Collection of biological and non-biological particles by new and used filters made from glass and electrostatically charged synthetic fibers

Abstract Synthetic filters made from fibers carrying electrostatic charges and fiberglass filters that do not carry electrostatic charges are both utilized commonly in heating, ventilating, and air-conditioning (HVAC) systems. The pressure drop and efficiency of a bank of fiberglass filters and a bank of electrostatically charged synthetic filters were measured repeatedly for 13 weeks in operating HVAC systems at a hospital. Additionally, the efficiency with which new and used fiberglass and synthetic filters collected culturable biological particles was measured in a test apparatus. Pressure drop measurements adjusted to equivalent flows indicated that the synthetic filters operated with a pressure drop less than half that of the fiberglass filters throughout the test. When measured using total ambient particles, synthetic filter efficiency decreased during the test period for all particle diameters. For particles 0.7–1.0 μm in diameter, efficiency decreased from 92% to 44%. It is hypothesized that this reduction in collection efficiency may be due to charge shielding. Efficiency did not change significantly for the fiberglass filters during the test period. However, when measured using culturable biological particles in the ambient air, efficiency was essentially the same for new filters and filters used for 13 weeks in the hospital for both the synthetic and fiberglass filters. It is hypothesized that the lack of efficiency reduction for culturable particles may be due to their having higher charge than non-biological particles, allowing them to overcome the effects of charge shielding. The type of particles requiring capture may be an important consideration when comparing the relative performance of electrostatically charged synthetic and fiberglass filters.

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Practical implications
Electrostatically charged synthetic filters with high initial efficiency can frequently replace traditional fiberglass filters with lower efficiency in HVAC systems because properly designed synthetic filters offer less resistance to air flow. Although the efficiency of charged synthetic filters at collecting non-biological particles declined substantially with use, the efficiency of these filters at collecting biological particles remained steady. These findings suggest that the merits of electrostatically charged synthetic HVAC filters relative to fiberglass filters may be more pronounced if collection of biological particles is of primary concern.

Introduction

Airborne infectious particles have long been a concern in hospitals and other health-care facilities. These particles may be introduced directly by patients, visitors, staff, or with outside air brought into the building or by activities such as cleaning and remodeling that may resuspend settled particles. With recognition of threats posed by bioterrorism and emerging infectious diseases, the presence of biological particles in the air of other large public and commercial buildings has also become a pressing concern.

Filters present in heating, ventilating, and air-conditioning (HVAC) systems in commercial and public buildings can reduce the concentrations of biological and non-biological particles in the structures. The National Institute for Occupational Safety and Health (NIOSH, 2002, 2003) has emphasized the value of upgrading the efficiency of filtration used in large buildings to protect their occupants in case of

biological or radiological attacks. The American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) has published standards by which manufacturers can measure and report filter performance using terms such as dust spot efficiency and minimum efficiency reporting value (MERV) (ASHRAE, 1992, 1999). Guidelines for health-care facilities published by the American Institute of Architects (Facility Guidelines Institute, 2006) recommend a MERV 14 or 90% dust spot efficiency final filter preceded by a MERV 8 or 30% dust spot efficiency pre-filter for all areas used for inpatient care, treatment, and diagnosis, and a MERV 17 or 99.97% efficient HEPA type A final filter (IEST, 2005) preceded by a MERV 8 or 30% dust spot efficiency pre-filter in protective environments such as bone marrow treatment units. Citing a report that most commercial buildings usually install HVAC filters ranging from only MERV 5 to MERV 8 (ASHRAE, 2003), a working group has recommended that public buildings replace existing filters with the highest efficiency filters that do not diminish airflow to the building appreciably, install filters in outdoor air intakes, minimize air leakage around filters in the air-handling units (AHUs) of HVAC systems, and replace clogged filters expeditiously (Hitchcock et al., 2006).

New technologies for air filtration continue to be developed. Filters made from synthetic polymer fibers are used commonly now instead of traditional fiberglass filters. Many of these synthetic fibers are designed to hold a stationary electrostatic charge intended to enhance the performance of the filters. As biological or non-biological particles are generated, they become electrically charged (John, 1980). Electrostatic fields created by the charged synthetic fibers enhance collection of these particles. Because of this improved single fiber efficiency, the advantage to using electrostatically charged synthetic fibers is that fewer and larger fibers should be required to collect the same fraction of incoming particles relative to traditional glass fibers (Brown, 1993). Fewer and larger fibers correspond to less resistance to airflow through the filters. A newly installed, well-designed filter made from electrostatically charged synthetic fibers should collect particles with the same efficiency as a fiberglass filter and with less resistance to airflow, or it should collect particles with higher efficiency for the same resistance to airflow. A filter's resistance to the flow, typically measured as pressure drop across the filter, is positively related to energy usage and costs and inversely related to the ability of an AHU blower to move air through the system. Thus, electrostatically charged synthetic filters offer the potential to remove biological and non-biological particles from ventilation air more effectively than fiberglass filters without impacting energy costs or the ability to move air through the building.

