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Air sampling filtration media: Collection efficiency for respirable size-selective sampling

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ABSTRACT

The collection efficiencies of commonly used membrane air sampling filters in the ultrafine particle size range were investigated. Mixed cellulose ester (MCE; 0.45, 0.8, 1.2, and 5 μm pore sizes), polycarbonate (0.4, 0.8, 2, and 5 μm pore sizes), polytetrafluoroethylene (PTFE; 0.45, 1, 2, and 5 μm pore sizes), polyvinyl chloride (PVC; 0.8 and 5 μm pore sizes), and silver membrane (0.45, 0.8, 1.2, and 5 μm pore sizes) filters were exposed to polydisperse sodium chloride (NaCl) particles in the size range of 10–400 nm. Test aerosols were nebulized and introduced into a calm air chamber through a diffusion dryer and aerosol neutralizer. The testing filters (37 mm diameter) were mounted in a conductive polypropylene filter-holder (cassette) within a metal testing tube. The experiments were conducted at flow rates between 1.7 and 11.2 l min^{-1}. The particle size distributions of NaCl challenge aerosol were measured upstream and downstream of the test filters by a scanning mobility particle sizer (SMPS). Three different filters of each type with at least three repetitions for each pore size were tested. In general, the collection efficiency varied with airflow, pore size, and sampling duration. In addition, both collection efficiency and pressure drop increased with decreased pore size and increased sampling flow rate, but they differed among filter types and manufacturer. The present study confirmed that the MCE, PTFE, and PVC filters have a relatively high collection efficiency for challenge particles much smaller than their nominal pore size and are considerably more efficient than polycarbonate and silver membrane filters, especially at larger nominal pore sizes.

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Introduction

Membrane filter media have been widely used for more than 60 years to characterize airborne particles (First and Silverman 1953; Sherwood and Greenhalgh 1960; Sherwood 1997). Air sampling with filters is the most common approach to assessing personal exposure to airborne hazards, and the performance of filter media has been investigated previously (Liu et al. 1983; Lippmann 1995; Spurny 1998; Hinds 1999). Liu et al. (1983) introduced a unipolar diffusion charging-based electrostatic precipitation method (e.g., electrical aerosol detector) to determine filter collection efficiencies instead of light-scattering technology and they reported changes in collection efficiency due to pressure drop and challenged aerosol sizes. The collection efficiencies (η) of 76 different air sampling filters were characterized as a function of four different sizes of monodisperse aerosols and four pressure drop values. Lee and Mukund (2001) reported that although filter manufacturing technology has been improved, comprehensive studies have not been available since the 1980s.

Over the past two decades, the filtration of airborne nanoparticles has attracted much attention because of the potential adverse health effects posed to workers and consumers (Oberdorster 2000). Two different filtration test methodologies have been used for challenges in this nano-size scale with spherical or sphere-like particles such as dioctylpthalate (DOP) and sodium chloride (NaCl). One filtration test system provided discrete penetration results using monodisperse aerosols by counting particle concentration at both upstream and downstream locations simultaneously (e.g., with a TSI 8160 Automated filter tester system; Kim et al. 2007; Japuntich et al. 2007; Li et al. 2012). Another test system was developed to measure polydisperse aerosols (range of 10–400 nm) at both upstream and downstream

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locations by a scanning mobility particle sizer (SMPS; Balazy et al. 2006; Japuntich et al. 2007; Eninger et al. 2008; Lore et al. 2011). One of the studies (Japuntich et al. 2007) found that the two different approaches showed agreement in collection efficiency of the tested filters.

The collection efficiency and pressure drop of the filters was strongly dependent on filter type, pore size, porosity, particle size, and airflow velocity (Stafford and Ettinger 1972; Caroff et al. 1973; Liu and Lee 1976; John and Reischl 1978; Lee and Liu 1980; Lee 1981; Liu et al. 1983; Montassier et al. 1996; Spurny 1998; Zikova et al. 2015). In addition, some researchers reported variation in collection efficiency with different loading characteristics (Sioutas et al. 1999) and a shift in particle penetration characteristics over time (Yamamoto et al. 2004). In these studies, filter collection efficiency was generally defined by a function of particle diameter (Dp) and the filter face velocity (u), but there are limited experimental systems to determine the collection efficiency and pressure drop characteristics at flow rates appropriate for respirable size-selective sampling (e.g., between 1.7 and 11.2 l min^{-1}) and comparison data of filters from different sources is limited. New types of filter media have become commercially available and many previously tested filters are no longer available.

Collection efficiency is an important factor for filter selection. Filters with smaller pore sizes generally have higher collection efficiencies but also have higher pressure drops that a personal sampling pump might not be able to overcome during full-shift air sampling. The objective of the present study is to determine the collection efficiency of commonly used air sampling filters in nanoparticle size ranges at various sampling flow rates for respirable size selective sampling. In addition to strengthening and updating information of collection efficiency on commercial filters in the current market, this information has immediate application in filter selection and informs the theory of how pressure drop across different filter types changes with pore size and sampling flow rates.

Methods

Commercial filter media selection

Table 1 presents the matrix of test parameters. Five different types of filter commonly used for air sampling in occupational hygiene including mixed cellulose ester (MCE; 0.45, 0.8, 1.2, and 5 μm pore sizes), polycarbonate (0.4, 0.8, 2, and 5 μm pore sizes), polytetrafluoroethylene (PTFE; 0.45, 1, 2, and 5 μm pore sizes), polyvinyl chloride (PVC; 0.8 and 5 μm pore sizes), and silver membrane (0.45, 0.8, 1.2, and 5 μm pore sizes) were selected.

