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Respiratory protection against airborne nanoparticles: a review

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Abstract As a precautionary measure, it is often recommended that workers take steps to reduce their exposure to airborne nanoparticles through the use of respiratory protective devices. The purpose of this study was to provide a review and analysis of the research literature and current recommendations on respirators used for protection against nanoparticles. Key research findings were that studies with particles as small as 4 nm have shown that conventional single-fiber filtration theory can be used to describe the filtration performance of respirators and that the most penetrating particle size for respirators equipped with commonly used electrostatic filter media is in the range of 30–100 nm. Future research needs include human laboratory and workplace protection factor studies to measure the respirator total inward leakage of nanoparticles. Industrial hygienists and safety professionals should continue to use traditional respirator selection guidance for workers exposed to nanoparticles.

Keywords Respirator · Respiratory protection · Filtration · Nanoparticle · EHS · Occupational safety and health · Aerosols

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Introduction

Nanoparticles have been defined as engineered materials having at least one dimension between 1 and 100 nm in size (NIOSH 2006). Nanoparticles often exhibit unique physical and chemical properties, but little is known about what effect these properties may have on human health. Research has shown that the particle size, shape, surface area, charge, chemical properties, solubility, oxidant generation potential, and degree of agglomeration can influence the toxicity of nanoparticles. As with any inhalation hazard, potential health risks from nanoparticles are a function of the magnitude (concentration) and duration of the exposure. These risks are increasingly important for workers who may be exposed to airborne nanoparticles during their production, handling, or manipulation. While some risks have been identified, more research is needed to better understand the routes and levels of exposure to workers and to fully evaluate the toxicity of nanoparticles.

The use of respiratory protection is often needed when engineering and administrative controls do not keep worker inhalation exposures below a regulatory limit or an internal target control. The decision to use respiratory protection should be based upon professional judgment, hazard assessment, and risk management practices (Schulte et al. 2008). In the United States, when respirators are required in the workplace, the Occupational Safety and Health (OSHA) respiratory protection standard is used to ensure that the respirators are used safely and correctly to provide expected levels of protection (OSHA 1998). The OSHA respiratory protection standard requires that employers provide their employees with respirators that have been certified by the National Institute for Occupational Safety and Health (NIOSH). NIOSH certifies several types of respirators (e.g., disposable filtering facepiece, half-mask elastomeric, full facepiece, powered, airline, self-contained, etc.) that can provide different levels of expected protection to airborne particulate when used in the context of a complete respirator program, including fit testing. To assist respiratory protection managers and safety professionals, NIOSH has published respirator selection criteria (NIOSH 2004). The advantages and disadvantages of the various respirator classes are described elsewhere (ISO 2008; NIOSH 2006).

The purpose of this study is to provide a review of, and analyze the existing literature on filter penetration, face seal leakage, and protection factors against submicron particulate with a focus on nanoparticles. Recommendations made by various governmental and safety organizations and suggestions for future research will also be discussed.

Methods

A computerized literature search was undertaken in December 2008 utilizing ISI Web of Knowledge and Ovid database for relevant articles using the search terms “aerosol and respirator and filtration”, “aerosol and respirator and leakage”, “particles and respirator and leakage”, “nanoparticles and respirator”, “nanoparticles and leakage”, “nanoparticles and penetration”, “nanoparticles and filter and penetration”, and “nanoparticles and filtration”. Bibliographies of selected articles were also searched for relevant articles. A web-based search of relevant electronic references was performed using the same aforementioned search terms. Using the titles and abstracts obtained from the searches, articles and electronic documents were selected for inclusion in the review based upon the date of publication (focus on articles published since 2000) and relevance to nanoparticles and respiratory protection. Current guidance documents (2006–2008) from consensus standards organizations, safety groups, and government bodies were also reviewed for relevance.

Results

Using the search terms described above, over 500 literature references and hundreds of web pages were initially reviewed. The large number of references available on these topics is a good indicator of the interest in this topic. Because of the large number of references obtained during the computerized literature and electronic searches, the actual number of sources reviewed in detail was prioritized to focus on articles that were most recent (published since 2000) and were relevant for respiratory protection against nanoparticles. For research topics in which few recent papers were available, sources from any time period were reviewed. Sources containing redundant information were also excluded from the review. A total of 43 sources served as the databases for this study, including 26 articles from the peer-reviewed literature, 16 electronic references from consensus standards organizations and governmental agency sources, and one text book.