A consideration in the use of charged synthetic filters, however, is that their efficiency declines as they collect dust. Several laboratory studies showed this efficiency reduction with use (Baumgartner and Löffler, 1986; Jodeit and Löffler, 1984; Lathrache et al., 1986). Having tested the efficiency of electrically charged respiratory protection filters against seven different industrial dusts, Brown et al. (1988) observed efficiency reductions that they linked to electrical properties and size distribution of the collected particles. Walsh and Stenhouse (1997, 1998) showed that particle size, charge, and composition had a significant effect on the loading characteristics of mixed-fiber, electrically active filters. Barrett and Rousseau (1998) found that electrostatically charged filter media with large diameter fibers exhibited excellent initial filtration performance. However, when these media collected aerosol particles, the penetration increased dramatically with little change in pressure drop. The most likely explanation for these observations was that collected dust particles insulated the stationary electrical charges on the fibers, rendering them less effective with time.

Raynor and Chae (2004) evaluated the performance of fiberglass and electrostatically charged synthetic filters in operating HVAC systems for 19 weeks. They found substantial, statistically significant efficiency reductions for the synthetic filters after only a few weeks of use. The fiberglass filters showed little change. However, the charged synthetic medium used in this study was not designed optimally because both the initial efficiency and pressure drop for the fiberglass and synthetic filters were similar; a properly designed synthetic filter medium should have had a substantially lower pressure drop than a fiberglass filter with the same efficiency. Raynor and Chae (2003) found that reductions in efficiency observed in measurements on filters used in operating HVAC systems were not reflected in dust loading tests conducted according to ASHRAE Standard 52.2 (ASHRAE, 1999). These differences in performance between real filtration and dust loading tests are probably due to the differences in composition, size distribution, and charge distribution of atmospheric particles collected in the HVAC systems and the dust used in the ASHRAE Standard tests.

Wang (2001) suggested a need for further studies on the effect of dust loading because there is a marked gap between the theory and experimental evidence for the change in collection efficiency with particle loading in a filter in the presence of electrostatic forces.

For biological particles, the effectiveness of a filter depends on the characteristics of the filter, the size distribution of the viable particles, the face velocity of the air, and the type of particle. Biological particles can be spheres, ovoids, rods, or more complex shapes and exist as populations that span a range of sizes. The

ability of a fiberglass or synthetic filter to collect particles, whether biological or not, will be a function of particle size, shape, and charge, among other factors.

When the amount of electrical charge on many similar airborne particles is measured, results indicate that a broad distribution of charge is present on the particles. More importantly, Mainelis et al. (2001) discovered that the range of charges on biological particles was much broader than the range of charges on non-biological particles produced in the same way. For *Bacillus subtilis* bacterial spores aerosolized from a suspension using a nebulizer, the authors observed particle charges ranging from −12 000 to +9000 elemental charges. When sodium chloride particles were generated using the same nebulizer, the authors found particle charges ranging mostly from −400 to +400 elemental charges. If biological particles generally carry a higher level of charge than non-biological particles, charged synthetic filters may be particularly effective at collecting them. In addition, even charged fibers shielded by previously collected particles may exert a strong enough electrical field to capture more highly charged biological particles.

The filtration of biological particles has not been tested systematically to compare fiberglass and electrostatically charged synthetic media. In addition, the ability of new and used HVAC filters to capture biological particles has not been assessed. This study was designed to compare the performance of a well-designed commercial brand of charged synthetic filters to a brand of uncharged fiberglass filters.

Materials and methods

Measurements of efficiency and pressure drop were taken over a period of 13 weeks for filters installed in operating HVAC systems at the University of Minnesota Medical Center in Minneapolis. The two AHUs used in this test are located in the mechanical space on the eighth floor of the building, sharing a common air intake. Additional measurements of filtration efficiency for both biological and non-biological particles were carried out on new and used filters in a small test duct.

