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Simple Respiratory Protection—Evaluation of the Filtration Performance of Cloth Masks and Common Fabric Materials Against 20–1000 nm Size Particles

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A shortage of disposable filtering facepiece respirators can be expected during a pandemic respiratory infection such as influenza A. Some individuals may want to use common fabric materials for respiratory protection because of shortage or affordability reasons. To address the filtration performance of common fabric materials against nano-size particles including viruses, five major categories of fabric materials including sweatshirts, T-shirts, towels, scarves, and cloth masks were tested for polydisperse and monodisperse aerosols (20–1000 nm) at two different face velocities (5.5 and 16.5 cm s^{-1}) and compared with the penetration levels for N95 respirator filter media. The results showed that cloth masks and other fabric materials tested in the study had 40–90% instantaneous penetration levels against polydisperse NaCl aerosols employed in the National Institute for Occupational Safety and Health particulate respirator test protocol at 5.5 cm s^{-1}. Similarly, varying levels of penetrations (9–98%) were obtained for different size monodisperse NaCl aerosol particles in the 20–1000 nm range. The penetration levels of these fabric materials against both polydisperse and monodisperse aerosols were much higher than the penetrations for the control N95 respirator filter media. At 16.5 cm s^{-1} face velocity, monodisperse aerosol penetrations slightly increased, while polydisperse aerosol penetrations showed no significant effect except one fabric mask with an increase. Results obtained in the study show that common fabric materials may provide marginal protection against nanoparticles including those in the size ranges of virus-containing particles in exhaled breath.

Keywords: fabric material; H1N1; H5N1; infectious aerosol; influenza; pandemic; particle penetration; respiratory protection

INTRODUCTION

The outbreaks of avian influenza A (H5N1) and the recent novel influenza virus A (H1N1) pandemic are major health problems (WHO, 2006, 2009). To reduce exposure to infectious influenza aerosols, several government agencies and nongovernment organizations have recommended a number of nonpharmaceutical interventions, including respiratory protection. The Centers for Disease Control and Prevention (CDC) recommends the use of National Institute for Occupational Safety and Health (NIOSH)-approved respirators for reducing exposure to infectious aerosols such as those that cause severe acute respiratory syndrome (SARS) and novel influenza (H1N1) (CDC, 2001, 2003, 2004, 2009). The use of large number of respirators created a demand during the spread of SARS in the USA (Srinivasan *et al.*, 2004). Recently, CDC predicted that the need for disposable N95 respirators could exceed 90 million for the protection of healthcare

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workers for an outbreak of 42 days of influenza A (H5N1), indicating a possible shortage of respirators (Bailar *et al.*, 2006; CDC, 2006).

The issue of a respirator shortage during a widespread influenza pandemic was addressed by the Institute of Medicine (IOM), which released a report entitled 'Reusability of Facemasks during an Influenza Pandemic. Facing the flu' (Bailar *et al.*, 2006). One of the recommendations was to conduct research on the effectiveness of woven cloth masks for the transmission of influenza virus because cloth masks may be the only option available for some individuals during a pandemic. Research on alternative respiratory protective materials, including common fabric materials such as T-shirts, handkerchiefs, and scarves, was also recommended (Bailar *et al.*, 2006). In the absence of respirators, some individuals may use improvised common fabric materials for respiratory protection while entering a contaminated environment, such as when caring for an infected family member at home. These household materials are not designed for respiratory protection and their use may provide a false sense of protection because their effectiveness against larger and <1000 nm size particles including viruses is not well understood. This indicates that further studies are needed to better understand the filtration performance of cloth masks and common fabric materials against a wide range of particle sizes, including the size of many viruses.

