of the test particles was a key factor affecting the electret filter performance. Our recent study (Gao et al., 2015) conducted on the electret filter samples indicated that combustion particles penetrated more readily than NaCl particles, which could be attributed to different chemical properties of the two types (more details are provided below).

The NIOSH certifies FFRs by evaluating the filter performance under a constant flow of 85 L/min. Numerous studies have been conducted to determine the filtration efficiency under constant flow regime (Chen et al., 1990; Chen and Willeke, 1992; Eshbaugh et al., 2009; Martin et al., 2000; Qian et al., 1998). However, the result obtained under constant flow may not accurately predict the filter performance under actual breathing conditions as a human breathing pattern is much more complex and features a cyclic nature. Therefore, in this study we used a cyclic flows produced by a breathing machine to mimic human breathing.

A few studies have been published concerning the relative humidity (RH) influencing the respirator performance. The effect of RH on the filter efficiency varies depending on the aerosols type, particles size as well as the filter material (Newnum, 2010). One study showed that the penetration of the non-hygroscopic particles increased as RH increased (Minguel, 2003). However, for hygroscopic particles such as NaCl, the penetration decreased with increasing the RH since the particle size increased by absorbing water from the ambient air. Kim et al. (2006) reported that the effect of RH on penetration of particles below 100 nm was not significant. At higher RH, the adherence between fibers and particles increases due to an increase in the
Consequently, the fibers are able to capture more particles from the air stream, i.e., the aerosol penetration decreases with increasing RH. However, this phenomenon has been shown to be pronounced specifically for coarse particles (with aerodynamic diameter above 2.5 µm) at higher RH (Brown, 1993). While Yang and Lee (2005) reported that RH had no effect on the filter performance by comparing the filter penetrations of NaCl particles under RH = 30% and 70%, the effect was demonstrated at higher RH. Several studies (Haghighat et al., 2012; Lkezaki et al., 1995; Lowkis and Motyl, 2001; Mahdavi et al., 2015; Mostofi et al., 2011; Cheng et al., 2006) have shown that the performance of electret filters decreases with increasing RH. For instance, Haghighat et al. (2012) tested N95 FFRs filters under three RH of 10%, 30% and 70% at a constant flow rate of 85 L/min and found that the penetration of the filters increased with the increasing RH. It should be noted that NIOSH certification testing program for FFRs includes preconditioning in a chamber at RH = 85% ± 5% RH and a temperature of 38 ± 2.5 ºC for 25 ± 1 hours. We hypothesize that a humidity-associated partial or full discharge of the fibers of electret filters (material used in N95 FFRs) may significantly compromise the filter performance. The water vapor could condense on the electret fibers, which would produce a “discharging” effect.

The present research effort is a follow-up to the study of Gao et al. (2015) performed using the same challenge aerosols. Similar to our earlier study, this investigation aimed at evaluating the penetration of particles aerosolized by combustion (plastic particles in particular) through filter samples of N95 FFRs and comparing the results to the penetration of the “standard” challenge aerosol (NaCl). The main difference is that in the current effort we tested the whole facepieces and utilized a manikin-based protocol. The tested N95 respirator was fully sealed using silica adhesive on the plastic manikin headform in order to test the filter efficiency,
whereas the previous investigation examined the performance of 76-mm diameter filter samples cut from the N95 FFRs. Additionally, this study was conducted under the cyclic (not constant) breathing condition. The main goal of this study was to investigate the particle penetration through N95 filters challenged with particles generated by combustion of plastic and compare the data to the penetration of NaCl particles. The second goal was to investigate the effect of humidity on the filtration performance of N95 FFRs.

Materials and Methods

Respirators and Challenge Aerosols

Two widely used N95 FFRs labeled as N95 FFR-A and N95 FFR-B were tested in this study. The N95 FFR-B has a plastic mesh shell to support the physical structure of the filter media and prevent collapsing during regular use as well as under hot and humid conditions. Both the FFRs tested do not have exhalation valves which results in the exhaled breath coming in full contact with the filter media. In an FFR equipped with an exhalation valve, the exhaled breath is essentially directed to the outside through the valve, which could reduce moisture build up inside the facepiece.

Two challenge aerosols including plastic combustion particles and NaCl particles were generated (one at a time). The plastic particles were produced by burning a plastic polypropylene straw (Home sense™, Kroger Co., Cincinnati, OH, USA) (19 cm long and 0.5 cm diameter, 0.6± 0.01 g) held in a caliper. The plastic straw was ignited by a lighter and left for burning until completely consumed. The sampling devices were started to collect data 15 minutes after the completion of the plastic burning, which allowed the plastic particles to reach a
spatial uniformity (He et al., 2014a). We were specifically interested in testing the plastic particles as our previous study showed that they penetrated through the N95 FFR filters more readily than the other two types of combustion particles (wood and paper) (Gao et al., 2015). Additionally, plastic aerosols were of interest due to adverse health effects associated with their exposure (Simoneit et al., 2005). The NaCl aerosols were continuously generated using a particle generator (Model 8026, TSI Inc., Shoreview, MN, USA) from a water suspension with NaCl dissolved at 0.02 g/ml. A period of 20 minutes was allowed for NaCl particles to reach the homogeneous stage in the test chamber.

Relative Humidity

The respirators were tested against challenge aerosols at two RHs: ≈ 20% and ≈ 80%. These levels represent dry and moderately humid conditions, respectively. RH = 20% was the natural humidity inside the chamber. In order to establish the higher RH, a steam vaporizer (V150SG2UPC, KAZ Inc., Southboro, MA, USA) was utilized. The RH in the test chamber was measured using a digital psychrometer (SAM990DW, General Tools & Instruments, New York, NY, USA). Prior to testing, the N95 FFRs were placed under the tested RH for about 30 min before generating aerosol.

Experimental Design and Test Conditions

The experimental set-up shown in Figure 2-1 has been described in detail elsewhere (He et al., 2013b). All the tests were conducted in an exposure chamber (volume = 3.6 × 2.4 × 2.6 m³, L×W×H). Table 2-1 summarizes the experimental conditions. The tested N95 FFR (either N95 FFR-A or N95 FFR-B) was properly positioned and fully sealed along the contact area of the manikin headform using the silica adhesive. The headform has a facial length of (11.43 ±
0.35) cm and width of (12.53 ± 0.25) cm, which is categorized into Cell 3 (small faces) of the NIOSH bivariate panel, developed by using the database of a total of 3997 respirator users (Zhuang et al., 2007). A 1-inch diameter copper pipe connected the nose and mouth area of the manikin with the breathing simulator. Two sampling probes were inserted: one in the breathing area inside the respirator cavity and one outside of the respirator. The two sampling lines were controlled by a high-speed 2-way electromagnetic valve, which was manually operated to alternate measurements of the inside (C_in) and outside (C_out) aerosol concentrations.

The aerosol was measured with two devices. A P-Trak condensation particle counter (Model 8525, TSI Inc., Shoreview, MN, USA) counted particles across the size range measuring the total aerosol concentration. The Mini Wide Range Aerosol Spectrometer [a Nanoparticle Aerosol Monitor Model 1320 in combination with an optical particle counter (OPC) Model 1.108, both from Grimm Technologies, Inc., Ainring, Germany)] measured the particle size distribution as well as the total concentration. The concentration C_out was measured during the first 5 minutes, followed by the measurement of C_in for 10 minutes, and then C_out was measured again over the last 5 minutes. In each test, the outside concentration was calculated as an average of the C_out values measured over the two 5-minute periods. Thus, the natural decay of the aerosol concentration in the chamber was accounted for; it was relatively small: 15% for NaCl particles and 35% for plastic combustion particles as measured over 20 min at no air exchange applied in the exposure chamber during the experiment. The particle penetration (P_total) was calculated as (C_in/C_out) × 100%. The air was supplied using the Breathing Recording and Simulation System (BRSS, Koken Ltd., Tokyo, Japan) via a high efficiency particulate air (HEPA) filter. The BRSS is capable of establishing various breathing patterns by adjusting the flow rate and the breathing frequency. For this study, we selected two cyclic flows with mean inspiratory flow (MIF) rates.
of 30 L/min and 85 L/min and a breathing frequency of 25 breaths/min. These conditions represent human breathing under the low and moderate workloads, respectively (Sherwood, 2006; Tortora and Anagnostakos, 1990).

Data Analysis

Data analysis was performed using SAS version 9.3 (SAS Institute Inc., Cary, NC, USA). Paired t-test was deployed to evaluate the difference between plastic combustion particles and NaCl particles. Four-way analysis of variance (ANOVA) was used to evaluate the effects of challenge aerosol, RH, MIF, respirator type, as well as the interactions between relative humidity and the other variables. Three-way ANOVA test was utilized to examine the significance of challenge aerosol, RH, and MIF after stratifying the data by respirator type. Paired t-test was used to examine the difference between the total particle penetrations obtained using the aerosol concentrations measured by the condensation particle counter and the aerosol size spectrometer. Correlation analysis was performed to evaluate the association between the two. For the size-specific particle penetration, the effect of particle size was analyzed by one-way ANOVA. The differences were considered significant if p-values calculated from the above statistical tests were below 0.05.

Results and Discussion

Total Particle Penetration (P_total)

The total particle penetration obtained for the two tested N95 FFRs challenged with plastic combustion particles and NaCl particles is presented in Figure 2-2 and Figure 2-3 as measured using a P-Trak and a Grimm aerosol size spectrometer, respectively. According to
measurements conducted with the P-Trak, the total penetration values for combustion aerosol at RH $\approx 20\%$ and MIF $= 30\; \text{L/min}$ were 1.38\% and 2.10\%, respectively, for N95 FFR-A and N95 FFR-B. These values increase as MIF increased to 85 L/min. The penetration also showed higher values as the humidity was raised to 80\%. The higher penetrations for combustion particles was observed for RH $\approx 80\%$ and MIF $= 85\; \text{L/min}$: 7.03\% for N95 FFR-A and 8.61\% for N95 FFR-B. The measurements using the Grimm instrument revealed similar trends with the maximum total penetration values of 6.05\% for N95 FFR-A and 7.16\% for N95 FFR-B measured at the highest tested RH and MIF. It is noted that these levels exceed the 5\% NIOSH certification criterion established for N95 respirators. In all cases presented for the P-Trak measurements and all, but one, cases presented for the Grimm measurements, the results of paired t-test showed that the penetration of plastic combustion particles was significantly higher ($p < 0.05$) than that of NaCl particles, regardless of RH, MIF and respirator type. The four-way and three-way ANOVA tests also showed that aerosol type was a significant factor ($p < 0.05$) affecting the filter performance (Table 2-2, Table 2-4). This finding is consistent with previous reports (He et al., 2013b; Ji et al., 2003). In our recent study (Gao et al., 2015), we discussed why the plastic combustion particles may penetrate through an N95 “electret” filter material more readily than NaCl particles. In brief, we believe that the particles and gaseous compounds originated by burning plastic contain hydrophobic molecules, which, similarly to oil aerosols, are capable of degrading the “electret” filter (Gao et al., 2015; Tennal et al., 1991; Teuten et al., 2007). Since the N95 filter material is not resistant to oil, it may be affected by the compounds produced from burning plastic. Whether the combustion gases affect filter performance was beyond the scope of this research, but is suggested as an area of future studies. The “oily” particles generated by combustion may partially charge-neutralize the fibers and consequently reduce their collection efficiency, which,
in turn, increases the aerosol penetration into the respirator. Unlike an N95 FFR, a P95 type (designed to protect against “oily” aerosols) was found to feature the same collection efficiency for plastic combustion particles and NaCl particles (Gao et al., 2015), which supports our interpretation. Other factors that could explain the significantly different penetration levels observed between plastic combustion particles and NaCl particles may include the difference in their particle size distributions (discussed below), as well as in the particle shape, density, charge, surface properties and possibly other characteristics between the plastic combustion particles and NaCl particles. For example, Zhou and Cheng (2016) suggested that NaCl particles do not as readily penetrate the N95 FFRs as engineered nanoparticles due to their different electrostatic properties.

The total particle penetration values measured with a P-Trak when testing N95 FFR-A under the cyclic flow condition was compared to the results obtained with the flat filter samples made of the same material under constant flow (Gao et al., 2015). Table 2-3 shows the results of this comparison. In the quoted study, the test conditions were established so that the face velocity for the flat filter sample was equal to the face velocity of the whole respirator under the constant flow. It was noted that the penetration of particles under cyclic flow (determined in this study) was 1.5- to 2.2-fold higher than that measured under the corresponding constant flow (the quoted study). This may be attributed to the differences in filter surfaces (cup-like versus flat) and flow dynamics (cyclic versus constant).

1. Effect of RH on $P_{total}$

As shown in Figure 2-2, the total particle penetration increased with the increasing RH. For NaCl particles, while $P_{total}$ increased significantly ($p < 0.05$) when RH was raised from 20 to 80%, it did not exceed the 5% NIOSH respirator certification criterion (except a minor excess
observed for N95 FFR-B at MIF = 85 L/min). In contrast, almost all $P_{\text{total}}$ values obtained for plastic combustion particles exceeded 5%. The four-way and three-way ANOVA tests indicated that the effect of humidity was significant (Table 2-2, Table 2-4), which is in agreement with the results of other studies (Minguel, 2003; Moyer et al., 1989; Newnum, 2010). Some older studies suggested that electrical discharge occurred on filter fibers at high RH (Ackley, 1982; Moyer et al., 1989). As the charges decrease, the filter efficiency decreases as well, which results in a greater $P_{\text{total}}$. Other possible explanations for decreasing the filter efficiency with the humidity increase have been discussed in the literature. For example, Raynor and Leith (1999) indicated that humid air might help form small water droplets at intersections of fibers. These droplets could coalesce and cover the fibers, thus impeding their ability to collect. Haghighat et al. (2012) stated that at high RH salt particles such as NaCl might undergo deliquescence and interact with the filter as larger droplets. Gupta et al. (1993) speculated that the droplets could fill the interstitial spaces of the filter. This may negatively affect the filter performance. Our findings along with the above interpretation of the RH effect are consistent with the experimental investigation of Mahdavi et al. (2015) who suggested that NaCl particles were partially or totally hydrated at high RH, which reduced their electrostatic attraction to the filter.

2. Effect of MIF and Respirator Type on $P_{\text{total}}$

Besides the challenge aerosol type and humidity, other factors such as MIF and respirator type were also evaluated in this study. As seen from Table 2-2, the effect of MIF on $P_{\text{total}}$ was significant ($p < 0.05$). Penetration increased with the increasing MIF, which is in agreement with previous reports (Eshbaugh et al., 2009; He et al., 2014b). Respirator type was found to be a significant factor as well. None of the three interactions between RH and other variables (RH
and challenge aerosol, RH and MIF, RH and respirator type) had a significant effect on the respirator performance.

3. **P<sub>total</sub> data: Aerosol Size Spectrometer versus Condensation Particle Counter**

   The total aerosol concentrations measured with the aerosol size spectrometer was obtained by combining all the channels between 15 to 900 nm. The particle size range in which P-Trak condensation particle counter measures the total concentration is approximately 20 – 1000 nm. In spite of the differences in the size range and operational principles, the paired t-test revealed that the P<sub>total</sub> values determined with the two devices were not significantly different (p > 0.05). Additionally, as shown in Figure 2-4, a significant correlation between the P<sub>total</sub> measured with P-Trak and Grimm was observed with the slope of 0.81 and the R<sup>2</sup> value of 0.87.

**Particle Size Specific Penetration (P<sub>dp</sub>)**

   Figure 2-5 presents the size specific particle penetration obtained with two tested N95 FFRs at MIFs = 30 L/min and 85 L/min and RH ≈ 20% and ≈ 80% while exposed to two challenge aerosols (plastic combustion and NaCl). For N95 FFR-A, data analysis revealed that particle size had a significant effect on penetration of both tested aerosols (p < 0.05), which was consistent with our previous results (He et al., 2013c). For both types of challenge aerosols, the shapes of the penetration curves obtained in dry and humid air environments were about the same. Quantitatively, the difference between penetration levels found at two RHs decreased with increasing MIF (see the distances between two curves of the same color in Fig. 2-5A). Within the tested particle size range, the penetration under high RH exceeded that under low RH, regardless of MIF and challenge aerosol. The peaks were observed at 80 nm for NaCl and 35-46 nm for combustion particles, respectively. The difference in the most penetrating particle size
likely reflects different physical properties of the two types of aerosol particles relevant to the particle-filter interaction, including, but not limited to, the particle shape, surface area, and effective density (Boskovic et al., 2005; Vaughn and Ramachandran, 2002). The MPPS data are comparable to the recently published results obtained for the N95 filter samples made of the same material (Gao et al., 2015). The size-specific penetration values obtained for the N95 FFR-A device with NaCl particles were approximately between 0.01 and 7.69%; for plastic combustion particles the range was 0.72 – 8.58%.

For N95 FFR-B, the trend was more complex. The penetration values were higher than those obtained for the N95 FFR-A, indicating that N95 FFR-B was not as efficient as N95 FFR-A. One-way ANOVA indicated that particle size was a significant factor affecting the penetration when the respirator was challenged with either of the aerosols. As shown in Figure 2-5B, the curves representing the two challenge aerosols are closer to each other compared to the similar curves presented for the N95 FFR-A. The MPPSs obtained for the two challenge aerosols lay closer for both tested RH and MIF. The latter may be attributed to the electric charge on the fibers of the respirator filter. We believe that the bipolar charging of the N95 FFR-B filter is not sufficient to cause a pronounced size selectivity of P_{dp}. This suggests a lower difference in penetration between combustion particles and NaCl. Similar to the results observed on N95 FFR-A, the filtration performance of N95 FFR-B decreased with increasing RH, except a few points obtained under MIF of 85 L/min.

Effect of Particle Size Distribution of the Challenge Aerosol on Penetration

The information about the MPPSs obtained for the two challenge aerosols in relation to their particle size distribution helps interpreting the findings about the difference in total
penetrations. Both size distributions – for NaCl and plastic combustion particles – were close to log-normal with a count median diameter (CMD) and a geometric standard deviation (GSD) of 80 nm and 5.9, respectively, for NaCl particles, and 59 nm and 4.8, respectively, for combustion particles.

It was observed that the peak of the particle size distribution was close to the MPPS value for combustion particles, which was not the case for NaCl particles. This suggests that the fraction of particles with sizes close to MPPS was greater for the plastic combustion aerosol as compared to NaCl aerosol, which contributes to the higher penetration level observed for the combustion particles versus NaCl.

**Limitations and Future Work**

First, the findings of this study are limited to specific (although extensively used) N95 FFR models. Future efforts are needed to examine if the results of this investigation are fully applicable to other filter materials and respirator models. Second, this study is focused on the respirator filter efficiency (the tested device was sealed on the manikin), but does not address the role of the faceseal leakage, which may represent a prominent particle penetration pathway. Third, the study used the aerosol generated by burning plastic as an example of combustion particles. However, combustion aerosols can be generated by different materials, which vary from one another in terms of the particle size and charge distributions, chemical composition and other factors that may affect the respirator filter performance. Thus, other challenge aerosols should be investigated in future research efforts. Finally, the interpretation of the findings of this study is of a limited utilization given that no chemical characterization of the gases/vapors generated by combustion was performed.
**Conclusions**

This study evaluated the penetration of combustion and NaCl particles through N95 FFRs sealed on a manikin headform and tested under simulated cyclic breathing flow. Filter penetration of N95 FFRs measured using particles generated by combustion of plastic was higher than the value determined with a NaCl challenge aerosol. This was most likely due to the compounds produced from burning plastic. A similar finding was reported in our companion study (Gao *et al*., 2015), which was conducted with N95 filter samples at constant inhalation flow conditions. From this perspective, R95 or P95 FFRs should, probably, be considered as better alternatives for first responders since they may be exposed to similar combustion products in the air. Increasing the RH reduced the respirator filtration performance against both the NaCl and plastic combustion challenge aerosols. The findings presented in this study are limited to the respirators tested and may not necessarily be applied to all N95 FFRs and all plastic combustion aerosols.
CHAPTER 3

Performance of Facepiece Respirators and Surgical Masks against Surgical Smoke: Simulated Workplace Protection Factor Study

Introduction

Surgical smoke is an aerosol hazard unique to the surgical operating room (OR). It is generated by electrocautery used in virtually all standard surgical facilities as a means of performing surgical dissection of various tissues. Electrocautery is a process in which an electrical current is passed through a resistant metal wire electrode. The heated electrode is then applied to the tissue for dissection or hemostasis (Pollock et al., 2008). Given the positioning of surgical personnel over and around the surgical patient, surgical smoke is often directly in the path of their respiratory field. The Occupational Safety and Health Administration (OSHA) estimates that 500,000 workers are exposed to laser and electrocautery smoke each year (OSHA, 2007).

There have been significant concerns about exposure to surgical smoke, and about the adequacy of standard surgical masks (SMs) to protect personnel in the OR. Surgical smoke contains known carcinogens as well as viable biologic particles (Barrett and Garber, 2003). Carcinogenic and neurotoxic compounds were found in surgical smoke aerosols generated from porcine tissue as well as during human surgical procedures (Krones et al., 2007; Sahaf et al., 2007). A review by Biggins and Renfree (2002) reported the failure of SMs to provide appropriate protection to healthcare personnel and suggested establishing new standards to reduce the risks. Other studies have revealed that SMs are insufficient for providing adequate protection against surgical smoke (Barrett and Garber, 2003; Alp et al., 2006).
Exposure to surgical smoke aerosol has relevance to public health settings due to the presence of small particles. Weber et al. (1993) tested eight SMs and found that for fine particles (< 1,000 nm) the penetration through these masks ranged from 20% to nearly 100%. Studies conducted with two SMs sealed on a manikin headform indicated that for particles of 10–80 nm in diameter (including MS2 virions), the filter penetration was 20.5% to 84.5% (Balazy et al., 2006a; Balazy et al., 2006b). Since SMs have a comparatively poor fit, faceseal leakage represents a prominent penetration pathway. This is especially true for small particles, e.g., those in the size range of influenza A virions (Booth et al., 2013) as well as virions causing Human Papilloma Virus (HPV), Severe Acute Respiratory Syndrome (SARS), and Middle East Respiratory Syndrome (MERS). Although N95 filtering facepiece respirators (FFRs) are more efficient than SMs [their N95 filter is certified by the National Institute of Occupational Safety and Health (NIOSH) to allow no more than 5% penetration], penetration of ultrafine particles (<100 nm) through some N95 FFRs may exceed this threshold (Balazy et al., 2006a). The highest filter penetration values were observed for particles of 30–70 nm in diameter, which includes the size of several respiratory pathogenic virions (Zheng and Baker, 2006; Mettenleiter and Sobrino, 2008), as well as a substantial fraction of surgical smoke particles (Bruske et al., 2008; Andreasson et al., 2009).

NIOSH recommends combining general room ventilation with local exhaust ventilation (LEV) to control the airborne particles generated by surgical smoke (NIOSH, 1996a). However, due to the variability of surgical smoke and its potential hazards, the implementation of personal protective equipment (PPE) is also needed to protect healthcare workers in operating rooms. The Association for periOperative Registered Nurses (AORN) recognizes the hazard of the surgical smoke. AORN also urges the use of PPE and evacuation and filtration of smoke through an
appropriate system (AORN, 2008). They recommend using fit-tested surgical N95 filtering facepiece respirators or high-filtration masks to protect against surgical smoke (AORN, 2008; Benson et al., 2013). However these recommendations are not regulatory requirements, and presently the use of N95 FFRs in ORs is primarily limited to procedures involving HPV. Overall, SMs remains the standard protection devices in ORs. Recently, so-called “N95 Surgical Mask Respirators” (SMRs) have been introduced. The SMRs are cleared by the Food and Drug Administration (FDA) for use in ORs, and certified by NIOSH to receive an N95 grade (although the NIOSH does not evaluate FFRs for surgical use). However, little is known about the performance of either SMs or SMRs against surgical smoke. Rozzi et al. (2012) investigated the absorption capabilities of organic vapor FFRs against the aromatic hydrocarbons generated in surgical smoke, but neither this nor similar investigations addressed the particulate matter component. A higher grade FFR (N100) was pilot-studied against surgical smoke from porcine tissue (Koehler et al., 2014). One of these facepieces was modified by creating a face seal (FS) made of ethylene vinyl acetate foam that was affixed to the inner perimeter of the respirator, replacing the stock face seal. The modification significantly improved the respirator performance by minimizing the face seal leakage. It is acknowledged that N100 FFRs have limitations for deployment in ORs due to their exhalation valve component. However, it is still important to generate data about the efficiency of these highest grade face pieces against surgical smoke because it will help determine the feasibility of making appropriate design modifications to other respirators, e.g., N95 SMRs (that have no exhalation valves), in order to maximize their performance.

The protection provided by a respirator at a workplace is typically assessed by determining its workplace protection factor (WPF) measured under specific conditions. One way
to quantify the WPF is through the simulated workplace protection factor (SWPF). SWPF is measured in a controlled laboratory setting while the wearer performs exercises mimicking the actual work procedures.

The purpose of our study was to determine the SWPFs against surgical smoke for two SMs and two N95 SMRs (both currently approved for OR use), as well as for a conventional and newly-developed N100 FFR.

**Materials and Methods**

**Respirator Selection**

Commercially available SMs (Model 1800NL, 3M, St. Paul, MN, and Model 14683, Kimberly Clark, Neenah, WI) and N95 FFRs marketed as SMRs (Model 1860 and Model 1870, 3M, St. Paul, MN) were selected for this study. The above devices were labeled as SM1, SM2, N95 SMR1, and N95 SMR2, respectively. The SM1 and SM2 were originally designed to reduce the contamination of others in the wearer’s surrounding to airborne pathogens that he/she may aerosolize during exhalation; SMs are also used to reduce the potential exposure of the wearer to blood and body fluids. The N95 SMR1 and N95 SMR2 are intended to be deployed during laser surgery, electrocautery and other procedures which utilize powered medical instruments. All four selected SMs and SMRs (see Table 3-1) are equipped with a malleable metallic nosepiece to form the bridge of the nose.

Additionally, two higher-grade FFRs were evaluated in this study. One was an original commercially available N100 FFR (Model 8233, 3M, St. Paul, MN); the other was the same FFR modified with a novel FS, labeled as FS Prototype N100 (Koehler et al., 2014). The model of the selected N100 FFR was also shown in Table 3-1.
Challenge Aerosol

The surgical smoke was generated by electrocautery dissection of porcine muscle tissue, as described previously by several investigators (Hensman et al., 1998; Weld et al., 2007). A standard electrosurgical generator was used as the energy source for the cautery procedures (Valleylab Force FX, Covidien, Boulder, CO). Electrocautery dissection was performed utilizing a standard electrosurgical pencil (Valleylab E2516, Covidien, Boulder, CO) at a setting of 40 watts for both cutting and coagulation, using a blend mode.

Human Subject Selection

Ten human subjects representing healthcare workers were recruited for this study: 5 adult males and 5 adult females. All of the subjects except one experienced surgeon were recruited from research staff and students of the University of Cincinnati’s College of Medicine. The subjects were notified about the potential hazard of surgical smoke exposure before conducting the experiment and were provided with a written consent to participate. The research protocol was approved by the University of Cincinnati Institutional Review Board (IRB). Before the experiment, each subject completed the OSHA respirator medical clearance questionnaire administered by the University Occupational Pulmonary Program.