Experimental setup and aerosol measurement

Figure 1 shows the schematic diagrams of experimental setup. Polydisperse NaCl particles were generated from 0.34% (v/v) NaCl solution using a 6-jet Collison Nebulizer (CN25, BGI, Inc. 2001, Waltham, MA, USA) and introduced into a dilution chamber that was built for a previous study (Lee et al. 2012) through a diffusion dryer (Model 3062, TSI Inc., Shoreview, MN, USA) and 2 mCi Kr-85 aerosol neutralizer (Model 3012A, TSI Inc.). The test setup was able to provide enough time to evaporate water and allow the NaCl particles to dry and to reach the Boltzmann equilibrium charge distribution before delivery into the test filter media (Orr et al. 1958; Tang and Murkelwitz 1984; Hinds 1999). Sodium chloride was selected because it is commonly used in many respirator certification standard procedures to evaluate filter performance against solid particles (NIOSH 1996; Eninger et al. 2008). The size distribution of the NaCl particles was determined by an SMPS (Model 3936, water-based condensation particle counter, Model 3787 and Electrostatic Classifier, Model 3080, TSI, Inc., Shoreview, MN, USA) with a differential mobility analyzer (DMA, Model 3081, TSI, Inc., Shoreview, MN, USA). The SMPS was operated with an in-line orifice aerosol inlet impactor ($d_{50} = 0.071$ cm) at an aerosol sample flow rate of 0.6 l min^{-1} with a sheath flow rate of 6 l min^{-1}. In order to maintain accuracy of the condensation particle counts, particle number concentration was kept below 2.5×10^6 particle cm^{-3} by using make-up air at ~0.45 l min^{-1} through a high-efficiency particulate air (HEPA) capsule filter (Product No. 12144, Gelman Science Inc., Ann Arbor, MI, USA). Each particle size distribution scan took 135 s (included a retrace of 15 s) so that one completed test was 270 s. The count median diameter (CMD) was 68.7 nm and geometric standard deviation (GSD) of the test aerosol was 1.94. The particle size ranged from 10.4 to 412 nm (64 channels per decade) for high-resolution measurements. The challenge NaCl aerosol concentrations were kept greater than 10^5 particles cm^{-3} in the scanning channels in order to minimize penetration error as filter penetration was less than 0.01% (Japuntich et al. 2007; Lore et al. 2011). The test filter mounting assembly is similar to that required by European Standard EN1822-3 (High efficiency air filters (EPA, HEPA, and ULPA) - Part 3: Testing flat sheet filter media) (CEN 2009). Recommended sampling flow rates for respirable size selective samplers were selected (Lee et al. 2010) and controlled by mass flow controllers (MFC; Model GFC-17/37, Aalborg Instruments & Controls, Inc., Orangeburg, NY, USA) based upon the ranges of recommended

Table 1. List of filter tested and summary of collection efficiency results.

Filter	Brand	Pore size (μm)	Flow rate (l min^{-1})	Collection efficiency range% Minimum[a]	Collection efficiency range% Maximum[a]	Initial pressure dro[b] (kPa)	Delta pressure dropp[c] (kpa)
MCE	SKC	0.45	1.7	99.64	100	2.50	0.04
			2.5	98.82	100	3.74	0.01
			4.4	99.99	100	6.10	0.02
			11.2	**	**	**	**
	SKC	0.8	1.7	99.99	100	0.88	0.00
			2.5	99.99	100	1.22	0.01
			4.4	100.00	100	2.07	0.02
			11.2	**	**	**	**
	SKC	1.2	1.7	100.00	100	0.70	0.02
			2.5	99.76	100	1.06	0.02
			4.4	100.00	100	1.73	0.01
			11.2	**	**	**	**
	SKC	5	1.7	99.81	100	0.36	0.01
			2.5	99.87	100	0.51	0.02
			4.4	99.70	100	0.90	0.03
			11.2	99.17	100	2.27	0.11
	Millipore	0.45	1.7	99.99	100	2.75	0.007
			2.5	99.72	100	4.06	0.07
			4.4	99.97	100	7.51	0.12
			11.2	**	**	**	**
	Millipore	0.8	1.7	99.99	100	0.92	0.01
			2.5	99.91	100	1.36	0.02
			4.4	99.96	100	2.34	0.06
			11.2	99.99	100	6.17	0.46
	Millipore	1.2	1.7	99.99	100	0.753	0.010
			2.5	99.97	100	0.990	0.027
			4.4	99.99	100	1.74	0.067
			11.2	99.93	100	4.55	0.497
	Millipore	5	1.7	99.84	100	0.350	0
			2.5	99.73	100	0.487	0.010
			4.4	99.36	100	0.813	0.023
			11.2	98.86	100	2.21	0.280
	Gelman	0.8	1.7	99.74	100	1.46	0.017
			2.5	99.94	100	2.06	0.017
			4.4	99.99	100	3.60	0.053
			11.2	**	**	**	**
Polycarbonate	SKC	0.4	1.7	99.50	100	2.54	0.213
			2.5	98.98	100	4.89	0.460
			4.4	98.24	100	7.22	1.03
			11.2	99.48	100	14.8	2.08
	SKC	0.8	1.7	74.83	100	1.12	0.297
			2.5	94.17	100	1.60	0.463
			4.4	95.11	100	2.51	1.08
			11.2	96.55	100	7.52	3.50
	Millipore	2	1.7	73.41	100	1.39	0.577
			2.5	81.21	100	1.99	1.05
			4.4	86.24	100	3.57	2.65
			11.2	94.54	100	9.33	8.92
	Millipore	5	1.7	22.48	96	0.517	0.083
			2.5	54.94	97	0.687	0.577
			4.4	65.07	94	1.20	3.74
			11.2	79.03	99	2.81	16.9
	Poretics	0.4	1.7	99.50	100	2.39	0.240
			2.5	99.49	100	3.53	0.437
			4.4	99.57	100	5.73	0.890
			11.2	**	**	**	**
PTFE	SKC	0.45	1.7	99.98	100	1.65	0.040
			2.5	99.99	100	2.37	0.057
			4.4	99.74	100	4.32	0.177
			11.2	99.83	100	9.83	1.05
	SKC	2	1.7	99.34	100	0.423	0.027
			2.5	99.53	100	0.636	0.040
			4.4	98.94	100	1.41	0.263
			11.2	99.39	100	2.64	0.690
	Pall	2	1.7	99.85	100	0.433	0.020
			2.5	99.89	100	0.600	0.040
			4.4	99.78	100	0.997	0.100
			11.2	99.69	100	2.53	0.370