The knowledge on the filtration performance of improvised materials for particulates is limited, however. Previous studies challenged the improvised materials with large-size biological and inert particles and reported varying levels of protection for different size particles (Guyton *et al.*, 1959; Cooper *et al.*, 1983a,b). In one study, the filtration efficiency of a number of fabric materials was tested using human subjects. The authors reported that the filtration efficiency of single layer of bath towel, cotton shirt, handkerchief, and other materials was in the 28–73% range against *Bacillus globigii* aerosols of 2000 nm mass median diameter (Guyton *et al.*, 1959). Another study measured the effectiveness factor obtained from filtration efficiency and pressure drop for different common fabric materials using a manikin (Cooper *et al.*, 1983a). Fabric materials were challenged with mineral oil aerosol particles of 410–4800 nm diameter size and the effectiveness factor calculated. For many fabric materials including shirt, sheet, towel, and handkerchief, the effectiveness factor decreased with decreasing particle size from 4800 to 410 nm, indicating further decrease in the respiratory protection for virus-containing particles <410 nm (Cooper *et al.*, 1983a).

Recent studies showed that patients, as well as control subjects, generate significant levels of submicron as well as larger size particles including the size of many viruses during breathing, coughing, and talking (Fairchild and Stampfer, 1987; Papineni and Rosenthal, 1997; Edwards *et al.*, 2004; Yang *et al.*, 2007; Fabian *et al.*, 2008; Blachere *et al.*, 2009; Lindsley *et al.*, 2010). Although some viruses can be quite small (~20 nm), they are often generated by humans as larger size particles (e.g. attached to mucus secretions). For example, one study (Fabian *et al.*, 2008) showed 87% of particles in exhaled breath of influenza-infected patients were under 1000 nm in diameter and the rest of the particles larger than that size. Similarly, the transmission of infectious diseases through exposure to smaller and >1000 nm size aerosols has been reviewed (Fiegel *et al.*, 2006; Hall, 2007). Although much debate still exists on the relative contributions of the various routes of disease transmission (e.g. inhalation, contact, and droplet) (IOM, 2009), infected individuals produce smaller size particles (<1000 nm) that can travel long distances and larger size particles (~10000 nm) capable of reaching shorter distances. Some individuals may improvise fabric materials for emergency respiratory protection to reduce inhalation of infectious aerosols, indicating the need for further studies to assess their filtration performance against a wide range of particle sizes. In this study, household fabric materials and cloth masks were challenged with polydisperse as well as monodisperse particles in the 20–1000 nm size range, which include the size of many viruses and initial penetration levels measured and compared with those values obtained for N95 respirator filter media. In this study, we hypothesized that cloth masks and fabric materials would capture some aerosol but would exhibit high variability because they were not designed for that purpose.

MATERIALS AND METHODS

Fabric materials

Common fabric materials of five major categories including sweatshirts, T-shirts, towels, scarves, and cloth masks were selected for aerosol penetration tests (Table 1). Table 1 also shows the fiber composition of fabric materials and the resistance levels measured at 5.5 cm s^{-1} face velocity. The fiber composition for cloth masks is not available. Fabric materials for each category were randomly selected

Table 1. Fabric materials tested for particle penetration measurements

Fabric material	Description	Model 1	Model 2	Model 3
Cloth mask	Brand name	Respro	Breathe Health	Breathe Health
		Bandit Mask	Cloth Mask	Fleece Mask
	Fiber composition	Not available	Not available	Not available
	Resistance (mm water)	2.0 ± 0.3	3.2 ± 0.7	1.2 ± 0.1
Sweatshirt	Brand name	Norma Kamali Tunic	Hanes	Faded Glory
	Fiber composition	85% Cotton/ 15% polyester	70% Cotton/ 30% polyester	60% Cotton/ 40% polyester
	Resistance (mm water)	2.0 ± 0.1	1.1 ± 0.1	0.4 ± 0.1
T-shirt	Brand name	Dickies	Hanes	Faded Glory
	Fiber composition	99% Cotton/ 1% polyester	100% Cotton	60% Cotton/ 40% polyester
	Resistance (mm water)	1.6 ± 0.2	1.6 ± 0.1	0.9 ± 0.1
Towel	Brand name	Pem America	Pinzon	Aquis
	Fiber composition	100% Cotton	100% Cotton	80% Polyester/ 20% nylon
	Resistance (mm water)	3.8 ± 0.2	7.9 ± 0.8	3.7 ± 0.2
Scarf	Brand name	Today's Gentleman	Walmart	Seed Supply
		Pocket square	Fleece	Cotton
	Fiber composition	100% Cotton	100% Polyester	100% Cotton
	Resistance (mm water)	5.9 ± 0.1	2.0 ± 0.1	1.4 ± 0.1