Fit Testing

Prior to evaluating the respirator/mask performance in the exposure chamber with surgical smoke, the subjects underwent fit testing while wearing the two N95 SMRs and two N100 FFRs according to the OSHA fit testing protocol (OSHA 29 CFR 1910.134). An SM is not subject for the OSHA fit testing. After the fit testing, the subjects were introduced into the chamber for the SWPF study immediately.

Sodium chloride (NaCl) particles were generated using a particle generator (Model 8026,
TSI Inc., Shoreview, MN) to create a sufficient ambient concentration to obtain measurable protection factors with highly-efficient respirators. The overall fit factor (FF) was measured and recorded by the PortaCount Plus (Model 8020, TSI Inc., Shoreview, MN) operating with an N95-Companion (Model 8095, TSI Inc., Shoreview, MN). The fit factor is calculated as the aerosol concentration outside of the respirator divided by its concentration inside of the respirator when a subject is performing a specific set of procedures (OSHA 29 CFR 1910.134). The passing criterion of FF is 100.

**Experimental Setup**

The experimental setup is presented in Figure 3-1. While inside the exposure chamber (volume = 3.6×2.4×2.6 m³), a subject wearing a tested respirator or SM under the test performed electrocautery dissection on a section of animal muscle tissue located on a surgical table mimicking a conventional surgical procedure. Each of the ten subjects wore each of the six tested PRD in a random order. The height of the surgical table was approximately 1 m above the ground, a typical height in ORs. The choice of the surgical equipment utilized, the distance from the cautery to the test subject, and the cautery settings, were all determined by an experienced board-certified surgeon with over 10,000 hours of surgical electrocautery experience. The subjects were trained in the techniques of electrocautery dissection by the same surgeon, who was also a subject in the study.

The surgical smoke aerosol generated during this procedure was sampled in the breathing zone directly outside the respirator/mask (representing the inhalation exposure of an unprotected individual) as well as inside the respirator/mask (representing the inhalation exposure of a wearer). The in-respirator sampling line, which is shown as a clear tube in Figure 1B was connected to the probe located at the breathing zone of the RPD; the ambient air sampling line is
shown as a blue tube in this figure. The inlets of the two respective sampling lines were located 6 cm from each other. The same sampling configuration was used in fit testing. The aerosol concentrations and particle size distributions of the inside- and outside-sampled aerosol (C_{in} and C_{out}, respectively) were measured by The Mini Wide Range Aerosol Spectrometer (Nanoparticle Aerosol Monitor, Model 1320, Grimm Technologies, Inc., Ainring, Germany) in combination with an optical particle counter (OPC) (Model 1.108, Grimm Technologies, Inc., Ainring, Germany). The inside and outside concentration measurements were controlled by a high speed 2-way electromagnetic valve. The outside concentration was measured for 6 minutes following by a 12 minutes inside measurement; subsequently, the outside concentration was measured again for 6 minutes. The average concentration of the two 6-minute outside concentration measurements was calculated and recorded as C_{out}. The average concentration of the continuous 12-minute inside concentration measurement was calculated and recorded as C_{in}. The SWPF was determined as C_{out}/C_{in}. The data were recorded in a particle size range of 25–1,150 nm. Based on the total aerosol concentrations measured across this size range, the total protection factor (SWPF_{total}) was calculated. Additionally, the particle size selectivity of the aerosol measurement allowed determining SWPFs for different particle sizes (SWPF_{dp}). These were recorded within a narrower range of 25–290 nm because the particle concentrations inside of the tested N95 and N100 FFRs were almost zero for particles larger than 290 nm. The corresponding mean sizes for the 10 selected channels were 25, 35, 45, 60, 85, 115, 145, 180, 265, and 290 nm.

During the smoke generation process, the exposure chamber was ventilated using a pre-installed ventilation and high-efficiency particulate air (HEPA) filtration system operating at an air exchange rate of 5 Air Exchanges per hour (AEH). The modern OR facilities operate at least at 20 AEH of which 4 AEH comes from the ambient air (Facility Guidelines Institute, 2014). At
the same time, some ORs operate at lower air exchange rates. We have intentionally chosen a relatively low exchange rate to establish the most conservative assessment with the highest feasible concentration level of smoke particles.

**Data Analysis**

The data analysis was performed using SAS version 9.3 (SAS Institute Inc., Cary, NC). For each respiratory protective device (RPD), geometric mean (GM) and geometric standard deviation (GSD) of SWPF were calculated. The statistical analyses were applied after performing a log-transformation of the data. Paired t-test was used to test the difference between different RPDs. Two-way ANOVA was deployed to evaluate the effects of subjects and particle sizes on the size-selective SWPFs. P-values below 0.05 represented a significant difference.

**Results and Discussion**

**Concentration and Particle Size Distribution of the Surgical Smoke in the Breathing Zone**

The total aerosol particle concentration measured in the breathing zone of the experienced surgeon who was exposed to the surgical smoke level ranged from $0.708 \times 10^6$ to $1.080 \times 10^6$ particles/cm$^3$ (Mean $\approx 0.946 \times 10^6$ particles/cm$^3$ and SD $= 0.111 \times 10^6$), which was around 1,000 times higher than the background level. At the same time, the size-specific concentration levels were substantially below the upper threshold limits of the aerosol instrument. The particle size distributions generated in five experiments (Tests I through V) are presented in Figure 3-2. The curves have a similar shape; four of them peak at a particle size of 115 nm and one at 145 nm. The tests with other subjects generally generated similar particle size distribution curves although the total particle concentration levels were lower, which can be attributed to their limited experience in operating the electrocautery equipment. It was noticed that some
subjects did not apply the electrocautery pencil to the tissue as frequently as it was demonstrated by surgeon, which could produce a lower level of smoke. With regard to the above between-subject variability and other factors influencing the aerosol concentration and particle size distribution in the breathing zone, it should be acknowledged that in an actual operating setting, electrocautery use in different surgical procedures involving various tissues would likewise have an effect on the concentration and particle size distribution of the generated surgical smoke.

The surgical smoke particle concentration measured in this study was relatively high compared to the levels found by Hohlfeld et al. (2008). One explanation for the difference may be that the measurements were conducted during different surgical procedures utilizing different aerosol instruments (Hohlfeld et al. used a condensation particle counter). Additionally, the higher concentration measured in the present study may be attributed to lower air exchange rate established in our chamber. It is also noted that in the quoted study the aerosol sampling was performed at the side of the anesthetist, rather than directly in front of the surgeon’s mask, as in our OR setup. This greater distance from the surgeon’s breathing zone may explain their findings of lower particle concentrations. While acknowledging the above differences, it is recognized that the ambient aerosol concentration level does not affect the outcome of this effort because SWPF is a non-dimensional parameter.

**Simulated Workplace Protection Factor (SWPF<sub>total</sub>)**

Figure 3-3 presents the values of SWPF<sub>total</sub> for the six tested RPDs. The SWPF<sub>total</sub> values for SM1 and SM2 were close to 1 with GM = 1.49, GSD = 1.95 (SM1) and GM = 1.76, GSD = 1.71 (SM2), indicating essentially no protection. The difference in SWPF<sub>total</sub> between SM1 and SM2 was not significant (p>0.05, Table 3-2). Some particle size-selective SWPF values obtained for SMs were actually below 1, indicating that the aerosol concentrations inside the
SMs were higher than outside. This counter-intuitive finding can be attributed to the fact that the same aerosol instrument was deployed alternating between the inside and outside measurements, which were conducted at different time points introducing an uncertainty, which affects the SWPF. The uncertainty is particularly apparent when the SWPF is close to 1. Overall, a very low efficiency of SMs observed in this study is consistent with previous reports (Dixon and Nelson, 1984; Zhuang et al., 2003; Reponen et al., 2011).

The SWPF\textsubscript{total} of both N95 SMRs were significantly higher than the values of SMs (p < 0.01, Table 3-2). Both N95 SMRs offered a measurable level of protection: GM = 263, GSD = 2.17 and GM = 208, GSD = 2.31, respectively. Their SWPF\textsubscript{total} values exceeded 100 (the fit test passing level) and, by far, exceed 10 (the OSHA’s assigned protection factor). It is noted that the protection factor offered by these N95 respirators is higher than the minimum requirement for their filter material alone. The difference between SWPF\textsubscript{total} values obtained for the two N95 SMRs was not significant (p>0.05, Table 3-2).

The two N100 FFRs demonstrated significantly – about an order of magnitude – higher protection compared to N95 SMRs (p < 0.01, see Table 3-2): GM = 1,089 and GSD = 2.08 for the control N100 FFR and GM = 2,199 and GSD = 2.05 for the FS Prototype N100 FFR. The difference between SWPF\textsubscript{total} values obtained for the two N100 FFRs was also significant (p < 0.05, Table 3-2). Thus, the modified faceseal component of the N100 FFR (FS Prototype N100 FFR) was capable of significantly improving the protection provided by a highly efficient N100 FFR. Since the N100 FFR’s design modification was concerned exclusively with the peripheral area, the difference in SWPF\textsubscript{total} can be attributed solely to the improved fit of the respirator to the user’s face.

In summary, the SWPF\textsubscript{total} results suggest that, in contrast to the NIOSH certified
respiratory protection devices such as N95 and N100, SMs could not protect healthcare workers against surgical smoke in ORs. It is acknowledged though that while SMs are widely used in healthcare environments, they were not originally designed to reduce the wearer’s exposure to aerosols. While we recognize that conventional N100 FFRs (equipped with exhalation valves) are not practical for human OR use, the data obtained with the FS prototype demonstrate the potential of the new faceseal technology for implementation on various types of respirators.

**Correlation between SWPF\textsubscript{total} and Fit Factor (FF) Determined for N95 SMRs**

Two out of ten subjects (20%) did not pass the fit test with SMR1, and eight out of ten (80%) did not pass it with SMR2 (FF<100). In three cases out of 20 (15%), the SWPF\textsubscript{total} was below 100 (including two cases in which the subjects failed the fit test). The relationship between SWPF\textsubscript{total} and FF is presented in Figure 3-4. None of the correlations (either for SMR1, or for SMR2, or for both data sets combined) were significant (p>0.05). The slopes of log(SWPF\textsubscript{total}) against log(FF) were as follows: 0.19 for SMR1, 1.01 for SMR2, and 0.35 for the two combined; all had rather low coefficient of correlation R\textsuperscript{2}.

All ten subjects wearing SMR2, and seven out of ten subjects wearing SMR1 produced data points above the 1:1 line, indicating that the SWPF exceeded the corresponding FF in the majority of the tests. This suggests that while no significant correlation was found between the two factors, the FF can serve as a conservative estimate of the SWPF.

The relationship between FF and SWPF\textsubscript{total} obtained in this study confirms the observations of Zhuang *et al.* (2003), who conducted fit testing on 15 workers and then assigned them, with the same respirators, to their routine jobs while measuring the WPFs. The investigators reported lack of correlation between FF and WPF for FFs ≥ 500 (p>0.05). One reason may be that the OSHA fit testing protocol requires very specific body movements, which
may not fully represent actual workplace activities. Likewise, the breathing rates may be
different when a worker performs fit testing vs. when he/she conducts the workplace activities.

**Particle Size Specific Simulated Workplace Protection Factor (SWPF\textsubscript{dp})**

The protection factors offered by the six tested RPDs worn on ten subjects are plotted in
Figure 3-5 against the particle sizes. Each curve represents the SWPF\textsubscript{dp} data obtained for a
subject wearing a specific RPD. A clear trend representing the effect of particle size was
observed only on the two N100 FFRs. Statistical analysis shows that between-subject variability
was a strongly significant factor affecting their SWPF\textsubscript{dp} (p<0.01), indicating the SWPF\textsubscript{dp} varies
significantly depending on the subject regardless of the type of RPDs (see Table 3-3).

If the dominant particle penetration pathway was a filter, the SWPF would be dependent
on the particle size since the filter penetration is generally size-dependent (Kulkarni et al., 2011).
Electret filters used in high-efficiency respirators offer very high protection against very small
particles (20–30 nm) as well as against much larger particles ( > 200 nm) leaving the room for
the most penetrating particle size (MPPS) in-between; the exact MPPS value depends on the
filter characteristics and face velocity. This is consistent with the SWPF data shown for FS100
and N100 FFRs for which the particle size had a significant effect, indicating that an appreciable
percentage of particles measured inside the respirator penetrated through the filter (relative to
penetration through the faceseal leakage). In contrast, if the faceseal leakage served as the major
penetration pathway, the penetration may not be significantly affected by the particle size, at
least for the essentially inertialess surgical smoke particles. Thus, the data suggest that most of
the particles, which penetrated through an SM or an N95 SMR, utilize the faceseal leakage
pathway.

Finally, although the present investigation specifically addressed surgical smoke, as was
noted earlier, the particle sizes involved are in the same range as virions causing influenza, HPV, SARS, and MERS (Zheng and Baker, 2006; Rota et al., 2003; Zaki et al., 2012). Since the RPDs studied here are frequently incorporated for public health use, the findings herein may have application to various public health scenarios, e.g., those involving infectious aerosols.

Conclusions

Our study results strongly suggest that SMs do not provide measurable protection to OR workers against surgical smoke. More efficient N95 SMRs are capable of reducing the inhalation exposure to surgical smoke by over two orders of magnitude (SWPF$_{\text{total}} = 208–263$). Given the fact that the particle size was not a significant factor affecting the performance of SMs and SMRs, we concluded that the faceseal leakage was the main penetration pathway for the surgical smoke particles to enter into the tested SMs and the N95 SMRs.

The N100 FFRs, both the control and FS Prototype versions, offered the highest protection against surgical smoke (SWPF$_{\text{total}} = 1,089–2,199$). In contrast to SMs and the N95 SMRs, the particle size was a significant factor affecting the performance of these N100 FFRs, which suggest that the filter penetration pathway likely dominated over the faceseal leakage component.

The SWPF$_{\text{total}}$ obtained for the newly-developed FS Prototype N100 FFR significantly exceeded that of the control N100 FFR, the difference being due to the improved fit of the FFR to the user’s face. This finding may have relevance to the design of N95 SMRs, as well as other RPDs, since faceseal leakage was the predominant pathway of smoke particle penetration in the SMRs we tested. If the improvements demonstrated herein on the N100 FFRs are achievable on N95 SMRs, it would represent an important advance in the design of RPDs for OR personnel.
CHAPTER 4

Performance of an Improperly Sized and Stretched-out Loose-fitting Powered Air-purifying Respirator: Manikin-based Study

Introduction

The Powered Air-Purifying Respirators (PAPRs) certified by the National Institute for Occupational Safety and Health (NIOSH) are used in a variety of occupational environments to reduce worker’s exposure to gaseous and/or particulate contaminants. To receive approval from NIOSH, PAPRs must meet the certification requirements of 42 CFR 84 (NIOSH, 1996b). However, NIOSH does not indicate how to choose an appropriately sized PAPR facepiece for an individual. In addition, user instructions do not always address “sizing” of facepieces when more than one size is available. Prior to this study, the implications of using an improperly sized PAPR facepiece have not been evaluated.

The Occupational Safety and Health Administration (OSHA) has published and enforces assigned protection factor (APF) for respiratory protective equipment. The APFs for PAPRs vary from 25 to 1,000 depending on the type of facepiece selected (half mask, full facepiece, helmet/hood, or loose-fitting facepiece) (OSHA, 2006). While having the loose-fitting facepiece has the lowest APF of 25, this facepiece has several advantages compared to tight-fitting negative pressure air-purifying respirators: they require no fit testing, feature no breathing resistance, provide cooling, and may be worn by workers with corrective eyewear (Roberge, 2008; Johnson et al., 2008). These advantages are preferred by the healthcare workers (HCWs)
according to the survey conducted by Baig et al. (2010).

In a loose-fitting PAPR system, the ambient air supplied to the wearer is powered by a battery-operated fan. When the wearer’s level of exertion is mild, the PAPR is intended to supply air flow which is measurably greater than the inhalation flow, thus establishing a positive pressure inside the facepiece during the majority of the breathing cycle. As the level of exertion increases, the breathing rate increases as well resulting in a greater minute volume. Consequently, the pressure inside the facepiece could become negative near the peak of each inhalation cycle, thus allowing the contaminated air to enter into the facepiece. This “over-breathing” could compromise the performance of a loose-fitting PAPR (Mackey et al., 2005). The problem may be more pronounced if the facepiece is improperly sized to the worker’s head, which increases the size of the gap between the worker’s face and the facepiece. Field experience has shown that some companies tend to order a single size facepiece (typically large), instead of purchasing an appropriately sized facepiece for each individual. This practice may simplify ordering and inventory, but it does not recognize the need to choose a properly sized PAPR facepiece for an individual when different sizes are available.

Numerous studies have been conducted on the performance of the NIOSH-certified N95 filtering facepiece respirators (FFRs) (Cho et al., 2009; Cho et al., 2010; Grinshpun et al., 2009; Roberge et al., 2010a; Roberge et al., 2010b) and elastomeric half-masks (He et al., 2013a; He et al., 2014a). However, only a few investigations have addressed the protection offered by the PAPRs. For example, Cohen et al. (2001) obtained simulated workplace protection factors (SWPFs) for five PAPR models representing different brands and facepiece styles. These respirators were tested on 12 volunteers performing 12 exercises to simulate real workplace activities. The SWPF range for the loose-fitting hooded PAPRs was 240 to > 250,000,
suggesting a high degree of protection as well as a large variance among the SWPFs. However, none of the investigations involving PAPRs intentionally tested improperly sized loose-fitting facepieces or explored the potential effect of a damaged (stretched-out) facepiece on PAPR performance. A damaged facepiece is a reality in some workplace settings given that this type of respirator may be used/re-used over a long time, often shared among employees, and may not be routinely removed from service when inspection programs are less than optimal.

The purpose of this investigation was to evaluate the protection level of improperly sized loose-fitting PAPR facepieces by using a manikin with cyclic breathing. Flows were selected to represent breathing at moderate, medium-to-high, high and strenuous workloads. Similar tests using constant flows were conducted to further investigate the mechanism of the particle penetration into the tested facepiece. This study was designed to evaluate the following factors: facepiece type, breathing flow rate and the role of facepiece exhaust holes on the performance of improperly sized loose-fitting PAPRs. A stretched-out facepiece was also investigated to provide quantitative information that may be of value for respirator program administrators.

**Materials and Methods**

**Powered Air-Purifying Respirator (PAPR) with Loose-fitting Facepiece**

A commonly used PAPR (EVA, Bullard Company, KY) certified by NIOSH was selected for testing in this study. Selection was based on availability. One of the authors was responsible for training workers on proper use, including positioning of the facepiece and assistance with size selection, since more than one size was available. It contains a blower unit which draws air through a High-Efficiency Particulate Air (HEPA) filter and delivers the purified air into the facepiece. Among the two flow rates, 198 and 240 L/min, offered by the blower, the lower one
was used in this study to produce a conservative situation whereby inhalation flow could feasibly exceed the blower flow. The lower blower flow rate provides a longer duration of operation and produces less noise. Consequently, users often find the lower blower flow advantageous. For comparison, NIOSH requires at least 6 ft³/min (170 L/min) during field use and this lower blower flow exceeds this requirement. Two versions of loose-fitting facepieces, 20LFL (Facepiece A, size “large”) and 20LF2L (Facepiece B, size “large”) of the same brand (Bullard Company, Cynthiana, KY) were used in this study. Facepiece B was designed for a narrow face. A stretched-out 20LFL facepiece (Facepiece C, size “large”) was also evaluated in this study to simulate a “damaged” facepiece in a workplace. It was created by donning the facepiece onto an oversized manikin headform until the facepiece became stretched out and lost elasticity. It should be noted that we have observed respirators in the field with even greater levels of damage than the one used in this study. Figure 4-1 demonstrates that Facepiece C features a larger gap between the face and the facepiece compared to the other two facepieces (A and B).

The tested respirators are designed with exhaust holes (approximately 6 mm diameter) located near the chin area on the loose-fitting facepiece. These holes make the facepiece more comfortable to wear, help to keep the facepiece from coming off the face, and reduce air flow noise. However, the “openings” may serve as a penetration pathway for particles to enter the facepiece. In order to evaluate the effect of the exhaust holes, additional tests were conducted with Facepieces A, B, and C using duct tape to cover the holes on both sides of the facepiece. The number of the exhaust holes was 12 (6 on the left side and 6 on the right side) for Facepieces A and C, and 14 (all in the middle) for the Facepiece B.

**Experimental Design and Conditions**

The experimental setup is presented in Figure 4-2. The tests were performed in an
exposure chamber (volume = 3.6×2.4×2.6 m³). As shown in Figure 4-2, the tested facepiece was donned on a manikin headform. The facial dimensions of the manikin fell into Cell 2 (considered as a small face) of the NIOSH Bivariate Panel. (Zhuang et al., 2007) The mouth and nostrils on the headform were open for inhalation and exhalation, to more closely mimic human breathing flow patterns. The breathing was performed using the electromechanical Breathing Recording and Simulation System (BRSS; Koken Ltd., Tokyo, Japan), which generated a sinusoidal flow pattern (Haruta et al., 2008). A 1-inch diameter copper pipe was mounted and extended to the mouth and nostrils of the manikin to allow the movement of air in and out of the BRSS. Four cyclic flows with mean inspiratory flow (MIF) rates of 30, 55, 85, and 135 L/min were applied. All had the same breathing frequency of 25 breaths/min. The above-specified MIFs were established to represent breathing at moderate, medium-to-high, high and strenuous workloads (He et al., 2013a). A HEPA filter was placed between the manikin headform and the BRSS to keep particles from re-entering the facepiece during exhalation so that the concentration measured inside the facepiece reflected solely the aerosol penetrated from the ambient environment and no particle inside the facepiece has an opportunity to be counted more than once. One sampling probe was installed to measure the aerosol concentration inside the facepiece (C_in), and the other was placed 24 cm away from the inside probe to measure the outside concentration (C_out). Both probes were connected to a switching valve, which could be switched to sample the aerosol either inside or outside of the facepiece. The challenge aerosol was generated with a particle generator (Model 8026, TSI Inc., Shoreview, MN) from a suspension containing 2 g of NaCl and 100 g of sterile, Millipore-filtered water. The generator was operated for 30 min before the testing to allow the challenge aerosol to reach a temporal homogenous concentration (within ± 10%). The total aerosol concentration was measured with a
P-Trak condensation particle counter (Model 8525, TSI Inc., Shoreview, MN) operating in a size range of 20 to 1,000 nm. The fit factor determined on the manikin headform (manikin Fit Factor, mFF) was calculated as \( \frac{C_{\text{out}}}{C_{\text{in}}} \). The experimental conditions are summarized in Table 4-1.

**Cyclic and Constant Flow Regimes**

To further investigate the mechanism of the particle penetration into the tested facepiece, similar tests were conducted using constant inhalation flows. The flow rate (Q) ranged from 20 to 240 L/min with an increment of 20 L/min. The same experimental variables, including the facepiece type and exhaust holes condition, were applied under constant flow regime. The results of aerosol measurements conducted at the above-indicated constant inhalation flow rates (20, 40, 60, … L/min) were subjected to a linear regression approximation, to determine a rate-specific mFF for any Q between 20 and 240 L/min. The rate-specific mFF values were converted to penetration (= 1/mFF); the penetration values were then integrated as a function of time and time-weighted following a sinusoidal breathing pattern

\[
Q = Q_{\text{PIF}} \times \sin\left(\frac{2\pi t}{T}\right)
\]

Here \( Q_{\text{PIF}} \) is the peak inspiratory flow (PIF) rate, which is a direct function of the MIF, T is the period of the breathing cycle [at 25 breaths/min, \( T = \frac{1}{25 \text{ min}} \times 60 \text{ s/min} = 2.4 \text{ s} \)], and t is the time in seconds. This allowed us to calculate an integrated penetration and subsequently an integrated mFF for a cyclic flow regime corresponding to a specific \( Q_{\text{PIF}} \) and \( Q_{\text{MIF}} \). Further, each calculated mFF value was compared to the corresponding experimental result (obtained at the same MIF under cyclic flow conditions). Figure 4-3 schematically shows the flow rate as a function of time at MIF = 135 L/min and breathing frequency of 25 breaths/min (an example). It is seen that non-filtered air can enter a facepiece only during half of the breathing time (inhalation). The numerical integration was performed by dividing the first half a period into 20
equal time segments so that the total penetration is determined as a time-weighted average.

**Data Analysis**

SAS 9.3 (SAS Institute Inc, Cary, NC) was used to analyze the data. The mFF data were log-transformed before statistical analysis. The Geometric mean (GM) and the Geometric standard deviation (GSD) of mFF’s values were calculated for each set of condition. A three-way analysis of variance (ANOVA) was used to evaluate the effect of facepiece type, MIF and exhaust holes condition on the mFF. ANOVA with post-hoc pairwise comparisons was conducted to test the difference between the mFFs of each paired facepieces. Two-way ANOVA was used to study the significance of MIF and exhaust holes condition for each individual facepiece. P-values less than 0.05 were considered to denote significant differences.

**Results and Discussion**

**Manikin Fit Factors**

Figure 4-4 shows the mFF as a function of MIF for three tested facepieces. The mFF decreased exponentially with MIF increasing from 30 to 135 L/min. The experimentally determined mFF values ranged from 14 to 15,165. The highest mFF was observed at MIF = 30 L/min with Facepiece B while the lowest was found at MIF = 135 L/min with Facepiece C.

It is acknowledged that the mFFs obtained from the tests conducted using the manikin headform may overestimate the actual respiratory protection level in the field. When worn by respirator wearers, the facepiece may move given the continuous movement of the worker’s head. This is particularly true when the blower hose does not swivel at the point of connection to the facepiece. There is no consensus to designate an acceptable level of protection when a loose fitting PAPR is configured to a manikin. However, the OSHA designated APF for this type of
facepiece is 25. During fit testing, pass/fail criteria for tight-fitting negative pressure respirators is set at 10 times the APF. Consequently, another benchmark to evaluate PAPR performance would be to choose an mFF of 250 (10 x 25). Facepieces A (and B) had mFFs below 250 when the MIFs were greater than 90 L/min (and greater than 86 L/min for facepiece B) (see Figure 4-4a). Likewise, the performance of these two facepieces was considerably lower when breathing flow rates corresponded to high and strenuous workloads. mFF values obtained for Facepiece C were below 250 for all tested MIFs. At MIF ≈ 85 L/min, the mFF fell even below 25. It was concluded that Facepiece C offered very little protection even under conditions of light exertion. Thus, we recommend that stretched-out facepieces should be removed from use in a workplace setting that requires respiratory protection.

**Analysis of Factors Affecting mFF**

1. **Effect of Facepiece Type on mFF**

   As evident from Table 4-2, the effect of facepiece type on the performance of the loose-fitting PAPR was significant (p < 0.01). The mFFs of Facepiece C were significantly lower than those obtained for the other two facepieces (p < 0.05) while the difference between Facepieces A and B was not significant (p > 0.05, see Table 4-3). Facepiece C had the lowest mFF, followed by Facepieces A and B, suggesting that C offered the poorest fit on the manikin headform. This finding is consistent with our observations with respect to the size of the gap between the manikin face and facepiece, which was estimated to be approximately 19 cm², 22 cm² and 29 cm² for Facepieces A, B and C, respectively. While a threshold for unacceptable gap size was not identified in this study, the data for Facepiece C supports the need to replace facepieces when the gap size is increased due to loss of elasticity. The protection factor of such “damaged” facepieces decreases because a bigger gap area allows more particles to penetrate into the
facepiece.