(*Continued*)

Table 1. (*Continued*)

Filter	Brand	Pore size (μm)	Flow rate (l min^{-1})	Collection efficiency range% Minimum[a]	Collection efficiency range% Maximum[a]	Initial pressure dro[b] (kPa)	Delta pressure dropp[c] (kpa)
	Pall	5	1.7	94.76	100	1.78	0.723
			2.5	95.37	100	2.90	1.66
			4.4	95.28	100	4.76	5.37
			11.2	**	**	**	**
	Gelman	1	1.7	100	100	1.64	0.130
			2.5	99.03	100	2.66	0.497
			4.4	99.95	100	4.69	2.49
			11.2	99.66	100	**	**
PVC	SKC	0.8	1.7	99.78	100	1.02	0.060
			2.5	99.72	100	1.62	0.280
			4.4	99.58	100	1.86	0.123
			11.2	95.22	100	5.42	0.807
	SKC	5	1.7	96.08	100	0.277	0.013
			2.5	99.71	100	0.347	0.010
			4.4	99.45	100	0.657	0.040
			11.2	92.98	100	1.587	0.300
	Gelman	5	1.7	99.21	100	0.283	0.027
			2.5	99.11	100	0.467	0.130
			4.4	99.13	100	0.723	0.300
			11.2	98.26	100	1.91	0.380
	Millipore	0.8	1.7	99.84	100	1.94	0.007
			2.5	100.00	100	2.66	0.020
			4.4	99.93	100	**	**
			11.2	**	**	**	**
	Millipore	5	1.7	99.95	100	0.267	0.023
			2.5	99.64	100	0.350	0.047
			4.4	99.60	100	0.690	0.113
			11.2	98.73	100	1.86	0.487
Silver	SKC	0.8	1.7	94.02	100	0.663	0.170
			2.5	93.44	100	0.946	0.343
			4.4	93.20	100	1.63	0.557
			11.2	94.23	100	4.59	2.80
	Sterlitech	0.45	1.7	98.31	100	2.45	0.440
			2.5	98.23	100	3.56	0.783
			4.4	98.50	100	7.02	1.677
			11.2	**	**	**	**
	Sterlitech	0.8	1.7	95.14	100	0.697	0.170
			2.5	94.13	100	0.943	0.653
			4.4	92.69	100	1.68	0.727
			11.2	86.51	100	4.28	3.15
	Sterlitech	1.2	1.7	95.09	100	0.607	0.127
			2.5	93.89	100	0.850	0.327
			4.4	93.89	100	1.46	0.873
			11.2	93.65	100	3.82	2.95
	Sterlitech	5	1.7	47.34	100	0.136	0.020
			2.5	54.52	100	0.180	0.110
			4.4	42.10	100	0.317	0.077
			11.2	63.36	99	0.777	1.582

**Not available in this test condition.
[a]Measurements were conducted using three different filters for each filter type in conjunction with three time dependencies.
[b]Mean values obtained from three unloaded filters.
[c]Mean values obtained from three loaded filters.

sampling flow rates. The flow rates through the experimental setup were checked using a mass flowmeter (Model 4199, TSI Inc., Shoreview, MN, USA). The four flow rates chosen are flow rates specified for certain types of cyclones used to provide size-selective sampling for the respirable size fraction. The air velocity at the face of the filter was not measured directly. The velocity was instead calculated from the four nominal sampling flow rates (1.7, 2.5, 4.4, 11.2 l min^{-1}) by dividing the test volume flow rate by the inner effective filtration area (~9.1 cm^2) in the 37 mm cassette (corresponding to face velocities of 3.08–20.5 cm s^{-1}). The SMPS was used to count number particle concentration before (C_{in}) and after (C_{out}) each test filter media. Thus, the collection efficiency (η) was determined by the following equation:

$$\eta = 1 - \frac{C_{\text{out}}}{C_{\text{in}}} \quad [1]$$

A completed particle penetration measurement consisted of two samples from the upstream (C_{in}) and downstream (C_{out}) locations by switching a three-way