Test filters

The synthetic filter medium was made entirely of electrostatically enhanced polypropylene microfibers. Each filter, with nominal dimensions of 0.61 m wide × 0.61 m high × 0.0508 m deep, contained 44 pleats. Frames and gaskets provided effective sealing. The manufacturer rated the filters with an initial efficiency rating of MERV 14 (ASHRAE, 1999) and 90–95% efficient by the dust spot efficiency test (ASHRAE, 1992). As a result of additional testing to simulate actual use in commercial applications, the manufacturer rated the filters as corresponding to MERV 12 to account for efficiency reductions during use.

The fiberglass filters were made entirely of glass microfibers. Each filter, with nominal dimensions of 0.61 m wide × 0.61 m high × 0.305 m deep or 0.305 m wide × 0.61 m high × 0.305 m deep, contained 36 pleats. They were manufactured with two layers of glass fibers: coarse fibers on the upstream side and fine fibers on the downstream side. They were also rated by their manufacturer as MERV 14 and 90–95% efficient by the dust spot efficiency test.

Initially, the synthetic filters were installed in AHU #12 and the fiberglass filters were installed in AHU #8. After 1 week, the filters were switched between AHUs, where they remained for the rest of the 13-week test. This switch was done to check if the performance of the filters changed between the two AHUs. No noticeable changes were detected in the performance when they were exchanged.

HVAC systems

AHU #8 and AHU #12 were matched as closely as possible in terms of their capacity, building areas served, and total air volume delivered. Together, they delivered conditioned air to the general areas in the fifth, sixth, and seventh floors of the hospital. Properties and performance of the fans and motors in the AHUs are presented in Table 1.

At the entry to each AHU, outside ambient air mixed with return air from the building in a blending space. This blended air was drawn through automatic roll pre-filters with a dust spot efficiency of 15% and 70–80% arrestance tested in accordance with ASHRAE Standard 52.1 (ASHRAE, 1992). The pre-filtered air then moved through a pre-heater and cooling coil before entering the fan. After leaving the fan, the air passed through a filter bank holding the 12 main filters used in the test. The filters were arrayed in three rows and four columns in AHU #8. In AHU #12, nine 0.61 m × 0.61 m filters were arrayed in three rows and three columns with three 0.305 m × 0.61 m filters installed in an adjacent column. After passing through the main filters, the air was humidified before being

Table 1 Properties and performance of fans and motors in AHU #8 (synthetic filters) and AHU #12 (fiberglass filters)

Specifications	AHU #8	AHU #12
Fan type	Centrifugal	Centrifugal
Wheel diameter (m)	0.69	0.69
Motor power (hp)	40	30
Motor speed (rpm)	1750	1750
Maximum daily median flow during test period (m³/h)	36,500	33,500
Minimum daily median flow during test period (m³/h)	28,100	23,500

sent to the building. The delivered airflow rate, the return airflow rate, and heating, cooling and humidifying were controlled by a central computer system that responded to fluctuations in the air temperature and relative humidity of the spaces served by the HVAC systems.

Efficiency measurement in AHUs

Particles were sampled in each AHU at 36 locations upstream and downstream from the main filters (see Figure 1). These samples led to one complete set of efficiency measurements. The 36 sampling locations were selected according to American Conference of Governmental Industrial Hygienists ventilation guidelines (ACGIH, 2004). Upstream and downstream sampling locations were at the same horizontal and vertical positions relative to each filter bank.

Particles were sampled at 2.83 l/min through a long probe using a laser particle counter HHPC-6 (ART
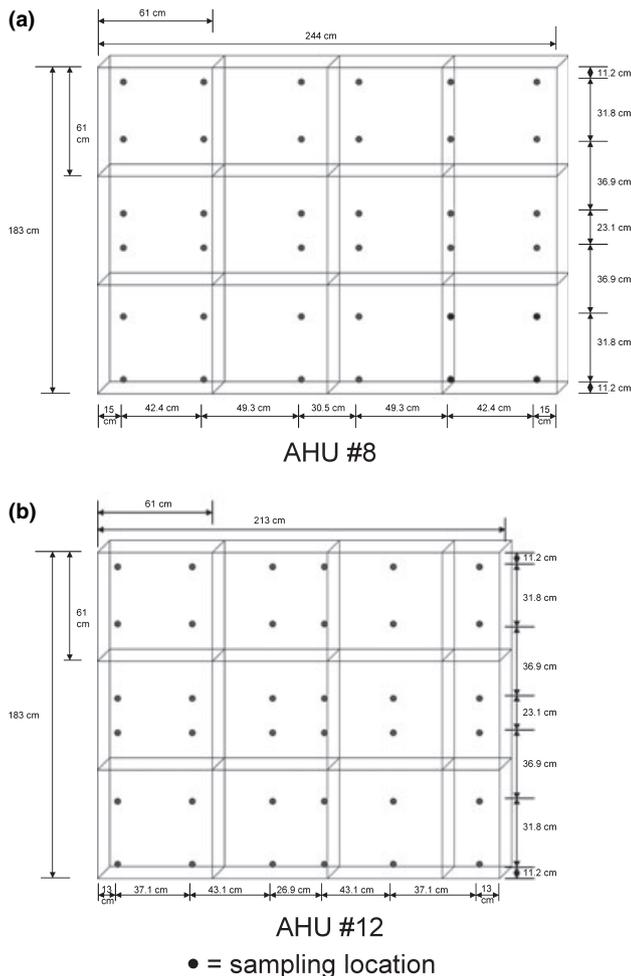