2. Effect of MIF on mFF

The effect of MIF on mFF was significant (p < 0.01, see Table 4-2). As shown in Figure 4-4, an exponential regression trend line between MIFs and fit factors was fitted on all the experimental conditions. The coefficient of determination (R^2) ranged from 0.95 to 0.99, indicating a very good fit of the data to the regression lines. The mFF value decreased exponentially with the increasing MIF for all the tested facepieces (the regression equations are presented in Figure 4-4). First, this decrease was likely associated with a widening gap size between the face and the facepiece. With the breathing becoming more intense (higher MIF), the gap was observed to enlarge, which allowed more particles to enter. Second, clean air was delivered by the blower through the orifice, which was located in the middle of the forehead; this made the air flow directed to the nose and mouth area greater than the flow supplied to the cheek area; the latter created a pressure gradient that enhanced the particle penetration into the facepiece through the gap near the cheek area. This effect became more pronounced at higher breathing flow rates.

It should be emphasized that at MIF=135 L/min, the calculated peak inspiratory flow (PIF) was 212 L/min, which exceeded the blower-delivered flow (198 L/min). This could cause a negative pressure inside of the facepiece over certain time intervals. The “over-breathing” caused by this negative pressure allowed the ambient particles to enter into the respirator, thus decreasing the protection factor. Although rare, PIF as high as 212 L/min could occur since instantaneous breathing flows over 400 L/min were reported by Mackey et al. (2005).

3. Effect of Exhaust Holes on mFF

The three-way ANOVA performed for all facepieces combined revealed that exhaust
holes condition did not significantly affect the mFF (p > 0.05, see Table 4-2). Under almost all the experimental conditions, the mFFs obtained with the exhaust holes covered were higher than those obtained with uncovered holes. The difference was significant only for Facepiece C (p < 0.05, see Table 4-4), which suggests that the effect of exhaust holes becomes more pronounced as the gap increases (see the change in p-values listed in “Exhaust holes condition” from Facepiece A to Facepiece C). One possible explanation is that a large gap around the chin may increase air turbulence through the exhaust holes by bringing in additional air and making the flow pattern inside more complex. Consequently, a greater particle deposition could occur on surfaces around the holes. Thus, the effect of the exhaust holes with larger gap is significant.

Comparison of the Calculated and Experimentally-obtained mFFs under Cyclic Flow

The trends observed in the experiments conducted under both flow conditions (cyclic and constant) were mostly similar. The mFF decreased exponentially as the constant inhalation flows increased. In addition, significance of the effects of facepiece type and flow rate on the performance of the PAPR with a loose-fitting facepiece was confirmed for the constant flow regime (see Table 4-5). The effect of exhaust holes was equally complex for both cyclic and constant flow regimes; its significance depended on the facepiece type (see Table 4-6).

Figure 4-5 shows the relationships between the calculated and experimentally-obtained mFFs under cyclic flow regime for all three facepieces and two exhaust holes conditions. A good correlation was observed in all cases. This suggests that the constant flow data can be used for predicting the protection within the range of 30 to 135 L/min offered by improperly-sized, loose-fitting PAPRs under cyclic breathing conditions.

In general, it is more challenging to interpret the mFF trends and identify the mechanisms governing the particle penetration into a facepiece based on the data obtained under cyclic flow
regime as compared to the “constant flow” results. Therefore, we used the experimental database obtained at $Q = \text{const}$ (data not shown) to explain our findings on the protection provided by a loose-fitting PAPR. Under the constant flow regime, the airflow delivered by the blower was counteracted by the increased inhalation flow, resulting in increased air turbulence in the mouth and nose area of the manikin headform. The turbulence enhanced the mixing of particles and might have affected the particle transport through the faceseal gap and/or exhaust holes, thus influencing the measurement of mFF. This effect may particularly occur at deep breathing, thus negatively affecting the protection provided by an improperly-sized, loose-fitting PAPR. Considering the complexity between cyclic and constant inhalation flow patterns, the similarity in mFF is remarkable.

**Limitation**

The study was limited to three loose-fitting facepieces of the same brand. Additionally, the study was focused only on loose-fitting PAPR facepieces, which were improperly sized. Further research is needed to examine the performance of the same loose-fitting PAPRs when they are properly sized to the wearers.

**Conclusions**

Based on the manikin-based testing of the two undamaged loose-fitting PAPR facepieces, the mFF decreased exponentially with increasing MIFs revealing rather low mFFs at high MIFs. These two facepieces provided relatively low protection (mFFs <250) at breathing flow rates corresponded to high and strenuous workloads. The mFF values of the stretched-out loose-fitting facepiece were significantly lower than those obtained for the undamaged facepieces; the former are unlikely to provide an acceptable level of protection even at a moderate workload.
Facepiece type and MIF were significant factors affecting the performance of the loose-fitting PAPRs. The effect of the exhaust holes condition was less significant and depended on the facepiece type. The model utilizing integrated mFF data obtained under constant flow regime is capable of predicting the protection offered by improperly-sized, loose-fitting PAPRs under cyclic breathing conditions. The results of this study suggest that respirator program administrators should ensure that loose-fitting facepieces are properly sized to employees and remove stretched-out facepieces from the workplace.
OVERALL CONCLUSIONS AND FUTURE DIRECTIONS

Overall Conclusions

In summary, aerosol type, breathing flow rate, particle size, relative humidity of the ambient air as well as respiratory type were all found to be significant factors affecting the performance of the respiratory protective devices. The type of challenge aerosol was significant when tested the N95 FFRs against combustion particles and NaCl particles. The aerosol produced by burning plastic penetrated at the highest level, followed by the aerosols produced by burning paper and wood. The penetration levels obtained by combustion particles were significantly higher than the value obtained from NaCl particles, indicating that the efficiency of N95 FFR filters obtained with the “model” NaCl aerosol challenge may not serve as a proper predictor of the filter efficiency against combustion particles. We believe that the gas-phase products (and possibly particles) generated during the combustion process degrade the filter of an N95 FFR. The mechanisms may be similar to the one, which has been demonstrated for oil-based aerosols that degrade N-type filters (N stands for “not resistant to oil”). The significant effect of respiratory model and facepiece model was observed on N95 FFR and PAPR, respectively, indicating the performance difference between different models of same type respiratory protective device. For the tested N95 FFRs, the effect of breathing flow rate was significant. The total particle penetration increased with increasing constant flow rate as well as MIF. The effect of particle size is complex and depends on the aerosol type and respirator type. Relative humidity of the ambient air was significant factor affecting the N95 FFR performance. It should be noted that testing the respirator under high RH is more representative than under low RH, given the fact that the humidity inside the respirator is high (RH close to 100%) because of
the moisture present in the air exhaled by a wearer. We observed that the penetration increased with the increasing RH, indicating that higher RH could reduce the filtration efficiency, which raises a concern about the usage of a wet respirator. The above raises a question about the validity of the widely used respirator performance evaluation protocol in which the penetration is measured by running a dry constant air flow through the respirator donned on a manikin headform (this simulates inhalation exclusively with no moisture supplied). The most recent examples are studies conducted with FFRs on a manikin under low RH conditions following the NIOSH testing procedure (Noti JD, et al., 2012; Roberge et al., 2010b). Our results show that the efficiency of an N95 FFR may be overestimated if tested at lower humidity. Respirator type was another significant factor affecting PRD performance. N100 and N95 FFRs performed much better than surgical masks against surgical smoke when wearing by the subjects. The improperly sized loose-fitting facepiece PAPR offered relatively low protection at high breathing rates. The stretched-out loose-fitting facepiece PAPR was unlikely to provide an acceptable level of protection even at a moderate workload.

This dissertation reported a substantial amount of data valuable for respirator manufacturers in designing better respirator protection devices. The work provides database to regulatory agencies and respiratory protection researchers, which is important for developing guidelines for the selection of appropriate respirators at a workplace.

**Research to Practice**

The dissertation research suggests the following three practical applications:
1. The efficiency of N95 FFR filters obtained with the NaCl aerosol challenge may not accurately predict (and rather overestimate) the filter efficiency against combustion particles, primarily because of the “oily” characteristic of the combustion particles. Therefore, R95 and P95 FFRs are recommended to be provided to the wearers. This is particularly relevant to the first responders and first receivers who are exposed to airborne particles at the scene, including those originated by combustion.

2. The finding that SWPF of the surgical mask is very low compared to the N95 FFRs while challenging with surgical smoke suggests that OR’s personnel may to reconsider using ineffective surgical masks and deploy NIOSH-certified FFRs instead.

3. The improperly sized loose-fitting PAPRs offer relatively low protection at very high breathing rates, which occur under high workloads. The stretched-out loose-fitting PAPR is unlikely to provide an acceptable level of protection even at moderate workloads. This emphasizes the need of selecting of properly sized loose-fitting facepiece for employees (when different sizes are available).

**Future Directions**

The following two main directions are being considered for the future research efforts:

1. In order to better evaluate the aerosol risk to OR healthcare workers, future studies should be conducted to measure the real workplace protection factor of RPDs under actual operating room conditions. Additionally, particle concentration and the
chemical composition of surgical smoke should be analyzed from samples collected in an OR.

2. Regarding the loose-fitting PAPR, the next step should be testing the performance of the same loose-fitting PAPRs when they are properly sized to the manikin. Subsequently, the workplace protection factor of the loose-fitting PAPRs (both improperly sized and properly sized) should be measured on workers in the field.
REFERENCES


Gao S, Kim J, Yermakov M. et al. (2015) Penetration of combustion aerosol particles through filters of


Figure 1-1. Experimental set-up ($^{85}$Kr electrical charge equilibrator was used only when generating NaCl particles)
Figure 1-2. Total particle penetration values (measured using a P-Trak) for an N95 FFR filter samples challenged with three combustion aerosols (wood, paper, and plastic) and NaCl particles under different inhalation flow rates ($Q_{\text{Respirator}}$). [The error bars were obtained from five to six replicates; Symbols “*” and “**” indicate significant differences (“*”: $p < 0.05$; “**”: $p < 0.01$) when comparing the NaCl to the combustion particles]
Figure 1-3. Size-selective particle penetration values for N95 FFR filter samples challenged with three combustion particles (wood, paper, and plastic) and NaCl particles. Each point represents the average value of five to six replicates. Symbols “*” and “**” indicate significant differences (“*”: p < 0.05; “**”: p < 0.01) when comparing the NaCl to the combustion particles.
Figure 1-4. Total particle penetration values (result of P-Trak) for R95 and P95 FFR filter samples challenged with three combustion particles (wood, paper, and plastic) and NaCl particles under the inhalation flow rate ($Q_{\text{Respirate}}$) of 85 L/min.
Figure 2-1. Experimental set-up
Figure 2-2. Total particle penetration values (measured using a P-Trak condensation particle counter) for two N95 FFRs donned on a manikin headform while challenged with plastic combustion particles and NaCl particles. The error bars were obtained from six replicates (“*”: p < 0.05)
Figure 2-3. Total particle penetration values (measured using a Grimm spectrometer) for two N95 FFRs donned on a manikin headform while challenged with plastic combustion particles and NaCl particles. The error bars were obtained from six replicates (**: p < 0.05)
Figure 2-4. Correlation between $P_{\text{total}}$ obtained from the P-Trak and Grimm measurement data.

$y = 0.81x + 0.90$

$R^2 = 0.87$

$p > 0.05$
Figure 2-5. Particle size-specific penetration values (measured using a Grimm spectrometer) for two N95 FFRs donned on a manikin headform while challenged with plastic combustion particles and NaCl particles. The error bars were obtained from six replicates.
Figure 3-1. Experimental set-up
Figure 3-2. Particle size distribution of surgical smoke measured in the breathing zone of the board-certified surgeon (the most experienced subject)
Figure 3-3. SWF_{\text{total}} for commercially available SMs and N95 SMRs widely used in ORs as well as for the new FS prototype N100 and a conventional N100 FFR (control). Asterisk denotes statistically significant difference (p<0.05). Note: SM and N95 SMR data represent the geometric means of 10 subjects (n=10) while the FS Prototype N100 and Control N100 data represent the geometric means of 9 subjects (n=9) since one subject did not wear the N100 FFRs appropriately.
Figure 3-4. Correlation between SWPF_{total} and the FF for ten subjects wearing N95 SMRs: the lines in red and green are the regression lines fit for the corresponding data points (SMR1 and SMR2, respectively); the line in black is the regression line fit for all the data points (red and green combined).
Figure 3-5. Particle size selective SWPFs
**Figure 4-1.** Tested loose-fitting facepieces (A: 20LFL; B: 20LF2L; C: stretched-out 20LFL).

**Figure 4-2.** Experimental setup modified from He et al., 2013a
BRSS = Breathing Recording and Simulation System; PAPR = Powered Air-Purifying Respirator
Figure 4-3. Flow rate as a function of time at PIF = 212 L/min (MIF = 135 L/min) and breathing frequency of 25 breath/min (schematics for numerical integration). The schematics is modified from Haruta et al. (2008)
Figure 4-4. mFF as a function of MIF for three facepieces (a: exhaust holes uncovered; b: exhaust holes covered) Each point (with the number listed) represents the geometric mean of three replicate measurements, and the bars represent the geometric standard deviation.
Figure 4-5. Correlation between calculated from constant flow regime (axis y) and experimentally-determined under cyclic flow regime (axis x) mFF values (a: exhaust holes uncovered; b: exhaust holes covered). For each four-point data set (marked by a specific color), the points from left to right represent MIFs of 135, 85, 55, and 30 L/min.
TABLES

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Table 1-1. Inhalation Flow Rates of the Filter Samples

<table>
<thead>
<tr>
<th>$Q_{Respirator}$ (L/min)</th>
<th>$V_{Respirator}$ (cm/s)</th>
<th>$Q_{Sample}$ (L/min) = $Q_{Respirator} \left( \frac{A_{Sample}}{A_{Respirator}} \right)^\dagger$</th>
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<tbody>
<tr>
<td>15</td>
<td>1.62</td>
<td>3.75</td>
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<td>30</td>
<td>3.25</td>
<td>7.50</td>
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<tr>
<td>55</td>
<td>5.95</td>
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<tr>
<td>85</td>
<td>9.20</td>
<td>21.3</td>
</tr>
</tbody>
</table>

$\dagger$ The adjustment was made to keep $V_{Respirator} = V_{Sample}$.

Table 1-2. Effects of the Aerosol Type and Inhalation Flow Rate on $P_{total}$ (Two-way ANOVA with Interaction)

<table>
<thead>
<tr>
<th>Source</th>
<th>DF</th>
<th>SS</th>
<th>MS</th>
<th>F-Value</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aerosol type</td>
<td>3</td>
<td>8.08</td>
<td>2.69</td>
<td>48.65</td>
<td>&lt; 0.0001</td>
</tr>
<tr>
<td>Inhalation flow rate</td>
<td>3</td>
<td>35.34</td>
<td>11.78</td>
<td>212.84</td>
<td>&lt; 0.0001</td>
</tr>
<tr>
<td>Inhalation flow rate* Aerosol type</td>
<td>9</td>
<td>3.44</td>
<td>0.38</td>
<td>6.91</td>
<td>&lt; 0.0001</td>
</tr>
</tbody>
</table>

DF: degree of freedom; SS: sum of squares; MS: mean square
Table 1-3. Pairwise Comparisons of $P_{\text{total}}$ for Challenge Aerosol Types (ANOVA with Post-hoc Pair-wise Comparisons)

<table>
<thead>
<tr>
<th>Aerosol type</th>
<th>Aerosol type</th>
<th>Estimate</th>
<th>SE</th>
<th>DF</th>
<th>T-value</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>NaCl Wood</td>
<td>-0.40</td>
<td>0.096</td>
<td>32</td>
<td>-4.16</td>
<td>&lt; 0.0001</td>
<td></td>
</tr>
<tr>
<td>NaCl Paper</td>
<td>-0.72</td>
<td>0.096</td>
<td>32</td>
<td>-7.54</td>
<td>&lt; 0.0001</td>
<td></td>
</tr>
<tr>
<td>NaCl Plastic</td>
<td>-1.11</td>
<td>0.096</td>
<td>32</td>
<td>-11.60</td>
<td>&lt; 0.0001</td>
<td></td>
</tr>
<tr>
<td>Paper Plastic</td>
<td>-0.39</td>
<td>0.096</td>
<td>32</td>
<td>-4.06</td>
<td>0.0018</td>
<td></td>
</tr>
<tr>
<td>Paper Wood</td>
<td>0.32</td>
<td>0.096</td>
<td>32</td>
<td>3.37</td>
<td>0.0117</td>
<td></td>
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<tr>
<td>Plastic Wood</td>
<td>0.71</td>
<td>0.096</td>
<td>32</td>
<td>7.44</td>
<td>&lt; 0.0001</td>
<td></td>
</tr>
</tbody>
</table>

Estimate: the difference in mean penetration values between the selected two materials; SE: standard error; DF: degree of freedom

Table 1-4. Pairwise Comparisons of $P_{\text{total}}$ for Inhalation Flow Rates (ANOVA with Post-hoc Pair-wise Comparisons)

<table>
<thead>
<tr>
<th>Inhalation flow rate, $Q_{\text{Respirator}}$</th>
<th>Inhalation flow rate, $Q_{\text{Respirator}}$</th>
<th>Estimate</th>
<th>SE</th>
<th>DF</th>
<th>T-value</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>15 15</td>
<td>30 30</td>
<td>-0.12</td>
<td>0.096</td>
<td>32</td>
<td>-1.29</td>
<td>0.2056</td>
</tr>
<tr>
<td>15 15</td>
<td>55 55</td>
<td>-0.83</td>
<td>0.096</td>
<td>32</td>
<td>-8.63</td>
<td>&lt; 0.0001</td>
</tr>
<tr>
<td>15 15</td>
<td>85 85</td>
<td>-2.16</td>
<td>0.096</td>
<td>32</td>
<td>-22.49</td>
<td>&lt; 0.0001</td>
</tr>
<tr>
<td>30 30</td>
<td>55 55</td>
<td>-0.70</td>
<td>0.096</td>
<td>32</td>
<td>-7.34</td>
<td>&lt; 0.0001</td>
</tr>
<tr>
<td>30 30</td>
<td>85 85</td>
<td>-2.04</td>
<td>0.096</td>
<td>32</td>
<td>-21.20</td>
<td>&lt; 0.0001</td>
</tr>
<tr>
<td>55 55</td>
<td>85 85</td>
<td>-1.33</td>
<td>0.096</td>
<td>32</td>
<td>-13.86</td>
<td>&lt; 0.0001</td>
</tr>
</tbody>
</table>

Estimate: the difference in mean penetration values between the selected two inhalation flow rates; SE: standard error; DF: degree of freedom
Table 2-1. Summary of experimental conditions

<table>
<thead>
<tr>
<th>Variable</th>
<th>Levels</th>
</tr>
</thead>
<tbody>
<tr>
<td>Respirator</td>
<td>N95 FFR-A and N95 FFR-B</td>
</tr>
<tr>
<td>Sealing condition</td>
<td>Fully sealed on the manikin</td>
</tr>
<tr>
<td>Challenge aerosol</td>
<td>NaCl; Plastic combustion</td>
</tr>
<tr>
<td>Flow rate</td>
<td>Cyclic flows (MIF = 30, 85 L/min)</td>
</tr>
<tr>
<td>Relative humidity</td>
<td>≈20%; ≈80%</td>
</tr>
<tr>
<td>Replicates</td>
<td>6</td>
</tr>
<tr>
<td><strong>Total runs</strong></td>
<td>$2 \times 1 \times 2 \times 2 \times 2 \times 6 = 96$</td>
</tr>
</tbody>
</table>

MIF: mean inspiratory flow

Table 2-2. Significance of effects produced by the challenge aerosol, RH, MIF, and respirator type as well as by their interactions on $P_{\text{total}}$

<table>
<thead>
<tr>
<th>Source</th>
<th>DF</th>
<th>SS</th>
<th>MS</th>
<th>F-value</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Challenge aerosol</td>
<td>1</td>
<td>19.32</td>
<td>19.32</td>
<td>27.98</td>
<td>0.0007</td>
</tr>
<tr>
<td>RH</td>
<td>1</td>
<td>20.31</td>
<td>20.31</td>
<td>29.42</td>
<td>0.0006</td>
</tr>
<tr>
<td>MIF</td>
<td>1</td>
<td>25.49</td>
<td>25.49</td>
<td>36.92</td>
<td>0.0003</td>
</tr>
<tr>
<td>Respirator type</td>
<td>1</td>
<td>7.89</td>
<td>7.89</td>
<td>11.42</td>
<td>0.0096</td>
</tr>
<tr>
<td>RH * challenge aerosol</td>
<td>1</td>
<td>0.18</td>
<td>0.18</td>
<td>0.27</td>
<td>0.6188</td>
</tr>
<tr>
<td>RH * MIF</td>
<td>1</td>
<td>1.32</td>
<td>1.32</td>
<td>1.92</td>
<td>0.2037</td>
</tr>
<tr>
<td>RH * Respirator type</td>
<td>1</td>
<td>0.13</td>
<td>0.13</td>
<td>0.18</td>
<td>0.6791</td>
</tr>
</tbody>
</table>

DF: degree of freedom; SS: sum of squares; MS: mean square
Table 2-3. Comparison of the total particle penetration values (%) obtained in two studies while the N95 FFR-A respirator/filter was challenged with the same aerosols

<table>
<thead>
<tr>
<th>Aerosol</th>
<th>This study(^1)</th>
<th>Gao et al. (2015) study(^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MIF, L/min</td>
<td>Constant flow, L/min</td>
</tr>
<tr>
<td>Combustion (plastic)</td>
<td>1.38±0.50 5.29±0.80</td>
<td>0.76±0.16 3.53±0.53</td>
</tr>
<tr>
<td>NaCl</td>
<td>0.56±0.13 1.98±0.34</td>
<td>0.25±0.07 1.29±0.25</td>
</tr>
</tbody>
</table>

\(^1\)Conducted with cyclic flows of MIF = 30 and 85 L/min; \(^2\)Conducted with constant flows of 30 and 85 L/min.

Table 2-4. Significance of effects produced by the challenge aerosol, RH and MIF on \(P_{\text{total}}\) of the two tested FFRs

<table>
<thead>
<tr>
<th>Respirator</th>
<th>Source</th>
<th>DF</th>
<th>SS</th>
<th>MS</th>
<th>F value</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>N95 FFR-A</td>
<td>Challenge aerosol</td>
<td>1</td>
<td>9.12</td>
<td>9.12</td>
<td>10.59</td>
<td>0.0341</td>
</tr>
<tr>
<td></td>
<td>RH</td>
<td>1</td>
<td>8.61</td>
<td>8.61</td>
<td>10.00</td>
<td>0.0341</td>
</tr>
<tr>
<td></td>
<td>MIF</td>
<td>1</td>
<td>10.20</td>
<td>10.20</td>
<td>11.85</td>
<td>0.0262</td>
</tr>
<tr>
<td>N95 FFR-B</td>
<td>Challenge aerosol</td>
<td>1</td>
<td>10.22</td>
<td>10.22</td>
<td>12.43</td>
<td>0.0243</td>
</tr>
<tr>
<td></td>
<td>RH</td>
<td>1</td>
<td>11.83</td>
<td>11.83</td>
<td>14.39</td>
<td>0.0192</td>
</tr>
<tr>
<td></td>
<td>MIF</td>
<td>1</td>
<td>15.57</td>
<td>15.57</td>
<td>18.94</td>
<td>0.0121</td>
</tr>
</tbody>
</table>
Table 3-1. Respiratory protective devices selected for the study

<table>
<thead>
<tr>
<th>ID</th>
<th>Company</th>
<th>Model Number</th>
<th>Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>SM1</td>
<td>3M</td>
<td>1800NL</td>
<td>Regular</td>
</tr>
<tr>
<td>SM2</td>
<td>KC</td>
<td>14683</td>
<td>Regular</td>
</tr>
<tr>
<td>N95 SMR1</td>
<td>3M</td>
<td>1860</td>
<td>Regular, Small</td>
</tr>
<tr>
<td>N95 SMR2</td>
<td>3M</td>
<td>1870</td>
<td>Regular</td>
</tr>
<tr>
<td>Control N100</td>
<td>3M</td>
<td>8233</td>
<td>Regular</td>
</tr>
<tr>
<td>Prototype FS100</td>
<td>3M (modified)</td>
<td>8233</td>
<td>Regular</td>
</tr>
</tbody>
</table>

Table 3-2. Results paired t-test comparing SWPF_{total} between the tested protective devices

<table>
<thead>
<tr>
<th>RPDs compared</th>
<th>Number of subjects</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>SM1 &amp; SM2</td>
<td>10</td>
<td>0.84</td>
</tr>
<tr>
<td>N95 SMR1 &amp; N95 SMR2</td>
<td>10</td>
<td>0.41</td>
</tr>
<tr>
<td>Prototype FS100 &amp; Control N100</td>
<td>9</td>
<td>0.04 (*)</td>
</tr>
<tr>
<td>SMs &amp; N95 SMRs</td>
<td>10</td>
<td>0.0013 (**)</td>
</tr>
<tr>
<td>SMs &amp; N100 FFRs (Prototype FS100+Control N100)</td>
<td>9</td>
<td>0.0009 (**)</td>
</tr>
<tr>
<td>N95 SMRs &amp; N100 FFRs (Prototype FS100+Control N100)</td>
<td>9</td>
<td>0.0022 (**)</td>
</tr>
</tbody>
</table>

Note: p < 0.05 (*); p < 0.01(**)
Table 3-3. Effects of subject and particle size on the performance of respiratory protective devices (two-way ANOVA)

<table>
<thead>
<tr>
<th>Protection device</th>
<th>Factor</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>SM1</td>
<td>Subject</td>
<td>&lt; 0.0001 (**)</td>
</tr>
<tr>
<td></td>
<td>Size</td>
<td>0.822</td>
</tr>
<tr>
<td>SM2</td>
<td>Subject</td>
<td>&lt; 0.0001 (**)</td>
</tr>
<tr>
<td></td>
<td>Size</td>
<td>0.384</td>
</tr>
<tr>
<td>N95 SMR1</td>
<td>Subject</td>
<td>&lt; 0.0001 (**)</td>
</tr>
<tr>
<td></td>
<td>Size</td>
<td>0.170</td>
</tr>
<tr>
<td>N95 SMR2</td>
<td>Subject</td>
<td>&lt; 0.0001 (**)</td>
</tr>
<tr>
<td></td>
<td>Size</td>
<td>0.129</td>
</tr>
<tr>
<td>Prototype FS100</td>
<td>Subject</td>
<td>&lt; 0.0001 (**)</td>
</tr>
<tr>
<td></td>
<td>Size</td>
<td>&lt; 0.0001 (**)</td>
</tr>
<tr>
<td>Control N100 FFR</td>
<td>Subject</td>
<td>0.004 (**)</td>
</tr>
<tr>
<td></td>
<td>Size</td>
<td>&lt; 0.0001 (**)</td>
</tr>
</tbody>
</table>

Note: p < 0.01 (**)
Table 4-1. Summary of the Experimental Conditions

<table>
<thead>
<tr>
<th>Variable</th>
<th>Levels</th>
</tr>
</thead>
<tbody>
<tr>
<td>Facepiece type</td>
<td>A, B, C</td>
</tr>
<tr>
<td>Exhaust holes condition</td>
<td>covered; uncovered</td>
</tr>
<tr>
<td>MIF</td>
<td>30, 55, 85, 135 L/min</td>
</tr>
<tr>
<td>Replicates</td>
<td>3</td>
</tr>
<tr>
<td>Total runs</td>
<td>$3 \times 2 \times 4 \times 3 = 72$</td>
</tr>
</tbody>
</table>

^ The cyclic flows of MIF = 30, 55, 85 and 135 L/min (PIF = 47.1, 86.4, 133.5 and 212.0 L/min, respectively) were applied at breathing rate of 25 breaths/min.