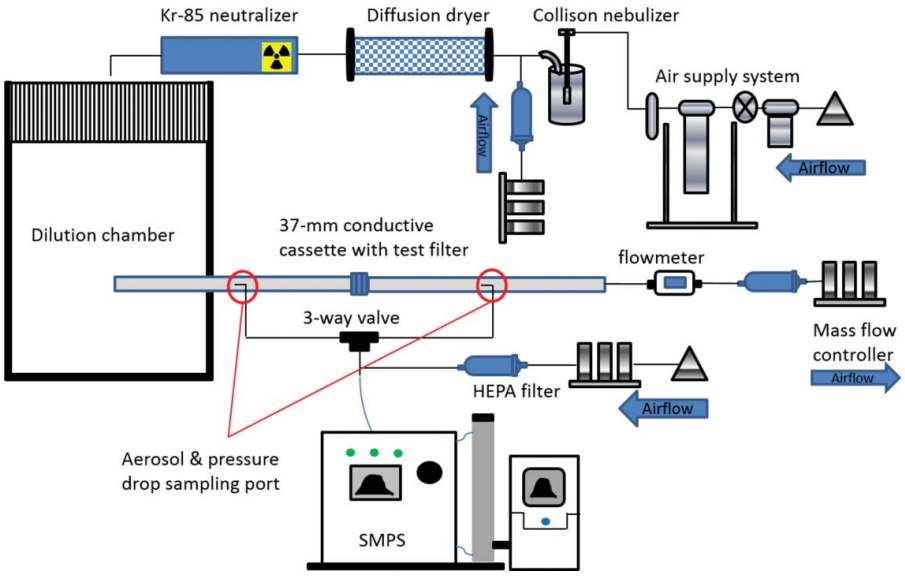

Figure 1. Experimental setup for filtration test system.

valve. The differential pressure across the filter medium was measured with one of three MK III handheld digital manometers dependent on pressure drop ranges (Models 475-00-FM, 475-0-FM, and 475-1-FM, Dwyer Instruments Inc. n.d., Michigan, IN, USA) and the manometer was attached to the pressure measuring points upstream and downstream. The filters were held within plastic press-fit cassettes, which were assembled using a pneumatic press (AOCSCLSR-2, Omega Specialty, Chelmsford, MA, USA) for cassette-closing, which allows an even and repeatable pressure to be applied across the surface of the cassette (Baron 2003). Leakage in assembled testing system was checked using a field cassette leak tester (SKC Inc., Eighty four, PA, USA) and sealed where necessary. In addition, pressure drop across the sampling system was compared with the average pressure drop across well-sealed sampling cassettes (Van den Heever 1994). For each test condition, three filters of each pore size were tested and three replicates of each test condition were performed. The total number of runs was 1044 runs for membrane filters (29 filter types with different pore sizes $\times$ 4 sampling flow rates $\times$ 3 filters $\times$ 3 replicates = 1044).

Statistical analysis

All data were analyzed using SAS/STAT software version 9.3 (SAS Institute, Cary, NC, USA). Descriptive statistics on minimum efficiency for each filter type were calculated using "proc means" (SAS). Not all filters tested could be analyzed for every combination of the independent variables (i.e., filters do not all have the same size or number of levels of pore sizes, and some filters were could not be tested at all flows rate due to large pressure drop). Thus, subsets of data were isolated so that the independent variables could be systematically analyzed. However, all filters in the study were analyzed for effects of flow rate and time using proc mixed to run two-way analysis of variances (ANOVAs). Higher order analyses were possible for those filters with varying pore sizes including MCE, polycarbonate, PVC, and silver membrane filter. For these filter types, data were analyzed in conjunction with time and flow rates in filters from each class, and was carried out utilizing "proc mixed" (SAS) to run three-way ANOVAs (pore size, flow rate, and time). Pairwise *post-hoc* differences were analyzed using Fishers Least Significant Difference test. All analyses were checked to ensure that the assumptions of the analysis were being met, and all differences were considered significant if probability <0.05.

Results

Table 1 lists a summary of the averaged collection efficiencies measured at varying test conditions. The collection efficiency of some filters was dependent on filter type, flow rate, pore size, and test duration. The average values of initial pressure drop (initial p) and the increase in pressure drop (Δp) when the tested filters were loaded with NaCl particles are also presented in Table 1. The collection efficiency typically increased with decreasing pore size and increasing flow rate, while pressure drop increased with increasing flow rate and decreasing pore size.

Comparison by filter types

The collection efficiencies of five different filter types with 5.0 μm pore size at flow rate 1.7 l min^{-1} are shown

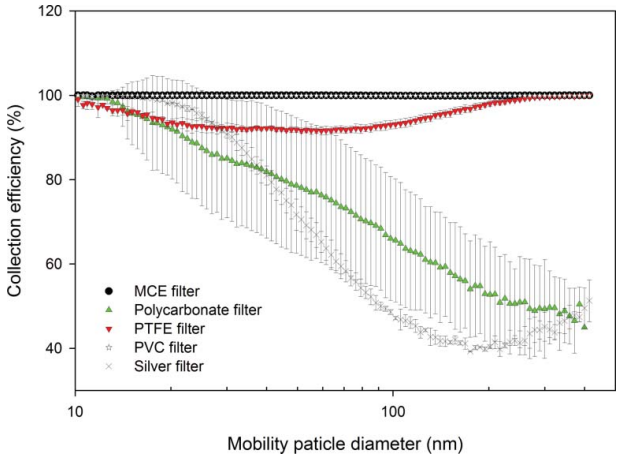

Figure 2. Average and standard deviation of collection efficiencies of five filters with 5 μm pore size tested with a nanoparticle diameter range of 10–400 nm at 1.7 l min^{-1}. Aerosol measurements were conducted using three different filters for each filter type ($n = 3$). Note that the two overlapping point symbols (MCE filter and PVC filter were denoted as solid circle and star symbols) are presented.

in Figure 2. The collection efficiencies of the MCE, PTFE, and PVC filters were >92% under all test conditions while the collection efficiencies of the polycarbonate and silver membrane filters were in the range of 40.23 to 99.61% and 38.58 to >99.99%, respectively. Descriptive statistics on minimum collection efficiency for each of the filter type are presented in Table 2.