Fig. 1 Layout of (a) AHU #8, in which synthetic filters were tested, and (b) AHU #12, in which fiberglass filters were tested. The locations of sampling points, the same for both upstream and downstream sampling, are indicated on the diagrams for each unit

Instruments, Grants Pass, OR, USA) with six size channels for particles: 0.3–0.5, 0.5–0.7, 0.7–1.0, 1.0–2.0, 2.0–5.0, and $> 5.0\ \mu m$. The sampling probe had an inner diameter of 0.95 cm and length of 3.66 m. A short piece of flexible tubing, 0.31 m long with an inner diameter of 1.27 cm, was used to connect the probe to the particle counter. The sampling probe was located 10 cm from the surface of filters for both upstream and downstream sampling.

Although isokinetic sampling was not possible due to the requirements of realigning and moving the sampling probe, the aspiration efficiency for particles of interest into the probe and transmission efficiency through the probe were calculated (Brockmann, 2001). Aspiration efficiency was determined to be 73% for particles 5 μm in diameter and transmission efficiency was calculated as 79%. The efficiency for smaller particles was higher. Although the aspiration and transmission efficiencies were less than 100%, the losses were relatively small for the particle diameters tested. In addition, the sampling probes and sampling lines were kept constant during measurements. Therefore, losses should not have biased the filtration efficiency measurements because they presumably occurred in the same proportions upstream and downstream from the test filters.

For each test, a single sample was taken at each of the 36 sampling locations upstream and downstream for both filter banks. The HHPC-6 was allowed to count the number of particles for 1 min at each sampling point. Each row in the 6×6 grid was sampled sequentially, alternating between the upstream and downstream locations to minimize the variation of the particle concentrations over time during the sampling.

The collection efficiency, η, was calculated at corresponding points for each particle size channel as:

$$\eta = 1 - \frac{C_d}{C_u} \tag{1}$$

where C_d is the number concentration of particles at the downstream location and C_u is the particle concentration at the upstream location. Thus, 36 measurements of η were taken for each test, for which the mean and standard deviation were calculated. Seven sets of measurements were carried out over 13 weeks. The fifth set of readings showed more variability than the others for unknown reasons, but they were still included in analyses.

Airflow rate measurement

The data for airflow rates over the entire test period were collected by a sensor that was controlled by the central computer system for the AHUs. Airflow rate was recorded by the computer system every 30 min. As the AHUs were turned off for maintenance or inspec-

tion on a few occasions, the median of each day was used to indicate the representative value for that day.

Because this computer system had sensors to measure flow, Q_2, in only the second of three ducts branching off from each AHU, additional measurements were conducted to obtain an estimate of the total volumetric airflow rate. During the 8 weeks from the start of testing, velocity pressure in all three ducts branching off from the AHU was measured 7 times to obtain the volumetric airflow rate in each duct using an inclined manometer and a pitot tube. The measurements were performed 5 m downstream from the filters and at either 25 points (5×5 traverse points) or 36 (6×6 traverse points) across the entire cross-sectional area in each duct according to ACGIH guidelines (ACGIH, 2004). The velocity pressure of airflow in each branch duct j ($j = 1, 2, 3$) was converted to velocity by

$$V_{j,i} = \sqrt{\frac{VP_{j,i}}{\rho}} \tag{2}$$

where $V_{j,i}$ is the velocity in duct j at location i, $VP_{j,i}$ is the velocity pressure reading in duct j at location i, and ρ is the air density. The values of $V_{j,i}$ were averaged for each branch duct j to yield $\bar{V}_j$. The volumetric airflow in each duct was then calculated using

$$Q_j = \bar{V}_j A_j \tag{3}$$

where Q_j is airflow rate in duct j and A_j is the cross-sectional area of duct j. The fraction F_j of the total airflow rate in each duct was calculated by the expression

$$F_j = \frac{Q_j}{\sum_{j=1}^{3} Q_j} \tag{4}$$

for all three ducts in each AHU. The effect of elevation in this calculation was neglected because of its small magnitude.