Table 4-2. Three-way ANOVA Results for the ln(mFF) as the Function of Facepiece Type, MIF, and Exhaust Holes Condition

<table>
<thead>
<tr>
<th>Source</th>
<th>DF</th>
<th>ANOVA SS</th>
<th>Mean Square</th>
<th>F Value</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Facepiece type</td>
<td>2</td>
<td>32.13</td>
<td>16.07</td>
<td>26.71</td>
<td>&lt; 0.01</td>
</tr>
<tr>
<td>MIF</td>
<td>3</td>
<td>52.65</td>
<td>17.55</td>
<td>29.18</td>
<td>&lt; 0.01</td>
</tr>
<tr>
<td>Exhaust holes condition</td>
<td>1</td>
<td>1.70</td>
<td>1.70</td>
<td>2.83</td>
<td>0.11</td>
</tr>
</tbody>
</table>

DF, degrees of freedom; SS, sum of squares.
Table 4-3. ANOVA with Post-hoc Pairwise Comparisons on the Effect of Facepiece Type

<table>
<thead>
<tr>
<th>Facepiece Type</th>
<th>Facepiece Type</th>
<th>Estimate</th>
<th>SE</th>
<th>DF</th>
<th>T Value</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>B</td>
<td>A</td>
<td>0.12</td>
<td>0.88</td>
<td>21</td>
<td>0.14</td>
<td>0.89</td>
</tr>
<tr>
<td>B</td>
<td>C</td>
<td>2.51</td>
<td>0.88</td>
<td>21</td>
<td>2.86</td>
<td>0.01</td>
</tr>
<tr>
<td>A</td>
<td>C</td>
<td>2.39</td>
<td>0.88</td>
<td>21</td>
<td>2.73</td>
<td>0.01</td>
</tr>
</tbody>
</table>

SE, standard error; DF, degrees of freedom.

Table 4-4. Two-way ANOVA Results for the ln(mFF) as the Function of MIF and Exhaust Holes Condition

<table>
<thead>
<tr>
<th>Facepiece Type</th>
<th>Source</th>
<th>DF</th>
<th>ANOVA SS</th>
<th>Mean Square</th>
<th>F Value</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>MIF</td>
<td>3</td>
<td>26.09</td>
<td>8.70</td>
<td>448.72</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td></td>
<td>Exhaust holes condition</td>
<td>1</td>
<td>0.01</td>
<td>0.01</td>
<td>0.31</td>
<td>0.62</td>
</tr>
<tr>
<td>B</td>
<td>MIF</td>
<td>3</td>
<td>32.49</td>
<td>10.83</td>
<td>110.77</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td></td>
<td>Exhaust holes condition</td>
<td>1</td>
<td>0.83</td>
<td>0.83</td>
<td>8.46</td>
<td>0.06</td>
</tr>
<tr>
<td>C</td>
<td>MIF</td>
<td>3</td>
<td>3.11</td>
<td>1.04</td>
<td>34.46</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td></td>
<td>Exhaust holes condition</td>
<td>1</td>
<td>1.62</td>
<td>1.62</td>
<td>53.66</td>
<td>&lt;0.01</td>
</tr>
</tbody>
</table>

DF, degrees of freedom; SS, sum of squares.
Table 4-5. Three-way ANOVA Results for the \( \ln(mFF) \) as the Function of Facepiece Type, Constant Inhalation Flow Rate, and Exhaust Holes Condition

<table>
<thead>
<tr>
<th>Source</th>
<th>DF</th>
<th>ANOVA SS</th>
<th>Mean Square</th>
<th>F Value</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Facepiece type</td>
<td>2</td>
<td>68.19</td>
<td>34.09</td>
<td>46.68</td>
<td>&lt; 0.01</td>
</tr>
<tr>
<td>Constant inhalation flow rate</td>
<td>11</td>
<td>708.18</td>
<td>54.48</td>
<td>74.58</td>
<td>&lt; 0.01</td>
</tr>
<tr>
<td>Exhaust holes condition</td>
<td>1</td>
<td>0.11</td>
<td>0.11</td>
<td>0.16</td>
<td>0.69</td>
</tr>
</tbody>
</table>

DF, degrees of freedom; SS, sum of squares.

Table 4-6. Two-way ANOVA Results for the \( \ln(mFF) \) as the Function of Constant Inhalation Flow Rate and Exhaust Holes Condition

<table>
<thead>
<tr>
<th>Facepiece Type</th>
<th>Source</th>
<th>DF</th>
<th>ANOVA SS</th>
<th>Mean Square</th>
<th>F Value</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Constant inhalation flow rate</td>
<td>11</td>
<td>377.00</td>
<td>29.00</td>
<td>308.98</td>
<td>&lt; 0.01</td>
</tr>
<tr>
<td></td>
<td>Exhaust holes condition</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.97</td>
</tr>
<tr>
<td>B</td>
<td>Constant inhalation flow rate</td>
<td>11</td>
<td>341.09</td>
<td>26.24</td>
<td>118.70</td>
<td>&lt; 0.01</td>
</tr>
<tr>
<td></td>
<td>Exhaust holes condition</td>
<td>1</td>
<td>1.17</td>
<td>1.17</td>
<td>5.28</td>
<td>0.027</td>
</tr>
<tr>
<td>C</td>
<td>Constant inhalation flow rate</td>
<td>11</td>
<td>67.61</td>
<td>5.20</td>
<td>13.40</td>
<td>&lt; 0.01</td>
</tr>
<tr>
<td></td>
<td>Exhaust holes condition</td>
<td>1</td>
<td>2.82</td>
<td>2.82</td>
<td>7.27</td>
<td>0.01</td>
</tr>
</tbody>
</table>

DF, degrees of freedom; SS, sum of squares.
APPENDIX: Peer Reviewed Publications
Penetration of Combustion Aerosol Particles Through Filters of NIOSH-Certified Filtering Facepiece Respirators (FFRs)

Shuang Gao,1 Jinyong Kim,1 Michael Yermakov,1 Yousef Elmashae,1 Xinjian He,2 Tiina Reponen,1 and Sergey A. Grinshpun1

1Center for Health-Related Aerosol Studies, Department of Environmental Health, University of Cincinnati, Cincinnati, Ohio
2Industrial and Management Systems Engineering, Statler College of Engineering and Mineral Resources, West Virginia University, Morgantown, West Virginia

Filtering facepiece respirators (FFRs) are commonly worn by first responders, first receivers, and other exposed groups to protect against exposure to airborne particles, including those originated by combustion. Most of these FFRs are NIOSH-certified (e.g., N95-type) based on the performance testing of their filters against charge-equilibrated aerosol challenges, e.g., NaCl. However, it has not been examined if the filtration data obtained with the NaCl-challenged FFR filters adequately represent the protection against real aerosol hazards such as combustion particles. A filter sample of N95 FFR mounted on a specially designed holder was challenged with NaCl particles and three combustion aerosols generated in a test chamber by burning wood, paper, and plastic. The concentrations upstream (Cup) and downstream (Cdown) of the filter were measured with a TSI P-Trak condensation particle counter and a Grimm Nanocheck particle spectrometer. Penetration was determined as (Cdown/Cup) × 100%. Four test conditions were chosen to represent inhalation flows of 15, 30, 55, and 85 L/min. Results showed that the penetration values of combustion particles were significantly higher than those of the “model” NaCl particles (p < 0.05), raising a concern about applicability of the N95 filters performance obtained with the NaCl aerosol challenge to protection against combustion particles. Aerosol type, inhalation flow rate and particle size were significant (p < 0.05) factors affecting the performance of the N95 FFR filter. In contrast to N95 filters, the penetration of combustion particles through R95 and P95 FFR filters (were tested in addition to N95) were not significantly higher than that obtained with NaCl particles. The findings were attributed to several effects, including the degradation of an N95 filter due to hydrophobic organic components generated into the air by combustion. Their interaction with fibers is anticipated to be similar to those involving “oily” particles. The findings of this study suggest that the efficiency of N95 respirator filters obtained with the NaCl aerosol challenge may not accurately predict (and rather overestimate) the filter efficiency against combustion particles.

INTRODUCTION

First responders and first receivers as well as some other groups of workers are often exposed to airborne particles containing hazardous materials which may cause various respiratory illnesses.1 For example, studies have shown that the first receivers who responded to the collapse of the World Trade Center have substantial loss in pulmonary function and increasing risk for developing a number of cancers.2, 3

Combustion process can generate a large amount of particles and gases that are known or anticipated to be harmful to both the environment and the health.4 Of particular importance is the combustion of ultrafine/nano-scale particles (<100 nm in size),5,6 which can penetrate deep into the lung; once deposited, some of these particles may cross the air-blood barrier and accumulate in other organs.7 Workers exposed to the combustion particles may be at risk for developing respiratory and cardiovascular problems.8,9 Characteristics such as particle size, shape, charge, surface area, chemical properties, and solubility may attribute to the particle toxicity and health effects.10

The NIOSH-certified filtering facepiece respirators (FFRs), e.g., N95-type devices, are commonly used in the workplace to protect against hazardous aerosols, including those generated by combustion.11 The certification is based on the...
Numerous studies have been performed to determine the filter efficiency of the FFRs against specific aerosols. One study conducted with two N99 and one N95 filters challenged with three viral aerosols and NaCl at inhalation flow rates of 30, 85, and 150 L/min, revealed that the filter penetration of the virions did not exceed that of the NaCl particles, suggesting that the NIOSH certification test generated adequate data for modeling the filter penetration of similarly sized virions. In another study, which tested the efficiency of N95 FFRs against silver and NaCl particles of 20–30 nm at 85 L/min, the investigators found that aerosol type had no significant effect on the penetration values. The penetration of combustion particles through FFR has been addressed only in a few investigations. He et al. tested an elastomeric half-mask equipped with P100 filters using particles generated by combustion of wood, paper, and plastic; it was found that the aerosol type significantly affected the filter penetration. To our knowledge, no similar investigation has been conducted with N95, P95, R95, and other filters commonly used in the field.

The aim of this study was to investigate the penetration of aerosol particles produced by combustion of wood, paper, and plastic through an N95 FFR filter and compare the data to the penetration of charge-equilibrated NaCl “model” particles. In addition to the challenge aerosol type, factors such as inhalation flow rate and particle size were also investigated. The R95 and P95 filters were also tested to help interpret the findings obtained with the N95 filter challenged with combustion particles.

### MATERIALS AND METHODS

#### Tested Filters

Filter samples taken from a widely used N95 FFR model (8110S, 3M Corp., MN) were tested in this study. This filter has an electrically charged layer—a feature which makes it more efficient. To further investigate the interaction between this filter medium and the combustion aerosol particles, R95 (8247, 3M Corp., MN) and P95 FFRs (64420 R20, Jackson safety, GA) filter samples were also tested (in contrast to the N-type, which stands for not resistant to oil degradation), the R- and P-types represent “resistant to oil degradation” and “oil proof”, respectively.

#### Challenge Aerosols

Three types of combustion particles, including wood, paper and plastic, were generated in a test chamber by burning a wood stick (24 cm long and 0.4 cm diameter, 1.9 ± 0.5 g), a sheet of paper (23 x 24 cm brown multifold paper towel, TABLE I. Inhalation Flow Rates of the Filter Samples

<table>
<thead>
<tr>
<th>(Q_{\text{Respirator}} ) (L/min)</th>
<th>(V_{\text{Respirator}} ) (cm/s)</th>
<th>(Q_{\text{Sample}} ) (L/min) = (Q_{\text{Respirator}} ) (( A_{\text{Sample}} / A_{\text{Respirator}} ))(^A)</th>
</tr>
</thead>
<tbody>
<tr>
<td>15</td>
<td>1.62</td>
<td>3.75</td>
</tr>
<tr>
<td>30</td>
<td>3.25</td>
<td>7.50</td>
</tr>
<tr>
<td>55</td>
<td>5.95</td>
<td>13.8</td>
</tr>
<tr>
<td>85</td>
<td>9.20</td>
<td>21.3</td>
</tr>
</tbody>
</table>

\(^A\)The adjustment was made to keep \( V_{\text{Respirator}} = V_{\text{Sample}} \).
2.1 ± 0.2 g), and a plastic straw (19 cm long and 0.5 cm diameter, 0.6 ± 0.01 g), respectively, using the protocol described elsewhere.\(^6\) The burning materials were held by a caliper with a water-filled basin right under it, and were ignited by a lighter. The measurement was started 15 min (time zero) after the complete burning of each material to allow the particles to reach a uniform concentration inside the test chamber. Based on our previous findings,\(^{17,18}\) we expected the particles to reach a concentration of 160,000–200,000 particles/cm\(^3\) at time zero; the “initial” particle concentrations for paper and plastic were expected to range from 280,000–330,000 particles/cm\(^3\). These concentration levels are within the measurement capabilities of the aerosol instruments utilized in this study.

The sodium chlorite particles were aerosolized using a particle generator (Model 8026, TSI Inc., MN) containing NaCl solution with a concentration of 0.02 g/mL. The generated particles, primarily 20–500 nm, were charge-equilibrated before challenging the filters by passing the aerosol through a 85Kr electrical charge equilibrator (Model 3054, TSI Inc., MN) placed between the generator and the filter sample holder. The generator produced a stable concentration (±17%) of NaCl particles at a level of about 160,000 particles/cm\(^3\).

It is acknowledged that in this study design, we charge-equilibrated NaCl particles but not combustion particles. The former was done to follow conventional filter testing protocols,\(^12\) while the combustion particles were not subjected to the same procedure in order to better simulate the field conditions.

Experimental Design

The experiments were conducted in a room-sized test chamber (volume = 24.3 m\(^3\)). The experimental setup is shown in Figure 1. The tested filter sample with a surface area of 45.34 cm\(^2\) (about a quarter of the whole respirator area) was mounted on a specially designed holder and challenged with one of the four aerosols. The sampling probes were placed upstream and downstream of the filter sample at the flow centerline. A high-speed 2-way electromagnetic valve was placed between the sampling probes and the measurement devices to allow an operator to switch between the upstream and downstream measurements. The holder was connected to an air sampling pump (SP-280, Air Diagnostics and Engineering Inc., ME) producing a constant inhalation air flow (Q). A mass flow meter (4050, TSI Inc., MN) with a range of 0–300 L/min was placed between the pump and the holder to monitor the flow rate. Four inhalation flow rates (Q\(_{\text{Sample}}\)) of 3.75, 7.50, 13.8, and 21.3 L/min were applied on the filter samples. With the sample areas (A\(_{\text{Sample}}\)) selected, these allowed matching the air face velocity through the filter sample and the whole respirator at inhalation flows (Q\(_{\text{Respirator}}\)) of 15, 30, 55, and 85 L/min, respectively (see Table I). The latter simulate low, moderate, high, and strenuous workload, respectively.\(^{21,22}\)

During the testing, the concentrations of each challenge aerosol were measured upstream (C\(_{\text{up}}\)) and downstream (C\(_{\text{down}}\)) of the tested filter with a P-Trak condensation particle counter (8525, TSI Inc., Shoreview, MN) operating within a size range of 20 to 1000 nm and a particle size spectrometer (Grimm Technologies, Inc., Ainring, Germany) consisting of a Nanocheck (Model 1320) and an optical particle counter (OPC) (Model 1.108). We focused primarily on the size range of 20–150 nm since our earlier experiments showed that 90% of combustion particles were in this range.\(^{17}\) The corresponding mean sizes for the selected channels were 26, 35, 46, 60, 80, 105, and 139 nm. Additionally, larger particles (up to 900 nm) were measured using the Grimm OPC, which allowed comparing the size-integrated (total) concentrations obtained with the Grimm particle size spectrometer and the P-Trak.

The size specific particle penetration values (P\(_{\text{dp}}\)) were determined for these sizes as

\[
P_{\text{dp}} = \frac{C_{\text{down,dp}}}{C_{\text{up,dp}}} \times 100\%.
\]

(1)

The total particle penetration (P\(_{\text{total}}\)) was determined from the P-Trak data as

\[
P_{\text{total}} = \frac{C_{\text{down, total}}}{C_{\text{up, total}}} \times 100\%.
\]

(2)

### Table II. Effects of the Aerosol Type and Inhalation Flow Rate on P\(_{\text{total}}\) (Two-way ANOVA with Interaction)

<table>
<thead>
<tr>
<th>Source</th>
<th>DF</th>
<th>SS</th>
<th>MS</th>
<th>F-Value</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aerosol type</td>
<td>3</td>
<td>8.08</td>
<td>2.69</td>
<td>48.65</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Inhalation flow rate</td>
<td>3</td>
<td>35.34</td>
<td>11.78</td>
<td>212.84</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Aerosol type</td>
<td>9</td>
<td>3.44</td>
<td>0.38</td>
<td>6.91</td>
<td>&lt;0.0001</td>
</tr>
</tbody>
</table>

DF: degree of freedom; SS: sum of squares; MS: mean square
The P-Trak was chosen for the total count because it has the same operating principle as a PortaCount respirator fit testing apparatus (8038, TSI Inc., Shoreview, MN) which is utilized for evaluating the fit factor of FFRs.

Data Analysis

Statistical data analysis was performed using SAS version 9.3 (SAS Institute Inc., Cary, NC). Two-way analysis of variance (ANOVA) was conducted to study the effects of inhalation flow rate, challenge aerosol type, and their interaction on the P\text{total}. T-test was used to evaluate the differences between NaCl and three combustion particles. One-way ANOVA was performed to study the effect of particle size. P-values less than 0.05 were considered significant.

RESULTS AND DISCUSSION

Total Particle Penetration (P\text{total})

The total particle penetration (P\text{total}) obtained for the N95 filters did not provide the same filtration efficiency against combustion particles. One possible explanation could be that of combustion particles. The difference in shape, density, charge, surface properties, and possibly other characteristics between the combustion particles and NaCl particles. Further investigation was undertaken to understand how these differences may affect the outcome (described below). It is noted, however, that although the N95 filters did not provide the same filtration efficiency against combustion particles as they did for NaCl, their collection efficiency was still above 95% (none of P\text{total} exceeded 5%), which is acceptable for the N95 filters.

For the three combustion materials, the penetration of plastic particles was the highest, followed by paper and wood. This finding is consistent with our previous studies, which were conducted using elastomeric half-mask with P100 filters.\(^6\)\(^{,}\)\(^{18}\)

The results obtained with the P-Trak were in agreement with the size-integrated data generated by the Grimm spectrometer in a range of 25–900 nm. No significant difference (p > 0.05) was observed between the total particle penetration obtained with the two aerosol measurement devices.

\begin{table}[h]
\centering
\caption{Pairwise Comparisons of P\text{total} for Challenge Aerosol Types (ANOVA with Post-hoc Pair-wise Comparisons)}
\begin{tabular}{|l|l|l|l|l|l|l|l|l|l|}
\hline
Aerosol type & Aerosol type & Estimate & SE & DF & T-value & p-value \\
\hline
NaCl & Wood & −0.40 & 0.096 & 32 & −4.16 & 0.0013 \\
NaCl & Paper & −0.72 & 0.096 & 32 & −7.54 & <0.0001 \\
NaCl & Plastic & −1.11 & 0.096 & 32 & −11.60 & <0.0001 \\
Paper & Plastic & −0.39 & 0.096 & 32 & −4.06 & 0.0018 \\
Paper & Wood & 0.32 & 0.096 & 32 & 3.37 & 0.0117 \\
Plastic & Wood & 0.71 & 0.096 & 32 & 7.44 & <0.0001 \\
\hline
\end{tabular}
\end{table}

Estimate: the difference in mean penetration values between the selected two materials; SE: standard error; DF: degree of freedom

\begin{table}[h]
\centering
\caption{Pairwise Comparisons of P\text{total} for Inhalation Flow Rates (ANOVA with Post-hoc Pair-wise Comparisons)}
\begin{tabular}{|l|l|l|l|l|l|l|l|l|l|}
\hline
Inhalation & Inhalation & Estimate & SE & DF & T-value & p-value \\
flow & rate, & & & & & & \\
Q\text{Respirator} & Q\text{Respirator} & & & & & & \\
\hline
15 & 30 & −0.12 & 0.096 & 32 & −1.29 & 0.2056 \\
15 & 55 & −0.83 & 0.096 & 32 & −8.63 & <0.0001 \\
15 & 85 & −2.16 & 0.096 & 32 & −22.49 & <0.0001 \\
30 & 55 & −0.70 & 0.096 & 32 & −7.34 & <0.0001 \\
30 & 85 & −2.04 & 0.096 & 32 & −21.20 & <0.0001 \\
55 & 85 & −1.33 & 0.096 & 32 & −13.86 & <0.0001 \\
\hline
\end{tabular}
\end{table}

Estimate: the difference in mean penetration values between the selected two inhalation flow rates; SE: standard error; DF: degree of freedom

ANOVA Results on the Effect of Challenge Aerosol

A two-way ANOVA with interaction showed that the type of the challenge aerosol has a strong significant effect on the performance of the N95 filter (p < 0.0001) (see Table II). Further analysis was undertaken using a pair-wise multiple comparison to assess the significance of the penetration difference when each challenge aerosol was compared with the other three challenge aerosols. As seen from Table III, all the differences were significant (p < 0.05).

ANOVA Results on the Effect of Inhalation Flow Rate

The total particle penetration increased with increasing constant flow rate. This could be explained by particle capture mechanisms, which are primarily diffusion and electrical charge interaction. These mechanisms are affected by the face velocity of the air flow, with higher face velocity resulting in a shorter residence time and, consequently, higher penetration level.
As shown in Table II, inhalation flow rate was a significant factor affecting $P_{\text{total}}$ ($p < 0.0001$). The interaction between the challenge aerosol and the inhalation flow rate had also a strong significance ($p < 0.0001$). Pair-wise comparison (Table IV) revealed that the differences among the data series of four flow rates were significant except the data series obtained at 15 and 30 L/min. One possible reason is that the flow rate increment (the interval between 15 and 30 L/min is only 15 L/min) is not large enough to significantly reduce the penetration levels.

**Size-Selective Particle Penetration ($P_{dp}$)**

The size-selective particle penetration values determined by Grimm Nanocheck are presented in Figure 3. While retrieving the particle size distribution data across the entire operational size range of this spectrometer, we found that, based on the aerosol type, 97–99% (by number) of combustion particles generated were within the selected range of 20 to about 150 nm. The figures represent four challenge aerosols and four inhalation flow rates.

Increasing the inhalation flow resulted in an increase in $P_{dp}$ values for all the tested combustion particles as well as NaCl particles, which is consistent with the results of previous studies conducted with N95 FFRs. The results of paired t-test showed that the difference between each paired flow rate was also significant ($p < 0.05$).

All three combustion particles featured significantly higher penetration values than NaCl regardless of the particle size and flow rate ($p < 0.05$). One-way ANOVA revealed that the particle size had a significant effect on the penetration of combustion particles ($p < 0.05$) while not being a significant factor ($p > 0.05$) for NaCl. In contrast, our earlier study on the efficiency of an N95 FFR against NaCl particles under

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**FIGURE 3**. Size-selective particle penetration values for N95 FFR filter samples challenged with three combustion particles (wood, paper, and plastic) and NaCl particles. Each point represents the average value of five to six replicates. Symbols “∗” and “∗∗” indicate significant differences (“∗”: $p < 0.05$; “∗∗”: $p < 0.01$) when comparing the NaCl to the combustion particles.
cyclic flows with mean inspiratory flows (MIFs) of 15, 30, 55, and 85 L/min (conducted using a Nano-ID (NPS500, Naneum, Canterbury, UK)) showed that the effect of particle size was significant. An important difference between these investigations is an instrument deployed for aerosol measurement. The sensitivity of the Grimm spectrometer (used in the present study) is not as high as that of the Nano-ID (used in the quoted study) at low penetration levels observed with NaCl. This may be, at least partially, a reason for ANOVA not yielding the penetration dependency on size. The disagreement can also be attributed to differences in the experimental design and flow regime used in these two studies, e.g., in the quoted investigation, cyclic flow regime was applied on a manikin headform wearing the N95 FFRs while in the present effort a constant flow regime was applied on the N95 FFR filters. In the cyclic regime, the returned clean air (exhalation) dilutes the aerosol inside the respirator. This “cleaning” effect is different for different particle sizes. Furthermore, some particles present inside the respirator cavity may deposit on the inner surface of the filter or move out through the filter and faceseal leakage during exhalation. These effects are also anticipated to be particle size dependent.

The most penetrating particle size (MPPS) varied depending on the aerosol type. For example, the curves obtained for NaCl were almost flat with a barely visible peak at about 70 nm; the penetration of wood steadily increased until the particle size reached 46 nm, then the \( P_{dp} \) started to decrease; the curves for paper were relatively flat reaching a small peak at 35 nm; the MPPS values for plastic particles were in the range of 46–80 nm. Overall, the MPPS for the tested N95 FFR filter against combustion particles was observed in the size range of 35–105 nm, which is consistent with the results of earlier studies reporting the MPPS values below 100 nm for the N95 FFRs. The MPPS is also dependent on the tested filter type. In one study that included a half-mask respirator with P100 filters, the MPPS for plastic particles fell in the range of 120–140 nm, while the MPPS for wood and paper was difficult to identify since the penetration curves were close-to-flat.

Interpretation of Data Obtained for an N95 Filter. Testing of R95 and P95 Filters

Generally, combustion particles, which are electrically charged, should be collected more efficiently by the N95 filter fibers than the charge-equilibrated (quasi-neutralized) NaCl particles. Thus, it was surprising to observe that the combustion particles penetrated through an N95 FFR filter significantly more readily than the “model” NaCl. We hypothesized that the “reverse” trend seen in our experiments can be, at least partially, attributed to the following. The combustion particles (as well as vapors originated when burning different materials) contain hydrophobic molecules (or hydrophobic portions of molecules). E.g., the plastic combustion has been shown to emit hydrophobic organic compounds. In this regard, having properties similar to oil particles (and in presence of “oily” vapors), the combustion particles may degrade an “electret” filter (media used for FFRs not resistant to oil, e.g., N95), if deposited on its fibers, thus increasing the aerosol penetration. This may be associated with the charge neutralization during the filter collection, dielectric shielding of fibers, and ionic conduction.

An additional experiment was conducted to examine the above interpretation. In contrast to the N95 filter type, the filters of R95 and P95 FFRs are designed to protect against oily particles; therefore, we repeated the particle penetration experiments using these two types of filters. We anticipated that since R95 and P95 filters are resistant to degradation associated with oil aerosols, we would observe no significant difference in penetration of combustion particles and NaCl particles, which would support our hypothesis.

As shown in Figure 4, the penetration values through R95 and P95 were extremely low as compared to N95, with the total particle penetration being below 0.15% for all the tested materials at \( Q_{\text{Respirator}} = 85 \text{ L/min} \). This finding is consistent with other studies.