The initial p ranges from 0.137 kPa for 5 μm pore size silver membrane filter (Pot No. 45337, Sterlitech Inc., Kent, WA, USA) at flow rate 1.7 l min^{-1} to 14.8 kPa for 0.4 μm pore size polycarbonate membrane filter (Pot No. 45337, SKC Inc., Eighty four, PA, USA) at flow rate 11.2 l min^{-1}. The initial p between filters were not significantly different while the Δp between the filters were significantly different in accordance with a two-way analysis of variation (ANOVA).

Comparison by sampling flow rate

The MCE, PTFE, and PVC filters showed no difference in collection efficiency at the various sampling flow rates. The collection efficiencies of the polycarbonate and silver filters with pore sizes >2 μm increased with increasing flow rate, whereas those with pore size <2 μm did not. The collection efficiency of the Millipore polycarbonate membrane filter with 2 μm pore size is shown in Figure 3. The collection efficiency at the most penetrating particle size (MPPS) was decreased from approximately 84% at 11.2 l min^{-1} to 54% at 1.7 l min^{-1}. The MPPS was increased by decreased flow rates. A similar trend was found with the silver membrane filters (data not shown here), although the collection efficiencies at each pore size were different. Note that the MMPS at the minimum collection efficiency decreased with increased sampling flow rate.

Comparison by pore size

The collection efficiencies of the PVC, MCE, and PTFE with small pore sizes (<1.0 μm) were >99% under all test conditions except for a few cases at the high flow rate (~11.2 l min^{-1}). The collection efficiency of the MCE and PVC filters with 5 μm pore size were >98% at 11.2 l min^{-1}. The collection efficiency of the PTFE filters with 5 μm pore size was in the range of 86% to >99.99% depending upon the test conditions. The collection efficiencies of polycarbonate and silver membrane filters with different pore size showed significant differences. Figure 4 illustrates the collection efficiency of Sterlitech silver membrane filter with four different pore sizes at 1.7 l min^{-1}.

Collection efficiencies of the polycarbonate and silver membrane filters are significantly different by pore sizes (ANOVA) while that of Millipore® MCE filters with 0.45, 0.8, 1.2, and 5 μm pore sizes and PVC (2 *vs.* 5 μm pore sizes, SKC Inc.) are not (probability >0.05). The relationship between pressure drop and flow rate with four different pore sizes of silver membrane filter is shown in Figure 5. The pressure drop increased with increased flow rate for all pore sizes.

Comparison by loading

In general, the collection efficiencies of the polycarbonate and silver membrane filters increased with increasing sampling time when the test particles were collected on the filters. Average and standard deviation of collection

Table 2. Descriptive statistics for minimum collection efficiency by five membrane filter type.

Filter type	Sample number	Mean	Median	Standard deviation	25th percentile	75th percentile
MCE	162	99.50	99.99	4.76	99.93	100.00
PTFE	171	99.02	99.86	2.25	99.39	99.98
Polycarbonate	171	85.32	98.01	22.2	78.49	99.70
PVC	171	98.85	99.74	2.96	99.24	99.91
Silver	168	86.46	96.07	20.3	84.88	99.34

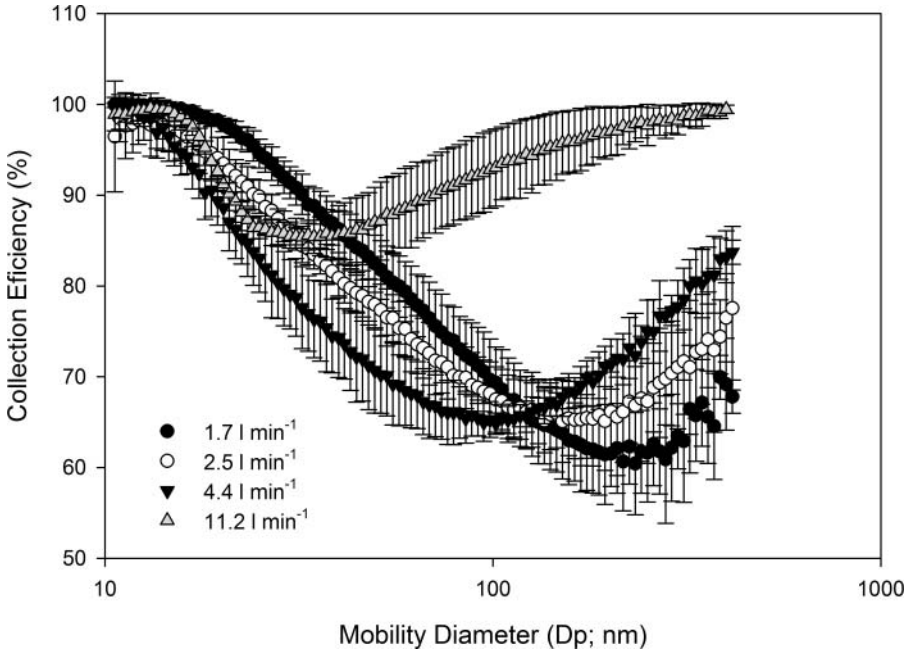

Figure 3. Collection efficiency of Millipore polycarbonate filter (2.0 μm pore size) at four different flow rates to illustrate the influence of sampling flow rate on collection efficiency. Note that aerosol measurements were conducted using three different filters in conjunction with first time dependency in three repetitions ($n = 3$).

