Journal of Occupational and Environmental Hygiene

ISSN: 1545-9624 (Print) 1545-9632 (Online) Journal homepage: http://www.tandfonline.com/loi/uoeh20

Filter penetration and breathing resistance evaluation of respirators and dust masks

Joel Ramirez & Patrick O'Shaughnessy

To cite this article: Joel Ramirez & Patrick O'Shaughnessy (2017) Filter penetration and breathing resistance evaluation of respirators and dust masks, Journal of Occupational and Environmental Hygiene, 14:2, 148-157, DOI: 10.1080/15459624.2016.1237027

To link to this article: http://dx.doi.org/10.1080/15459624.2016.1237027

Accepted author version posted online: 27 Sep 2016.
Published online: 27 Sep 2016.

JOURNAL OF OCCUPATIONAL AND ENVIRONMENTAL HYGIENE
2017, VOL. 14, NO. 2, 148–157
http://dx.doi.org/10.1080/15459624.2016.1237027

Taylor & Francis
Taylor & Francis Group

Filter penetration and breathing resistance evaluation of respirators and dust masks

Joel Ramirez and Patrick O'Shaughnessy

Department of Occupational and Environmental Health, College of Public Health, The University of Iowa, Iowa City, Iowa

ABSTRACT

The primary objective of this study was to compare the filter performance of a representative selection of uncertified dust masks relative to the filter performance of a set of NIOSH-approved N95 filtering face-piece respirators (FFRs). Five different models of commercially available dust masks were selected for this study. Filter penetration of new dust masks was evaluated against a sodium chloride aerosol. Breathing resistance (BR) of new dust masks and FFRs was then measured for 120 min while challenging the dust masks and FFRs with Arizona road dust (ARD) at 25°C and 30% relative humidity. Results demonstrated that a wide range of maximum filter penetration was observed among the dust masks tested in this study (3–75% at the most penetrating particle size ($p < 0.001$). The breathing resistances of the unused FFRs and dust masks did not vary greatly (8–13 mm H_2O) but were significantly different ($p < 0.001$). After dust loading there was a significant difference between the BR caused by the ARD dust layer on each FFR and dust mask. Microscopic analysis of the external layer of each dust mask and FFR suggests that different collection media in the external layer influences the development of the dust layer and therefore affects the increase in BR differently between the tested models. Two of the dust masks had penetration values < 5% and quality factors (0.26 and 0.33) comparable to those obtained for the two FFRs (0.23 and 0.31). However, the remaining three dust masks, those with penetration > 15%, had quality factors ranging between 0.04–0.15 primarily because their initial BR remained relatively high. These results indicate that some dust masks analysed during this research did not have an expected very low BR to compensate for their high penetration.

KEYWORDS
Breathing resistance; dust masks; filtering face-piece respirator; filter penetration; quality factor

Introduction

Of the many types of particulate respirators currently on the market are those referred to by the National Institute for Occupational Safety and Health (NIOSH) as a particulate filtering facepiece respirator (FFR).[1] NIOSH approves FFRs to ensure they provide a minimum level of protection against airborne particle inhalation in the workplace by following the certification procedures provided in 42 CFR 84.[2]

Currently, unapproved "dust masks" are also widely available. Dust masks are typically advertised by companies or manufacturers as providing protection against nuisance particulates or "non-harmful household dust."[3] Their construction ranges from that similar to a typical cup-shaped FFR[3] to cloth-based units that either strap to the face[4] or are pulled up over the face.[5] A hybrid of these designs is marketed for use by off-road vehicle drivers and agricultural workers.[6]

It should be expected that any business that requires its employees to wear a respirator will supply them with those that have been approved by NIOSH. However, given their wide availability, there is the concern that dust masks may be worn by workers in some work settings such as those associated with small, independently operated farms and construction businesses where workers purchase and use particulate inhalation protection on a voluntary basis. Dust masks are also commonly worn for non-occupational uses, for example to minimize inhalation of pollen and other asthma triggers. They have also been designed for recreational use, such as when operating open motorized vehicles to protect against dust from dirt roads and off-road tracks. However, with limited

CONTACT Patrick O'Shaughnessy patrick-oshaughnessy@uiowa.edu Occupational and Environmental Health, College of Public Health, 100 CPHB, S320, Iowa City, IA 52242.
Color versions of one or more of the figures in the article can be found online at www.tandfonline.com/uoeh.

published research on the performance of dust masks, it is unknown how protective dust masks may be to the wearer.

Not unexpectedly, there has been little research on the performance of dust masks in the occupational health literature. Early research on dust mask performance revealed a large range of penetration measurements, between 1.0–55% depending on mask type.[7,8] Recent research has focused on the performance of cloth-based masks primarily in the context of protection against ambient aerosols and infectious influenza aerosols. Rengasamy et al. obtained very high penetration measurements (>80%) through cloth-based masks of a sodium chloride (NaCl) aerosol as a surrogate for ambient aerosols.[9] Likewise, Jung et al. measured a wide range of penetration values from 0.5% for a "quarantine" mask to 97% for a handkerchief.[10]

Breathing resistance

No studies could be found that directly related the comfort of FFRs while worn by workers to the measured breathing resistance (BR) caused by the FFR filter media. However, some studies included survey questions that suggest BR is a factor with regards to user satisfaction while wearing FFRs. For example, Popendorf et al.[11] found that FFRs were rated worst for "breathing ease" by agricultural workers given a variety of different respirator types such as a half-face respirator and a powered-air purifying respirator. Bryce et al.[12] reported slight disagreement (mean of 3.1 on a six-point Likert scale) among 136 healthcare workers with the statement, "The N95 respirator does not make me short of breath." Meyer et al.[13] found a significant "breathing discomfort" of an FFR with "thick filtering material" compared to another FFR and half-mask respirators with particulate filters during laboratory tests of respiratory protection devices among 30 workers from four factories.