Remarkably, for R95 and P95 filters, the penetration levels of combustion particles were not higher than that of NaCl. We believe it is because, unlike an N95, these two filters were “non-degradable” or “less degradable” which supports our above interpretation of the effect of particle type. Furthermore, opposite to the test results obtained with an N95 filter, the R- and P-type filters allowed penetrating fewer combustion particles than NaCl particles in most experimental conditions (with an exception of plastic particles penetrating through a P95 filter) (\( p < 0.05 \)). Unlike NaCl aerosol that passed the
electrical charge equilibrator, combustion particles carried some electric charges, which enhanced their deposition on fibers. The net charge is not expected to be substantial though because the freshly-generated particles were allowed to interact with air ions for 15 min before the measurement began, which should have led to their partial neutralization. The charge neutralization rate of combustion particles is unknown, which is a limiting factor for our data interpretation involving the particle charge. In any case, because of their design, the R- and P-type filters were not subjected to substantial degradation due to exposure to combustion aerosols – the phenomenon caused the “reverse” trend for the N95 filter.

Other possible mechanisms that may explain the differences in penetration of combustion and NaCl particles through an N95 filter include the formation of loose agglomerates on the fibers, neutralization or reduction of charge occurring on fiber due to deposition of oppositely charged particles, as well as chemical reaction.\(^{30}\)

CONCLUSIONS

Performance of the N95 FFR filter was significantly affected by the aerosol type and inhalation flow rate. The penetration of combustion particles through an N95 respirator filter was significantly higher than that of the “model” NaCl particles (\(p < 0.05\)), raising a concern about applicability of the N95 filters performance obtained with the NaCl aerosol challenge to protection against combustion particles. The findings were attributed to several effects, including the degradation of an N95 filter due to hydrophobic organic components originated in the air during combustion. Their interaction with fibers is anticipated to be similar to those involving “oily” particles. Additional experiments with oil-resistant and oil-proof FFR filters supported our explanation. The total penetration increased with an increasing flow rate regardless of particle types. Particle size was also found to be a significant factor on the penetration of combustion particles. The findings of this study suggest that the efficiency of N95 respirator filters obtained with the NaCl aerosol challenge may not accurately predict (and rather overestimate) the filter efficiency against combustion particles.

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Performance of N95 FFRs against Combustion and NaCl Aerosols in Dry and Moderately Humid Air: Manikin-based Study

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ABSTRACT

Objectives: The first objective of this study was to evaluate the penetration of particles generated from combustion of plastic through NIOSH-certified N95 filtering facepiece respirators (FFRs) using a manikin-based protocol and compare the data to the penetration of NaCl particles. The second objective was to investigate the effect of relative humidity (RH) on the filtration performance of N95 FFRs.

Methods: Two NIOSH-certified N95 FFRs (A and B) were fully sealed on a manikin headform and challenged with particles generated by combustion of plastic as well as NaCl particles. The tests were performed using two cyclic flows (with mean inspiratory flow rates, MIF = 30 L/min and 85 L/min, representing human breathing under low and moderate workload conditions), and two RH levels (≈20% and ≈80%, representing dry and moderately humid air). The total and size-specific particle concentrations inside (C_in) and outside (C_out) of the respirators were measured with a condensation particle counter and an aerosol size spectrometer. The penetration values (C_in/C_out) were calculated after each test.

Results: The challenge aerosol, relative humidity, mean inspiratory flow rate, and respirator type had significant (p < 0.05) effects on the performance of the manikin-sealed FFR. Its efficiency significantly decreased when the FFR was tested with plastic combustion particles compared to NaCl aerosols. For example, at RH ≈ 80% and MIF = 85 L/min, as much as 7.03% and 8.61% of combustion particles penetrated N95 respirators A and B, respectively. The plastic combustion particles and gaseous compounds generated by combustion likely degraded the electric charges on fibers, which increased the particle penetration. Increasing breathing flow rate or humidity increased the penetration (reduced the respirator efficiency) for all tested aerosols. The effect of particle size on the penetration varied depending on the challenge aerosol and respirator type. It was observed that the peak of the size distribution of combustion particles almost coincided with their most penetrating particle size, which was not the case for NaCl particles. This finding was utilized for the data interpretation.

Conclusions: N95 FFRs have lower filter efficiency when challenged with contaminant particles generated by combustion, particularly when used under high humidity conditions compared to NaCl particles.
Keywords: plastic combustion particles, relative humidity, N95, filtering facepiece respirator, penetration
INTRODUCTION

Air-purifying respirators are commonly used in the U.S. for protection against job hazards. According to a voluntary survey conducted on U.S. employers regarding the use of respiratory protective devices, 95% of the workers used air-purifying devices (BLS/NIOSH, 2003). The N95 filtering facepiece respirators (FFRs) are the most popular air-purifying respirators. They are expected to filter out at least 95% of airborne particles (“N” stands for non-oil-resistant). The National Institute for Occupational Safety and Health (NIOSH) estimates that 20 million American workers, including healthcare providers, firefighters, first-responders, and construction workers use respirators every day for reducing exposure to airborne hazards (NIOSH, 2013). First responders such as emergency medical personnel and police – the first people who arrive at the scene of emergency and possibly exposed to elevated levels of hazardous materials present in flame and smoke – are often equipped with N95 FFRs (as evident from the response to the 9/11 terrorist attacks in New York and Washington). In various working environments, airborne combustion particles may be generated by burning plastic, wood, paper, cotton, and other construction materials, of which, open burning of plastic is particularly dangerous to the workers’ health.

Burning of plastic generates black smoke containing decomposition compounds, which contaminate the ambient air and cause harmful exposures (Karasek and Tong, 1985; Simoneit et al., 2005; Tong et al., 1984; Fu et al., 1997). The chemical compounds generated by plastic burning include carbon monoxide, hydrogen cyanide, dioxin, acrolein, formaldehyde, etc. (Guidotti and Clough, 1992). These compounds may be present at the levels substantially exceeding their recommended exposure limits (RELs), which can cause health impairments and death (Milkovits, 2006). Some hazardous compounds have been shown to adhere to particles,
which results in a deeper penetration into the respiratory tract, causing toxicological effects.

(Genovesi, 1980; Karasek and Tong, 1985; Kulkarni et al., 2011). The health effects of exposure to smoke and fumes from plastic burning have been associated with various occupational diseases, including heart disease, lung cancer, asthma and emphysema, nausea, headaches, and damages in the nervous system (Timonen et al., 2006; Schulte et al., 2008).

NIOSH generates charge neutralized sodium chloride (NaCl) particles of approximately 300 nm mass median aerodynamic diameter as the challenge aerosols to test the filtration efficiency of N95 FFRs (42 CFR Part 84), by using automated filter tester (TSI 8130, TSI Inc., Shoreview, MN, USA). The referred size was originally assumed to be near the most penetrating particle size for N95 FFRs, which has been questioned in several studies (Lee et al., 2008; Martin et al., 2000). It has not been demonstrated that NaCl particles can be used as a universal aerosol that can accurately simulate aerosols produced by combustion for the filter/respirator testing purposes. Particles aerosolized from different sources feature different properties such as size distribution, charge distribution, and chemical composition, which can influence the filter performance (Balazy et al., 2006; Eninger et al., 2008; He et al., 2013a; Lathrache and Fissan, 1986; Lathrache et al., 1986; Martin and Moyer, 2000). For example, Balazy et al. (2006) who challenged two N95 FFRs with MS2 virus concluded that some N95 FFRs may not provide 95% filter efficiency against airborne virions that are smaller than the conventionally used 300-nm NaCl particles. Walsh and Stenhouse (1997) reported that factors such as size, charge and composition of aerosol particles had significant effects on the filter performance; furthermore, these investigators stated that the charge of the test particles was a key factor affecting the electret filter performance. Our recent study (Gao et al., 2015) conducted on the electret filter samples indicated that combustion particles penetrated more
readily than NaCl particles, which could be attributed to different chemical properties of the two types (more details are provided below).

The NIOSH certifies FFRs by evaluating the filter performance under a constant flow of 85 L/min. Numerous studies have been conducted to determine the filtration efficiency under constant flow regime (Chen et al., 1990; Chen and Willeke, 1992; Eshbaugh et al., 2009; Martin et al., 2000; Qian et al., 1998). However, the result obtained under constant flow may not accurately predict the filter performance under actual breathing conditions as a human breathing pattern is much more complex and features a cyclic nature. Therefore, in this study we used a cyclic flows produced by a breathing machine to mimic human breathing.

A few studies have been published concerning the relative humidity (RH) influencing the respirator performance. The effect of RH on the filter efficiency varies depending on the aerosols type, particles size as well as the filter material (Newnum, 2010). One study showed that the penetration of the non-hygroscopic particles increased as RH increased (Minguel, 2003). However, for hygroscopic particles such as NaCl, the penetration decreased with increasing the RH since the particle size increased by absorbing water from the ambient air. Kim et al. (2006) reported that the effect of RH on penetration of particles below 100 nm was not significant. At higher RH, the adherence between fibers and particles increases due to an increase in the capillary force. Consequently, the fibers are able to capture more particles from the air stream, i.e., the aerosol penetration decreases with increasing RH. However, this phenomenon has been shown to be pronounced specifically for coarse particles (with aerodynamic diameter above 2.5 µm) at higher RH (Brown, 1993). While Yang and Lee (2005) reported that RH had no effect on the filter performance by comparing the filter penetrations of NaCl particles under RH = 30% and 70%, the effect was demonstrated at higher RH. Several studies (Haghighat et al., 2012;
Lakezaki et al., 1995; Lowkis and Motyl, 2001; Mahdavi et al., 2015; Mostofi et al., 2011; Cheng et al., 2006) have shown that the performance of electret filters decreases with increasing RH. For instance, Haghighat et al. (2012) tested N95 FFRs filters under three RH of 10%, 30% and 70% at a constant flow rate of 85 L/min and found that the penetration of the filters increased with the increasing RH. It should be noted that NIOSH certification testing program for FFRs includes preconditioning in a chamber at RH = 85% ± 5% RH and a temperature of 38 ± 2.5 ºC for 25 ± 1 hours. We hypothesize that a humidity-associated partial or full discharge of the fibers of electret filters (material used in N95 FFRs) may significantly compromise the filter performance. The water vapor could condense on the electret fibers, which would produce a “discharging” effect.

The present research effort is a follow-up to the study of Gao et al. (2015) performed using the same challenge aerosols. Similar to our earlier study, this investigation aimed at evaluating the penetration of particles aerosolized by combustion (plastic particles in particular) through filter samples of N95 FFRs and comparing the results to the penetration of the “standard” challenge aerosol (NaCl). The main difference is that in the current effort we tested the whole facepieces and utilized a manikin-based protocol. The tested N95 respirator was fully sealed using silica adhesive on the plastic manikin headform in order to test the filter efficiency, whereas the previous investigation examined the performance of 76-mm diameter filter samples cut from the N95 FFRs. Additionally, this study was conducted under the cyclic (not constant) breathing condition. The main goal of this study was to investigate the particle penetration through N95 filters challenged with particles generated by combustion of plastic and compare the data to the penetration of NaCl particles. The second goal was to investigate the effect of humidity on the filtration performance of N95 FFRs.
MATERIALS AND METHODS

Respirators and Challenge Aerosols

Two widely used N95 FFRs labeled as N95 FFR-A and N95 FFR-B were tested in this study. The N95 FFR-B has a plastic mesh shell to support the physical structure of the filter media and prevent collapsing during regular use as well as under hot and humid conditions. Both the FFRs tested do not have exhalation valves which results in the exhaled breath coming in full contact with the filter media. In an FFR equipped with an exhalation valve, the exhaled breath is essentially directed to the outside through the valve, which could reduce moisture build up inside the facepiece.

Two challenge aerosols including plastic combustion particles and NaCl particles were generated (one at a time). The plastic particles were produced by burning a plastic polypropylene straw (Home sense™, Kroger Co., Cincinnati, OH, USA) (19 cm long and 0.5 cm diameter, 0.6± 0.01 g) held in a caliper. The plastic straw was ignited by a lighter and left for burning until completely consumed. The sampling devices were started to collect data 15 minutes after the completion of the plastic burning, which allowed the plastic particles to reach a spatial uniformity (He et al., 2014a). We were specifically interested in testing the plastic particles as our previous study showed that they penetrated through the N95 FFR filters more readily than the other two types of combustion particles (wood and paper) (Gao et al., 2015). Additionally, plastic aerosols were of interest due to adverse health effects associated with their exposure (Simoneit et al., 2005). The NaCl aerosols were continuously generated using a particle generator (Model 8026, TSI Inc., Shoreview, MN, USA) from a water suspension with
NaCl dissolved at 0.02 g/ml. A period of 20 minutes was allowed for NaCl particles to reach the homogeneous stage in the test chamber.

**Relative Humidity**

The respirators were tested against challenge aerosols at two RHs: ≈ 20% and ≈ 80%. These levels represent dry and moderately humid conditions, respectively. RH = 20% was the natural humidity inside the chamber. In order to establish the higher RH, a steam vaporizer (V150SG2UPC, KAZ Inc., Southboro, MA, USA) was utilized. The RH in the test chamber was measured using a digital psychrometer (SAM990DW, General Tools & Instruments, New York, NY, USA). Prior to testing, the N95 FFRs were placed under the tested RH for about 30 min before generating aerosol.

**Experimental Design and Test Conditions**

The experimental set-up shown in Figure 1 has been described in detail elsewhere (He et al., 2013b). All the tests were conducted in an exposure chamber (volume = 3.6 × 2.4 × 2.6 m³, L×W×H). Table 1 summarizes the experimental conditions. The tested N95 FFR (either N95 FFR-A or N95 FFR-B) was properly positioned and fully sealed along the contact area of the manikin headform using the silica adhesive. The headform has a facial length of (11.43 ± 0.35) cm and width of (12.53 ± 0.25) cm, which is categorized into Cell 3 (small faces) of the NIOSH bivariate panel, developed by using the database of a total of 3997 respirator users (Zhuang et al., 2007). A 1-inch diameter copper pipe connected the nose and mouth area of the manikin with the breathing simulator. Two sampling probes were inserted: one in the breathing area inside the respirator cavity and one outside of the respirator. The two sampling lines were
controlled by a high-speed 2-way electromagnetic valve, which was manually operated to alternate measurements of the inside ($C_{in}$) and outside ($C_{out}$) aerosol concentrations.

The aerosol was measured with two devices. A P-Trak condensation particle counter (Model 8525, TSI Inc., Shoreview, MN, USA) counted particles across the size range measuring the total aerosol concentration. The Mini Wide Range Aerosol Spectrometer [a Nanoparticle Aerosol Monitor Model 1320 in combination with an optical particle counter (OPC) Model 1.108, both from Grimm Technologies, Inc., Ainring, Germany)] measured the particle size distribution as well as the total concentration. The concentration $C_{out}$ was measured during the first 5 minutes, followed by the measurement of $C_{in}$ for 10 minutes, and then $C_{out}$ was measured again over the last 5 minutes. In each test, the outside concentration was calculated as an average of the $C_{out}$ values measured over the two 5-minute periods. Thus, the natural decay of the aerosol concentration in the chamber was accounted for; it was relatively small: 15% for NaCl particles and 35% for plastic combustion particles as measured over 20 min at no air exchange applied in the exposure chamber during the experiment. The particle penetration ($P_{total}$) was calculated as ($C_{in}/C_{out}$) × 100%. The air was supplied using the Breathing Recording and Simulation System (BRSS, Koken Ltd., Tokyo, Japan) via a high efficiency particulate air (HEPA) filter. The BRSS is capable of establishing various breathing patterns by adjusting the flow rate and the breathing frequency. For this study, we selected two cyclic flows with mean inspiratory flow (MIF) rates of 30 L/min and 85 L/min and a breathing frequency of 25 breaths/min. These conditions represent human breathing under the low and moderate workloads, respectively (Sherwood, 2006; Tortora and Anagnostakos, 1990).

**Data Analysis**
Data analysis was performed using SAS version 9.3 (SAS Institute Inc., Cary, NC, USA). Paired t-test was deployed to evaluate the difference between plastic combustion particles and NaCl particles. Four-way analysis of variance (ANOVA) was used to evaluate the effects of challenge aerosol, RH, MIF, respirator type, as well as the interactions between relative humidity and the other variables. Three-way ANOVA test was utilized to examine the significance of challenge aerosol, RH, and MIF after stratifying the data by respirator type. Paired t-test was used to examine the difference between the total particle penetrations obtained using the aerosol concentrations measured by the condensation particle counter and the aerosol size spectrometer. Correlation analysis was performed to evaluate the association between the two. For the size-specific particle penetration, the effect of particle size was analyzed by one-way ANOVA. The differences were considered significant if p-values calculated from the above statistical tests were below 0.05.

RESULTS AND DISCUSSION

Total Particle Penetration ($P_{\text{total}}$)

The total particle penetration obtained for the two tested N95 FFRs challenged with plastic combustion particles and NaCl particles is presented in Figure 2 and Figure 3 as measured using a P-Trak and a Grimm aerosol spectrometer, respectively. According to measurements conducted with the P-Trak, the total penetration values for combustion aerosol at RH $\approx$ 20% and MIF = 30 L/min were 1.38% and 2.10 %, respectively, for N95 FFR-A and N95 FFR-B. These values increase as MIF increased to 85 L/min. The penetration also showed higher values as the humidity was raised to 80%. The higher penetrations for combustion particles was observed for RH $\approx$ 80% and MIF = 85 L/min: 7.03% for N95 FFR-A and 8.61% for N95 FFR-B. The
measurements using the Grimm instrument revealed similar trends with the maximum total penetration values of 6.05% for N95 FFR-A and 7.16% for N95 FFR-B measured at the highest tested RH and MIF. It is noted that these levels exceed the 5% NIOSH certification criterion established for N95 respirators. In all cases presented for the P-Trak measurements and all, but one, cases presented for the Grimm measurements, the results of paired t-test showed that the penetration of plastic combustion particles was significantly higher (p < 0.05) than that of NaCl particles, regardless of RH, MIF and respirator type. The four-way and three-way ANOVA tests also showed that aerosol type was a significant factor (p < 0.05) affecting the filter performance (Table 2, Table 4). This finding is consistent with previous reports (He et al., 2013b; Ji et al., 2003). In our recent study (Gao et al., 2015), we discussed why the plastic combustion particles may penetrate through an N95 “electret” filter material more readily than NaCl particles. In brief, we believe that the particles and gaseous compounds originated by burning plastic contain hydrophobic molecules, which, similarly to oil aerosols, are capable of degrading the “electret” filter (Gao et al., 2015; Tennal et al., 1991; Teuten et al., 2007). Since the N95 filter material is not resistant to oil, it may be affected by the compounds produced from burning plastic. Whether the combustion gases affect filter performance was beyond the scope of this research, but is suggested as an area of future studies. The “oily” particles generated by combustion may partially charge-neutralize the fibers and consequently reduce their collection efficiency, which, in turn, increases the aerosol penetration into the respirator. Unlike an N95 FFR, a P95 type (designed to protect against “oily” aerosols) was found to feature the same collection efficiency for plastic combustion particles and NaCl particles (Gao et al., 2015), which supports our interpretation. Other factors that could explain the significantly different penetration levels observed between plastic combustion particles and NaCl particles may include the difference in
their particle size distributions (discussed below), as well as in the particle shape, density, charge, surface properties and possibly other characteristics between the plastic combustion particles and NaCl particles. For example, Zhou and Cheng (2016) suggested that NaCl particles do not as readily penetrate the N95 FFRs as engineered nanoparticles due to their different electrostatic properties.

The total particle penetration values measured with a P-Trak when testing N95 FFR-A under the cyclic flow condition was compared to the results obtained with the flat filter samples made of the same material under constant flow (Gao et al., 2015). Table 3 shows the results of this comparison. In the quoted study, the test conditions were established so that the face velocity for the flat filter sample was equal to the face velocity of the whole respirator under the constant flow. It was noted that the penetration of particles under cyclic flow (determined in this study) was 1.5- to 2.2-fold higher than that measured under the corresponding constant flow (the quoted study). This may be attributed to the differences in filter surfaces (cup-like versus flat) and flow dynamics (cyclic versus constant).

Effect of RH on $P_{total}$

As shown in Figure 2, the total particle penetration increased with the increasing RH. For NaCl particles, while $P_{total}$ increased significantly ($p < 0.05$) when RH was raised from 20 to 80%, it did not exceed the 5% NIOSH respirator certification criterion (except a minor excess observed for N95 FFR-B at MIF = 85 L/min). In contrast, almost all $P_{total}$ values obtained for plastic combustion particles exceeded 5%. The four-way and three-way ANOVA tests indicated that the effect of humidity was significant (Table 2, Table 4), which is in agreement with the results of other studies (Minguel, 2003; Moyer et al., 1989; Newnum, 2010). Some older studies
suggested that electrical discharge occurred on filter fibers at high RH (Ackley, 1982; Moyer et al., 1989). As the charges decrease, the filter efficiency decreases as well, which results in a greater $P_{\text{total}}$. Other possible explanations for decreasing the filter efficiency with the humidity increase have been discussed in the literature. For example, Raynor and Leith (1999) indicated that humid air might help form small water droplets at intersections of fibers. These droplets could coalesce and cover the fibers, thus impeding their ability to collect. Haghighat et al. (2012) stated that at high RH salt particles such as NaCl might undergo deliquescence and interact with the filter as larger droplets. Gupta et al. (1993) speculated that the droplets could fill the interstitial spaces of the filter. This may negatively affect the filter performance. Our findings along with the above interpretation of the RH effect are consistent with the experimental investigation of Mahdavi et al. (2015) who suggested that NaCl particles were partially or totally hydrated at high RH, which reduced their electrostatic attraction to the filter.

**Effect of MIF and Respirator Type on $P_{\text{total}}$**

Besides the challenge aerosol type and humidity, other factors such as MIF and respirator type were also evaluated in this study. As seen from Table 2, the effect of MIF on $P_{\text{total}}$ was significant ($p < 0.05$). Penetration increased with the increasing MIF, which is in agreement with previous reports (Eshbaugh et al., 2009; He et al., 2014b). Respirator type was found to be a significant factor as well. None of the three interactions between RH and other variables (RH and challenge aerosol, RH and MIF, RH and respirator type) had a significant effect on the respirator performance.

$P_{\text{total}}$ data: Aerosol Size Spectrometer versus Condensation Particle Counter
The total aerosol concentrations measured with the aerosol size spectrometer was obtained by combining all the channels between 15 to 900 nm. The particle size range in which P-Trak condensation particle counter measures the total concentration is approximately 20 – 1000 nm. In spite of the differences in the size range and operational principles, the paired t-test revealed that the $P_{\text{total}}$ values determined with the two devices were not significantly different ($p > 0.05$). Additionally, as shown in Figure 4, a significant correlation between the $P_{\text{total}}$ measured with P-Trak and Grimm was observed with the slope of 0.81 and the $R^2$ value of 0.87.

**Particle Size Specific Penetration ($P_{dp}$)**

Figure 5 presents the size specific particle penetration obtained with two tested N95 FFRs at MIFs = 30 L/min and 85 L/min and RH $\approx$ 20% and $\approx$ 80% while exposed to two challenge aerosols (plastic combustion and NaCl). For N95 FFR-A, data analysis revealed that particle size had a significant effect on penetration of both tested aerosols ($p < 0.05$), which was consistent with our previous results (He et al., 2013c). For both types of challenge aerosols, the shapes of the penetration curves obtained in dry and humid air environments were about the same. Quantitatively, the difference between penetration levels found at two RHs decreased with increasing MIF (see the distances between two curves of the same color in Fig. 5A). Within the tested particle size range, the penetration under high RH exceeded that under low RH, regardless of MIF and challenge aerosol. The peaks were observed at 80 nm for NaCl and 35-46 nm for combustion particles, respectively. The difference in the most penetrating particle size (MPPS) likely reflects different physical properties of the two types of aerosol particles relevant to the particle-filter interaction, including, but not limited to, the particle shape, surface area, and effective density (Boskovic et al., 2005; Vaughn and Ramachandran, 2002). The MPPS data are comparable to the recently published results obtained for the N95 filter samples made of the
same material (Gao et al., 2015). The size-specific penetration values obtained for the N95 FFR-A device with NaCl particles were approximately between 0.01 and 7.69%; for plastic combustion particles the range was 0.72 – 8.58%.

For N95 FFR-B, the trend was more complex. The penetration values were higher than those obtained for the N95 FFR-A, indicating that N95 FFR-B was not as efficient as N95 FFR-A. One-way ANOVA indicated that particle size was a significant factor affecting the penetration when the respirator was challenged with either of the aerosols. As shown in Figure 5B, the curves representing the two challenge aerosols are closer to each other compared to the similar curves presented for the N95 FFR-A. The MPPSs obtained for the two challenge aerosols lay closer for both tested RH and MIF. The latter may be attributed to the electric charge on the fibers of the respirator filter. We believe that the bipolar charging of the N95 FFR-B filter is not sufficient to cause a pronounced size selectivity of $P_{dp}$. This suggests a lower difference in penetration between combustion particles and NaCl. Similar to the results observed on N95 FFR-A, the filtration performance of N95 FFR-B decreased with increasing RH, except a few points obtained under MIF of 85 L/min.

**Effect of Particle Size Distribution of the Challenge Aerosol on Penetration**

The information about the MPPSs obtained for the two challenge aerosols in relation to their particle size distribution helps interpreting the findings about the difference in total penetrations. Both size distributions – for NaCl and plastic combustion particles – were close to log-normal with a count median diameter (CMD) and a geometric standard deviation (GSD) of 80 nm and 5.9, respectively, for NaCl particles, and 59 nm and 4.8, respectively, for combustion particles.
It was observed that the peak of the particle size distribution was close to the MPPS value for combustion particles, which was not the case for NaCl particles. This suggests that the fraction of particles with sizes close to MPPS was greater for the plastic combustion aerosol as compared to NaCl aerosol, which contributes to the higher penetration level observed for the combustion particles versus NaCl.

Limitations and Future Work

First, the findings of this study are limited to specific (although extensively used) N95 FFR models. Future efforts are needed to examine if the results of this investigation are fully applicable to other filter materials and respirator models. Second, this study is focused on the respirator filter efficiency (the tested device was sealed on the manikin), but does not address the role of the faceseal leakage, which may represent a prominent particle penetration pathway. Third, the study used the aerosol generated by burning plastic as an example of combustion particles. However, combustion aerosols can be generated by different materials, which vary from one another in terms of the particle size and charge distributions, chemical composition and other factors that may affect the respirator filter performance. Thus, other challenge aerosols should be investigated in future research efforts. Finally, the interpretation of the findings of this study is of a limited utilization given that no chemical characterization of the gases/vapors generated by combustion was performed.

CONCLUSIONS

This study evaluated the penetration of combustion and NaCl particles through N95 FFRs sealed on a manikin headform and tested under simulated cyclic breathing flow. Filter
penetration of N95 FFRs measured using particles generated by combustion of plastic was higher than the value determined with a NaCl challenge aerosol. This was most likely due to the compounds produced from burning plastic. A similar finding was reported in our companion study (Gao et al., 2015), which was conducted with N95 filter samples at constant inhalation flow conditions. From this perspective, R95 or P95 FFRs should, probably, be considered as better alternatives for first responders since they may be exposed to similar combustion products in the air. Increasing the RH reduced the respirator filtration performance against both the NaCl and plastic combustion challenge aerosols. The findings presented in this study are limited to the respirators tested and may not necessarily be applied to all N95 FFRs and all plastic combustion aerosols.