Fabric material composition and airflow resistance measured at 5.5 cm s^{-1} face velocity. 1 mm water gauge = 0.133 kPa.

from three different manufacturers based on availability. The commercial cloth masks were advertised as pollution and allergen masks and did not make any claim as to their effectiveness for submicron-size particles. It should be noted that none of the other fabric materials was designed to be used as a filtering media. N95 respirator filter media was tested in parallel with the fabric materials for comparison of the filtration performance against submicron-size aerosol particles.

Polydisperse aerosol penetration test method

Three samples from each fabric materials were tested for polydisperse NaCl aerosol (75 ± 20 nm count median diameter and a geometric standard deviation not exceeding 1.86) penetrations with a TSI 8130 Automated Filter Tester (TSI 8130) used for NIOSH particulate respirator certification (NIOSH, 2007). Penetration levels for 100 cm^2 samples were measured at two different face velocities 5.5 and 16.5 cm s^{-1} corresponding to 33 and 99 l min^{-1} flow rates. A standard face velocity of 5.3 cm s^{-1} is employed for testing various filter media. In this study, a face velocity closer to this value, i.e. 5.5 cm s^{-1}, and a relatively higher face velocity, 16.5 cm s^{-1}, were employed for testing the filtration performance of fabric materials. The flow rates are based on the area of the fabric material tested to achieve the face velocities employed in the study. Initial penetration levels of NaCl particles were measured for 1 min with no loading as conducted in the NIOSH 42 CFR 84 test protocol. Percentage penetration was determined as the ratio of particle concentration downstream to upstream multiplied by 100. Polydisperse aerosol is commonly used for filtration performance testing and allows comparison to standard filters made (N95, P2, P3, high efficiency particulate air, etc.).

Monodisperse aerosol penetration test method

Another set of three samples from each group of the same fabric models was tested against monodisperse NaCl particles using a TSI 3160 Fractional Efficiency Tester (TSI 3160) as described previously (Rengasamy *et al.*, 2007). Similar to polydisperse aerosols, penetration levels for 100 cm^2 samples were measured at face velocities 5.5 and 16.5 cm s^{-1}. Initial percentage penetration levels for 10 different monodisperse aerosols (20, 30, 40, 50, 60, 80, 100, 200, 300, and 400 nm) were measured for each sample. These monodisperse aerosol tests were conducted to better understand the filtration performance against <400 nm size particles. This size range is necessary to determine the aerosol size range of minimum efficiency.

Penetration of NaCl particles as a function of particle size from 500 to 1000 nm

Penetration levels for larger size particles (500–1000 nm) were measured as a function of particle size. Polydisperse NaCl aerosols were generated using a constant output atomizer (Model 3076; TSI, Inc.) and passed through a dryer, a ^{85}Kr neutralizer, and then into the Plexiglas box containing the test fabric material. The upstream and downstream aerosol number concentrations and size distributions (500–1000 nm range) were measured for 2 min alternately using a scanning mobility particle sizer (SMPS 3080; TSI, Inc.) in scanning mode and an ultrafine condensation particle counter as described previously (Rengasamy *et al.*, 2009a). Percentage penetration was calculated from the ratio of the particle number concentration downstream to the concentration upstream. These monodisperse aerosol tests were conducted to better understand the filtration performance against 500–1000 nm size particles.

Data analysis

The data were analyzed using the SigmaPlot® (Jandel Corporation) computer program. Average penetration values and 95% confidence intervals were calculated for each model.