Discussion

The two respirator types [air purifying respirators (APRs) and powered air purifying respirators (PAPRs)] most commonly used for protection against particulates (including nanoparticles) utilize filter media to collect/trap particles before they reach the users’ breathing zone. NIOSH certifies respirators in accordance with 42 Code of Federal Regulations Part 84 (NIOSH 1995). Among the various test methods and criteria NIOSH uses as part of the certification process, respirator filter performance testing is the one most affected by the particle size. Since respirator users are exposed to a variety of hazards in different scenarios, respirator certification filtration testing was designed to use a combination of very severe and "worst-case" test conditions (e.g., particle size, flow rates, etc.), so that filter performance in the workplace would not be worse (NIOSH 1995). The NIOSH certification test for N-designated respirators uses a polydisperse distribution of NaCl particles with a count median diameter (CMD) of 75 ± 20 nm and a geometric standard deviation (GSD) of <1.86 (NIOSH 2005a). For R- and P-designated respirators, NIOSH tests use a polydisperse distribution of dioctyl phthalate (DOP) particles with a CMD of 185 ± 20 nm and a GSD of <1.60 (NIOSH 2005b). For the log-normal distribution of NaCl aerosols used in the N series certification test, a broad range of particle sizes (e.g., 95% of the particles lie in the range of 22–259 nm) with a mass median diameter (MMD) of about 240 nm and a mass median aerodynamic diameter (MMAD) of about 300 nm is used to determine whether the respirator filter performance is at least 95%, 99%, or 99.97% efficient. Among the various respirator filter designations, N95 is by far the most commonly available followed by P100. A P100 filter is considered to be equivalent to a high efficiency particulate air (HEPA) filter. Most respirators made in the last decade containing N95 filter media use electret filter media. Electret or electrostatic filter media are produced by imparting a static electric charge on non-woven polymer fibers (e.g., polypropylene). Electret filter media are designed to improve the filter collection efficiency of submicron particles, without an increase in breathing resistance (pressure drop). Respirators utilizing electret filter media can generally be made lighter in weight and more compact than those composed of purely mechanical filter media. P100-class respirators can also be made with electret media (Barrett and Rousseau 1998).

A key parameter used in the respirator selection process is the Assigned Protection Factor (APF). The APF is the workplace level of respiratory protection that a respirator or class of respirators is expected to provide an employee when the employer implements a continuing, effective respiratory protection program (OSHA 2006). For APRs typically used for protection against particulate hazards, APF values ranging from 10 for half-mask devices [including filtering facepiece respirators (FFRs)] to 1,000 for PAPRs with a full facepiece. The APF values take into account a variety of factors including the total inward leakage (TIL) caused by: (1) penetration of particles directly through the filter and (2) leakage around the face/seal interface region. An APF of 50 implies that the respirator wearer is expected to have not more than 2% of the ambient particles in the breathing zone. A number of workplace studies have validated that workers receive expected levels of respiratory protection against particulate hazards of the size ranges typically found in most workplaces (Janssen and Bidwell 2007; Janssen et al. 2007). However, no workplace protection factor studies have been conducted on workplaces where significant exposures to nanoparticles are present.

For respiratory protection against nanoparticles, it is important to understand whether nanoparticles behave differently than larger particles in terms of their ability to penetrate directly through the filter or leak around the face/mask interface region.

Filtration and filtration studies

The mechanisms dictating particle capture by filter media are well-described (Hinds 1999). In general, single-fiber filtration theory predicts that particles larger than 300 nm are collected most efficiently by impaction, interception, and gravitational settling, while particles smaller than 200 nm are collected most efficiently by diffusion, electrostatic attraction, or polarization force effects. The intermediate region where none of the mechanisms are dominant is often called the most-penetrating particle size (MPPS). While single-fiber filtration theory is well established, some information gaps—namely, filtration of particles smaller than 20 nm and the MPPS of commercially available respirators—remained until recently.