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**DISCLAIMER**

Mention of commercial product or trade name does not constitute endorsement by the National Institute for Occupational Safety and Health. The findings and conclusions of this report are those of the authors and do not necessarily represent the views of the National Institute for Occupational Safety and Health.
REFERENCE


Timonen KL, Vanninen E, de Hartog J et al. (2006) Effects of ultrafine and fine particles and gaseous air pollution on cardiac autonomic control in gaseous air pollution on cardiac autonomic control in


Fig. 1. Experimental set-up (modified from He et al., 2013b)
Fig. 2. Total particle penetration values (measured using a P-Trak condensation particle counter) for two N95 FFRs donned on a manikin headform while challenged with plastic combustion particles and NaCl particles. The error bars were obtained from six replicates ("*": p < 0.05)
Fig. 3. Total particle penetration values (measured using a Grimm spectrometer) for two N95 FFRs donned on a manikin headform while challenged with plastic combustion particles and NaCl particles. The error bars were obtained from six replicates ("*": p < 0.05)
Fig. 4. Correlation between $P_{\text{total}}$ obtained from the P-Trak and Grimm measurement data.

$y = 0.81x + 0.90$

$R^2 = 0.87$

$p > 0.05$
Fig. 5. Particle size-specific penetration values (measured using a Grimm spectrometer) for two N95 FFRs donned on a manikin headform while challenged with plastic combustion particles and NaCl particles. The error bars were obtained from six replicates.
Table 1. Summary of experimental conditions

<table>
<thead>
<tr>
<th>Variable</th>
<th>Levels</th>
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</thead>
<tbody>
<tr>
<td>Respirator</td>
<td>N95 FFR-A and N95 FFR-B</td>
</tr>
<tr>
<td>Sealing condition</td>
<td>Fully sealed on the manikin</td>
</tr>
<tr>
<td>Challenge aerosol</td>
<td>NaCl; Plastic combustion</td>
</tr>
<tr>
<td>Flow rate</td>
<td>Cyclic flows (MIF = 30, 85 L/min)</td>
</tr>
<tr>
<td>Relative humidity</td>
<td>≈20%; ≈80%</td>
</tr>
<tr>
<td>Replicates</td>
<td>6</td>
</tr>
<tr>
<td>Total runs</td>
<td>2×1×2×2×2×6=96</td>
</tr>
</tbody>
</table>

MIF: mean inspiratory flow
Table 2. Significance of effects produced by the challenge aerosol, RH, MIF, and respirator type as well as by their interactions on $P_{\text{total}}$

<table>
<thead>
<tr>
<th>Source</th>
<th>DF</th>
<th>SS</th>
<th>MS</th>
<th>F-value</th>
<th>p-value</th>
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<tr>
<td>Challenge aerosol</td>
<td>1</td>
<td>19.32</td>
<td>19.32</td>
<td>27.98</td>
<td>0.0007</td>
</tr>
<tr>
<td>RH</td>
<td>1</td>
<td>20.31</td>
<td>20.31</td>
<td>29.42</td>
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<tr>
<td>MIF</td>
<td>1</td>
<td>25.49</td>
<td>25.49</td>
<td>36.92</td>
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<td>Respirator type</td>
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<td>7.89</td>
<td>7.89</td>
<td>11.42</td>
<td>0.0096</td>
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<tr>
<td>RH * challenge aerosol</td>
<td>1</td>
<td>0.18</td>
<td>0.18</td>
<td>0.27</td>
<td>0.6188</td>
</tr>
<tr>
<td>RH * MIF</td>
<td>1</td>
<td>1.32</td>
<td>1.32</td>
<td>1.92</td>
<td>0.2037</td>
</tr>
<tr>
<td>RH * Respirator type</td>
<td>1</td>
<td>0.13</td>
<td>0.13</td>
<td>0.18</td>
<td>0.6791</td>
</tr>
</tbody>
</table>

DF: degree of freedom; SS: sum of squares; MS: mean square
Table 3. Comparison of the total particle penetration values (%) obtained in two studies while the N95 FFR-A respirator/filter was challenged with the same aerosols

<table>
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<tr>
<th>Aerosol</th>
<th>This study 1</th>
<th>Gao et al. (2015) study 2</th>
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<tr>
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<td>MIF, L/min</td>
<td>Constant flow, L/min</td>
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<tr>
<td></td>
<td>30</td>
<td>85</td>
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<tr>
<td>Combustion (plastic)</td>
<td>1.38±0.50</td>
<td>5.29±0.80</td>
</tr>
<tr>
<td>NaCl</td>
<td>0.56±0.13</td>
<td>1.98±0.34</td>
</tr>
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1Conducted with cyclic flows of MIF = 30 and 85 L/min; 2Conducted with constant flows of 30 and 85 L/min.
Table 4. Significance of effects produced by the challenge aerosol, RH and MIF on $P_{\text{total}}$ of the two tested FFRs

<table>
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<th>Respirator</th>
<th>Source</th>
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<th>SS</th>
<th>MS</th>
<th>F value</th>
<th>p-value</th>
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<tr>
<td>N95 FFR-A</td>
<td>Challenge aerosol</td>
<td>1</td>
<td>9.12</td>
<td>9.12</td>
<td>10.59</td>
<td>0.0341</td>
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<tr>
<td></td>
<td>RH</td>
<td>1</td>
<td>8.61</td>
<td>8.61</td>
<td>10.00</td>
<td>0.0341</td>
</tr>
<tr>
<td></td>
<td>MIF</td>
<td>1</td>
<td>10.20</td>
<td>10.20</td>
<td>11.85</td>
<td>0.0262</td>
</tr>
<tr>
<td>N95 FFR-B</td>
<td>Challenge aerosol</td>
<td>1</td>
<td>10.22</td>
<td>10.22</td>
<td>12.43</td>
<td>0.0243</td>
</tr>
<tr>
<td></td>
<td>RH</td>
<td>1</td>
<td>11.83</td>
<td>11.83</td>
<td>14.39</td>
<td>0.0192</td>
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<tr>
<td></td>
<td>MIF</td>
<td>1</td>
<td>15.57</td>
<td>15.57</td>
<td>18.94</td>
<td>0.0121</td>
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Performance of Facepiece Respirators and Surgical Masks against Surgical Smoke: Simulated Workplace Protection Factor Study

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Performance of Facepiece Respirators and Surgical Masks against Surgical Smoke: Simulated Workplace Protection Factor Study

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ABSTRACT

Objective: Surgical smoke generated during electrocautery contains toxins which may cause adverse health effects to operating room (OR) personnel. The objective of this study was to investigate the performance of Surgical Masks (SMs), which are routinely used in ORs, more efficient N95 Surgical Mask Respirators (SMRs) and N100 Filtering Facepiece Respirators (FFRs), against surgical smoke.

Methods: Ten subjects were recruited to perform surgical dissections on animal tissue in a simulated OR chamber, using a standard electrocautery device, generating surgical smoke. Six respiratory protective devices (RPDs) were tested: two SMs, two SMRs, and two N100 FFRs [including a newly-developed faceseal (FS) prototype]. Fit testing was conducted before the experiment. Each subject was then exposed to the surgical smoke while wearing an RPD under the tests. Concentration inside ($C_{in}$) and outside ($C_{out}$) of the RPD were measured by a particle size spectrometer. The simulated workplace protection factor (SWPF) was determined by the ratio of $C_{out}$ and $C_{in}$ for each RPD-wearing subject.

Results: For the SMs, the geometric means of SWPF$_{\text{total}}$ (based on the total aerosol concentration) were 1.49 and 1.76, indicating minimal protection. The SWPF$_{\text{total}}$ values of the SMRs and N100 FFRs were significantly higher than those of the SMs: for the two SMRs, the SWPF$_{\text{total}}$ were 208 and 263; for the two N100s, the SWPF$_{\text{total}}$ values were 1,089 and 2,199. No significant difference was observed between either the two SMs or the two SMRs. The SWPF$_{\text{total}}$ for the novel FS prototype N100 FFR was significantly higher than the conventional N100 FFR. The correlation between SWPF$_{\text{total}}$ and fit factor (FF) determined for two N95 SMRs was not significant.

Conclusions: SMs do not provide measurable protection against surgical smoke. SMRs offer considerably improved protection versus SMs, while the N100 FFRs showed significant improvement over the SMRs. The FS prototype offered a higher level of protection than the standard N100 FFR, due to a tighter seal. While we acknowledge that conventional N100 FFRs (equipped with exhalation valves) are not practical for human OR use, the results obtained with the FS prototype demonstrate the potential of the new faceseal technology for implementation on various types of respirators.
Keywords: surgical smoke, surgical mask, filtering facepiece respirators, simulated workplace protection factor
INTRODUCTION

Surgical smoke is an aerosol hazard unique to the surgical operating room (OR). It is generated by electrocautery used in virtually all standard surgical facilities as a means of performing surgical dissection of various tissues. Electrocautery is a process in which an electrical current is passed through a resistant metal wire electrode. The heated electrode is then applied to the tissue for dissection or hemostasis (Pollock et al., 2008). Given the positioning of surgical personnel over and around the surgical patient, surgical smoke is often directly in the path of their respiratory field. The Occupational Safety and Health Administration (OSHA) estimates that 500,000 workers are exposed to laser and electrocautery smoke each year (OSHA, 2007).

There have been significant concerns about exposure to surgical smoke, and about the adequacy of standard surgical masks (SMs) to protect personnel in the OR. Surgical smoke contains known carcinogens as well as viable biologic particles (Barrett and Garber, 2003). Carcinogenic and neurotoxic compounds were found in surgical smoke aerosols generated from porcine tissue as well as during human surgical procedures (Krones et al., 2007; Sahaf et al., 2007). A review by Biggins and Renfree (2002) reported the failure of SMs to provide appropriate protection to healthcare personnel and suggested establishing new standards to reduce the risks. Other studies have revealed that SMs are insufficient for providing adequate protection against surgical smoke (Barrett and Garber, 2003; Alp et al., 2006).

Exposure to surgical smoke aerosol has relevance to public health settings due to the presence of small particles. Weber et al. (1993) tested eight SMs and found that for fine particles (< 1,000 nm) the penetration through these masks ranged from 20% to nearly 100%. Studies
conducted with two SMs sealed on a manikin headform indicated that for particles of 10–80 nm in diameter (including MS2 virions), the filter penetration was 20.5% to 84.5% (Balazy et al., 2006a; Balazy et al., 2006b). Since SMs have a comparatively poor fit, face seal leakage represents a prominent penetration pathway. This is especially true for small particles, e.g., those in the size range of influenza A virions (Booth et al., 2013) as well as virions causing Human Papilloma Virus (HPV), Severe Acute Respiratory Syndrome (SARS), and Middle East Respiratory Syndrome (MERS). Although N95 filtering facepiece respirators (FFRs) are more efficient than SMs [their N95 filter is certified by the National Institute of Occupational Safety and Health (NIOSH) to allow no more than 5% penetration], penetration of ultrafine particles (<100 nm) through some N95 FFRs may exceed this threshold (Balazy et al., 2006a). The highest filter penetration values were observed for particles of 30–70 nm in diameter, which includes the size of several respiratory pathogenic virions (Zheng and Baker, 2006; Mettenleiter and Sobrino, 2008), as well as a substantial fraction of surgical smoke particles (Bruske et al., 2008; Andreasson et al., 2009).

NIOSH recommends combining general room ventilation with local exhaust ventilation (LEV) to control the airborne particles generated by surgical smoke (NIOSH, 1996). However, due to the variability of surgical smoke and its potential hazards, the implementation of personal protective equipment (PPE) is also needed to protect healthcare workers in operating rooms. The Association for periOperative Registered Nurses (AORN) recognizes the hazard of the surgical smoke. AORN also urges the use of PPE and evacuation and filtration of smoke through an appropriate system (AORN, 2008). They recommend using fit-tested surgical N95 filtering facepiece respirators or high-filtration masks to protect against surgical smoke (AORN, 2008; Benson et al., 2013). However these recommendations are not regulatory requirements, and
presently the use of N95 FFRs in ORs is primarily limited to procedures involving HPV. Overall, SMs remains the standard protection devices in ORs. Recently, so-called “N95 Surgical Mask Respirators” (SMRs) have been introduced. The SMRs are cleared by the Food and Drug Administration (FDA) for use in ORs, and certified by NIOSH to receive an N95 grade (although the NIOSH does not evaluate FFRs for surgical use). However, little is known about the performance of either SMs or SMRs against surgical smoke. Rozzi et al. (2012) investigated the absorption capabilities of organic vapor FFRs against the aromatic hydrocarbons generated in surgical smoke, but neither this nor similar investigations addressed the particulate matter component. A higher grade FFR (N100) was pilot-studied against surgical smoke from porcine tissue (Koehler et al., 2014). One of these facepieces was modified by creating a faceseal (FS) made of ethylene vinyl acetate foam that was affixed to the inner perimeter of the respirator, replacing the stock face seal. The modification significantly improved the respirator performance by minimizing the faceseal leakage. It is acknowledged that N100 FFRs have limitations for deployment in ORs due to their exhalation valve component. However, it is still important to generate data about the efficiency of these highest grade facepieces against surgical smoke because it will help determine the feasibility of making appropriate design modifications to other respirators, e.g., N95 SMRs (that have no exhalation valves), in order to maximize their performance.

The protection provided by a respirator at a workplace is typically assessed by determining its workplace protection factor (WPF) measured under specific conditions. One way to quantify the WPF is through the simulated workplace protection factor (SWPF). SWPF is measured in a controlled laboratory setting while the wearer performs exercises mimicking the actual work procedures.
The purpose of our study was to determine the SWPFs against surgical smoke for two SMs and two N95 SMRs (both currently approved for OR use), as well as for a conventional and newly-developed N100 FFR.

MATERIALS AND METHODS

Respirator Selection

Commercially available SMs (Model 1800NL, 3M, St. Paul, MN, and Model 14683, Kimberly Clark, Neenah, WI) and N95 FFRs marketed as SMRs (Model 1860 and Model 1870, 3M, St. Paul, MN) were selected for this study. The above devices were labeled as SM1, SM2, N95 SMR1, and N95 SMR2, respectively. The SM1 and SM2 were originally designed to reduce the contamination of others in the wearer’s surrounding to airborne pathogens that he/she may aerosolize during exhalation; SMs are also used to reduce the potential exposure of the wearer to blood and body fluids. The N95 SMR1 and N95 SMR2 are intended to be deployed during laser surgery, electrocautery and other procedures which utilize powered medical instruments. All four selected SMs and SMRs (see Table 1) are equipped with a malleable metallic nosepiece to form the bridge of the nose.

Additionally, two higher-grade FFRs were evaluated in this study. One was an original commercially available N100 FFR (Model 8233, 3M, St. Paul, MN); the other was the same FFR modified with a novel FS, labeled as FS Prototype N100 (Koehler et al., 2014). The model of the selected N100 FFR was also shown in Table 1.

Challenge Aerosol
The surgical smoke was generated by electrocautery dissection of porcine muscle tissue, as described previously by several investigators (Hensman et al., 1998; Weld et al., 2007). A standard electrosurgical generator was used as the energy source for the cautery procedures (Valleylab Force FX, Covidien, Boulder, CO). Electrocautery dissection was performed utilizing a standard electrosurgical pencil (Valleylab E2516, Covidien, Boulder, CO) at a setting of 40 watts for both cutting and coagulation, using a blend mode.

**Human Subject Selection**

Ten human subjects representing healthcare workers were recruited for this study: 5 adult males and 5 adult females. All of the subjects except one experienced surgeon were recruited from research staff and students of the University of Cincinnati’s College of Medicine. The subjects were notified about the potential hazard of surgical smoke exposure before conducting the experiment and were provided with a written consent to participate. The research protocol was approved by the University of Cincinnati Institutional Review Board (IRB). Before the experiment, each subject completed the OSHA respirator medical clearance questionnaire administered by the University Occupational Pulmonary Program.

**Fit Testing**

Prior to evaluating the respirator/mask performance in the exposure chamber with surgical smoke, the subjects underwent fit testing while wearing the two N95 SMRs and two N100 FFRs according to the OSHA fit testing protocol (OSHA 29 CFR 1910.134). An SM is not subject for the OSHA fit testing. After the fit testing, the subjects were introduced into the chamber for the SWPF study immediately.

Sodium chloride (NaCl) particles were generated using a particle generator (Model 8026,
TSI Inc., Shoreview, MN) to create a sufficient ambient concentration to obtain measurable protection factors with highly-efficient respirators. The overall fit factor (FF) was measured and recorded by the PortaCount Plus (Model 8020, TSI Inc., Shoreview, MN) operating with an N95-Companion (Model 8095, TSI Inc., Shoreview, MN). The fit factor is calculated as the aerosol concentration outside of the respirator divided by its concentration inside of the respirator when a subject is performing a specific set of procedures (OSHA 29 CFR 1910.134). The passing criterion of FF is 100.

**Experimental Setup**

The experimental setup is presented in Figure 1. While inside the exposure chamber (volume = $3.6 \times 2.4 \times 2.6 \, \text{m}^3$), a subject wearing a tested respirator or SM under the test performed electrocautery dissection on a section of animal muscle tissue located on a surgical table mimicking a conventional surgical procedure. Each of the ten subjects wore each of the six tested PRD in a random order. The height of the surgical table was approximately 1 m above the ground, a typical height in ORs. The choice of the surgical equipment utilized, the distance from the cautery to the test subject, and the cautery settings, were all determined by an experienced board-certified surgeon with over 10,000 hours of surgical electrocautery experience. The subjects were trained in the techniques of electrocautery dissection by the same surgeon, who was also a subject in the study.

The surgical smoke aerosol generated during this procedure was sampled in the breathing zone directly outside the respirator/mask (representing the inhalation exposure of an unprotected individual) as well as inside the respirator/mask (representing the inhalation exposure of a wearer). The in-respirator sampling line, which is shown as a clear tube in Figure 1B was
connected to the probe located at the breathing zone of the RPD; the ambient air sampling line is shown as a blue tube in this figure. The inlets of the two respective sampling lines were located 6 cm from each other. The same sampling configuration was used in fit testing. The aerosol concentrations and particle size distributions of the inside- and outside-sampled aerosol ($C_{\text{in}}$ and $C_{\text{out}}$, respectively) were measured by a particle size spectrometer (Nanoparticle Aerosol Monitor, Model 1320, Grimm Technologies, Inc., Ainring, Germany) in combination with an optical particle counter (OPC) (Model 1.108, Grimm Technologies, Inc., Ainring, Germany). The inside and outside concentration measurements were controlled by a high speed 2-way electromagnetic valve. The outside concentration was measured for 6 minutes following by a 12 minutes inside measurement; subsequently, the outside concentration was measured again for 6 minutes. The average concentration of the two 6-minute outside concentration measurements was calculated and recorded as $C_{\text{out}}$. The average concentration of the continuous 12-minute inside concentration measurement was calculated and recorded as $C_{\text{in}}$. The SWPF was determined as $C_{\text{out}}/C_{\text{in}}$. The data were recorded in a particle size range of 25–1,150 nm. Based on the total aerosol concentrations measured across this size range, the total protection factor (SWPF$_{\text{total}}$) was calculated. Additionally, the particle size selectivity of the aerosol measurement allowed determining SWPFs for different particle sizes (SWPF$_{dp}$). These were recorded within a narrower range of 25–290 nm because the particle concentrations inside of the tested N95 and N100 FFRs were almost zero for particles larger than 290 nm. The corresponding mean sizes for the 10 selected channels were 25, 35, 45, 60, 85, 115, 145, 180, 265, and 290 nm.

During the smoke generation process, the exposure chamber was ventilated using a pre-installed ventilation and high-efficiency particulate air (HEPA) filtration system operating at an air exchange rate of 5 Air Exchanges per hour (AEH). The modern OR facilities operate at least
at 20 AEH of which 4 AEH comes from the ambient air (Facility Guidelines Institute, 2014). At the same time, some ORs operate at lower air exchange rates. We have intentionally chosen a relatively low exchange rate to establish the most conservative assessment with the highest feasible concentration level of smoke particles.

Data Analysis

The data analysis was performed using SAS version 9.3 (SAS Institute Inc., Cary, NC). For each respiratory protective device (RPD), geometric mean (GM) and geometric standard deviation (GSD) of SWPF were calculated. The statistical analyses were applied after performing a log-transformation of the data. Paired t-test was used to test the difference between different RPDs. Two-way ANOVA was deployed to evaluate the effects of subjects and particle sizes on the size-selective SWPFs. P-values below 0.05 represented a significant difference.

RESULTS AND DISCUSSION

Concentration and Particle Size Distribution of the Surgical Smoke in the Breathing Zone

The total aerosol particle concentration measured in the breathing zone of the experienced surgeon who was exposed to the surgical smoke level ranged from $0.708 \times 10^6$ to $1.080 \times 10^6$ particles/cm$^3$ (Mean $\approx 0.946 \times 10^6$ particles/cm$^3$ and SD = $0.111 \times 10^6$), which was around 1,000 times higher than the background level. At the same time, the size-specific concentration levels were substantially below the upper threshold limits of the aerosol instrument. The particle size distributions generated in five experiments (Tests I through V) are presented in Figure 2. The curves have a similar shape; four of them peak at a particle size of 115 nm.
observed and one at 145 nm. The tests with other subjects generally generated similar particle size distribution curves although the total particle concentration levels were lower, which can be attributed to their limited experience in operating the electrocautery equipment. It was noticed that some subjects did not apply the electrocautery pencil to the tissue as frequently as it was demonstrated by surgeon, which could produce a lower level of smoke. With regard to the above between-subject variability and other factors influencing the aerosol concentration and particle size distribution in the breathing zone, it should be acknowledged that in an actual operating setting, electrocautery use in different surgical procedures involving various tissues would likewise have an effect on the concentration and particle size distribution of the generated surgical smoke.

The surgical smoke particle concentration measured in this study was relatively high compared to the levels found by Hohlfeld et al. (2008). One explanation for the difference may be that the measurements were conducted during different surgical procedures utilizing different aerosol instruments (Hohlfeld et al. used a condensation particle counter). Additionally, the higher concentration measured in the present study may be attributed to lower air exchange rate established in our chamber. It is also noted that in the quoted study the aerosol sampling was performed at the side of the anesthetist, rather than directly in front of the surgeon’s mask, as in our OR setup. This greater distance from the surgeon’s breathing zone may explain their findings of lower particle concentrations. While acknowledging the above differences, it is recognized that the ambient aerosol concentration level does not affect the outcome of this effort because SWPF is a non-dimensional parameter.

**Simulated Workplace Protection Factor (SWPF_{total})**
Figure 3 presents the values of SWPF$_{\text{total}}$ for the six tested RPDs. The SWPF$_{\text{total}}$ values for SM1 and SM2 were close to 1 with GM = 1.49, GSD = 1.95 (SM1) and GM = 1.76, GSD = 1.71 (SM2), indicating essentially no protection. The difference in SWPF$_{\text{total}}$ between SM1 and SM2 was not significant (p>0.05, Table 2). Some particle size-selective SWPF values obtained for SMs were actually below 1, indicating that the aerosol concentrations inside the SMs were higher than outside. This counter-intuitive finding can be attributed to the fact that the same aerosol instrument was deployed alternating between the inside and outside measurements, which were conducted at different time points introducing an uncertainty, which affects the SWPF. The uncertainty is particularly apparent when the SWPF is close to 1. Overall, a very low efficiency of SMs observed in this study is consistent with previous reports (Dixon and Nelson, 1984; Zhuang et al., 2003; Reponen et al., 2011).

The SWPF$_{\text{total}}$ of both N95 SMRs were significantly higher than the values of SMs (p<0.01, Table 2). Both N95 SMRs offered a measurable level of protection: GM = 263, GSD = 2.17 and GM = 208, GSD = 2.31, respectively. Their SWPF$_{\text{total}}$ values exceeded 100 (the fit test passing level) and, by far, exceed 10 (the OSHA’s assigned protection factor). It is noted that the protection factor offered by these N95 respirators is higher than the minimum requirement for their filter material alone. The difference between SWPF$_{\text{total}}$ values obtained for the two N95 SMRs was not significant (p>0.05, Table 2).

The two N100 FFRs demonstrated significantly – about an order of magnitude – higher protection compared to N95 SMRs (p<0.01, see Table 2): GM = 1,089 and GSD = 2.08 for the control N100 FFR and GM = 2,199 and GSD = 2.05 for the FS Prototype N100 FFR. The difference between SWPF$_{\text{total}}$ values obtained for the two N100 FFRs was also significant (p < 0.05, Table 2). Thus, the modified face seal component of the N100 FFR (FS Prototype N100
FFR) was capable of significantly improving the protection provided by a highly efficient N100 FFR. Since the N100 FFR’s design modification was concerned exclusively with the peripheral area, the difference in SWPF_{total} can be attributed solely to the improved fit of the respirator to the user’s face.

In summary, the SWPF_{total} results suggest that, in contrast to the NIOSH certified respiratory protection devices such as N95 and N100, SMs could not protect healthcare workers against surgical smoke in ORs. It is acknowledged though that while SMs are widely used in healthcare environments, they were not originally designed to reduce the wearer’s exposure to aerosols. While we recognize that conventional N100 FFRs (equipped with exhalation valves) are not practical for human OR use, the data obtained with the FS prototype demonstrate the potential of the new faceseal technology for implementation on various types of respirators.

Correlation between SWPF_{total} and Fit Factor (FF) Determined for N95 SMRs

Two out of ten subjects (20%) did not pass the fit test with SMR1, and eight out of ten (80%) did not pass it with SMR2 (FF<100). In three cases out of 20 (15%), the SWPF_{total} was below 100 (including two cases in which the subjects failed the fit test). The relationship between SWPF_{total} and FF is presented in Figure 4. None of the correlations (either for SMR1, or for SMR2, or for both data sets combined) were significant (p>0.05). The slopes of log(SWPF_{total}) against log(FF) were as follows: 0.19 for SMR1, 1.01 for SMR2, and 0.35 for the two combined; all had rather low coefficient of correlation R^2.

All ten subjects wearing SMR2, and seven out of ten subjects wearing SMR1 produced data points above the 1:1 line, indicating that the SWPF exceeded the corresponding FF in the majority of the tests. This suggests that while no significant correlation was found between the
two factors, the FF can serve as a conservative estimate of the SWPF.

The relationship between FF and SWPF\textsubscript{total} obtained in this study confirms the observations of Zhuang \textit{et al.}, who conducted fit testing on 15 workers and then assigned them, with the same respirators, to their routine jobs while measuring the WPFs. The investigators reported lack of correlation between FF and WPF for FFs ≥ 500 (p>0.05) (Dixon and Nelson, 1984). One reason may be that the OSHA fit testing protocol requires very specific body movements, which may not fully represent actual workplace activities. Likewise, the breathing rates may be different when a worker performs fit testing vs. when he/she conducts the workplace activities.

\textbf{Particle Size Specific Simulated Workplace Protection Factor (SWPF\textsubscript{dp})}

The protection factors offered by the six tested RPDs worn on ten subjects are plotted in Figure 5 against the particle sizes. Each curve represents the SWPF\textsubscript{dp} data obtained for a subject wearing a specific RPD. A clear trend representing the effect of particle size was observed only on the two N100 FFRs. Statistical analysis shows that between-subject variability was a strongly significant factor affecting their SWPF\textsubscript{dp} (p<0.01), indicating the SWPF\textsubscript{dp} varies significantly depending on the subject regardless of the type of RPDs (see Table 3).