RESULTS

Polydisperse aerosol penetrations

Average penetration levels for the three different cloth masks were between 74 and 90%, while N95 filter media controls showed 0.12% at 5.5 cm s^{-1} face velocity (Fig. 1). The penetration levels increased significantly for the N95 control filter media but remained <5%, while none of the fabric materials showed any significant increase at 16.5 cm s^{-1} face velocity. Figure 2 shows polydisperse aerosol penetration levels for sweatshirts and T-shirts. Of the three sweatshirts, one model (Hanes) showed 40% penetration level at 5.5 cm s^{-1}, which increased to 57% at 16.5 cm s^{-1} face velocity. The other two models (Norma Kamali and Faded Glory) showed penetration levels in the 70–82% range at both

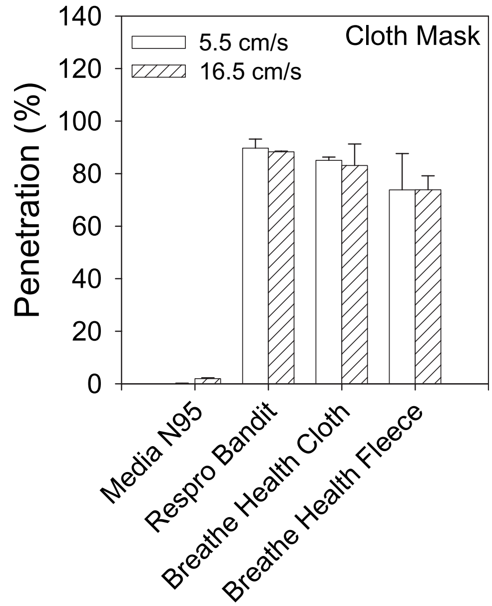

Fig. 1. Polydisperse NaCl aerosol penetration levels for cloth masks at two different face velocities. Error bars indicate 95% confidence level.

5.5 and 16.5 cm s^{-1} face velocities (Fig. 2a). At the same time, T-shirts showed penetration levels >86% at 5.5 cm s^{-1} with no significant increase at 16.5 cm s^{-1} (Fig. 2b). Average penetration levels for the three different model towels and scarves were in the 60–66% and 73–89% ranges, respectively, with no significant increase at 16.5 cm s^{-1} (Fig. 3a,b). Table 1 shows airflow resistance (in millimeter water) at 5.5 cm s^{-1} face velocity. In general, the resistance levels were less than or comparable to N95 filter material employed in the study (9.8 ± 0.2 cm water gauge; 1 cm water gauge = 1.33 kPa). A cotton towel model (Pinzon) and a scarf material (Today's Gentleman) showed slightly higher resistance levels than the other fabric materials. Slightly higher airflow resistance levels were obtained at 16.5 cm s^{-1}.

Monodisperse aerosol penetrations

Penetration levels for monodisperse aerosol particle (20–400 nm range) were combined with those for 500–1000 nm range particles measured as a function of particle size. For the cloth masks, monodisperse aerosol penetration levels (35–68%) for 20 nm size particles increased steadily, reached maximum (73–82%) at 100 nm range, plateaued up to 400 nm, and increased slightly up to 1000 nm at 5.5 cm s^{-1} face velocity (Fig. 4a). Slightly higher penetration levels were obtained at 16.5 cm s^{-1} face

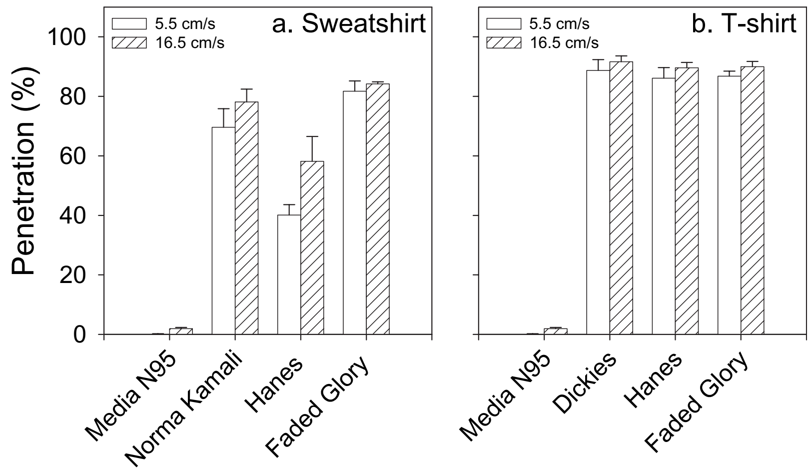

Fig. 2. Polydisperse NaCl aerosol penetration levels for sweatshirts and T-shirts at two different face velocities. Error bars indicate 95% confidence level.