Table 1 provides a summary of the studies found during the literature review that focus on the filtration performance of respirators against inert nanoparticles. Many of these studies include multiple particle sizes (from nanoparticles through the submicron range), flow rates, and respirator filter types. To simplify interpretation, information on particle penetration levels at the MPPS at a single flow rate (85 l/min) was extracted for the various respirators tested and included in the table. It is important to note that the test methods used by the authors of these studies involve measuring particle counts as a function of particle size and cannot be compared directly to the NIOSH certification criterion, which uses a different test method. The test methods used in Europe and the United States for certification and their relevance to

Table 1 Summary of studies on the filtration performance of respirators against inert nanoparticles (includes only articles that used particles <100 nm and were published in the period 2000–2009)

Study	Respirator type and numbers of models tested	Challenge aerosol	Flow rate (l/min)	MPPS (nm)	Penetration levels at MPPS (%)	Comments
Martin and Moyer (2000)	Three models of N95 FFRs	NaCl	85	50–100	~5.0 to 10.0	Also tested N99, R95, and P100 filter media with NaCl and DOP
Balazy et al. (2006)	Two models of N95 FFR	NaCl	85	40–50	~5.0 to 6.0	
Huang et al. (2007)	One model of N95 FFR	NaCl	85	50	5.8	Also discussed performance of an FFP1 but no penetration data provided
Rengasamy et al. (2007)	Five models of N95 FFR	NaCl	85	~40	1.4–5.2	Compared results with test method similar to NIOSH certification
Rengasamy et al. (2008b)	Two models N95 and two models of P100 FFRs	NaCl, Ag	85	40–50	N95: 2.3–4.3 P100: 0.007–0.009	Used three different test methods and compared results
Eninger et al. (2008b)	Two models of N99 FFRs and one model of N95 FFR	NaCl	85	< 100	N95: 4.8 N99: 4.3–5.9	Also studied other flow rates and particle types
Eshbaugh et al. (2009)	Two models each of N95 FFR and cartridges, P100 FFR and cartridges	NaCl	85	N95: 50 P100: 50–200	N95: 0.7–8.8 P100: 0.0004–0.048	Also studied higher flow rates
Rengasamy et al. (2009)	Two models each of N95, P100, FFP2, FFP3 FFRs	NaCl	85	30–60	N95: 2.3–4.3 P100: 0.007–0.009 FFP2:1.45–2.22 FFP3: 0.15–0.16	Used three different test methods and compared results

nanoparticle filtration are discussed in detail elsewhere (Eninger et al. 2008a; Rengasamy et al. 2009). Furthermore, the various studies referenced in the table use slightly different test systems with different methods for measuring particle sizes and counts. For example, several studies use a Wide Range Particle Spectrometer (WPS) (Balazy et al. 2006; Eninger et al. 2008b), while others use a Scanning Mobility Particle Sizer (SMPS) Spectrometer (Huang et al. 2007; Rengasamy et al. 2007; Rengasamy et al. 2008b, 2009; Eshbaugh et al. 2009).

As seen in Table 1, across the different NIOSH-certified respirator classes (P100, N99, and N95), and European designations (FFP1, FFP2, and FFP3) the MPPS was always at or below 200 nm. In all studies, respirators containing electret filter media consistently have their MPPS below 100 nm. In particular, the MPPS for N95 FFRs was between 40 and 60 nm. Analysis of the information in Table 1 also finds that particle penetration levels at the MPPS can vary widely. For example, Rengasamy et al. (2007) measured particle penetration levels for five different models of N95 FFRs when challenged with 11 different monodisperse NaCl particles ranging in size from 20 to 400 nm. Mean penetration levels for 40 nm particles ranged from 1.4% to 5.2%. Other studies have found particle penetration levels at the MPPS and 85 l/min for NIOSH-approved N95 FFRs as high as 8.8% (Eshbaugh et al. 2009) and ~10% (Martin and Moyer 2000). The wide variation in filtration performance at the MPPS seen from model-to-model can be attributed to a combination of factors including test-to-test variation, variability in the respirator manufacturing process, and respirator design considerations and trade-offs. Some manufacturers design their products to exceed regulatory standards, while others strive only to meet the minimum requirements (e.g., NIOSH certification requirements). Thus, achieving higher laboratory filtration performance at the MPPS may not be a design priority as long as the product meets the minimal requirements using the test method followed by the certification organization.