efficiencies and pressure drops of three different Millipore polycarbonate membrane filters with 2 μm pores at 1.7 l min^{-1} are plotted in Figure 6. All polycarbonate and silver membrane filters are significantly different by different sampling time except 0.8 μm pore size polycarbonate membrane filters (borderline significance, probability = 0.0536). It should be noted that it took the SMPS 270 s to complete the two scans for obtaining one set of collection efficiency data. The results in Figure 6a suggest that the collection efficiency changed so rapidly

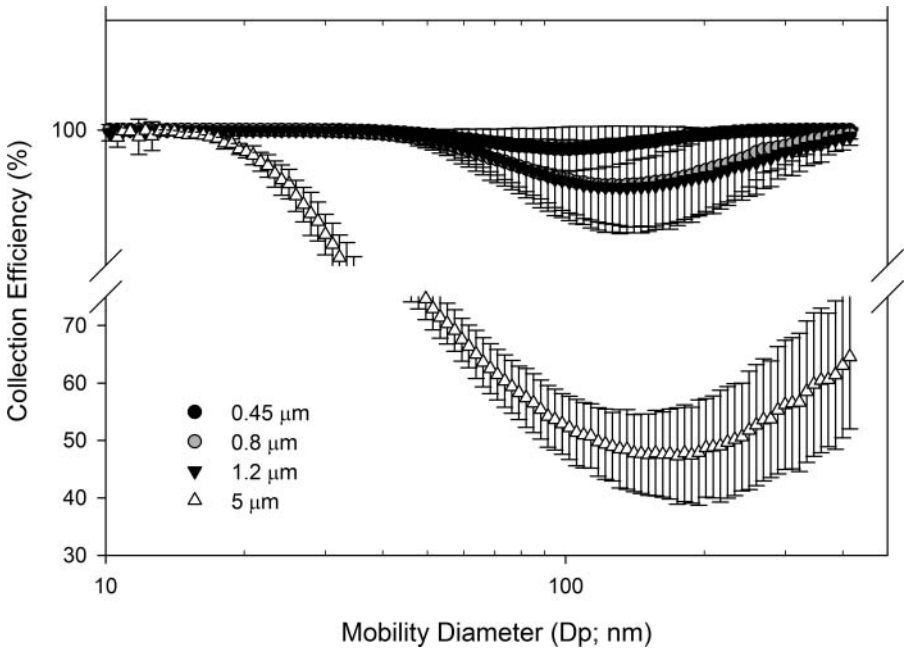

Figure 4. Collection efficiency of Sterlitech silver membrane filter at four different pore sizes at 1.7 l min^{-1}. Note that aerosol measurements were conducted using three different filters for each filter type in conjunction with time dependencies in three repetitions ($n = 9$).

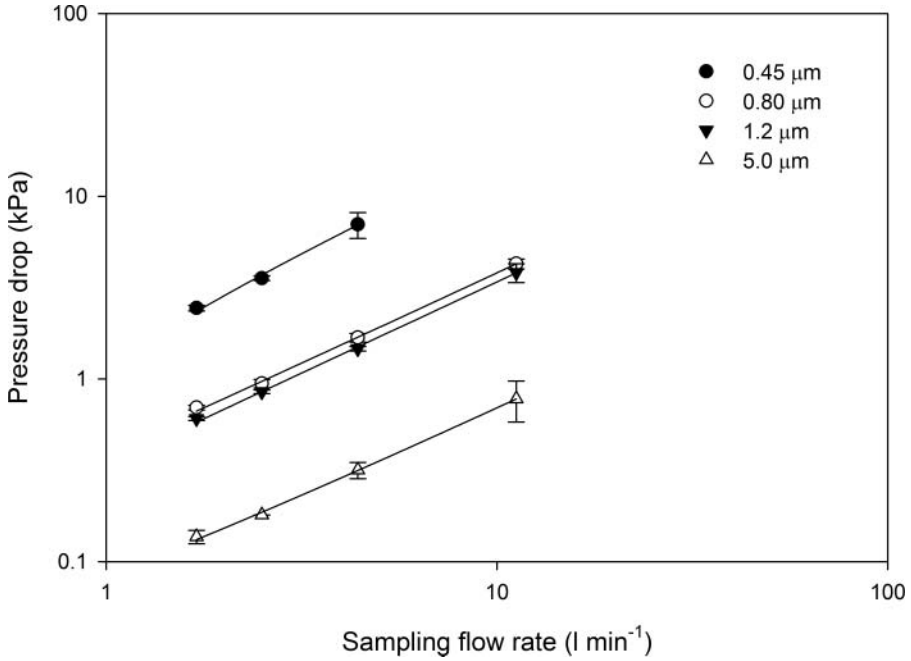

Figure 5. Pressure drop as a function of sampling flow rate for silver membrane filter with pore size diameters of 5, 1.2, 0.8, and 0.45 μm. Note that pressure drop measurements were conducted using three different unloaded filters for each filter type ($n = 3$).

for this particular type of filter that the change may be significant during each measurement spanning 270 s, which might result in large standard deviations in collection efficiency. Thus, the results shown in Figure 6a may not reflect the true collection efficiency and its evolution with time.