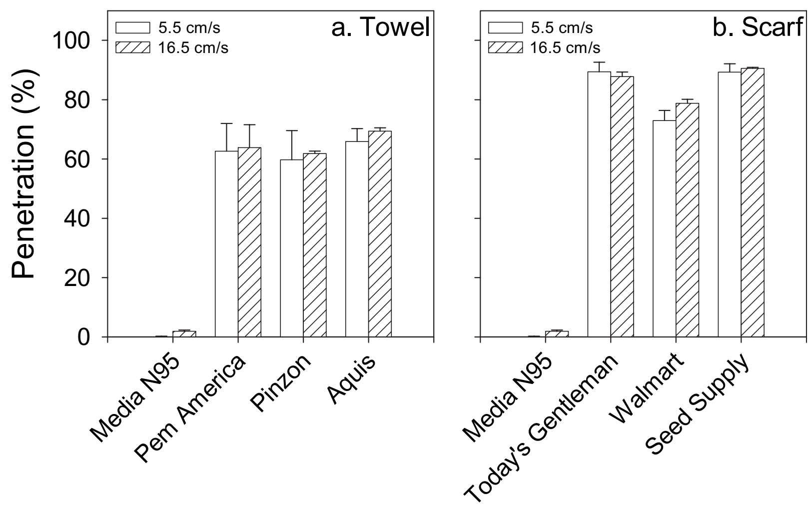

Fig. 3. Polydisperse NaCl aerosol penetration levels for towels and scarves at two different face velocities. Error bars indicate 95% confidence level.

velocity for the different size particles (20–1000 nm range) (Fig. 4b). Penetration levels for the three sweatshirt and T-shirt models were, respectively, in the 30–61% and 56–79% ranges for 20-nm size particles and increased to 80–93% and 89–97% for 1000 nm particles (Fig. 5a,c). A slight increase in penetration levels was obtained for 20–1000 nm size particles, which remained the same or decreased slightly with increasing particle sizes at 16.5 cm s^{-1} face velocity (Fig. 5b,d). In the case of towels and scarves, penetration levels varied from 9 to 74% for 20 nm size particles and increased monotonically at 5.5 cm s^{-1} face velocity (Fig. 6a,c). Penetration levels of different size particles increased at 16.5 cm s^{-1} face velocity at varying levels (Fig. 6b,d).

DISCUSSION

The results obtained in the study showed that cloth masks and other fabric materials tested in the study had 40–90% instantaneous penetration levels when challenged with polydisperse NaCl aerosols employed in the NIOSH particulate respirator test protocol at a face velocity of 5.5 cm s^{-1}. Similarly, varying levels of penetrations (9–98%) were

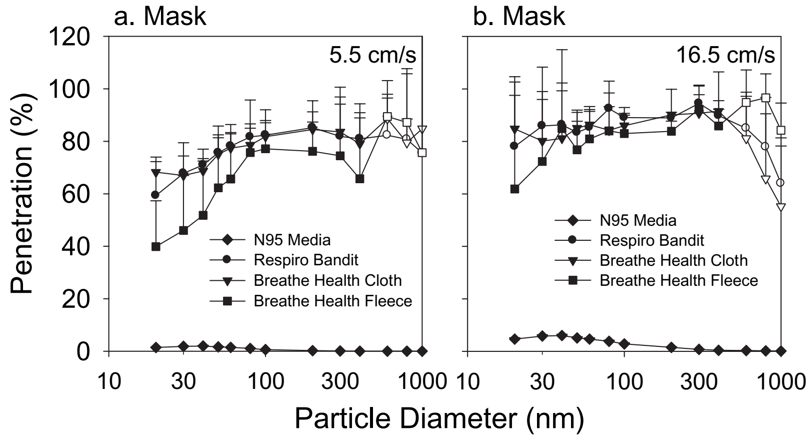

Fig. 4. Monodisperse aerosol penetration levels for cloth masks at two different face velocities. Error bars indicate 95% confidence level (closed symbols, TSI 3160 and open symbols, SMPS).