According to single-fiber filtration theory, below the MPPS, filtration efficiency will increase as particle size decreases. As particles approach molecular size, thermal rebound effects may cause deviation from single-fiber filtration theory. Thermal rebound occurs when the particles bounce through the filter due to their thermal velocity rather than becoming trapped upon collision with a fiber.

As a result, particle penetration through the filter will increase. The exact size at which thermal rebound will occur is unclear. Studies conducted using filter media have shown that there was no discernable deviation from classical single-fiber theory for particles as small as 2.5 nm (Heim et al. 2005; Kim et al. 2006, 2007). This trend also applies to the filters used in respirators. Rengasamy et al. (2008b) measured particle penetration down to 4 nm for NIOSH-certified N95 and P100 filtering facepiece respirators and European-certified FFP2 and FFP3 respirators (Rengasamy et al. 2009) and found no evidence for thermal rebound. Similar observations

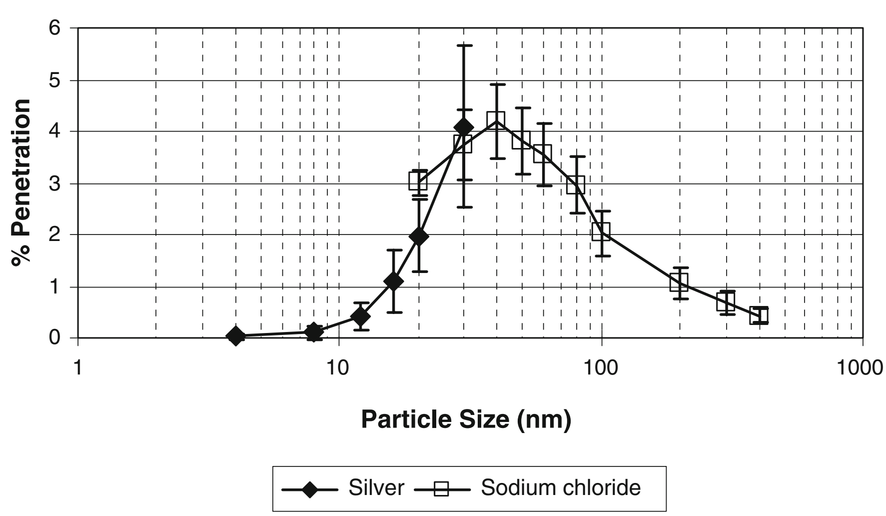

Fig. 1 Monodisperse silver (4–30 nm) and monodisperse NaCl (20–400 nm) aerosol particle penetration levels for one model of an N95 FFR. Each data point represents the mean and standard deviation from the evaluation of five respirators

were made by others for European-certified FFP1 respirators (Huang et al. 2007) and FFP3 filter media (Golanski et al. 2008).

The information in Table 1 and the filtration performance of respirator filter media for nanoparticles can also be illustrated graphically. Figure 1 shows a penetration curve for 4–400 nm size particles for a typical NIOSH approved N95 FFR. The data in this plot were described previously by Rengasamy et al. (2008b). Each data point consists of the average penetration level from replicate ($n = 5$) tests for monodisperse silver (4–30 nm) or monodisperse sodium chloride (20–400 nm) at 85 l/min flow rate. In this plot, the MPPS is 40 nm and the average penetration at the MPPS for this N95 FFR is 4.2%. As predicted by single-fiber filtration theory, particle penetration levels decline as particle size decreases below the MPPS. In this size region, diffusion provides significant opportunities for the particles to become trapped by the fibers.

While the MPPS values seen in Table 1 are consistently <200 nm, some variation can be seen and further discussion is necessary. The type of filter media (e.g., electret versus mechanical) used in the respirator plays the predominant role in defining its MPPS. Traditional single-fiber filtration theory predicts an MPPS of approximately 200–400 nm using modeling parameters associated with mechanical filters. Recent research has shown that once polarization forces for charged fibers are factored into those models, the MPPS values for electret media fall below 100 nm, consistent with the values seen in Table 1 (Balazy et al. 2006). Another parameter that affects the MPPS for a given respirator is the test conditions used. For example, the flow rate and breathing pattern play an important role (Haruta et al. 2008; Eshbaugh et al. 2009). In general, the MPPS shifts to a smaller particle size range at higher flow rates.