Breathing resistance (or pressure drop, ΔP) through a fibrous filter at a given airflow results from the restriction to flow caused by both the fabric layer and the particulate layer.[14–16] NIOSH requires that the initial (media-induced) inhalation BR should not exceed 35 mm H_2O (water column) when tested at 85 L min^{-1}.[17] However, Chen et al.[18] demonstrated that BR is less than 10 mm H_2O for most types of FFRs. The effect of particle loading when a challenge aerosol was applied to high efficiency particulate air (HEPA) filters on pressure drop has been studied by Letourneau et al.[19] and Novick et al.[16] Results from their experiments showed that pressure drop increases faster over time when the filter is challenged with smaller particles. Knowing whether these results on HEPA filters can be translated to particle filtering respirator media is important for understanding the change in BR of FFRs as they are used in a dusty environment.

Quality factor

Previous studies[7–10] suggest that the efficiency of dust masks is not consistent between models and can be much lower than the minimum of 95% collection efficiency established for N95 FFRs. If a dust mask has a low efficiency, it could be expected to also have a lower initial BR as air, and associated particles, travel through the filter media with less obstructions to flow. Given studies that suggest high BR is an undesirable aspect of wearing an FFR,[11–13] workers who purchase their own protective equipment may be likely to choose one simply because it is easier to breathe through without regard to whether it is also NIOSH-approved.

To normalize this inverse relationship between efficiency and BR, a quality factor (QF) can be calculated to compare dust masks and respirators.[20–22] A higher QF represents a better overall performance of the mask with regards to the combined influence of both efficiency and BR at the tested conditions.[23]

Study aims

Previous studies demonstrated that dust masks can have limited efficiency.[7–10] However, new dust mask technologies and designs have been developed and are being marketed, but their properties are not well known. Our overall goal was to compare the filter performance (penetration, most penetrating particle size (MPPS) and breathing resistance) among a representative set of dust masks relative to two different NIOSH approved N95 FFRs. A secondary goal was to evaluate the increase in BR of dust masks and FFRs with mass loading to a challenge aerosol over time. A final goal was to assess the QF values calculated for each of the dust masks and FFRs to determine whether any reduction in efficiency of a dust mask is compensated for by a lower BR to achieve a QF similar to that of an N95 FFR.

Methods

Dust mask and FFR characteristics

Five models of commercially available dust masks and two models of N95 FFRs from different manufacturers were selected for this study (Figure 1). The dust masks were selected to represent the range of currently available designs. The FFRs were chosen from two different manufacturers using different construction techniques from the 21 world-wide that produce NIOSH-approved FFRs.[24]

Figure 1. Images of dust masks and FFRs used in this study.

Dust Mask 1 (DM-1) was a cupped-shaped mask with a nose clip and two straps situated in the conventional manner to wrap around the neck and head (3 M 8661, St. Paul, MN). Dust Mask 2 (DM-2) consisted of a flat multilayer fabric with no nose clip and straps that wrapped around the ears (Breathe Healthy with Microbe Shield, Williamsburg, VA). Dust Mask 3 (DM-3) consisted of folded filter media with removable external felt support material; the straps wrapped around the ears and it contained exhalation valves (I Can Breathe, Chicago, IL). Dust Mask 4 (DM-4) was a cup-shaped mask with only one strap (MSA 10028549, Cranberry Twp, PA). Dust Mask 5 (DM-5) was similar in design to DM-3 except the internal filter media was supported by an outer neoprene layer; only one broad strap wrapped around the neck (RZ Mask, Chaska, MN.). DM-5 can be fitted with charcoal-laced filters but the model tested was equipped with their standard particulate filter media. FFR-1 (3 M 8510, St. Paul, MN) was a conventional cupped-shaped N95 with two straps and nose clip. FFR-2 (Moldex 2200, Culver City, CA) was cup-shaped with a flexible mesh over the filter material and with two straps.

A summary of the physical characteristics of the tested dust masks and FFRs is shown in Table 1. Dust mask and FFR mass was measured in a balance with a sensitivity of 1 mg (Mettler PE 360, Mettler-Toledo LLC, Columbus, OH). The thickness of each dust mask and FFR was measured using a digital caliper (Neiko 01407A, Gardena, CA). Scanning electron microscopy (SEM) (Hitachi S-4800, Hitachi High Technologies America, Inc., Schaumburg, IL) was used to measure fiber diameter. Mask surface area in contact with air was obtained by first cutting away the portion (approximately 1 cm wide) along the outside edge of the mask that forms a seal with the face, and then cutting radially into the mask to flatten it followed by scanning its image along with that of a ruled line. ImageJ software (National Institutes of Health (NIH), Bethesda, MD) was then used to determine the total surface area of the scanned image.

Test system

Two systems were utilized in this study to test the dust masks and FFRs (collectively referred to as "masks"). One system was designed to measure mask penetration and the other system to measure BR through unused masks and the BR under mass loading. The two test systems shared some components. In both cases, a mask was attached to a manikin head using rope caulk to provide a leak-proof seal. The manikin head was then placed in a cubic (38-cm sides), sealed, polycarbonate chamber (Figure 2). The manikin head was bored through the upper neck

Table 1. Dust mask and FFR characteristics (Mean ± S. D. for n = 5 each).