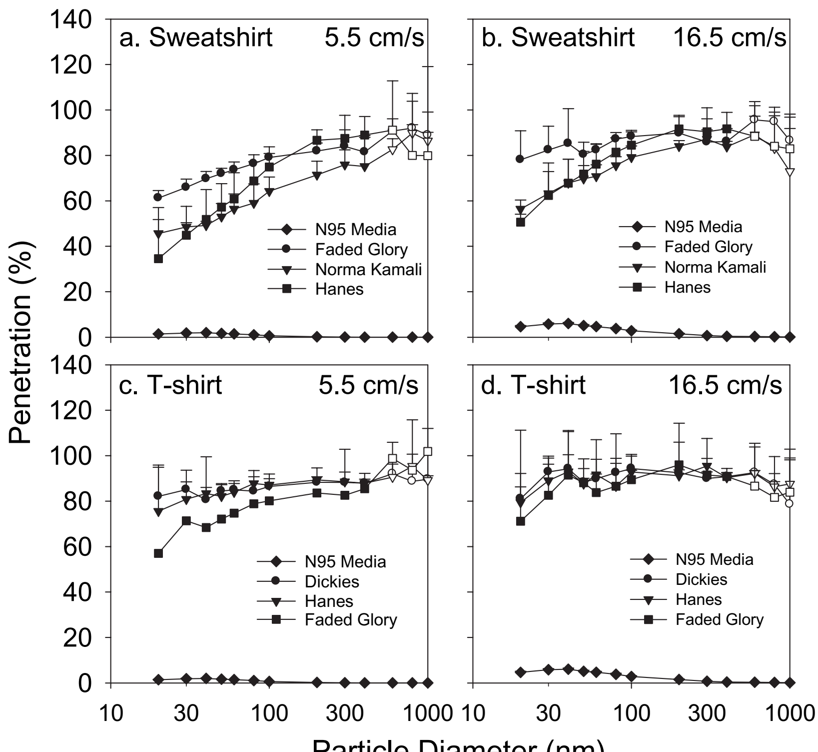

Fig. 5. Monodisperse aerosol penetration levels at two different face velocities for sweatshirts (a and b) and T-shirts (c and d). Error bars indicate 95% confidence level. (closed symbols, TSI 3160 and open symbols, SMPS).

obtained for different size monodisperse NaCl aerosol particles in the 20–1000 nm range. Monodisperse aerosol penetration curves for many fabric materials were similar to the curve for a mechanical filter indicating that electret charge was not incorporated in the fabric materials tested in the study. The penetration levels for these fabric materials against polydisperse, as well as monodisperse aerosols, were much higher than the values for the control N95 respirator filter media. A poor filtration performance is