If the dominant particle penetration pathway was a filter, the SWPF would be dependent on the particle size since the filter penetration is generally size-dependent (Kulkarni \textit{et al.}, 2011). Electret filters used in high-efficiency respirators offer very high protection against very small particles (20-30 nm) as well as against much larger particles (> 200 nm) leaving the room for the most penetrating particle size (MPPS) in-between; the exact MPPS value depends on the filter characteristics and face velocity. This is consistent with the SWPF data shown for FS100 and
N100 FFRs for which the particle size had a significant effect, indicating that an appreciable percentage of particles measured inside the respirator penetrated through the filter (relative to penetration through the face seal leakage). In contrast, if the face seal leakage served as the major penetration pathway, the penetration may not be significantly affected by the particle size, at least for the essentially inertialess surgical smoke particles. Thus, the data suggest that most of the particles, which penetrated through an SM or an N95 SMR, utilize the face seal leakage pathway.

Finally, although the present investigation specifically addressed surgical smoke, as was noted earlier, the particle sizes involved are in the same range as virions causing influenza, HPV, SARS, and MERS (Zheng and Baker, 2006; Rota et al., 2003; Zaki et al., 2012). Since the RPDs studied here are frequently incorporated for public health use, the findings herein may have application to various public health scenarios, e.g., those involving infectious aerosols.

CONCLUSIONS

Our study results strongly suggest that SMs do not provide measurable protection to OR workers against surgical smoke. More efficient N95 SMRs are capable of reducing the inhalation exposure to surgical smoke by over two orders of magnitude \((SWPF_{\text{total}} = 208–263)\). Given the fact that the particle size was not a significant factor affecting the performance of SMs and SMRs, we concluded that the face seal leakage was the main penetration pathway for the surgical smoke particles to enter into the tested SMs and the N95 SMRs.

The N100 FFRs, both the control and FS Prototype versions, offered the highest
protection against surgical smoke \((SWPF_{total} = 1,089–2,199)\). In contrast to SMs and the N95 SMRs, the particle size was a significant factor affecting the performance of these N100 FFRs, which suggest that the filter penetration pathway likely dominated over the faceseal leakage component.

The \(SWPF_{total}\) obtained for the newly-developed FS Prototype N100 FFR significantly exceeded that of the control N100 FFR, the difference being due to the improved fit of the FFR to the user’s face. This finding may have relevance to the design of N95 SMRs, as well as other RPDs, since faceseal leakage was the predominant pathway of smoke particle penetration in the SMRs we tested. If the improvements demonstrated herein on the N100 FFRs are achievable on N95 SMRs, it would represent an important advance in the design of RPDs for OR personnel.

ACKNOWLEDGEMENT

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REFERENCE


Fig. 1. Experimental set-up
Fig. 2. Particle size distribution of surgical smoke measured in the breathing zone of the board-certified surgeon (the most experienced subject)
Fig. 3. SWPF<sub>total</sub> for commercially available SMs and N95 SMRs widely used in ORs as well as for the new FS prototype N100 and a conventional N100 FFR (control). Asterisk denotes statistically significant difference (p<0.05). Note: SM and N95 SMR data represent the geometric means of 10 subjects (n=10) while the FS Prototype N100 and Control N100 data represent the geometric means of 9 subjects (n=9) since one subject did not wear the N100 FFRs appropriately.
Fig. 4. Correlation between SWPF\textsubscript{total} and the FF for ten subjects wearing N95 SMRs: the lines in red and green are the regression lines fit for the corresponding data points (SMR1 and SMR2, respectively); the line in black is the regression line fit for all the data points (red and green combined).
Fig. 5. Particle size selective SWPFs
Table 1. Respiratory protective devices selected for the study

<table>
<thead>
<tr>
<th>ID</th>
<th>Company</th>
<th>Model Number</th>
<th>Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>SM1</td>
<td>3M</td>
<td>1800NL</td>
<td>Regular</td>
</tr>
<tr>
<td>SM2</td>
<td>KC</td>
<td>14683</td>
<td>Regular</td>
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<tr>
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<td>3M</td>
<td>1860</td>
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<tr>
<td>N95 SMR2</td>
<td>3M</td>
<td>1870</td>
<td>Regular</td>
</tr>
<tr>
<td>Control N100</td>
<td>3M</td>
<td>8233</td>
<td>Regular</td>
</tr>
<tr>
<td>Prototype FS100</td>
<td>3M (modified)</td>
<td>8233</td>
<td>Regular</td>
</tr>
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</table>
### Table 2. Results paired t-test comparing SWPF\textsubscript{total} between the tested protective devices

<table>
<thead>
<tr>
<th>RPDs compared</th>
<th>Number of subjects</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>SM1 &amp; SM2</td>
<td>10</td>
<td>0.84</td>
</tr>
<tr>
<td>N95 SMR1 &amp; N95 SMR2</td>
<td>10</td>
<td>0.41</td>
</tr>
<tr>
<td>Prototype FS100 &amp; Control N100</td>
<td>9</td>
<td>0.04 (*)</td>
</tr>
<tr>
<td>SMs &amp; N95 SMRs</td>
<td>10</td>
<td>0.0013 (**)</td>
</tr>
<tr>
<td>SMs &amp; N100 FFRs (Prototype FS100+Control N100)</td>
<td>9</td>
<td>0.0009 (**)</td>
</tr>
<tr>
<td>N95 SMRs &amp; N100 FFRs (Prototype FS100+Control N100)</td>
<td>9</td>
<td>0.0022 (**)</td>
</tr>
</tbody>
</table>

Note: p < 0.05 (*); p < 0.01(**)
Table 3. Effects of subject and particle size on the performance of respiratory protective devices (two-way ANOVA)

<table>
<thead>
<tr>
<th>Protection device</th>
<th>Factor</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>SM1</td>
<td>Subject</td>
<td>&lt; 0.0001 (**)</td>
</tr>
<tr>
<td></td>
<td>Size</td>
<td>0.822</td>
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<tr>
<td>SM2</td>
<td>Subject</td>
<td>&lt; 0.0001 (**)</td>
</tr>
<tr>
<td></td>
<td>Size</td>
<td>0.384</td>
</tr>
<tr>
<td>N95 SMR1</td>
<td>Subject</td>
<td>&lt; 0.0001 (**)</td>
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<tr>
<td></td>
<td>Size</td>
<td>0.170</td>
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<tr>
<td>N95 SMR2</td>
<td>Subject</td>
<td>&lt; 0.0001 (**)</td>
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<tr>
<td></td>
<td>Size</td>
<td>0.129</td>
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<tr>
<td>Prototype FS100</td>
<td>Subject</td>
<td>&lt; 0.0001 (**)</td>
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<tr>
<td></td>
<td>Size</td>
<td>&lt; 0.0001 (**)</td>
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<tr>
<td>Control N100 FFR</td>
<td>Subject</td>
<td>0.004 (**)</td>
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<tr>
<td></td>
<td>Size</td>
<td>&lt; 0.0001 (**)</td>
</tr>
</tbody>
</table>

Note: p < 0.01(**)
Performance of an Improperly Sized and Stretched-out Loose-fitting Powered Air-purifying Respirator: Manikin-based Study

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ABSTRACT

The objective of this study was to investigate the protection level offered by a Powered Air-Purifying Respirator (PAPR) equipped with an improperly sized or stretched-out loose-fitting facepiece using constant and cyclic flow conditions. Improperly sized PAPR facepieces of two models as well as a stretched-out facepiece were tested. These facepieces were examined in two versions: with and without exhaust holes. Loose-fitting facepieces (size “large”) were donned on a small manikin headform and challenged with sodium chloride (NaCl) aerosol particles in an exposure chamber. Four cyclic flows with mean inspiratory flows (MIFs) of 30, 55, 85, and 135 L/min were applied using an electromechanical Breathing Recording and Simulation System (BRSS). The manikin Fit Factor (mFF) was determined as the ratio of aerosol concentrations outside (C_{out}) to inside (C_{in}) of the facepiece, measured with a P-Trak condensation particle counter (CPC). Results showed that the mFF decreased exponentially with increasing MIF. The mFF values of the stretched-out facepiece were significantly lower than those obtained for the undamaged ones. Facepiece type and MIF were found to significantly affect the performance of the loose-fitting PAPR. The effect of the exhaust holes was less pronounced and depended on the facepiece type. It was concluded that an improperly sized facepiece might potentially offer relatively low protection (mFF < 250) at high to strenuous workloads. The testing was also performed at a constant inhalation flow to explore the mechanism of the particle-facepiece interaction. Results obtained with cyclic flow pattern were consistent with the data generated when testing the loose-fitting PAPR under constant flow conditions. The time-weighted average values of mFF calculated from the measurements conducted under the constant flow regime were capable of predicting the protection under cyclic flow regime. The findings suggest that program administrators need to equip employees with properly sized facepieces and remove stretched-out ones from workplace. Manufacturers should emphasize the importance of proper sizing with their user instructions.
INTRODUCTION

The Powered Air-Purifying Respirators (PAPRs) certified by the National Institute for Occupational Safety and Health (NIOSH) are used in a variety of occupational environments to reduce worker’s exposure to gaseous and/or particulate contaminants. To receive approval from NIOSH, PAPRs must meet the certification requirements of 42 CFR 84.\(^{(1)}\) However, NIOSH does not indicate how to choose an appropriately sized PAPR facepiece for an individual. In addition, user instructions do not always address “sizing” of facepieces when more than one size is available. Prior to this study, the implications of using an improperly sized PAPR facepiece have not been evaluated.

The Occupational Safety and Health Administration (OSHA) has published and enforces assigned protection factor (APF) for respiratory protective equipment. The APFs for PAPRs vary from 25 to 1,000 depending on the type of facepiece selected (half mask, full facepiece, helmet/hood, or loose-fitting facepiece).\(^{(2)}\) While having the loose-fitting facepiece has the lowest APF of 25, this facepiece has several advantages compared to tight-fitting negative pressure air-purifying respirators: they require no fit testing, feature no breathing resistance, provide cooling, and may be worn by workers with corrective eyewear.\(^{(3,4)}\) These advantages are preferred by the healthcare workers (HCWs) according to the survey conducted by Baig et al.\(^{(5)}\).

In a loose-fitting PAPR system, the ambient air supplied to the wearer is powered by a battery-operated fan. When the wearer’s level of exertion is mild, the PAPR is intended to supply air flow which is measurably greater than the inhalation flow, thus establishing a positive pressure inside the facepiece during the majority of the breathing cycle. As the level of exertion increases, the breathing rate increases as well resulting in a greater minute volume.
Consequently, the pressure inside the facepiece could become negative near the peak of each inhalation cycle, thus allowing the contaminated air to enter into the facepiece. This “over-breathing” could compromise the performance of a loose-fitting PAPR.\(^6\) The problem may be more pronounced if the facepiece is improperly sized to the worker’s head, which increases the size of the gap between the worker’s face and the facepiece. Field experience has shown that some companies tend to order a single size facepiece (typically large), instead of purchasing an appropriately sized facepiece for each individual. This practice may simplify ordering and inventory, but it does not recognize the need to choose a properly sized PAPR facepiece for an individual when different sizes are available.

Numerous studies have been conducted on the performance of the NIOSH-certified N95 filtering facepiece respirators (FFRs)\(^{7-11}\) and elastomeric half-masks\(^{12,13}\). However, only a few investigations have addressed the protection offered by the PAPRs. For example, Cohen et al.\(^{14}\) obtained simulated workplace protection factors (SWPFs) for five PAPR models representing different brands and facepiece styles. These respirators were tested on 12 volunteers performing 12 exercises to simulate real workplace activities. The SWPF range for the loose-fitting hooded PAPRs was 240 to \(> 250,000\), suggesting a high degree of protection as well as a large variance among the SWPFs. However, none of the investigations involving PAPRs intentionally tested improperly sized loose-fitting facepieces or explored the potential effect of a damaged (stretched-out) facepiece on PAPR performance. A damaged facepiece is a reality in some workplace settings given that this type of respirator may be used/re-used over a long time, often shared among employees, and may not be routinely removed from service when inspection programs are less than optimal.
The purpose of this investigation was to evaluate the protection level of improperly sized loose-fitting PAPR facepieces by using a manikin with cyclic breathing. Flows were selected to represent breathing at moderate, medium-to-high, high and strenuous workloads. Similar tests using constant flows were conducted to further investigate the mechanism of the particle penetration into the tested facepiece. This study was designed to evaluate the following factors: facepiece type, breathing flow rate and the role of facepiece exhaust holes on the performance of improperly sized loose-fitting PAPRs. A stretched-out facepiece was also investigated to provide quantitative information that may be of value for respirator program administrators.

MATERIALS AND METHODS

Powered Air-Purifying Respirator (PAPR) with Loose-fitting Facepiece

A commonly used PAPR (EVA, Bullard Company, KY, USA) certified by NIOSH was selected for testing in this study. Selection was based on availability. One of the authors was responsible for training workers on proper use, including positioning of the facepiece and assistance with size selection, since more than one size was available. It contains a blower unit which draws air through a High-Efficiency Particulate Air (HEPA) filter and delivers the purified air into the facepiece. Among the two flow rates, 198 and 240 L/min, offered by the blower, the lower one was used in this study to produce a conservative situation whereby inhalation flow could feasibly exceed the blower flow. The lower blower flow rate provides a longer duration of operation and produces less noise. Consequently, users often find the lower blower flow advantageous. For comparison, NIOSH requires at least 6 ft³/min (170 L/min) during field use and this lower blower flow exceeds this requirement. Two versions of loose-
fitting facepieces, 20LFL (Facepiece A, size “large”) and 20LF2L (Facepiece B, size “large”) of the same brand (Bullard Company, KY, USA) were used in this study. Facepiece B was designed for a narrow face. A stretched-out 20LFL facepiece (Facepiece C, size “large”) was also evaluated in this study to simulate a “damaged” facepiece in a workplace. It was created by donning the facepiece onto an oversized manikin headform until the facepiece became stretched out and lost elasticity. It should be noted that we have observed respirators in the field with even greater levels of damage than the one used in this study. Figure 1 demonstrates that Facepiece C features a larger gap between the face and the facepiece compared to the other two facepieces (A and B).

The tested respirators are designed with exhaust holes (approximately 6 mm diameter) located near the chin area on the loose-fitting facepiece. These holes make the facepiece more comfortable to wear, help to keep the facepiece from coming off the face, and reduce air flow noise. However, the “openings” may serve as a penetration pathway for particles to enter the facepiece. In order to evaluate the effect of the exhaust holes, additional tests were conducted with Facepieces A, B, and C using duct tape to cover the holes on both sides of the facepiece. The number of the exhaust holes was 12 (6 on the left side and 6 on the right side) for Facepieces A and C, and 14 (all in the middle) for the Facepiece B.

**Experimental Design and Conditions**

The experimental setup is presented in Figure 2. The tests were performed in an exposure chamber (volume = 3.6×2.4×2.6 m³). As shown in Figure 2, the tested facepiece was donned on a manikin headform. The facial dimensions of the manikin fell into Cell 2 (considered as a small face) of the NIOSH Bivariate Panel.(15) The mouth and nostrils on the
headform were open for inhalation and exhalation, to more closely mimic human breathing flow patterns. The breathing was performed using the electromechanical Breathing Recording and Simulation System (BRSS; Koken Ltd., Tokyo, Japan), which generated a sinusoidal flow pattern.\(^{(16)}\) A 1-inch diameter copper pipe was mounted and extended to the mouth and nostrils of the manikin to allow the movement of air in and out of the BRSS. Four cyclic flows with mean inspiratory flow (MIF) rates of 30, 55, 85, and 135 L/min were applied. All had the same breathing frequency of 25 breaths/min. The above-specified MIFs were established to represent breathing at moderate, medium-to-high, high and strenuous workloads.\(^{(12)}\) A HEPA filter was placed between the manikin headform and the BRSS to keep particles from re-entering the facepiece during exhalation so that the concentration measured inside the facepiece reflected solely the aerosol penetrated from the ambient environment and no particle inside the facepiece has an opportunity to be counted more than once. One sampling probe was installed to measure the aerosol concentration inside the facepiece \(\left( C_{\text{in}} \right) \), and the other was placed 24 cm away from the inside probe to measure the outside concentration \(\left( C_{\text{out}} \right) \). Both probes were connected to a switching valve, which could be switched to sample the aerosol either inside or outside of the facepiece. The challenge aerosol was generated with a particle generator (Model 8026, TSI Inc., MN, USA) from a suspension containing 2 g of NaCl and 100 g of sterile, Millipore-filtered water. The generator was operated for 30 min before the testing to allow the challenge aerosol to reach a temporal homogenous concentration \((\text{within } \pm 10\%)\). The total aerosol concentration was measured with a P-Trak condensation particle counter (Model 8525, TSI Inc., MN, USA) operating in a size range of 20 to 1,000 nm. The fit factor determined on the manikin headform \(\text{manikin Fit Factor, mFF} \) was calculated as \(\frac{C_{\text{out}}}{C_{\text{in}}}\). The experimental conditions are summarized in Table I.
**Cyclic and Constant Flow Regimes**

To further investigate the mechanism of the particle penetration into the tested facepiece, similar tests were conducted using constant inhalation flows. The flow rate \( Q \) ranged from 20 to 240 L/min with an increment of 20 L/min. The same experimental variables, including the facepiece type and exhaust holes condition, were applied under constant flow regime. The results of aerosol measurements conducted at the above-indicated constant inhalation flow rates (20, 40, 60, … L/min) were subjected to a linear regression approximation, to determine a rate-specific mFF for any \( Q \) between 20 and 240 L/min. The rate-specific mFF values were converted to penetration \( (= 1/\text{mFF}) \); the penetration values were then integrated as a function of time and time-weighted following a sinusoidal breathing pattern

\[
Q = Q_{\text{PIF}} \times \sin(2\pi t/T)
\]

Here \( Q_{\text{PIF}} \) is the peak inspiratory flow \( (\text{PIF}) \) rate, which is a direct function of the MIF, \( T \) is the period of the breathing cycle \( \text{[at 25 breaths/min, } T = (1/25 \text{ min})(60 \text{ s/min}) = 2.4 \text{ s}] \), and \( t \) is the time in seconds. This allowed us to calculate an integrated penetration and subsequently an integrated mFF for a cyclic flow regime corresponding to a specific \( Q_{\text{PIF}} \) and \( Q_{\text{MIF}} \). Further, each calculated mFF value was compared to the corresponding experimental result (obtained at the same MIF under cyclic flow conditions). Figure 3 schematically shows the flow rate as a function of time at MIF = 135 L/min and breathing frequency of 25 breaths/min (an example). It is seen that non-filtered air can enter a facepiece only during half of the breathing time (inhalation). The numerical integration was performed by dividing the first half a period into 20 equal time segments so that the total penetration is determined as a time-weighted average.

**Data Analysis**
SAS 9.3 (SAS Institute Inc, Cary, NC) was used to analyze the data. The mFF data were log-transformed before statistical analysis. The Geometric mean (GM) and the Geometric standard deviation (GSD) mFF’s values were calculated for each set of condition. A three-way analysis of variance (ANOVA) was used to evaluate the effect of facepiece type, MIF and exhaust holes condition on the mFF. ANOVA with post-hoc pairwise comparisons was conducted to test the difference between the mFFs of each paired facepieces. Two-way ANOVA was used to study the significance of MIF and exhaust holes condition for each individual facepiece. P-values less than 0.05 were considered to denote significant differences.

RESULTS AND DISCUSSION

Manikin Protection Factors

Figure 4 shows the mFF as a function of MIF for three tested facepieces. The mFF decreased exponentially with MIF increasing from 30 to 135 L/min. The experimentally determined mFF values ranged from 14 to 15,165. The highest mFF was observed at MIF = 30 L/min with Facepiece B while the lowest was found at MIF = 135 L/min with Facepiece C.

It is acknowledged that the mFFs obtained from the tests conducted using the manikin headform may overestimate the actual respiratory protection level in the field. When worn by respirator wearers, the facepiece may move given the continuous movement of the worker’s head. This is particularly true when the blower hose does not swivel at the point of connection to the facepiece. There is no consensus to designate an acceptable level of protection when a loose fitting PAPR is configured to a manikin. However, the OSHA designated APF for this type of facepiece is 25. During fit testing, pass/fail criteria for tight-fitting negative pressure respirators is set at 10 times the APF. Consequently, another benchmark to evaluate PAPR performance
would be to choose an mFF of 250 (10 x 25). Facepieces A (and B) had mFFs below 250 when the MIFs were greater than 90 L/min (and greater than 86 L/min for facepiece B) (see Figure 4a). Likewise, the performance of these two facepieces was considerably lower when breathing flow rates corresponded to high and strenuous workloads. mFF values obtained for Facepiece C were below 250 for all tested MIFs. At MIF ≈ 85 L/min, the mFF fell even below 25. It was concluded that Facepiece C offered very little protection even under conditions of light exertion. Thus, we recommend that stretched-out facepieces should be removed from use in a workplace setting that requires respiratory protection.

Analysis of Factors Affecting mFF

Effect of Facepiece Type on mFF

As evident from Table II, the effect of facepiece type on the performance of the loose-fitting PAPR was significant (p < 0.01). The mFFs of Facepiece C were significantly lower than those obtained for the other two facepieces (p < 0.05) while the difference between Facepieces A and B was not significant (p > 0.05, see Table III). Facepiece C had the lowest mFF, followed by Facepieces A and B, suggesting that C offered the poorest fit on the manikin headform. This finding is consistent with our observations with respect to the size of the gap between the manikin face and facepiece, which was estimated to be approximately 19 cm², 22 cm² and 29 cm² for Facepieces A, B and C, respectively. While a threshold for unacceptable gap size was not identified in this study, the data for Facepiece C supports the need to replace facepieces when the gap size is increased due to loss of elasticity. The protection factor of such “damaged” facepieces decreases because a bigger gap area allows more particles to penetrate into the facepiece.
Effect of MIF on mFF

The effect of MIF on mFF was significant (p < 0.01, see Table II). As shown in Figure 4, an exponential regression trend line between MIFs and fit factors was fitted on all the experimental conditions. The coefficient of determination ($R^2$) ranged from 0.95 to 0.99, indicating a very good fit of the data to the regression lines. The mFF value decreased exponentially with the increasing MIF for all the tested facepieces (the regression equations are presented in Figure 4). First, this decrease was likely associated with a widening gap size between the face and the facepiece. With the breathing becoming more intense (higher MIF), the gap was observed to enlarge, which allowed more particles to enter. Second, clean air was delivered by the blower through the orifice, which was located in the middle of the forehead; this made the air flow directed to the nose and mouth area greater than the flow supplied to the cheek area; the latter created a pressure gradient that enhanced the particle penetration into the facepiece through the gap near the cheek area. This effect became more pronounced at higher breathing flow rates.

It should be emphasized that at MIF=135 L/min, the calculated peak inspiratory flow (PIF) was 212 L/min, which exceeded the blower-delivered flow (198 L/min). This could cause a negative pressure inside of the facepiece over certain time intervals. The “over-breathing” caused by this negative pressure allowed the ambient particles to enter into the respirator, thus decreasing the protection factor. Although rare, PIF as high as 212 L/min could occur since instantaneous breathing flows over 400 L/min were reported by Mackey et al.\textsuperscript{(6)}

Effect of Exhaust Holes on mFF

The three-way ANOVA performed for all facepieces combined revealed that exhaust holes condition did not significantly affect the mFF (p > 0.05, see Table II). Under almost all the
experimental conditions, the mFFs obtained with the exhaust holes covered were higher than those obtained with uncovered holes. The difference was significant only for Facepiece C ($p < 0.05$, see Table IV), which suggests that the effect of exhaust holes becomes more pronounced as the gap increases (see the change in p-values listed in “Exhaust holes condition” from Facepiece A to Facepiece C). One possible explanation is that a large gap around the chin may increase air turbulence through the exhaust holes by bringing in additional air and making the flow pattern inside more complex. Consequently, a greater particle deposition could occur on surfaces around the holes. Thus, the effect of the exhaust holes with larger gap is significant.

**Comparison of the Calculated and Experimentally-obtained mFFs under Cyclic Flow**

The trends observed in the experiments conducted under both flow conditions (cyclic and constant) were mostly similar. The mFF decreased exponentially as the constant inhalation flows increased. In addition, significance of the effects of facepiece type and flow rate on the performance of the PAPR with a loose-fitting facepiece was confirmed for the constant flow regime (see Table V). The effect of exhaust holes was equally complex for both cyclic and constant flow regimes; its significance depended on the facepiece type (see Table VI).

Figure 5 shows the relationships between the calculated and experimentally-obtained mFFs under cyclic flow regime for all three facepieces and two exhaust holes conditions. A good correlation was observed in all cases. This suggests that the constant flow data can be used for predicting the protection within the range of 30 to 135 L/min offered by improperly-sized, loose-fitting PAPRs under cyclic breathing conditions.

In general, it is more challenging to interpret the mFF trends and identify the mechanisms governing the particle penetration into a facepiece based on the data obtained under cyclic flow regime as compared to the “constant flow” results. Therefore, we used the experimental database
obtained at $Q = \text{const}$ (data not shown) to explain our findings on the protection provided by a loose-fitting PAPR. Under the constant flow regime, the airflow delivered by the blower was counteracted by the increased inhalation flow, resulting in increased air turbulence in the mouth and nose area of the manikin headform. The turbulence enhanced the mixing of particles and might have affected the particle transport through the faceseal gap and/or exhaust holes, thus influencing the measurement of mFF. This effect may particularly occur at deep breathing, thus negatively affecting the protection provided by an improperly-sized, loose-fitting PAPR. Considering the complexity between cyclic and constant inhalation flow patterns, the similarity in mFF is remarkable.

**Limitation**

The study was limited to three loose-fitting facepieces of the same brand. Additionally, the study was focused only on loose-fitting PAPR facepieces, which were improperly sized. Further research is needed to examine the performance of the same loose-fitting PAPRs when they are properly sized to the wearers.

**CONCLUSION**

Based on the manikin-based testing of the two undamaged loose-fitting PAPR facepieces, the mFF decreased exponentially with increasing MIFs revealing rather low mFFs at high MIFs. These two facepieces provided relatively low protection (mFFs <250) at breathing flow rates corresponded to high and strenuous workloads. The mFF values of the stretched-out loose-fitting facepiece were significantly lower than those obtained for the undamaged facepieces; the former are unlikely to provide an acceptable level of protection even at a moderate workload. Facepiece type and MIF were significant factors affecting the performance of the loose-fitting
PAPRs. The effect of the exhaust holes condition was less significant and depended on the facepiece type. The model utilizing integrated mFF data obtained under constant flow regime is capable of predicting the protection offered by improperly-sized, loose-fitting PAPRs under cyclic breathing conditions. The results of this study suggest that respirator program administrators should ensure that loose-fitting facepieces are properly sized to employees and remove stretched-out facepieces from the workplace.