DM and FFR models	Number of layers	Mass (g)	Total Thickness (mm)	Surface area (cm^2)	Fiber diameter (μm) External layer	Middle layer	Internal layer
DM-1	3	6.46 ± 0.29	0.93 ± 0.05	151.6 ± 1.9	21.8 ± 2.9	7.9 ± 5.2	24.9 ± 5.1
DM-2	2	16.53 ± 0.65	0.52 ± 0.06	185.6 ± 0.7	14.1 ± 1.3		7.4 ± 1.2
DM-3[a]	2	12.39 ± 0.58	1.15 ± 0.16	123.6 ± 0.4	15.5 ± 5.2		6.5 ± 0.9
DM-4	1	3.17 ± 0.14	0.68 ± 0.02	157.3 ± 0.5	7.8 ± 3.9		
DM-5[a]	3	55.73 ± 0.08	0.88 ± 0.07	177.3 ± 1.1	19.2 ± 2.5	12.5 ± 2.4	5.8 ± 2.2
FFR-1	3	10.48 ± 0.13	1.71 ± 0.09	162.5 ± 1.2	22.1 ± 5.3	5.4 ± 3.2	15.4 ± 1.3
FFR-2	2	14.33 ± 0.54	1.98 ± 0.14	188.2 ± 0.4	5.1 ± 4.6		15.5 ± 1.2

[a]Filter media is contained within additional material.

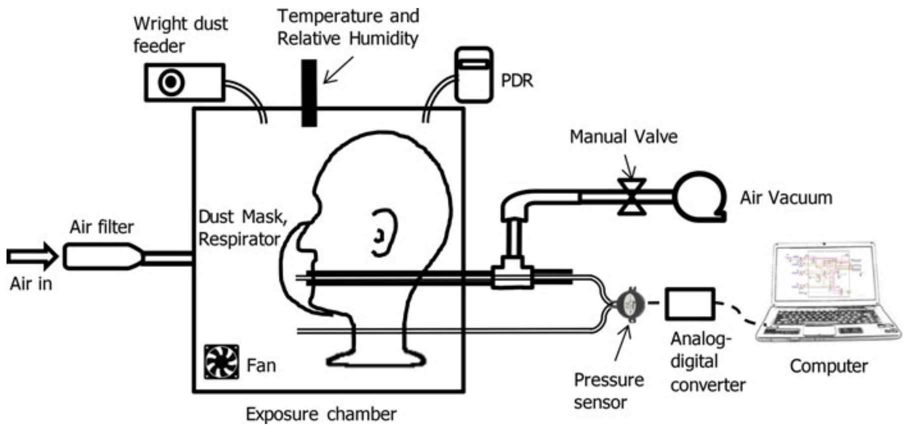

Figure 2. Schematic of the test system used to measure breathing resistance (BR) of the dust masks and FFRs.

to hold a sample tube that extended into the space just below the mask to measure ambient conditions. A second tube was bored to extend out of the mouth and into the space inside the mask to measure filtered air (in-mask) conditions. These two tubes were used either to measure mask penetration or mask pressure drop depending on the instrument connected to the ends of the two tubes that extended out of the chamber. Also shown in Figure 2 is an outer tube containing the in-mask sampling tube through which the main airstream flowed. Air filters were connected to an inlet hole in the side of the chamber to remove particles from the make-up air that entered the chamber.

Penetration testing

Mask penetration was carried out as described in detail in Ramirez and O'Shaughnessy.[25] In brief, penetration was determined while following 42 CFR Part 84.181 in terms of challenge aerosol (NaCl) and flow rate (85 L min^{-1}), but without also pre-conditioning the masks at 38°C and 85% relative humidity. Instead, the masks were stored at the same environmental conditions (25°C and 30% relative humidity) as those maintained during the penetration test. The NaCl aerosol was generated with the use of a Collison nebulizer from a 2% solution. During this test, a scanning mobility particle sizer (SMPS) consisting of an electrostatic classifier (Model 3080, TSI Inc., Shoreview, MN) in combination with a condensation particle counter (CPC) (Model 3785, TSI Inc., Shoreview, MN) was used to size and count particles within 108 channels ranging between 14–685 nm. Using the SMPS to measure the size distribution of the NaCl aerosol resulted in a count median mobility diameter of 90 nm with a geometric standard deviation of 2.0. This aerosol, consisting primarily of nanoparticles, is needed to accurately determine the MPPS which, for most filter media, occurs below 500 nm.

Mask penetration, P, (Eq. (1)) was determined from measurements of the concentration inside (C_{in}) the mask and outside (C_{out}) the mask for every SMPS size channel:

$$P = \frac{C_{in}}{C_{out}} \tag{1}$$

The SMPS channel containing the maximum penetration was identified from a spreadsheet analysis and the median diameter of that channel was reported as the MPPS for the tested mask together with the corresponding maximum penetration value, P_{max}.

Breathing resistance testing

Face mask BR was evaluated using mass loading at a constant flow rate using the experimental set-up shown in Figure 2. A Wright Dust Feed (BGI Inc., Waltham, MA) was used to introduce Arizona Road Dust (ARD) (Dust Coarse, ISO 12103-1 A4, Powder Technology Inc., Burnsville, MN) inside the chamber. This dust type was chosen because it is a well-characterized standard powder type containing a known composition of inorganic particles. An aerosol photometer (Personal DataRam, PDR-1200, Thermo Fisher Scientific Inc., Waltham, MA) was located at the top of the chamber to monitor dust concentration inside the chamber over time to ensure that it remained steady during each trial. A concentration near 30 mg m^{-3} was maintained during each trial. Given that Thomas et al.[26] did not find a relationship between concentration and BR, this high chamber concentration was maintained to shorten the trial time needed to demonstrate the relationship between mask dust loading and BR.