The impact of the MPPS falling within the nanoparticle size region also needs to be addressed. In the development of the test method used for NIOSH respirator certification, penetration of approximately 300 nm (MMAD) particles was considered to be the worst case because these particles were considered to be in the MPPS range (NIOSH 1995). However, as seen in Table 1 and discussed above, for electret filter media commonly in use today, the MPPS has shifted to the nanoparticle range which creates a challenge for the test protocol used for NIOSH respirator certification. In the NIOSH certification test protocol, most of the particles penetrating through the filter are measured simultaneously using a forward light scattering photometer (i.e., mass-based detection). As discussed previously, the NIOSH certification protocol uses a polydisperse challenge aerosol of either NaCl (75 ± 20 nm, CMD) or DOP (185 ± 20 nm, CMD). Similarly, the European certification test method also uses a polydisperse aerosol challenge and involves mass-based detection using photometry. Photometers measure the amount of light scattered by the particles in the light path and is proportional to aerosol mass over certain size ranges (Eninger et al. 2008a). However, as noted in a recent review, this type of instrumentation (e.g., TSI 8130) is not capable of measuring the light scattering of all particles <100 nm (Eninger et al. 2008a). It has been suggested that NIOSH may want to consider future revisions to the filtration test used for certification to include a count-based method (Eninger et al. 2008a). As noted in several studies (Martin and Moyer 2000; Rengasamy et al. 2007; Eninger et al. 2008a), penetration levels for monodisperse particles measured using a particle counter (count-based) were higher than penetration levels measured using a photometric detector (mass-based).

To better understand the relationships between the mass-based particle detection scheme used in the NIOSH certification test and the count-based detection methods highlighted in Table 1, Rengasamy and co-workers investigated the correlation between particle penetration levels measured using the existing NIOSH certification protocol for N series APRs and the particle penetration levels found using monodisperse particles at the MPPS (using a condensation particle counter). In one study, they found a good correlation ($r = 0.95$) for five N95 FFRs (e.g., respirators that performed better using the NIOSH certification test also had higher filter efficiencies against monodisperse 40 nm nanoparticles). A similar observation was found in a subsequent study (Rengasamy et al. 2009) involving N95, FFP2, FFP3, and P100 class respirators.

Figure 2 is a plot showing the correlation of the particle penetration levels found by the mass-based (TSI 8130 used in the NIOSH certification test) and the counting-based method (TSI 3160 used in the Rengasamy studies cited in Table 1) using the combined data from two studies (Rengasamy et al. 2007, 2009).

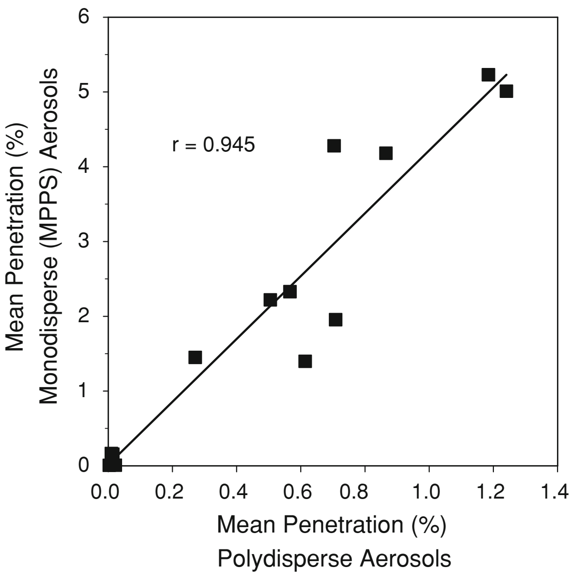

Fig. 2 Correlation of polydisperse (nominal CMD 75 nm with GSD <1.86) and monodisperse MPPS (30–60 nm) sodium chloride aerosol penetrations for N95, P100, FFP2, and FFP3 filtering facepiece respirator models tested in previous studies. Results demonstrate that particle penetration levels seen at the MPPS (from a count-based method) are correlated with penetration levels measured using the polydisperse test aerosol test (mass-based method)