The values of F_j were averaged for the seven measurements made of the flows in each AHU. The averaged values are presented in Table 2. Because continuous monitors operated only in duct 2 in each unit, the measured fractions allowed the calculation of total flow through the AHU from measurements of the flows in duct 2 using the expression

$$Q_{total} = \frac{Q_{2,median}}{F_2} \tag{5}$$

in which Q_{total} is the total flow through an AHU and $Q_{2,median}$ is the median airflow through duct 2 for a given day.

Pressure drop measurement

The pressure drops across the filter banks were measured by reading the values on the inclined manometers attached to AHUs #8 and #12 thirteen times during the 13-week test period. The measurement for pressure drop started after the two kinds of filters were switched between AHUs #8 and #12. Pressure drop is proportional to the velocity through the medium in HVAC filters (Brown, 1993). Because AHUs #8 and #12 had different cross-sectional areas and operated at flows that varied with the demands of the spaces they served, the pressure drop measurements were normalized to the velocity of the air entering the filter bank to allow for a valid comparison of the test filters. Pressure drop readings from the inclined manometer were adjusted to a velocity of 2.54 m/s (500 fpm) across the filter bank using

$$\Delta P_{adjusted} = \frac{(\Delta P_{observed})(A_{bank})(2.54 \text{ m/s})}{Q_{total}} \tag{6}$$

in which $\Delta P_{observed}$ is the reading from the inclined manometer, $\Delta P_{adjusted}$ is the pressure drop adjusted to 2.54 m/s, and A_{bank} is cross-sectional area of the filter bank (not the surface are of the filter medium). For each day evaluated, the median value of Q_{total} was utilized in the computation of $\Delta P_{adjusted}$.

Biological particle tests

Additional tests, including filtration efficiency for culturable biological particles, were carried out in a small duct system, shown in Figure 2, that processed
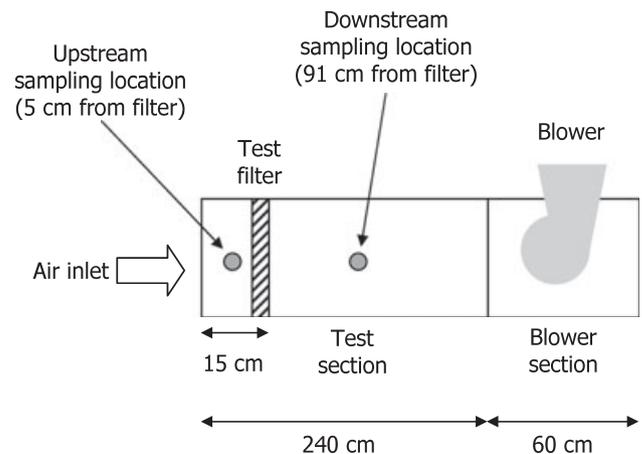
Table 2 The fractional distribution of airflow rate in each duct

	AHU #8 (synthetic media)	AHU #12 (fiberglass media)
Duct 1	0.132 ± 0.0056	0.250 ± 0.0032
Duct 2[a]	0.618 ± 0.0075	0.552 ± 0.0083
Duct 3	0.251 ± 0.0080	0.197 ± 0.0086

Values are means ± standard deviations.
[a]Duct 2 has a sensing system for airflow rate.

Fig. 2 Schematic diagram of small test duct apparatus

ambient outdoor air. The duct system was made of rectangular galvanized steel duct with a 0.61 m × 0.61 m cross section. The straight duct was 3 m long. Air was drawn through the apparatus by a centrifugal fan with a 0.40 m wheel diameter driven by a 1 hp motor operating at 1075 rpm. The system was mounted on four small wheels for convenient mobility, and was about 10 cm off the ground. An inclined manometer measured pressure drop across the test filter. A damper was installed to adjust the airflow.