Previous studies[16,19,26] demonstrated that ΔP in HEPA filters varies with particle size. Therefore, impactor sampling was conducted during preliminary trials. An 8-stage Marple personal cascade impactor (Model 290, Thermo-Fisher Scientific, Waltham, MA) operating at 2 L min^{-1} was used to sample the particle size of ARD. The method described by O'Shaughnessy and Raabe[27] was used to determine the mass median aerodynamic diameter (MMAD) and geometric standard deviation (GSD) of the ARD inside the chamber. The measured MMAD of the ARD aerosol was 6.0 µm with a GSD of 3.7 and therefore represents an aerosol typical of those found in a workplace containing a wide distribution of relatively large inorganic particles.

To simulate inhaled air, a vacuum pump pulled air from upstream to downstream of the masks at 55 L min^{-1}, a flow rate considered to be moderate breathing by workers.[28] Temperature and relative humidity were maintained at room conditions (23°C, 44%) by a dedicated laboratory air-handling system and were monitored with a factory-calibrated environmental sensor (Q-Trak, TSI, Shoreview, MN) protruding through a port in the top of the chamber.

A calibrated differential pressure sensor (Series 646B, Dwyer Instruments Inc., Michigan City, IN) measured BR across a mask with a full scale accuracy of ± 2% (1.27 mm H_2O). As shown in Figure 2, the pressure sensor was connected to the ambient and in-mask tubes in order to measure the difference in pressures occurring in their corresponding air spaces. BR measurements were made every 5 s during the 120-min trial period.

Experimental design

To start a trial, a mask was sealed to the face of a manikin head with 1-cm diameter rope caulk pressed firmly to eliminate leakage. To test for possible leakage between a mask and the manikin face, the BR was measured with the pressure sensor while pulling air through at 85 L min^{-1}. Based on results from preliminary and ongoing trials the BR did not vary appreciably between masks of the same type. Therefore, leakage was suspected if the BR measurement was lower than the expected range for that mask type. In that case, the mask was removed and recaulked or discarded. Following the leak test, a penetration test was performed with the NaCl aerosol. Five trials were performed per mask type, each with a different mask.

A second set of tests was conducted to determine the effect of dust loading on BR over time using the larger ARD aerosol. For this test, a new mask (not used in the penetration test) was weighed and sealed to the manikin head. A faceseal check was performed and the BR test was then performed for 120 min. At the end of the test period, the mask was removed from the manikin head and reweighed. Three trials per mask were performed. The mask types were randomly tested.

Areal dust density and quality factor calculations

Starting from an initial pressure drop caused by the unused filter media, the breathing resistance testing procedures resulted in an increase in BR through a mask with loading by the ARD aerosol. However, BR is influenced the superficial face velocity, V (m min^{-1}), of the particle-laden air approaching the media. For the same air flow rate, Q, through the mask, V will differ depending on the surface area, A_f, of the filter media where:

$$V = Q/A_f. \quad (2)$$

Likewise, when a mask is challenged with an aerosol, the change in BR with time will depend on the aerosol concentration, C (mg m^{-3}). Therefore, to normalize the results obtained for masks with different A_f and loaded under potentially different C, it was necessary to compare BR relative to the mass of dust collected per mask filter area or "areal dust density", W (g m^{-2}):[16,19,29]

$$W(t) = CVt. \quad (3)$$

The photometer was used to verify that concentrations were relatively stable during a trial. However, C in (3) was determined from Q (55 L min^{-1}) and the mask net weight established over the 120-min trial. The initial pressure drop due to the mask filter media was subtracted from the measured total pressure drop due to both the media and the dust layer to obtain the pressure drop due to the dust layer, ΔP_D. ΔP_D was then related to the values of $W(t)$ calculated for every minute of the 120 min trial. Results indicated that all mask types acquired a W of at least 40 g m^{-2}. Therefore, $W = 40$ g m^{-2} was used as the basis of comparison of the corresponding ΔP_D (mm H_20) values achieved by the different mask types.

The quality factor (QF) was calculated using the mask maximum penetration, P_{max}, and initial BR values measured for unused dust masks and respirators:[23]

$$QF\left(mm^{-1}H_2O\right) = \frac{ln\,(1/P_{max})}{BR}. \quad (4)$$

Given that, for the same mask type, different masks were used during the multiple trials associated with the penetration and BR tests, the QF was computed from the average P_{max} and average BR for a mask type. This process, therefore, resulted in one QF value per mask type.

Statistical analysis

Five dust mask models and two N95 FFR models were analyzed to assess differences in the means of the MPPS, penetration, BR, and ΔP_D resulting from the multiple trials conducted for each mask type. All comparisons were

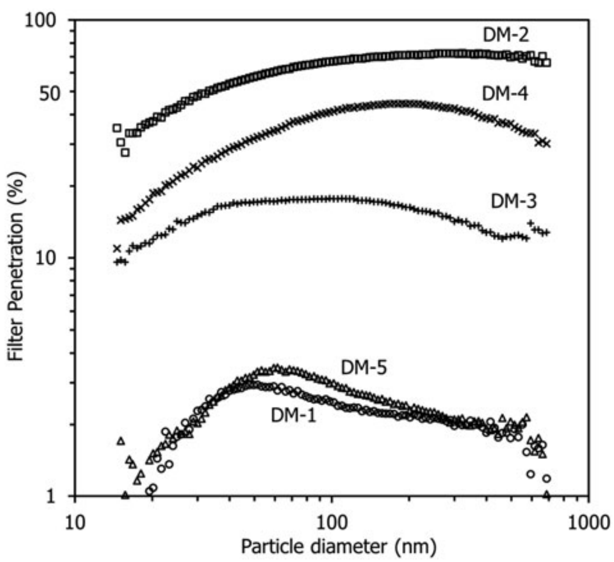

Figure 3. Penetration of NaCl aerosol through dust masks. Each point plotted represents the average of the penetration measured over five trials for a size channel. The solid line represents the 5% certification limit.

conducted as an analysis of variance (ANOVA) with statistical significance accepted at $\alpha = 0.05$ level. Tukey's multiple comparison procedure was used to determine differences among dust mask and FFR models. Mask penetration and MPPS were tested for normality using the Anderson-Darling test and found to be normally distributed. Data were exported to Minitab® (Ver. 17, Minitab Inc., State College, PA) to perform the statistical analysis.