As expected, a good correlation ($r = 0.945$) was found. Thus, respirators with smaller particle penetration levels measured using the mass-based method (used in the NIOSH certification test) also have lower monodisperse particle penetration levels at the MPPS. Establishing a good correlation between the two methods is not surprising given that changes in filtration performance follow a consistent trend as a function of particle size (see Fig. 1). The ability to use the mass-based filtration testing equipment, which are much easier to maintain and less expensive to purchase than count-based filtration test equipment, to estimate filtration performance for nanoparticles is important since it can be used to screen out respirators with poorer laboratory filtration performance. Indeed, in a study on the filtration performance of dust masks (i.e., facemasks that are not NIOSH approved) against nanoparticles, the mass-based filtration test (using the TSI 8130) provided a good estimate ($r = 0.99$) of particle penetration levels for dust masks at their MPPS (Rengasamy et al. 2008a). The two dust masks with penetration levels between 5% and 15% (using the mass-based filtration test) exhibited monodisperse particle penetration levels at the MPPS of 14.7% and 24.2%, while the best performing dust mask (1.0% penetration using the mass-based filtration test) also had the best count-based laboratory filtration performance (monodisperse particle penetration of 4.3% at the MPPS).

Face seal leakage studies

Face seal leakage at the interface region where the respirator comes in contact with the wearer's face is a major component of TIL. Achieving good fit is critical for reducing worker exposure to an inhalation hazard (including nanoparticles) via respiratory protection. Thus, OSHA's respiratory protection standard makes fit testing, a requirement to ensure that a specific respirator model and size provides an acceptable fit to that worker. However, even a respirator that provides an acceptable level of fit can only reduce worker exposure and not eliminate exposure completely. There will always be some leakage resulting from gaps in the face/mask interface region. The overall amount of leakage expected during respirator use is reflected in the APF value designated for each respirator type. Thus, FFRs with an APF of 10 are expected to have higher leakage than a full facepiece respirator with an APF of 50. The question that often arises is whether nanoparticles are more or less likely to penetrate through gaps in the face sealing area than larger particles or gases and vapors. Unfortunately, there is no data specific to respirator face seal leakage of nanoparticles, although numerous studies on larger particles and gases/vapors have been performed.

One of the first face seal leak studies of particles was by Hinds and Kraske (1987). They evaluated the performance of half-mask and single-use respirators by investigating particle penetration and leaks. The respirator was mounted on a manikin in a chamber and exposed to 100–11,344-nm-sized oleic acid particles. Particle penetration through the filter and the artificially induced leaks were measured at different flow rates between 2–150 L/min. The results showed that particle leakage depended on particle size, although penetration levels were similar for particle sizes <1,000 nm. Similar studies were carried out using a human subject for particles ranging from 70 to 4,400 nm size (Holton et al. 1987). Leakage of particles through three holes in the body of a half-mask respirator was measured. They also saw little difference in penetration (leakage) for particles between 200 and 1,000 nm. Similar to Hinds and Kraske, penetration levels dropped off significantly for particles larger than 1,000 nm. A unique finding of the Holton study was the decrease in leakage for particles $<$200 nm. These findings were attributed to inertial entry losses for particles $>$1,000 nm and diffusional losses of particles $<$200 nm. Subsequent studies confirmed that aerosol penetration is only moderately dependent upon particle size in the submicron ($<$1,000 nm) range, but the particle size is a major factor for particles larger than 1,000 nm (Chen et al. 1992).

Other studies investigated the face/mask interface leakage using test agents of different physical states such as aerosols and gases. Myers et al. (1991) evaluated quantitative assessments of face seal leakage as a function of leak size, particle size, and physical state of the test material using a manikin test system coupled to a breathing machine. Polystyrene latex beads (PSL) and acetone vapor were the challenge agents in this study. Leakage of PSL particles decreased with increasing diameter size from 0.36 to 2.5 μm. They also showed that the leakage of acetone vapor was higher than that of PSL particles, suggesting that fit test utilizing a gaseous challenge agent may be a more critical test in terms of leakage than fit tests utilizing an aerosol. These findings were partially refuted in a more recent study comparing the fit factors measured using vapor challenges to those measured using an aerosol challenge (Gardner et al. 2004). A control aerosol (720 nm) and test vapors including sulfur hexafluoride (SF_6) and isoamyl acetate (IAA) were used for the leakage studies through full facepiece respirators using a manikin head form. The simulated respiratory fit factor measurements for the monodisperse control aerosol correlated with SF_6 and IAA. This study suggested that the leakage of submicron particles was similar to that of vapor challenges in mask studies. The study also found that vapor challenges can interact with mask materials making correlation studies with aerosols (that do not interact with mask materials) challenging.