The collection efficiency of MCE, PTFE, and PVC filters did not show noticeable difference with increased sampling time but through *post-hoc* comparisons and interaction contrasts in some cases significant differences were observed (probability <0.05) due to very small standard deviations (<4.78%).

Discussion

Characterization of collection efficiency

The collection efficiencies of 76 different filters were previously evaluated from a factorial combination of four different pore sizes (0.035, 0.10, 0.30, and 1 μm) and four different pressure drops (1–30 cm Hg; Liu et al. 1983). In the present study, experiments were conducted using a factorial combination of filter type, sampling flow rate (between 1.7 and 11.2 l min^{-1}, which corresponded to face velocities of 3.08–20.5 cm s^{-1}), pore size (four different pore sizes for MCE, PTFE, polycarbonate, and silver membrane filter, and two different pore sizes for PVC), and three time dependency with three repetitions. The present study produced consistent results with the Liu et al. (1983) study.

General consideration on selection of filter

- **Filter type**—The polycarbonate and silver membrane filter had significantly lower collection efficiency in the particle size range of 10.0–412 nm compared to other membrane filters (MCE, PTFE, and PVC filters; $p < 0.05$). There was no noticeable difference between minimum collection efficiency between the MCE, PTFE, and PVC filters; in most cases the collection efficiencies were ~99%, in agreement with previous work (John and Reischl 1978; Liu et al. 1983; Zikova et al. 2015). The difference in collection efficiency between the filters is attributable to differences in their physical structure. For example, MCE, PTFE, and PVC have three distinct layers with upper, intermediate, and lower surface structures and gas flow through the filter follows an irregular path through the complex pore structure. The published pore-size for these types of filters is actually a nominal value based on a bubble-point test (Lindsley 2015). In contrast, a polycarbonate filter has a uniform structure throughout with a narrow range of pore sizes. They consist of a very smooth and translucent surface with straight-through capillary holes across the membrane structure (Lippmann 1995; Spurny 1998; Baron and Willeke 2001). The polycarbonate filter therefore has a higher possibility that particles smaller than the nominal pore size can get through the pores compared to other filters. Zikova et al. (2015) reported