Results

Mask penetration and MPPS

A wide range of penetration values was obtained between the dust masks as shown in Figure 3. The corresponding MPPS and P_{max} obtained for each dust mask and FFR are also enumerated in Table 2 together with an indication of their variability across trials. Penetration results were obtained for the two FFRs during the previous study[25] that utilized the same test system and are given in Table 2 for comparison. The penetration of the dust masks ranged from 3–74% and 3–5% for the FFRs. Mean P_{max} values were significantly different ($p < 0.001$) between dust masks and FFRs. Tukey's multiple comparison procedure revealed that the mean P_{max} of the DM-2 and DM-4 were significantly higher than all other dust masks and FFRs.

The MPPS also varied greatly between the tested dust masks and FFRs (Table 2) with a range of 51–411 nm for the dust masks and 42–51 nm for the FFRs. The mean MPPS for the tested dust masks were significantly different ($p < 0.001$). Although not as clearly separated as for the penetration values, Tukey's multiple comparison procedure showed that the MPPS for several dust masks, especially DM-2 and DM-4, were significantly higher than for the other dust masks and FFRs.

Breathing resistance and quality factor

Table 2 provides the initial BR values for the dust masks and FFRs. Table 2 also shows the dust layer BR at $W = 40$ g m^{-2} and quality factor (QF) estimates. The initial BR values ranged between 12–13 mm H_2O for the FFRs and between 8–13 mm for the dust masks. The initial BR was statistically different between the FFRs and some of the dust masks, with DM-2 and DM-4 being significantly lower than all others ($p < 0.001$).

An example of the increase in BR (ΔP_D) developed by the accumulating ARD dust layer is given in Figure 4. As shown in Figure 4, there was some variability in that increase between trials using different masks of the same type, which was typical of the other masks as well. A vertical line in Figure 4 highlights the ΔP_D values obtained for the three trials at an areal dust density of 40 g m^{-1}. ΔP_D at 40 g m^{-1} varied between 2.8–13.4 mm H_2O among the dust masks and between 1.7–7.2 mm H_2O among the two FFRs. There was a statistical difference between DM-4 and all other dust masks and FFRs ($p < 0.001$), whereas the other dust masks were, in general, not different from the FFRs.

Table 2. Summary of dust mask and FFR study outcomes (Mean ± S.D.).

Dust Mask and FFR models	MPPS (nm)		Maximum Penetration (%)		Initial BR (mm H_2O)		Dust Layer BR (mm H_2O)[b]		QF (mm^{-1} H_2O)
DM-1	51 ± 9	C[a]	3.1 ± 1.6	C	10.7 ± 0.2	BC	6.1 ± 0.9	BC	0.33
DM-2	411 ± 125	A	74.3 ± 5.9	A	8.1 ± 0.2	D	2.8 ± 1.1	BC	0.04
DM-3	108 ± 17	BC	17.2 ± 13.6	C	11.5 ± 0.8	ABC	7.1 ± 0.2	B	0.15
DM-4	186 ± 40	B	47.2 ± 12.1	B	9.8 ± 0.4	CD	13.4 ± 1.8	A	0.08
DM-5	59 ± 4	C	3.5 ± 1.6	C	12.8 ± 1.5	A	7.0 ± 4.0	B	0.26
FFR-1	42 ± 5	C	2.8 ± 0.7	C	11.9 ± 0.2	AB	1.7 ± 0.3	C	0.31
FFR-2	50 ± 5.4	C	5.1 ± 1.6	C	13.2 ± 0.4	A	7.2 ± 1.8	B	0.23

[a]Letters indicate results from the Tukey's analysis where masks with the same letter are not significantly different.
[b]The pressure drop due to the dust layer developed when there was an areal dust density on the filter of 40 g m^{-2}.

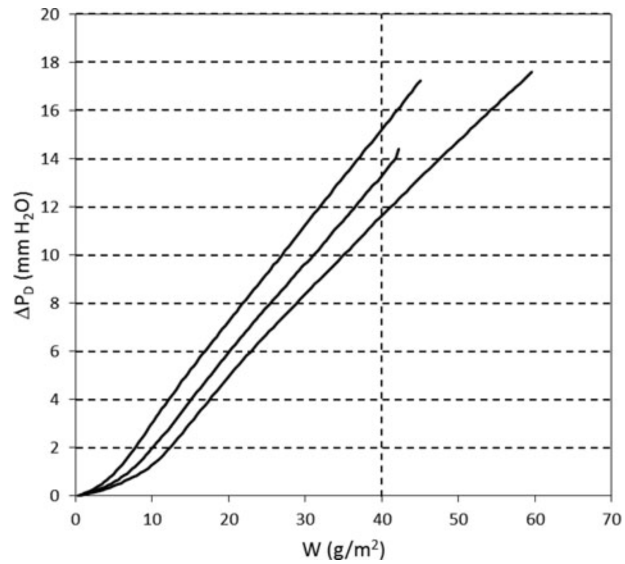

Figure 4. Increase in dust layer pressure drop, ΔP_D, relative to areal dust density, W, for the three breathing resistance trials conducted with DM-4 filters. A vertical line at $W = 40$ g/m^2 highlights the associated pressure drop at that comparative areal dust density.