The leakage studies discussed earlier are somewhat limited because they tend to isolate the face seal leakage component by artificially creating controlled leak sites of different sizes. In general, artificial static leaks on manikins or headforms are not representative of leaks found on respirators when worn by humans. During normal respirator wear, studies have shown that leak sites tend to be dynamic and fluctuate in size (Krishnan et al. 1994; Janssen and Weber 2005; Janssen et al. 2007). Furthermore, the sheer number of parameters that affect these kinds of face seal leakage measurements (e.g., particle size, leak size/shape, flow rate, design/size/location/depth of sampling probe, mixing inside the respirator, particle charge, etc.) make comparison across studies difficult.

However, some common themes from the literature do emerge. The controlled studies suggest that particle leakage is influenced by a number of factors including particle size. More importantly, the data suggest that particles are unlikely to penetrate through gaps caused by poor fit more than gases and vapors. Additional information on nanoparticle leakage can also be obtained from research studies on respirator fit test methods. A commonly used fit test method uses ambient particles to measure fit factors. One version (Portacount® Pro Respirator Fit Tester, model 8030) measures ambient particles ranging from 20 to ~1,000 nm, while the other version (Portacount® Pro+ Respirator Fit Tester, model 8038) only measures ambient nanoparticles in the 40–60 nm range. Various laboratory studies have validated the use of ambient and generated aerosol (e.g. corn oil) fit test methods. For example, one study found that fit factors measured using ambient and generated aerosol fit tests correlated (R^2 values of 0.78 and 0.81, respectively) with Freon-113 exposures (Coffey et al. 1998). Thus, respirator fit tests using ambient or generated aerosol-based methods should provide users assurance that they are obtaining expected levels of protection regardless of the physical state of the contaminant. More studies are needed to confirm that this trend holds for smaller nanoparticles as well. Toward this objective, NIOSH has initiated studies to determine whether face seal leakage of nanoparticles is consistent with the leakages observed for gases/vapors and larger particles.

Protection factor studies

The studies described in the two previous sections focus on the two primary components of TIL, namely, filter penetration and face seal leakage. However, studies that measure protection factors (or TIL) in laboratory or workplace settings involving human test subjects will provide more information on the relative contributions of these sources and will enable more informed respirator selection decisions. Unfortunately, protection factor studies are challenging to perform. The inherent difficulties in measuring nanoparticles further complicate the matter. Thus, no WPF studies utilizing workers exposed to nanoparticles have been performed to date. This is an area where additional research is needed.

While no WPF studies have been done using nanoparticles, several studies have focused on larger particles. For example, studies using half-mask N95 FFRs (Janssen et al. 2007) and full facepiece APRs (Janssen and Bidwell 2007) have confirmed that respirator performance is consistent with APF values, when used in the context of a respiratory protection program including fit testing.

A unique laboratory-based approach to measuring TIL as a function of particle size was recently described (Lee et al. 2008). In their study, four NIOSH-certified N95 FFR models were donned by human test subjects and exposed to 40–1,300 nm particles as measured by an electrical low pressure impactor (ELPI). Protection factors were smallest for particles between 80 and 200 nm (aerodynamic diameter). The geometric mean of the protection factors for all four models across all particle sizes tested was 21.5; however, wide model-to-model variation was observed, suggesting that some of the FFR models may not be able to achieve their expected APF levels at some particle sizes. These interesting findings provide further support for the need for WPF studies.