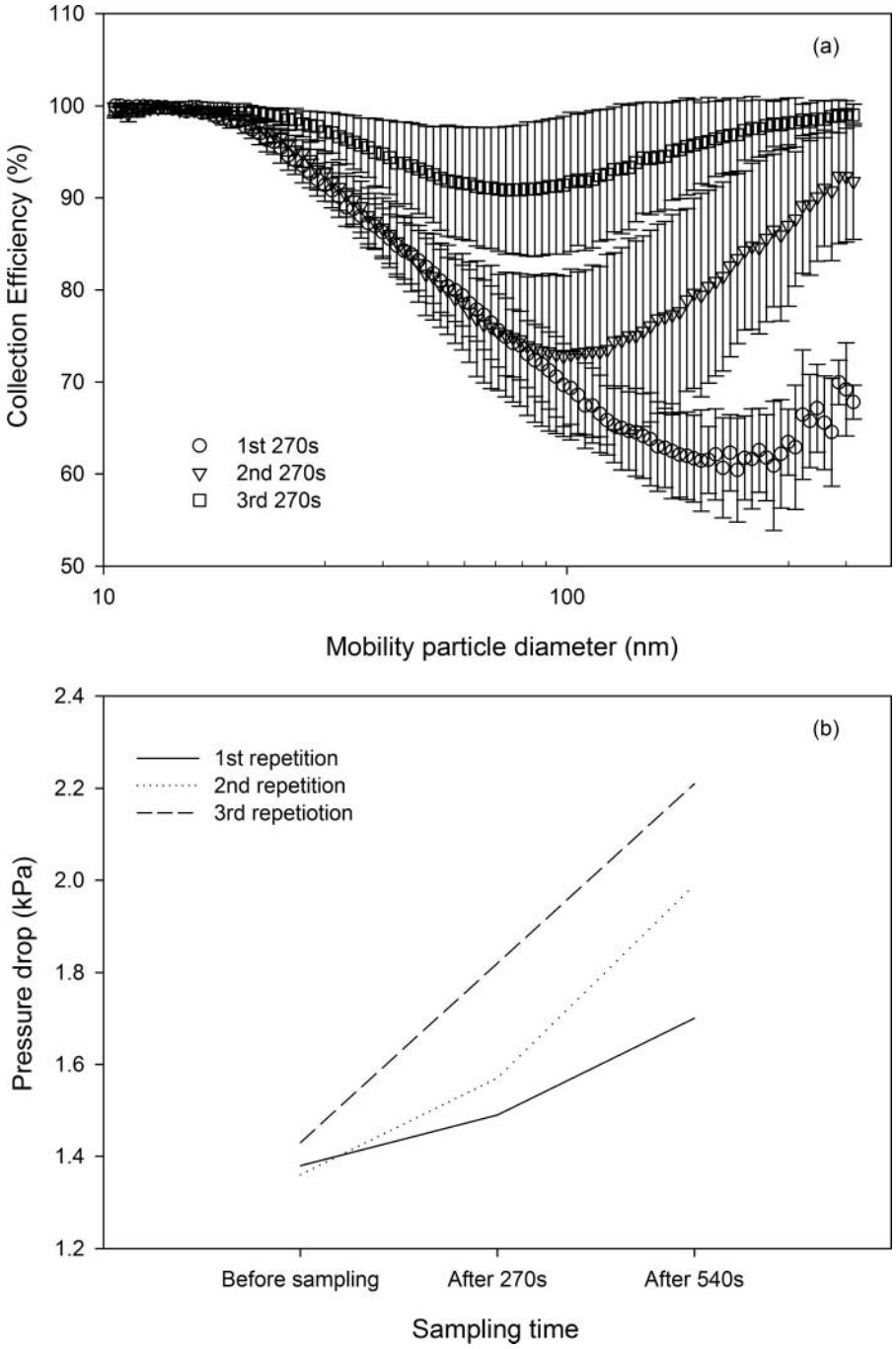

Figure 6. (a) The influence of time course shift on collection efficiency and (b) experimental time dependency of pressure drop for 2.0 μm Millipore polycarbonate pore filter with 1.7 l min^{-1} sampling flow rate at three various sampling time period. Note that both collection efficiency and pressure drop measurements were conducted using three different filters for each filter type in conjunction with time independency in three repetitions ($n = 9$).

that the highest penetration was found in the polycarbonate filter. Gentry et al. (1982) found that the penetration of Nuclepore filters with 2 and 5 μm pore size varied from 40% to 76% (~23%–60% collection efficiencies) and 70%–86% (~14%–30% collection efficiencies) at face velocities in range of 0.8–6.6 cm s^{-1}. Burton et al. (2007) also found that the polycarbonate filter showed low collection efficiency for particles <100 nm. The lowest collection efficiencies, 49% and 22% were observed for 1 and 3 μm pore size polycarbonate filter when a flow rate of 4 l min^{-1} was used. The silver membrane filters are made from 99.7% pure metallic silver by a powder-metallurgical process, which results in a filter

with a relatively uniform porosity through which particles smaller than the nominal pore size can also penetrate. Silver membrane filters with 0.8 μm pore size are used for sampling and direct on-filter measurement of respirable crystalline silica (MDHS 101, HSE 2005) but in our test not all results exceeded 95% collection efficiency. The present study confirmed that the collection efficiency were mostly dependent on filter type with an additional contribution from other parameters (see below).

- **Sampling flow rate**—Liu and Lee (1976) and Montassier et al. (1996) indicated that the MPPS decreased with increasing flow velocity. The present study produced results consistent with the previous studies. Collection efficiency curves show a minimum U-shape that moves toward small size diameter as sampling flow rate increases (Spurny 1998), which might be attributable to particle accumulation around the rim of capillary pores by diffusion and interception leading to a narrowing of pore size even for short sampling duration (Yamamoto et al. 2004). In addition, an increasing flow rate increases the likelihood of impaction and decreases the time for diffusion as a particle passes through the filter (Brock 1983). Montassier et al. (1996) and Cyrs et al. (2010) observed that the pressure drop increased with increasing face velocity. The pressure drop was also found to be dependent upon the filter face velocity and formed a linear relationship, in agreement with the previous published study (Zikova et al. 2015).
- **Pore size**—The collection efficiency generally increases with decreasing pore sizes (Lippmann 1995) but certain membrane filters (MCE, PTFE, and PVC) with large pore sizes can retain particles smaller than their nominal pore size (Liu and Lee 1976). The present study produced results consistent with these previous studies. On the other hand, polycarbonate and silver membrane filters exhibited low collection efficiency when the particle size is smaller than the filter pore size (McCammon and Woebkenberg 1998). The pressure drop was also found to be strongly dependent on pore size across the filter, in agreement with previous work (Zikova et al. 2015).
- **Loading**—Pressure drop and collection efficiency are a function of clogging, i.e., both increase over time during particle collection (Spurny et al. 1969). Yamamoto et al. (2004) also indicated that the change in penetration characteristics could be initiated even before particle clogs. This finding is observed in the present study (Figure 6a and b). Sioutas et al. (1999) indicated that an increase in the pressure drop across a Nuclepore filter with particle loading is proportional to the filter face velocities ranging from 4 to 52 cm s^{-1}.

Conclusions

The collection efficiency of commercially available and commonly used porous membrane filters for air sampling has been evaluated using polydisperse NaCl particles and SMPS. In general, the collection efficiency varied with airflow, pore size, and sampling duration. In addition, both collection efficiency and pressure drop increased with decreased pore size and increased sampling flow rate, but they differed among filter types and manufacturer. The present study confirmed that MCE, PTFE, and PVC filters have a relatively high collection efficiency for challenge particles much smaller than their nominal pore size and are considerably more efficient than polycarbonate and silver membrane filters, especially at larger nominal pore sizes. The collection efficiency of polycarbonate and silver membrane filters varied with flow rate, pore size, and time duration. Although collection efficiency increased with decreased pore size and increased flow rate so also did pressure drop across the filter.

Disclaimer

The findings and conclusions in this report are those of the 455 authors and do not necessarily represent the views of the National Institute for Occupational Safety and Health (NIOSH). Mention of any company or product does not constitute endorsement by the NIOSH.

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