Figure 5 shows SEM images of the external layer of each mask loaded with ARD at the end of the 120-min trial. Differences in dust cake formation can be seen across mask type depending on the composition of the external layer of the mask. For example, DM-4 and FFR-2 show a very dense dust layer established on small-diameter fibers that may contribute to the high ΔP_D values determined for that dust mask and FFR. Conversely, DM-1, DM-2, and FFR-1 have larger, more loosely bound fibers with associated low ΔP_D values.

The QF values shown in Table 2 ranged between 0.04–0.33 mm^{-1} H_2O. FFR-1 and DM-1 resulted in the highest QF with values of 0.31 and 0.33 mm^{-1} H_2O, respectively. DM-2 and DM-4 resulted in the lowest QF with values of 0.04 and 0.08 mm^{-1} H_2O, respectively.

Discussion

Study results demonstrate that unused dust masks had P_{max} values that varied greatly and three of the dust masks exceeded a P_{max} of 5%. The large variation in penetration among the dust masks obtained in this study coincides with results obtained by Rengasamy et al. who tested the penetration of a diverse set of FFRs, dust masks, and cloth types following standard methods[2] and found penetration values between 40–90%.[9]

Results also revealed a broad range in the MPPS between dust mask models. An observed MPPS greater

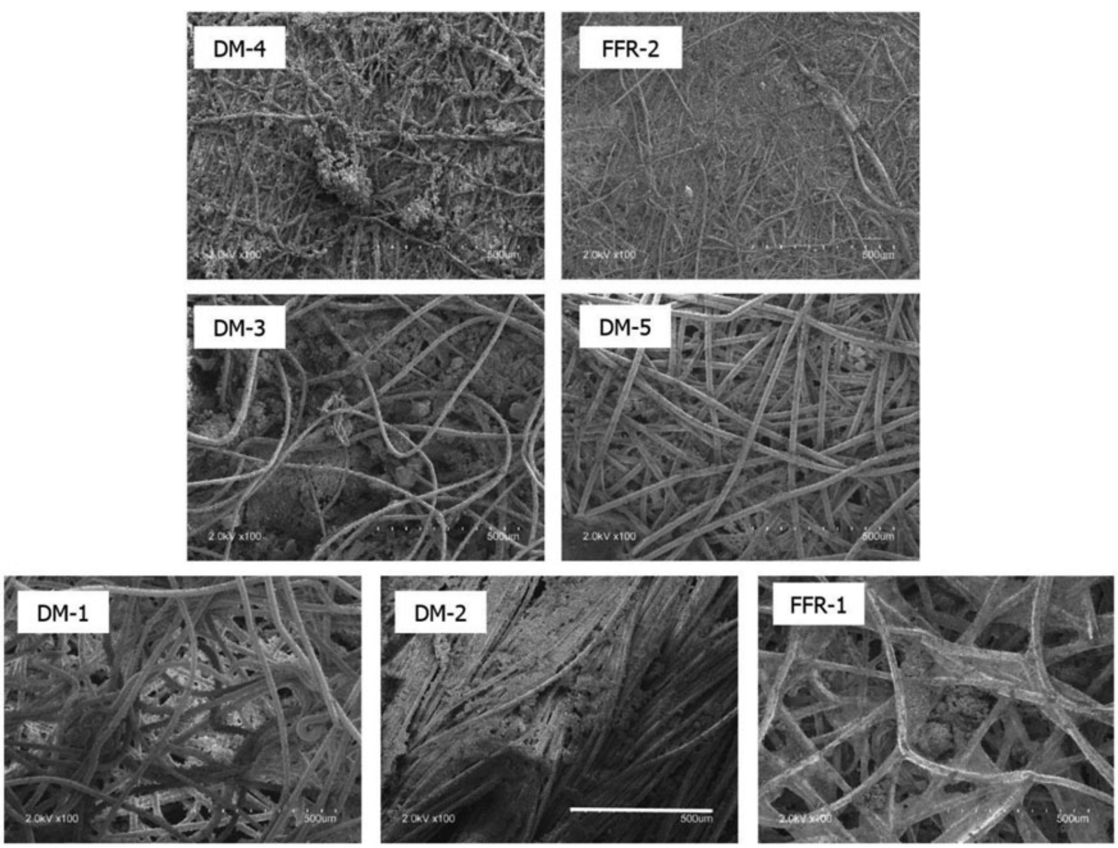

Figure 5. SEM images of external layer of ARD-loaded dust masks and FFRs (X100 for each image). Images are presented in order of highest to lowest breathing resistance at 40 g m^{-2}. The white bar indicates 500 μm.

than 100 nm is indicative of masks that do not have electrostatic fibers in their filtering media.[30–33] On that basis, the results obtained in this study suggest that DM-1 and DM-5 contain electrostatic fibers in their filtering media while the other dust masks do not.