Respirator recommendations

Table 2 is a summary of recent recommendations from internationally recognized consensus standards organizations (CSOs), government agencies, and a representative university safety organization. Analysis of these recommendations provides a "window" into how the research discussed above is being put into practice. The lack of occupational exposure

Table 2 Summary of recent respirator recommendations from consensus standards organizations, safety organizations, and government agencies to reduce nanoparticle inhalation exposure

Organization	Chemical(s)	Recommendation
NIOSH (2005c)	Ultrafine titanium dioxide	For most job tasks involving only TiO_2 exposure a properly fit-tested half-facepiece particulate respirator will provide protection up to 10 times the respective REL[a]
NIOSH (2006)	General	States "NIOSH-certified respirators should provide the expected levels of protection"
ASTM (2007)	General	Refers to the U.S. NIOSH Approaches to Safe Nanotechnology (NIOSH 2006) for most current guidance on respirator protection for nanomaterials
FIOSH (2007)	General	Where technical protection measures are not sufficient or cannot be put into place, personal protection measures—such a respiratory protection (e.g. filters of protection levels P2, FFP2, P3 or FFP3, to be selected in the hazard assessment)—are a suitable step
IRSST (2007)	General	Wearing a full-face mask with high performance filters (over 99.97% efficient) is recommended
BSI (2008)	General	High efficiency filters (P3 and FFP3 type) should always be used
ISO (2008)	General	The choice of respirator type will depend upon the specific task and the materials being handled
MIT's EHS Office (2008)	General	Recommends disposable P100 respirators
U.S. DOE (2008)	General	If respirators are to be used for protections against engineered nanoparticles, select and use half-mask, P100 cartridge-type respirators or respirators that provide a higher level of protection
U.S. EPA (2008)	Siloxane-modified alumina nanoparticles	Recommends NIOSH-approved respirator with an OSHA Assigned protection factor of at least 10
U.S. EPA (2008)	Siloxane-modified silica nanoparticles	Recommends NIOSH-approved respirator with an OSHA assigned protection factor of at least 10

[a] REL is recommended exposure limit

limits (OELs) for many types of nanomaterials makes specific recommendations difficult. Although industrial hygienists and safety professionals do have preliminary TiO_2 exposure limits from NIOSH (2005c), recent guidance from the British Standards Institute (BSI 2008) with size specific risk assessment information, and a recent pre-manufacturing notice for siloxane-modified silica and alumina nanoparticles from the Environmental Protection Agency (EPA 2008) to use as starting points for risk assessment. All the organizations recognize that respiratory protective devices will reduce worker exposure to airborne nanoparticles. The range of respirator types recommended span the gamut from disposable FFRs and half-mask APRs (with an OSHA APF of 10) to full facepiece APRs (with an OSHA APF of 50). Although the filter media rating will not change the APF value for a given respirator type, several organizations advised the use of P100 (or the European equivalent P3/FFP3) filter media. This suggestion may be reasonable for workplace settings in which worker exposure consists of a large percentage of nanoparticles near the MPPS for N95, P2/FFP2, or P1/FFP1 rated filters. In fact, in the OSHA APF final rule discussion, it was recommended that employers take this information into account during the respirator selection process. As noted earlier (Rengasamy et al. 2007), this could be accomplished by choosing a respirator with a higher APF or by choosing a respirator with higher level of laboratory filtration performance (e.g., changing from an N95 to a P100).

Conclusions

Recent data demonstrate that single-fiber filtration theory can be used to describe the filtration performance of the types of filters used in APRs against particles <100 nm in size. The MPPS is in the 30–100 nm range, but can vary based upon the type of filter media and the test conditions. Laboratory filtration of monodisperse nanoparticles at the MPPS has also been shown to vary widely (e.g., 1.4 to ~10% for N95 FFRs), even for commercially available respirators that have been certified to an internationally recognized filtration performance standard. Several studies have confirmed that no evidence for thermal rebound effects was seen for particles as small as 4 nm. Nanoparticles are expected to have lower abilities to penetrate the face seal interface area than larger particles, but the question of particle-size-dependent leakage has not been fully answered. Limited studies have been done with >100 nm particles, and results between studies are often difficult to compare. The greatest need for further research involves human laboratory or workplace studies (e.g., WPF studies) to measure TIL for respirators used for protection against nanoparticles. Analysis of the scientific data summarized in this paper from studies on laboratory filtration performance, face seal leakage, and TIL suggest that industrial hygienists and safety professionals should continue to use traditional respirator selection guidance based on OSHA APF values until WPF studies can be performed, which can serve as the basis for updated recommendations.

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