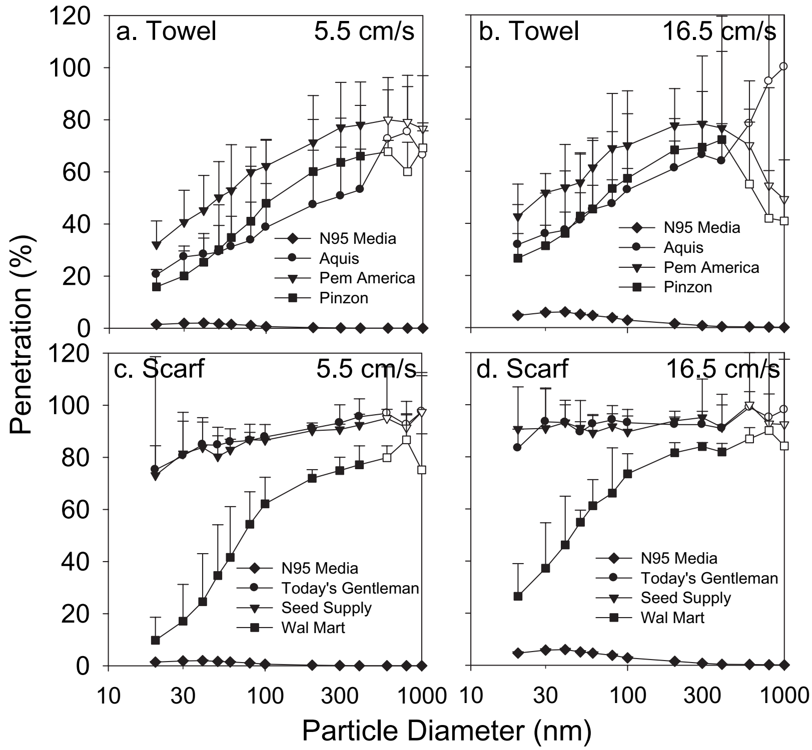

Fig. 6. Monodisperse aerosol penetration levels at two different face velocities for towels (a and b) and scarves (c and d). Error bars indicate 95% confidence level. (closed symbols, TSI 3160 and open symbols, SMPS).

expected for improvised fabric materials because these materials are not designed for respiratory protection.

The wide variation in penetration levels obtained for many fabric materials tested in our study agree with the penetration results reported previously (Guyton *et al.*, 1959; Cooper *et al.*, 1983a). For example, the filtration efficiency (i.e. inverse of the penetration) of fabric materials was in the range of 3–33% (penetration range 67–97%) for 1000 nm particles at 5.5 cm s^{-1} face velocity that is comparable to the filtration efficiency (27–73%) of single-layer fabric materials against *B. globigii* particles (2000 nm) at a breathing flow rate of 10 l min^{-1} (Guyton *et al.*, 1959). The increase in efficiency can be attributed to the efficient capturing of larger size *B. globigii* particles. Similarly, the penetration values measured in our study 56–94% and 67–97% for 400 and 1000 nm size particles, respectively, at 5.5 cm s^{-1} face velocity are similar compared to 54 and 59% penetrations for 400 and 1000 nm size particles, respectively, at 1.5 cm s^{-1} face velocity reported previously (Cooper *et al.*, 1983a).

The filtration efficiency of improvised fabric materials is comparable to some commonly used Federal Drug Agency-cleared surgical masks and unapproved dust masks (Oberg and Brosseau, 2008; Rengasamy *et al.*, 2008; Rengasamy *et al.*, 2009b). For example, previous studies showed that some surgical masks had high penetration levels against similar size polydisperse as well as monodisperse aerosols at a similar face velocity (Rengasamy *et al.*, 2009b). Two of the five surgical masks showed 51–89% penetration levels against polydisperse aerosols. Similarly, three dust mask models had high penetration levels (81–89%) for polydisperse aerosol particles (Rengasamy *et al.*, 2008). Thus, the penetration results obtained in the study indicate that the filtration performance of fabric materials is similar in some aspects to some surgical masks to reduce the transmission of infectious diseases. However, this study did not evaluate the fabric materials for protection against droplets and liquid splashes.

The use of fabric materials may provide only minimal levels of respiratory protection to a wearer against virus-size submicron aerosol particles (e.g. droplet nuclei). This is partly because fabric materials show only marginal filtration performance against virus-size particles when sealed around the edges. Face seal leakage will further decrease the respiratory protection offered by fabric materials. As expected, a previous study using a manikin showed greater particle penetration for loosely held fabric materials than fully sealed materials around edges (Guyton *et al.*, 1959). Interestingly, however, some studies have reported that improvised fabric materials can provide a good fit and measurable protection level against test aerosols (Dato *et al.*, 2006; Sandee *et al.*, 2009). In one study, fit factors between 13 and 67 were obtained for three subjects using hand-fashioned masks out of a Hanes T-shirt, a modest level of protection to the wearer (Dato *et al.*, 2006). Similarly, home-made face masks made of tea cloths tested on human subjects provided marginal protection as measured by a PortaCount® Plus (TSI, Inc.) that also uses 20–1000 nm size ambient air particles compared to surgical and CE-marked FFP2 masks (Sandee *et al.*, 2009). The authors reported protection factor levels of 2–3, 4–6, and 66–141 for tea cloths, surgical masks, and FFP2 masks, respectively, under various test conditions. The fabric materials tested in our study might also be expected to provide marginal levels of respiratory protection for 20–1000 nm aerosols (droplet nuclei). Fabric materials may provide respiratory protection levels (i.e. total inward leakage) similar to the levels obtained using some surgical masks, which have been measured to be <10 (Oberg and Brosseau, 2008). Thus, the use of improvised fabric materials may be of some value compared to no protection at all when respirators are not available. Moreover, fabric materials would not suffer from limited supplies unlike respirators and surgical masks for emergency protection.