ACKNOWLEDGMENT

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REFERENCES

### Table I. Summary of the Experimental Conditions

<table>
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<th>Variable</th>
<th>Levels</th>
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<tr>
<td>Facepiece type</td>
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<tr>
<td>Exhaust holes condition</td>
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<tr>
<td>MIF</td>
<td>30, 55, 85, 135 L/min (^A)</td>
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<td>Replicates</td>
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<tr>
<td>Total runs</td>
<td>3×2×4×3=72</td>
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\(^A\) The cyclic flows of MIF = 30, 55, 85 and 135 L/min (PIF = 47.1, 86.4, 133.5 and 212.0 L/min, respectively) were applied at breathing rate of 25 breaths/min.
Table II. Three-way ANOVA Results for the $\ln(mFF)$ as the Function of Facepiece Type, MIF, and Exhaust Holes Condition

<table>
<thead>
<tr>
<th>Source</th>
<th>DF</th>
<th>ANOVA SS</th>
<th>Mean Square</th>
<th>F Value</th>
<th>p-value</th>
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<td>Facepiece type</td>
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<td>MIF</td>
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<td>17.55</td>
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<td>1.70</td>
<td>1.70</td>
<td>2.83</td>
<td>0.11</td>
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DF, degrees of freedom; SS, sum of squares.
Table III. ANOVA with Post-hoc Pairwise Comparisons on the Effect of Facepiece Type

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<th>Facepiece Type</th>
<th>Facepiece Type</th>
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<th>DF</th>
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<td>B</td>
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<td>B</td>
<td>C</td>
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<td>A</td>
<td>C</td>
<td>2.39</td>
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<td>21</td>
<td>2.73</td>
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SE, standard error; DF, degrees of freedom.
Table IV. Two-way ANOVA Results for the $ln(mFF)$ as the Function of MIF and Exhaust Holes Condition

<table>
<thead>
<tr>
<th>Facepiece Type</th>
<th>Source</th>
<th>DF</th>
<th>ANOVA SS</th>
<th>Mean Square</th>
<th>F Value</th>
<th>p-value</th>
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<td>A</td>
<td>MIF</td>
<td>3</td>
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<tr>
<td>B</td>
<td>MIF</td>
<td>3</td>
<td>32.49</td>
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<td>C</td>
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DF, degrees of freedom; SS, sum of squares.
Table V. Three-way ANOVA Results for the $\ln(m_{FF})$ as the Function of Facepiece Type, Constant Inhalation Flow Rate, and Exhaust Holes Condition

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<tr>
<th>Source</th>
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<td>0.69</td>
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DF, degrees of freedom; SS, sum of squares.
<table>
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<tr>
<th>Facepiece Type</th>
<th>Source</th>
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<td>Exhaust holes condition</td>
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<td>2.82</td>
<td>2.82</td>
<td>7.27</td>
<td>0.01</td>
</tr>
</tbody>
</table>

DF, degrees of freedom; SS, sum of squares.
Figure 1. Tested loose-fitting facepieces (A: 20LFL; B: 20LF2L; C: stretched-out 20LFL).
Figure 2. Experimental setup modified from He et al., 2013.
BRSS = Breathing Recording and Simulation System
PAPR = Powered Air-Purifying Respirator
Figure 3. Flow rate as a function of time at PIF = 212 L/min (MIF = 135 L/min) and breathing frequency of 25 breath/min (schematics for numerical integration). The schematics is modified from Haruta et al. (2008)
Figure 4. mFF as a function of MIF for three facepieces (a: exhaust holes uncovered; b: exhaust holes covered) Each point (with the number listed) represents the geometric mean of three replicate measurements, and the bars represent the geometric standard deviation.
Figure 5. Correlation between calculated from constant flow regime (axis y) and experimentally-determined under cyclic flow regime (axis x) mFF values (a: exhaust holes uncovered; b: exhaust holes covered). For each four-point data set (marked by a specific color), the points from left to right represent MIFs of 135, 85, 55, and 30 L/min.
Performance of Electret Filters for Use in a Heating, Ventilation and Air Conditioning System and an Automotive Cabin against Combustion and NaCl Particles

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ABSTRACT

This study was conducted to investigate the performance of a high-efficiency Heating, Ventilation and Air Conditioning (HVAC) filter and a top-of-the line Automotive Cabin Air (ACA) filter challenged with particles generated by the combustion of paper, wood, and plastic as well as with NaCl particles. The collection of submicron particles was examined under conditions representing two typical indoor air flow rates for the HVAC filter and two cabin fan control levels for the ACA filter. For the HVAC filter, almost all the collection efficiency values exceeded 80%; for the ACA filter, the collection efficiencies were much lower (< 40%) for all the tested aerosols and flow rates. Both filters demonstrated lower collection efficiency for combustion aerosols as compared to NaCl. This finding was consistent for all tested particle sizes and flow rates. The difference was always statistically significant in terms of the total efficiency (combining all sizes); however, the size-specific analysis of the differences revealed that the significance level varied with the particle size and flow rate. When tested under their operational flow conditions, the HVAC filter showed significantly better performance than the ACA filter. It was concluded that the filter performance characteristics of the HVAC and ACA filters obtained using well-established salt aerosol challenges may not accurately predict the performance of these filters against combustion aerosol particles. The difference was attributed to the interactions between the particles and filter fibers.

Keywords: HVAC filter; Automotive cabin air filter; Combustion aerosols; NaCl; Collection efficiency.

INTRODUCTION

Indoor exposure to submicrometer-sized and nano-sized particles, including those generated by combustion, has received increased attention. Combustion particles infiltrate homes from outdoors; they are also generated by various indoor activities (Stephens and Siegel, 2013). A significant association between acute asthma and increased levels of residential wood smoke particles has been reported (Boman et al., 2003). Recently, the International Agency for Research on Cancer (IARC) classified indoor emissions from the household combustion of biomass fuels (primarily wood) as “probably carcinogenic to humans (group 2A)” (Bolling et al., 2009). Moreover, indoor exposure to air containing combustion aerosols has been associated with adverse health effects including respiratory problems and the impairment of cardiovascular function. In particular, nano-sized particles, including those originating from combustion of different materials, have been linked to health effects such as fibrosis, chronic inflammatory lung disease, metal fume fever, and cancer (Donaldson et al., 2005).

Vehicle exhaust particles and smoke produced by burning materials are constituents of particulate matter in urban residential areas. In addition, during daily commutes, drivers and passengers are exposed to high concentrations of aerosol pollutants emitted by mobile sources, primarily on-road vehicles. Approximately 50% of the population in the USA has a one-way daily commute time, between home and work, of more than 30 min (Zhu et al., 2007). It has been shown that exposure to air pollutants in an automobile cabin is particularly high because of the proximity of passengers to relatively concentrated emissions from other automobiles...
and the rapid air exchange rate inside the vehicle (Park et al., 2010).

Stationary filters are installed in the Heating, Ventilation, and Air Conditioning (HVAC) systems of buildings to reduce indoor exposure to aerosols, including hazards produced by combustion. Similarly, to reduce exposure to airborne particles inside vehicles, Automotive Cabin Air (ACA) filters are used. The efficiency of particle removal by HVAC and ACA filters depends on the air velocity, particle size, particle shape, filter material, and environmental factors (Stephens, 2012). The filter performance is traditionally evaluated using conventional test aerosols, mostly potassium chloride (KCl) particles, according to the ANSI/ASHRAE standard (ASHRAE, 2012) or, in some protocols, charge-equilibrated sodium chloride (NaCl) particles (Halvorsen et al., 1994; NIOSH, 1995; Ji et al., 2003; Shi, 2012). NaCl aerosol has characteristics similar to KCl aerosol (Shi, 2012). However, the question is whether the performance data obtained with the salt particles adequately represent the characteristics of the filters against real aerosol hazards, which may have different particle size and shape, etc. Most of the current standards for testing HVAC filters (including the ASHRAE Standard 52.2, EN779) do not incorporate measurements of the removal efficiency with nano-sized particles (Stephens and Siegel, 2013). According to the International Standards Organization standard, the ACA filters are tested using particles larger than 300 nm (ISO, 2001), thus generating no information relevant to the control of nano-sized particles, including those originated by combustion.

The present study was conducted to examine the performance of a widely used high-efficiency HVAC filter (and a top-of-the-line electrostatic ACA filter) against aerosol particles generated by the combustion of paper, wood, and plastic (mostly represented by a nano-sized fraction) as compared to the performance of these filters against NaCl aerosol particles. The filter performance was quantified in terms of the particle collection efficiency and pressure drop.

MATERIALS AND METHODS

Test Filters

A commercially available MERV14 HVAC filter (16 × 25 × 5 in³ ≈ 41 × 63 × 13 cm³, Pleated panel type, Nordic Pure, Inc., Celina, TX, USA) and an ACA filter (8.5 × 8.5 × 1.4 in³ ≈ 21.6 × 21.6 × 3.6 cm³, Pleated panel type, Denso, Long Beach, CA, USA) were tested in this study. According to Standard 52.2, the MERV 14 filter should remove more than 90% of airborne particles within a range of 1.0 to 10.0 μm and more than 75% of airborne particles between 0.3 and 1.0 μm (ASHRAE, 2012). The filter manufacturer refers to the performance testing using challenge aerosols such as tobacco smoke, pollen, dust mite debris, mold spores, dust and dander. No similar information is available with respect to the efficiency of the selected ACA filter; the preliminary performance-based evaluation suggested that this filter is one of the most efficient among automobile cabin aerosol filters. Both filters chosen for this study are made of electrostatically charged media (electret filters).

Rectangular samples, area A_sample = 4.0 × 5.0 inches for HVAC filter (1/20 of the total area) and 2.0 × 2.6 inches for ACA filter (approximately 1/14 of the total area), were cut from the commercial filters to be utilized for testing. We chose the dimensions of the samples sizes so that the available air supply units and filter holders could be deployed and a uniform flow distribution through the filter surfaces could be assured (to minimize the boundary effects). In the experiments, the flow rates through the samples, Q_sample, were established to achieve the same face velocity, V, as in the full-size filters under the operational conditions set by their manufacturers (Q_filter), see Table 1. The testing was conducted at air flow conditions representing two ventilation flow rates for the tested HVAC filter (Q = 75 CFM ≈ 127 m³ h⁻¹ and 150 CFM ≈ 254 m³ h⁻¹) and two ventilation flow rates for the tested ACA filter (Q = 57 CFM ≈ 97 m³ h⁻¹ and 115 CFM = 195 m³ h⁻¹). According to ANSI/ASHRAE Standard 62.2, a ventilation air flow of 150 CFM is recommended for a living space with three bedrooms and a floor area of 3,500–4,000 ft² = 325–372 m² (ASHRAE, 2013). The flow rates chosen for testing the ACA filter, 57 and 115 CFM, were referred to by Park et al. (2010) as those produced in the automobile cabin under moderate ventilation (fan set at level “2”) and high ventilation (level “4”), respectively. It is acknowledged that the HVAC and ACA filters were tested under their operational flow rates, which resulted in different face velocities (V_{HVAC} < V_{ACA}).

Pressure Drop Measurement

The pressure drop through the tested filters was measured with a Maneghelic® gauge (Series 2000, Dwyer Instruments Inc., Michigan City, IN, USA) operating in a range from 0 to 10 mm H₂O. Measurements were conducted at two specific flow rates Q_sample listed in Table 1 for each filter. The pressure drop values were recorded before and after the filter performance testing.

Test Aerosols

The combustion aerosols were generated inside a room-size test chamber (142 × 95 × 102 inches³ ≈ 3.6 × 2.4 × 2.6

<table>
<thead>
<tr>
<th>Filter</th>
<th>Flow rate, Q_{filter} (CFM)</th>
<th>Face velocity, V (cm s⁻¹)</th>
<th>Flow rate, Q_{sample}²</th>
<th>Flow rate, Q_{filter} (CFM)</th>
<th>Face velocity, V (cm s⁻¹)</th>
<th>Flow rate, Q_{sample}²</th>
</tr>
</thead>
<tbody>
<tr>
<td>HVAC</td>
<td>75</td>
<td>13.7</td>
<td>3.75</td>
<td>106</td>
<td>13.7</td>
<td>3.75</td>
</tr>
<tr>
<td></td>
<td>150</td>
<td>27.4</td>
<td>7.5</td>
<td>212</td>
<td>27.4</td>
<td>7.5</td>
</tr>
<tr>
<td>ACA</td>
<td>57</td>
<td>57.8</td>
<td>4.11</td>
<td>116</td>
<td>57.8</td>
<td>4.11</td>
</tr>
<tr>
<td></td>
<td>115</td>
<td>117</td>
<td>8.28</td>
<td>234</td>
<td>117</td>
<td>8.28</td>
</tr>
</tbody>
</table>

²Q_{Sample} = Q_{Filter} × (A_{Sample}/A_{Filter}) to assure the same face velocity through the sample and the whole filter.
m³, L × W × H) by burning wood (24-cm pellet, 1.9 ± 0.5 g), paper (23 × 24 cm brown multifold paper towel, 2.1 ± 0.2 g), and plastic (20.5-cm flexible straw, 0.57 ± 0.01 g) – one material at a time. Each tested material was held with a caliper, ignited using a long-reach lighter, and completely burnt inside the test chamber. After an active burning, a combustion aerosol was allowed to reach a relatively stable particle size distribution and a homogenous concentration – a 5 min period preceding the test. In addition, for comparison testing, the filter performance evaluation was conducted with a well-established NaCl aerosol challenge. The NaCl particles were aerosolized using a particle generator (Model 8026, TSI Inc., Shoreview, MN, USA) and charge-equilibrated by passing through a ⁸⁵Kr electrical charge equilibrator (Model 3054, TSI Inc., Shoreview, MN, USA) in the test chamber.

Experimental Design

The experimental setup is presented in Fig. 1. The test filters were mounted on a specially designed holder. The burning was initiated at a distance of approximately 2 m from the holder.

A P-Trak ultrafine particle counter (UPC) (8525, TSI Inc., Shoreview, MN, USA; operational range from 20 nm to > 1,000 nm) was used to measure the total concentrations upstream (C_up) and downstream (C_down) of the test filter. Additionally, an aerosol spectrometer consisting of a Model 1320 nanoparticle aerosol monitor, and a Model 1.108 optical particle counter (OPC) (Grimm Technologies Inc., Ainring, Germany) was used for size-selective measurement in parallel with the P-Trak. Considering the size distributions of the tested aerosols (mostly nano-sized and some submicrometer particles), we recorded the data generated by nanoparticle aerosol monitor between 20 and 300 nm and OPC data from 300 to 900 nm (the spectrometer capable of measuring in a wider particle size range). The nanoparticle module measures a mobility particle diameter while the OPC module measures the optical diameter. For the Grimm instrument, a total concentration value was determined by integrating at least ten scans recorded by the aerosol spectrometer over 1 min each. For P-Trak, the total concentration value was calculated as an average of at least ten readings (the recording time was set to be also 1 min).

Resulting from the data collected with each of the two instruments, the filter collection efficiency (η) was calculated as follows:

\[ \eta = 1 - \frac{C_{\text{down}}}{C_{\text{up}}} \times 100 \, (\%) \]  

The overall collection efficiency (derived from measuring the total particle concentrations) and the size-specific collection efficiencies (derived from the particle size selective measurement) were determined using the above equation. Each experiment was performed in five or six replicates, and the mean and standard deviation of the filter collection efficiency were calculated accordingly.

Data Analysis

The statistical analysis was performed using Microsoft Excel 2010 (Microsoft Corp., Redmond, WA, USA) and SPSS version 12.0 (SPSS Inc., Chicago, IL, USA). The t-test was used to analyze the differences in the total and size-specific particle collection efficiencies between NaCl and each of the combustion aerosols for each filter and a corresponding flow rate. The t-test was also used to examine the differences in total particle collection efficiency measured with the Grimm aerosol spectrometer and the P-Trak UPC. A one-way analysis of variance (ANOVA) was conducted to determine the significance of the differences in filter collection efficiency between the three combustion aerosols.

Fig. 1. Experimental set-up.
RESULTS AND DISCUSSION

Pressure Drop Measurement

The pressure drop values obtained for the tested filters are presented in Table 2. For the HVAC filter, the pressure drop was as low as 0.2 and 0.4 mm H\textsubscript{2}O at face velocities of 13.7 and 27.4 cm s\textsuperscript{-1} (correspond to Q\textsubscript{Filter} of 75 and 150 CFM), respectively. Higher values were obtained when testing the ACA filter (Table 2). The pressure drop should increase linearly as the face velocity increases (Liu et al., 2011); the experimental data support this expectation for the HVAC filter, but not precisely for the ACA filter, which is likely associated with the limit of detection of the Magnehelic\textsuperscript{®} gauge (0.05 mm H\textsubscript{2}O) as well as the boundary effects.

The values presented in Table 2 are much lower than those presented in the ASHRAE Standard 52.76, which lists 375 Pa (approximately 3.82 mm H\textsubscript{2}O) at 3.375 m\textsuperscript{3} hour\textsuperscript{-1} (approximately 1.986 CFM). The finding is not surprising considering that our HVAC testing protocol adopted the ANSI/ASHRAE Standard 62.2, which utilizes much lower air flow rates (see above) and consequently produces lower pressure drop values. The study of Stephens and Siegel (2013) performed with MERV-13 and MERV-16 filters at 930–940 CFM reported the pressure drops of 4.1 and 2.5 mm H\textsubscript{2}O, respectively (the quoted paper did not provide an explanation why a lower pressure drop corresponded to a higher efficiency filter, which seems counter-intuitive). For ACA filters, Park et al. (2010) reported pressure drop values of 1.2 and 2.4 mm H\textsubscript{2}O at face velocities of 60 and 120 cm s\textsuperscript{-1}, respectively, which, again, were greater than those measured in our experiments. Although Park et al. did not specify the ACA filter model they tested, we noted that the latter had a supporting layer, which could cause a higher pressure drop (the model used in our test did not have an additional layer). Additionally, the differences may be associated with filter characteristics such as thickness and packing density that influence the pressure drop.

Particle Size Distributions of Combustion Aerosols

Fig. 2 presents the particle size distributions measured for the three combustion aerosols (paper, wood, and plastic) as well as for the NaCl aerosol. The temperature (Mean ± STD) and relative humidity (Mean ± STD) were (20.5 ± 1.2)\textdegree C and (20.5 ± 4.8)\%, respectively. The peak particle sizes for all four fell between 40 and 50 nm. At least 95% of the particles were in the size range of 20 to 150 nm. This is also consistent with previous studies (Baxter et al., 2010; He et al., 2013). To ensure sufficient particle number concentrations (especially downstream of the tested filters), the particle size-specific collection efficiency values were determined within a narrower range, 20–150 nm, in 8 channels.

Total Collection Efficiency

The total collection efficiencies obtained from the UPC measurements are presented in Fig. 3. For the HVAC filter, all the values determined at the low flow rate (Q\textsubscript{Filter} = 75 CFM), except plastic, were above 90%; at Q\textsubscript{Filter} = 150 CFM, the values, again with an exception of plastic, exceeded 80% (Fig. 3(a)). The same filter collected NaCl particles more efficient than combustion particles: 98% at 75 CFM and 94% at 150 CFM. The difference was statistically significant (p < 0.05) for both flow rates. The findings are generally consistent with the collection efficiencies anticipated based on the MERV 14 filter rating [although no direct comparison can be made given that our tests involved lower particle sizes compared to the filter testing standard (ASHRAE, 2012)]. The collection efficiencies obtained with the ACA filter were much lower: approx. 20% for all combustion aerosols at both tested flow rates. Sodium chloride particles were collected at significantly greater efficiency (> 30%) although this level was still rather low from the practical standpoint (Fig. 3(b)). Overall, the results indicate that the tests with the NaCl challenge consistently overestimated the filter performance against combustion aerosol particles.

As shown in Table 3, a type of combustion aerosol was a significant factor affecting the collection efficiency of the HVAC filter (ANOVA, p < 0.01). The filter collection efficiency was the lowest for plastic particles followed by paper and wood, regardless of the flow rate. For the ACA filter, no significant differences in collection efficiency were observed between different combustion aerosols at either flow rate (ANOVA, p > 0.05).

The total particle collection efficiency values determined based on the measurements conducted by the non-size-selective P-Trak UPC agreed with the data obtained the Grimm spectrometer (by integrating over the size range of 20 to 900 nm). No significant difference in the measured collection efficiency between the two devices was observed (p > 0.05). This agreement suggests that both measurement techniques can be successfully used interchangeably to quantify the total concentration of combustion particles, at least under the test conditions applied in this study.

### Particle Size Specific Collection Efficiency

The size-specific collection efficiencies of the HVAC and ACA filters are presented in Figs. 4 and 5. At Q\textsubscript{Filter} = 75 CFM, the HVAC filter was more than 90% efficient for all measured particle sizes and all aerosols except plastic; for plastic, the lowest collection efficiency (about 80%) was identified for particles close to 50 nm in diameter. At

<table>
<thead>
<tr>
<th>Filter</th>
<th>Flow rate Q\textsubscript{Filter} (CFM)</th>
<th>Face velocity (cm s\textsuperscript{-1})</th>
<th>Pressure (mm H\textsubscript{2}O)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HVAC</td>
<td>75</td>
<td>13.7</td>
<td>0.23 ± 0.06</td>
</tr>
<tr>
<td></td>
<td>150</td>
<td>27.4</td>
<td>0.43 ± 0.06</td>
</tr>
<tr>
<td></td>
<td>57</td>
<td>57.8</td>
<td>0.37 ± 0.06</td>
</tr>
<tr>
<td>ACA</td>
<td>115</td>
<td>116</td>
<td>0.63 ± 0.06</td>
</tr>
</tbody>
</table>
Fig. 2. Particle size distributions of three combustion aerosols and NaCl aerosol.

Fig. 3. Total particle collection efficiency of the HVAC (a) and ACA (b) filters determined with a UPC. Symbols * and ** denote statistically significant difference (* p < 0.05, ** p < 0.01). Each data point presents an average of 5-6 repeats, error bars present standard deviation.

Q_{Filter} = 150 CFM, only NaCl particles were removed with a > 90% efficiency (except one size, about 80 nm, for which the efficiency was 87%) while the particles produced by combustion of paper and wood were collected mostly at 80–90% efficiency; for plastic combustion particles, the collection efficiency at the higher flow rate was as low as approx. 62% at 46 nm. In conclusion, across the particle size range tested, the NaCl particles were collected more efficiently than the combustion particles under both flow rates (Fig. 4). For paper and plastic combustion aerosols,
Table 3. A type of combustion aerosol (paper, wood, and plastic) as a factor affecting the filter collection efficiency (ANOVA results).

<table>
<thead>
<tr>
<th>Filter</th>
<th>Flow rate (Q_{\text{Filter}}) (CFM)</th>
<th>SS(^a)</th>
<th>DF(^b)</th>
<th>Mean Square</th>
<th>(F) value</th>
<th>(p)-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>HVAC</td>
<td>75</td>
<td>198.30</td>
<td>2</td>
<td>99.15</td>
<td>19.10</td>
<td>&lt; 0.01</td>
</tr>
<tr>
<td></td>
<td>150</td>
<td>46.05</td>
<td>2</td>
<td>23.03</td>
<td>8.30</td>
<td>&lt; 0.01</td>
</tr>
<tr>
<td>ACA</td>
<td>57</td>
<td>21.07</td>
<td>2</td>
<td>10.53</td>
<td>0.96</td>
<td>0.41</td>
</tr>
<tr>
<td></td>
<td>115</td>
<td>2.55</td>
<td>2</td>
<td>1.27</td>
<td>0.10</td>
<td>0.91</td>
</tr>
</tbody>
</table>

\(^a\)SS: sum of squares; \(^b\)DF: degrees of freedom.

Fig. 4. Size-specific collection efficiency of the HVAC filter against combustion and NaCl aerosol particles. Each data point presents an average of 5–6 repeats, error bars present standard deviation.

this difference was significant \((p < 0.05)\) across the particle size range of 20 to 105 nm at both flow rates (the only exception was 80 nm at 75 CFM). For wood, although all the collection efficiency values fell below the corresponding values obtained for NaCl, the difference failed to reveal statistical significance for most of the particle sizes.

For the ACA filter operating at \(Q_{\text{Filter}} = 57\) CFM, all size-specific collection efficiencies were below 40% for all combustion aerosols as well as NaCl (with one exception for NaCl: 42% at 80 nm). For the tested combustion materials, the collection efficiency was around 30% in the particle size range from 20 to 150 nm, which is notably lower than that of NaCl particles. However, this difference was significant for some particle sizes, but was not significant \((p > 0.05)\) for most. At \(Q_{\text{Filter}} = 115\) CFM, the size-specific collection efficiencies fell below 30% with two exceptions such as NaCl at 80 and 105 nm (35% and 31%, respectively). As seen from Fig. 5, the collection efficiency values obtained for all three combustion aerosols fell consistently below the NaCl values. However, this difference was found statistically significant \((p < 0.05)\) only for plastic combustion aerosol, but fell short of significance for paper and wood.

Our findings for ACA filters do not contradict the previously reported performance characteristics of cabin air filters against KCl particles, which listed a 43.9% collection for 100 nm particles at a face velocity of 10.8 cm s\(^{-1}\), as
Fig. 5. Size-selective collection efficiency of the ACA filter against combustion and NaCl aerosol particles. Each data point presents an average of 5–6 repeats, error bars present standard deviation.

well as a 69.3% and 65.2% collection for PM$_{2.5}$ at face velocities of 60 and 120 cm s$^{-1}$, respectively (Qi et al., 2008, Park et al., 2010).

In summary, for all tested particle sizes, the combustion aerosol particles penetrated both tested filters, HVAC and ACA, more readily than NaCl particles. While the difference appeared to be consistent across the size range (Figs. 4 and 5), it was not always statistically significant. At the same time, the cumulative effect determined in terms of the total collection efficiency (involving all the sizes) was significant for all tested conditions ($p < 0.05$), which is in full agreement with the analysis of data presented in Fig. 3.

**Data Interpretation**

The main finding of this study is that the combustion particles were less efficiently collected by both HVAC and ACA filters than NaCl particles. Possible reasons are discussed below. Combustion of different materials releases particles and vapors containing hydrophobic molecules (or hydrophobic portions of molecules). e.g., burning plastic is known to emit hydrophobic organic compounds (Teuten et al., 2007). Similar to oil particles or vapors, the combustion particles may degrade filters with electrically charged fibers if deposited on these fibers (Biermann et al., 1982; Tennal et al., 1991). This is likely to be the case for any “electret” filter material, including the tested HVAC (and possibly ACA) filter media. The effect decreases the filter collection efficiency due to partial charge neutralization (Biermann et al., 1982), dielectric shielding of fibers, and ionic conduction (Tennal et al., 1991). Other possible mechanisms that may explain the differences in penetration of combustion and NaCl particles through the tested filters include the formation of loose agglomerates on the fibers, neutralization or reduction of charge occurring on fiber due to deposition of oppositely charged particles, as well as chemical reaction (Barrett and Rousseau, 1998). The above mechanisms have been considered in our recent studies (Grinshpun et al., 2013, 2014; Gao et al., 2015), which reported similar differences in collecting combustion and NaCl particles by an N95 NIOSH-certified respirator filter.
CONCLUSIONS

The pressure drop of the HVAC filter and the ACA filter used in this study did not exceed 0.6 mm H2O, which is lower than the levels reported in previous investigations, where the authors apparently tested filter materials characterized by greater resistance and/or used different testing protocols (e.g., higher flow rates).

In contrast to the HVAC filter that collected > 90% of NaCl particles and > 60% of combustion particles regardless of their size under all tested conditions, the ACA filter exhibited notably lower efficiency (mostly below 40%). Based on the total aerosol concentration measurement, the HVAC and ACA filters demonstrated significantly lower collection efficiency for combustion particles compared to NaCl particles at all the tested air flow rates (p < 0.05). For both filters, the particle size-specific collection efficiency of all combustion aerosols was lower than that of NaCl with the significance level varying with the particle size and flow rate.

Differences in collection of aerosol particles of different type are attributed to the interactions between particles and the fibers of electret filters. This process is influenced by the particles’ morphology as well as the charges and surface properties of the particles and fibers.

In conclusion, the performance characteristics of the stationary filters, such as the tested HVAC and ACA, obtained using a well-established protocol involving salt particles as the challenge aerosol may not accurately predict (and rather overestimates) the air purification level provided by these filters against combustion aerosol particles.

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