Test filters included one new fiberglass filter and one new electrostatically charged synthetic filter. These were the same kinds of filters used in the hospital AHUs. In addition, one fiberglass filter and one synthetic filter that had been removed from the hospital AHUs after 13 weeks of use were evaluated. Efficiency was measured both for all atmospheric particles (non-biological and biological atmospheric particles together) and separately for culturable biological atmospheric particles.

To evaluate efficiency for all particles, an optical particle counter (Royco 5250; Hach Ultra Analytics, Grants Pass, OR, USA) with eight channels for particles ranging from 0.5 to 25 μm in diameter was utilized to measure particle size distributions upstream and downstream from the test filter. Each size distribution measurement used a 5-l air sample collected over 5 min. The sampling locations were along the centerline of the duct. The probe to the particle counter was positioned 5 cm away from the filter surface for the upstream samples and 0.91 m from the surface for downstream samples. Care was taken to minimize sampling bias between the upstream and downstream measurements. By adjusting the airflow damper, the pressure drop across each filter was matched to the pressure drop measured in the AHUs of the hospital to facilitate comparisons with hospital HVAC system conditions. For new filters of both types, the initial pressure drops measured in the hospital were used. For used filters, the final pressure drops were utilized.

Efficiency for the new filters was measured with the optical particle counter on four occasions, whereas the efficiency of the used filters was measured three times. On each occasion for each filter, size-specific particle concentrations upstream and downstream were measured at least five times. The measurements alternated between upstream and downstream locations to minimize effects of variations in the particle concentrations over the sampling period. The multiple measurements on each occasion were pooled to produce a single value of efficiency for each filter and particle diameter according to Equation 1. Efficiency data from multiple occasions were averaged for the various filters and standard deviations were calculated.

Measurements of culturable particle efficiency were performed using the same test filters evaluated with the optical particle counter. A single Andersen-type Six-

Stage Viable Impactor (Thermo Electron Corporation, Waltham, MA, USA) was used to sample and size culturable particles. During a test, the entire impactor was placed into the test duct alternately on the upstream and downstream sides of the test filter at approximately the same distances as the optical particle counter probe. Five separate tests were carried out for each of the new filters and four for each of the used filters. The impactor sampled at a flow rate of 28.3 l/min. Sampling times in early tests were 5 min upstream and 15 min downstream. Later tests collected sample volumes of 100 l upstream and 1000 l downstream to increase the numbers of colonies present in the downstream samples. An assumption inherent with the use of different sampling intervals is that incoming culturable particle concentrations were constant throughout a test. Aspiration efficiencies for the impactor should be high for all particle sizes sampled (Brockmann, 2001).

The particles were sampled onto Petri dishes containing malt extract agar (MEA) and incubated at 25°C (typical room temperature) for 4 days or 37°C (typical body temperature) for 5 days. After incubation, the number of colony-forming units (CFUs) on the dishes were counted regardless of morphology. Using positive hole correction (Macher, 1999), the number of CFUs on the plates was adjusted to account for multiple particles being sampled through the same hole in the impactor stage. Concentrations in CFU/m^3 were computed from the corrected CFU counts and the sample volume. Biological particle collection efficiency for each stage of the impactor was calculated from upstream and downstream concentrations according to Equation 1.

For each of the four test filters evaluated in this part of the study, efficiency measurements for culturable particles 0.65–4.7 μm as measured with the Andersen viable impactor were compared statistically to corresponding efficiency measurements for all incoming ambient particles as measured by the Royco optical particle counter using a two-sample *t*-test with an equal variance assumption in Microsoft Excel. This task was simplified because the size intervals on the optical particle counter, which are selectable, were chosen to correspond to the size intervals on the impactor. In addition, efficiency for the corresponding new and used filters as measured both for culturable particles using the impactor and for all incoming particles with the optical particle counter were compared using the same statistical test.

Results

Figure 3 shows the pressure drop across the filters adjusted to an equal velocity as a function of time after installation for the entire period of the hospital study. Curves from linear regressions are drawn through the
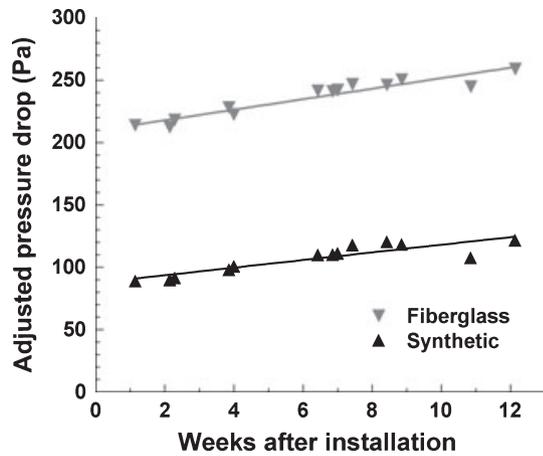
Fig. 3 Pressure drop adjusted using Equation 6 to a velocity of 2.54 m/s (500 fpm) entering the filter banks as a function of time after installation for both the fiberglass and synthetic filters in the hospital air-handling units. Data points indicate individual pressure drop readings. Curves represent linear regressions fit to the data for each type of filter