Some of the fabric materials tested in this study had relatively better filtration performance than others. For example, the Hanes sweatshirt showed less penetration levels against polydisperse aerosols at 5.5 cm s^{-1} face velocity compared to other fabric materials. Similarly, monodisperse aerosol penetration values for particles <60 nm size were less for Hanes sweatshirt. However, the penetration values for >60 nm size particles were higher similar to the penetrations for other sweatshirts and the reason for the discrepancy is not clear. The filtration performance of the towels (Aquis, Pinzon, and Pem America) and one scarf (Walmart) against <100 nm size monodisperse aerosol particles was relatively better than the other fabric materials. Moreover, filtration performance of the fabric materials showed no correlation with the airflow resistance levels. Filtration of polydisperse aerosol particles was effective by 100% cotton fabrics in one case, while 100% polyester, 100% cotton, or cotton/polyester combination was better for nanoparticle (<100 nm) range. Filtration performance of the fabric material cannot be estimated *a priori* from material composition because it is mostly dependent on fiber characteristics, including diameter, charge, and packing density. Moreover, the finished fabric products do not carry information on fiber properties involved in particle filtration. Thus, the selection process for a better performing improvised fabric material may be difficult for a common user. In spite of the poor performance, fabric materials may provide some level of protection against the transmission of infectious aerosols when used in combination with other protective measures. Recently, a review paper analyzed the data obtained from seven case–control studies on the intervention measures of SARS transmission (Jefferson *et al.*, 2009). The authors concluded that a combination of several measures including the use of respiratory protection devices, gloves, and other hygienic practices may reduce the spread of infectious diseases considerably than by a single method. Moreover, cloth masks and fabric materials covering the mouth and nose may serve as a reminder to not touch those areas with the hands serving to minimize contact transmission and reduce exposure to liquid splashes and droplets, although these premises would need to be confirmed experimentally.

The limitations of our study include that only a few types of fabric materials were tested in the study. Some fabric materials not tested in the study may perform better. None of the materials had been worn or laundered, which could also affect filtration performance. Moreover, face seal leakage of aerosol particles was not measured, which is a critical component of respiratory protection. Further studies on respiratory protection of common fabric materials on human subjects for an even wider size range (20–5000 nm) of aerosol particles (e.g. to include more data on filtration performance against droplets) would be helpful to better assess the value of common fabric materials to reduce exposure to infectious aerosols.

CONCLUSION

Common fabric materials and cloth masks showed a wide variation in penetration values for polydisperse (40–90%) as well as monodisperse aerosol particles in the 20–1000 nm range (40–97%) at 5.5 cm s^{-1} face velocity. The penetration levels obtained for fabric materials against both polydisperse and monodisperse aerosols were much higher than the value for the control N95 respirator filter media but were in the range found for some surgical masks in previous studies. Penetrations of monodisperse aerosol particles slightly increased at 16.5 cm s^{-1} face velocity, while polydisperse aerosols showed no significant effect except one fabric mask with an increase. The penetration values obtained for common fabric materials indicate that only marginal respiratory protection can be expected for submicron particles taking into consideration face seal leakage.

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Disclaimer—Mention of commercial product or trade name does not constitute endorsement by the NIOSH. The findings and conclusions of this report are those of the authors and do not necessarily represent the views of the NIOSH.

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