An unexpected result was the large difference in the dust layer pressure drop, ΔP_D, at $W = 40$ g m^2 observed between dust masks and FFRs with ARD mass loading. Theoretically, a growing dust layer supported by filter media results in an increasing pressure drop (BR) that is dependent on the properties of the dust layer and not on the properties of the filter media.[29] The observed variability in ΔP_D for the same W may be explained by the difference in the dust layer formed on the surface of the dust masks and FFRs. Results from this study suggest that these differences in ΔP_D for the same W are related to different filter fiber diameter, fiber density, and electrostatic charge in the external filter layer of the dust masks and FFRs. SEM images taken of the dust masks and FFRs surface after they were loaded show differences in dust layer deposition on the masks. As those illustrations demonstrate, particle deposition is scattered across the external layer of some dust masks and FFRs while in other dust masks and FFRs particles are more densely deposited on the external layer. For example, the SEM image of FFR-1 shows the thick fibers of the external layer where particles are deposited but there is little dust layer formation on the surface. In comparison, DM-4, with thinner fibers on the external layer, shows more dust layer formation.

Other studies have demonstrated that the formation of a dust layer can depend on filter media qualities. Barrett and Rousseau[34] showed that the dust layer can form at a different rate depending on the diameter and density of filter fibers. For example, the smaller, denser fibers of a fiberglass filter loads quickly compared to that of a filter with electret media with its larger, less dense fibers. Cho et al.[21] also observed differences in the increase in BR across several respirator types when loaded with welding fume. They stated that respirators designed for capturing welding fumes should have an outermost layer designed to slow dust layer development and thus lower the rate of increase in BR. As in the study by Barrett and Rousseau,[34] they also showed that an external layer composed of thick fibers will slow the formation of a dust layer.

The QF associates mask penetration and BR to obtain a qualifying value to rate respirator performance. Both a low penetration and low BR represents the highest possible QF. A typical mask will have a QF resulting from the compromise of having either a low penetration and relatively high BR or having a high penetration and relatively low BR. However, DM-2 had a very high penetration (70%), but the initial BR value of 8 mm H_2O was not low enough to offset that high penetration in order to obtain a QF value comparable to the FFRs tested. DM-3 and DM-4 showed a similar effect but to a lesser extent. By calculation given the penetration values obtained for DM-2, DM-3 and DM-4, to obtain a QF similar to FFR-1, a very low BR (1–6 mm H_2O) would be needed to compensate for their high penetration. Therefore, our results indicate that the lower performance by some dust masks in terms of high penetration is not offset by a significant decrease in BR.

There are several limitations of this work. Some leakage between the mask and manikin may have occurred beyond our ability to detect it. However, after every experimental trial, the seal between the mask and manikin was examined and no seal failure was observed. Only a limited number of dust masks and FFRs models were tested in this study. Others dust masks and FFRs models may perform differently. Cost and worker comfort of dust masks and FFRs were not evaluated.

Conclusions

Five different dust masks were tested in a laboratory setting to evaluate the maximum penetration of a NaCl aerosol. Results from this study demonstrated a wide range in maximum penetration among the dust masks tested. Maximum penetration among three of the dust masks were above the 5% minimum level needed to achieve NIOSH approval as an N95 designated FFR.

Both the initial BR and the increase in BR with mass loading of five dust masks and two NIOSH-approved N95 FFRs were experimentally tested in this study. The dust masks with the highest aerosol penetration also had the lowest initial BR. However, the range in initial BR was not as large as expected given the very large difference in initial BR between the mask types. Results demonstrated that the increase in BR with mass loading was different between the tested dust masks and FFRs. Differences in the structures of the external layer may influence particle deposition and affect BR differently between the tested models.

We did not observe a substantial reduction in BR to compensate for the high penetration of some dust masks. Therefore, assuming BR is an important criteria for face mask users, then some of the dust masks analyzed during this research did not have the expected low BR relative to a high penetration that would justify their use.

Funding

This research was supported (in part) by a pilot project grant from the Heartland Center for Occupational Health and Safety at the University of Iowa. The Heartland Center is supported by Training Grant No. T42OH008491 from the Centers for Disease Control and Prevention/National Institute for Occupational Safety and Health. Dr. Ramirez also received financial support from the Heartland Center while conducting this research.

References

[1] **National Institute for Occupational Safety and Health (NIOSH):** "NIOSH-Approved Particulate Filtering Facepiece Respirators." Available at https://www.cdc.gov/niosh/npptl/topics/respirators/disp_part/ (accessed June 20, 2016)

[2] "Non-powered air-purifying particulate filter efficiency level determination," Code of Federal Regulations, Title 42, Part 84 (2000). pp. 593–594.

[3] "3MTM Home Dust Mask." Available at http://solutions.3m.com/wps/portal/3M/en_US/3M-Safety-NA/Safety/Product-Catalog/~/3M-Home-Dust-Mask?N=5927440+3294427459+3294529207&rt=rud (accessed June 20, 2016).

[4] "Antimicrobial Masks." Available at http://www.breathehealthy.com/about-our-masks/antimicrobial-masks/ (accessed June 20, 2016).

[5] "Five and Diamond Dust Masks." http://fiveanddiamond.com/collections/dust-masks (accessed June 20, 2016).

[6] "RZ Industries." Available at https://www.rzmask.com/ (accessed June 20, 2016).

[7] **Cherrie, J., R. Howie, and A. Robertson:** The performance of nuisance dust respirators against typical industrial aerosols. *Ann. Occup. Hyg. 31*:481–491 (1987).

[8] **Wake, D., and R. Brown:** Measurements of the filtration efficiency of nuisance dust respirators against respirable and non-respirable aerosol. *Ann. Occup. Hyg. 32*:295–315 (1988).

[9] **Rengasamy, S., B. Eimer, and R. Shaffer:** Simple respiratory protection—evaluation of the filtration performance of cloth masks and common fabric materials against 20–1000 nm size particles. *Ann. Occup. Hyg. 54*(7):789–798 (2010).