data points. Toward the beginning of the test period, the adjusted pressure drops across the two kinds of filters were significantly different. The initial $\Delta P_{\text{adjusted}}$ across the fiberglass filters was 214 Pa, which was about 2.4 times the $\Delta P_{\text{adjusted}}$ of 89 Pa across the synthetic filters. The $\Delta P_{\text{adjusted}}$ increased during the test by 45 Pa for the fiberglass filters and only 33 Pa for the synthetic filters.

Figure 4a shows the collection efficiency as a function of the geometric mean of the lower and upper particle diameters for each size interval 5.0 μm or smaller for the fiberglass filters on the first and last day their efficiency was measured. Data points are connected by straight lines. The efficiency for the fiberglass filters did not change significantly in 85 days of testing. Efficiency as a function of particle diameter is shown for synthetic filters in Figure 4b for the first and last day they were evaluated. The synthetic media showed a significant decrease in efficiency between day 2 of operation in the HVAC system and day 90. Figure 4a,b also indicates that the clean synthetic filters had slightly greater total particle collection efficiency than the clean fiberglass filters, especially for particles smaller than 0.7 μm in diameter.

Figure 5 shows data for fiberglass and synthetic filter efficiency as a function of time for the entire duration of the test for particle diameters ranging from 0.3 to 5.0 μm. The plots show both data points and second-order curves fit to the data. The fiberglass filters exhibited little change in efficiency for any particle size throughout the test period. The synthetic filters exhibited a steady efficiency decrease during the first 7 weeks of testing. During the remainder of the test period, however, the synthetic filter efficiency remained relatively steady. The absolute efficiency decrease was largest for particles smaller than 1.0 μm in diameter.
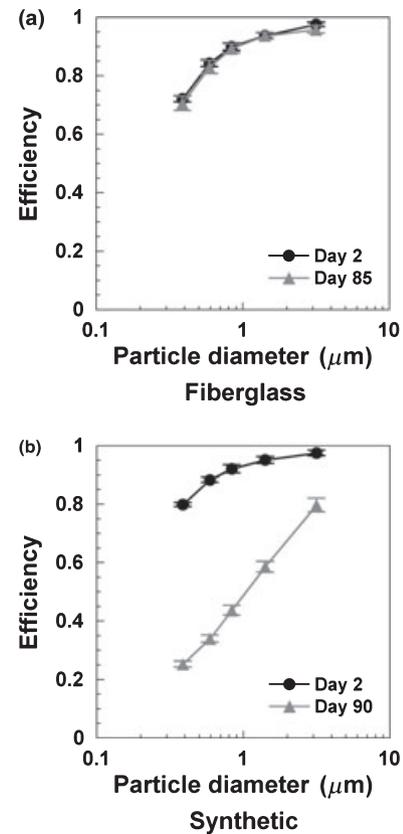

Fig. 4 Efficiency as a function of light scattering particle diameter (a) for fiberglass filters on their first day of testing (day 2) and final day of testing (day 85) and (b) for synthetic filters on their first day of testing and final day of testing (day 90). Data points representing mean efficiency at each particle diameter are connected by straight lines. Plotted diameters represent the geometric mean of the lower and upper diameter for size intervals on the particle counter. Error bars represent 95% confidence intervals for the mean efficiency

In the small test duct, obtaining sufficient culturable particles was a challenge. Culture plates incubated at 37°C did not yield sufficient colonies for meaningful efficiency calculations. At 25°C, more CFUs were observed. However, for the final plate in the impactor, corresponding to particles 0.65–1.1 μm in aerodynamic diameter, only four of five tests on new filters and two of four tests on used filters had sufficient counts to be included in the data analysis.