[10] **Jung, H., J. Kim, S. Lee, J. Lee, P. Tsai, and C. Yoon:** Comparison of filtration efficiency and pressure drop in anti-yellow sand masks, quarantine masks, medical masks, general masks, and handkerchiefs. *Aerosol Air. Qual. Res. 14*(14):991–1002 (2014).

[11] **Popendorf, W., J. Merchant, S. Leonard, L. Burmeister, and S. Olenchock:** Respirator protection and acceptability among agricultural workers. *Appl. Occup. Environ. Hyg. 10*(7):595–605 (1995).

[12] **Bryce, E., L. Forrester, S. Scharf, and M. Eshghpour:** What do healthcare workers think? A survey of facial protection equipment user preferences. *J. Hosp. Infect. 68*:241–247 (2008).

[13] **Meyer, J.P., M. Hery, J. Herrault, G. Hubert, D. Francois, G. Hecht, and M. Villa:** Field study of subjective assessment of negative pressure half-masks. Influence of the work conditions on comfort and efficiency. *Appl. Ergon*. 331–338 (1997).

[14] **Brown, R.C.:** Modern concepts of air filtration applied to dust respirators. *Ann. Occup. Hyg. 33*:615–644 (1989).

[15] **Novick, V., P. Higgins, B. Dierkschiede, C. Abrahamson, W. Richardson, P. Monson, and P. Ellison:** *Efficiency and Mass Loading Characteristics of a typical HEPA Filter Media Material*. Lemont, IL: Engineering Physics Division, Argonne National Laboratory, 1990.

[16] **Novick, V., P. Monson, and P. Ellison:** The effect of solid particle mass loading on the pressure drop of HEPA filters. *J. Aerosol Sci. 23*:657–665 (1992).

[17] **National Institute for Occupational Safety and Health:** *Determination of Inhalation Resistance Test, Air Purifying Respirators Standard Test Procedure (STP) (Procedure No. TEB-APR-STP-0007)*. U.S. Department of Health and Human Services, September 2012.

[18] **Chen, C. C., M. Lehtimäki and K. Willeke:** Loading and filtration characteristics of filtering facepieces, *Am. Ind. Hyg. Assoc. J. 54*(2):51–60 (1993).

[19] **Letourneau, P., P. Mulcey, and J. Vendel:** Effect of dust loading on the pressure drop and efficiency of HEPA filters. *Filtr. Separat. 24*(4):265–267 (1987).

[20] **Wake, D., A. Bowry, B. Crook, and R. Brown:** Performance of respirator filters and surgical masks against bacterial aerosols. *J. Aerosol Sci. 28*:1311–1329 (1997).

[21] **Cho, H.W., C.S. Yoon, J.H. Lee, S.J. Lee, A. Viner, and E. Johnson:** Comparison of pressure drop and filtration efficiency of particulate respirators using welding fumes and sodium chloride. *Ann. Occup. Hyg. 55*:666–680 (2011).

[22] **Huang, S.H., C.W. Chen, Y.M. Kuo, C.Y. Lai, R. McKay, and C.C. Cheu:** Factors affecting filter penetration and quality factor of particulate respirators. *Aerosol Air Qual. Res. 13*:162–171 (2013).

[23] **Hinds, W.:** *Aerosol Technology*. New York: Wiley Interscience Publication, 1999. pp.188.

[24] "NIOSH-Approved N95 Particulate Filtering Facepiece Respirators." Available at https://www.cdc.gov/niosh/npptl/topics/respirators/disp_part/n95list1.html (accessed June 20, 2016).

[25] **Ramirez, J., and P. O'Shaughnessy:** The effect of simulated air conditions on n95 filtering face-piece respirators performance. *J. Occup. Environ. Hyg. 13*:491–500 (2016).

[26] **Thomas, D., P. Penicot, P. Contal, D. Leclerc, and J. Vendel:** Clogging of fibrous filters by solid aerosol particles experimental and modelling study. *Chem. Eng. Sci. 56*:3549–3561 (2001).

[27] **O'Shaughnessy, P., and O. Raabe:** A Comparison of cascade impactor data reduction methods. *Aerosol Sci. Tech. 37*:187–200 (2003).

[28] **Janssen, L.L., N.J. Anderson, P.E. Cassidy, R.A. Weber, and T.J. Nelson:** Interpretation of inhalation airflow measurements for respirator design and testing. *J. Internat. Soc. Respirat. Protect. 22*:122–141 (2005).

[29] **Cooper, C.D., and F.C. Alley:** *Air Pollution Control*. 4th ed. Long Grove, IL: Waveland Press, 2011. pp. 195–198.

[30] **Fardi, B., and B.Y.H. Liu:** Performance of disposable respirators. *Part. Part. Syst. Charact. 8*:308–3014 (1991).

[31] **Balazy, A., M. Toivola, T. Reponen, A. Podgorski, A. Zimmer, and S. Grinshpun:** Manikin-based

performance evaluation of n95 filtering-facepiece respirators challenged with nanoparticles. *Ann. Occup. Hyg. 50*:259–269 (2006).

[32] **Eshbaugh, J.P., P.D. Gardner, A.W. Richardson, and K.C. Hofacre:** N95 and P100 Respirator Filter Efficiency under High Constant and Cyclic Flow. *J. Occup. Environ. Hyg. 6*:52–61 (2009).

[33] **Rengasamy, S., R. BerryAnn and J. Szalajda:** Nanoparticle filtration performance of filtering facepiece respirators and canister/cartridge filters. *J. Occup. Environ. Hyg. 10*:519–525 (2013).

[34] **Barrett, L., and A. Rousseau:** Aerosol loading performance of electret filter media. *Am. Ind. Hyg. Assoc. J. 59*:538–539 (1998).