Figure 6a,c presents filter efficiency as a function of particle diameter for, respectively, clean fiberglass and electrostatically charged synthetic filters as measured in the AHUs at the hospitals and as measured in the small duct system for all particles and for only culturable biological particles incubated at 25°C. In this figure, the diameter plotted for the efficiency results for all ambient particles is a light scattering diameter as measured by the HHPC-6 or Royco 5250 optical particle counters. The diameter for the culturable biological particle data is an aerodynamic particle diameter as measured by the viable impactor.
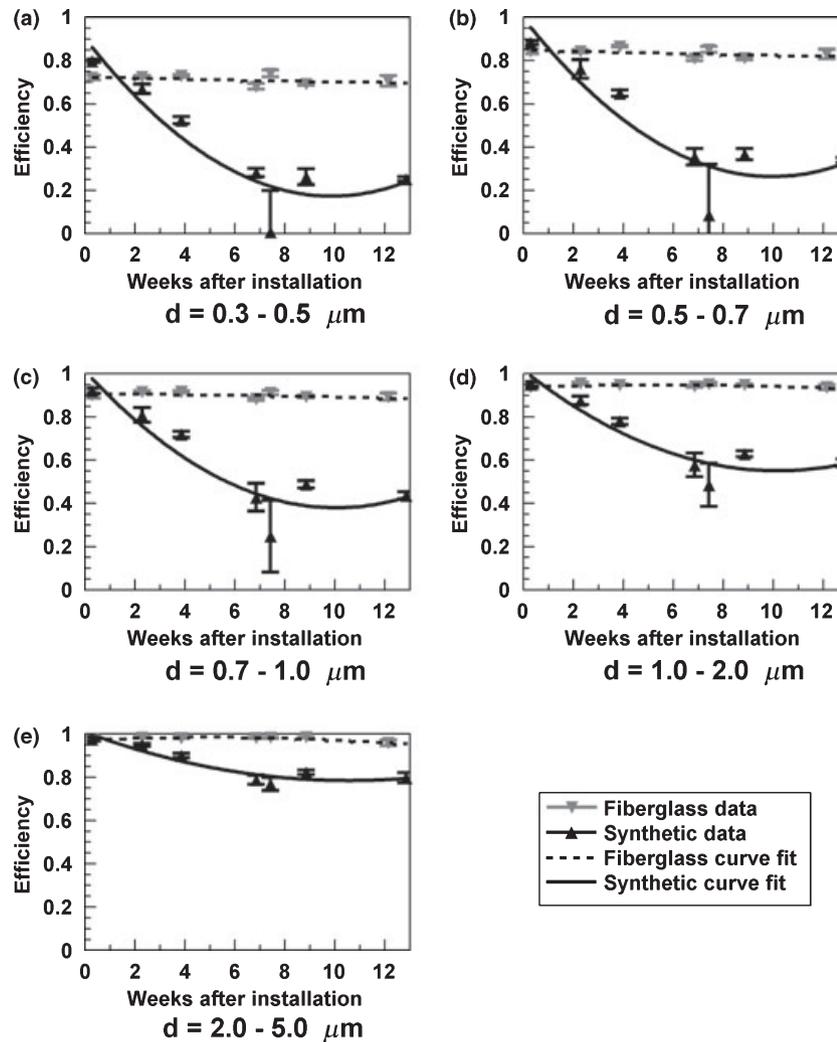
Fig. 5 Efficiency as a function of time after the filters were installed for particles with light scattering diameters of (a) 0.3–0.5 μm, (b) 0.5–0.7 μm, (c) 0.7–1.0 μm, (d) 1.0–2.0 μm, and (e) 2.0–5.0 μm. Data points represent mean efficiency at each time. Error bars indicate 95% confidence intervals for the mean efficiency. Curves are second-order polynomials fit to the data

Figure 6b,d shows results equivalent to Figure 6a,c for used filters. They include data taken on the final days of testing in the hospital AHUs and measurements performed in the small duct system for all particles and for culturable particles incubated at 25°C.

Table 3 shows the results of t-tests comparing the efficiency measurements made using the optical particle counter and the viable impactor in the small duct apparatus on each of the four test filters used in this part of the study. Over the diameter range evaluated, the only differences significant at the $P < 0.05$ level were for the used fiberglass filter in the 0.65–1.1 μm range and the used synthetic filter in all four diameter ranges evaluated. Table 4 shows t-test results for comparisons of efficiency measurements on new filters to efficiency measurements on used filters made in the small duct system with both the Royco optical particle counter and the Andersen viable impactor. For the particle diameters evaluated, no significant differences were observed between the new and used fiberglass filters. For the electrostatically charged synthetic filters, the efficiency measured by the optical particle counter for the used filters was significantly lower than the efficiency for the clean filters. However, the efficiency for the synthetic filters measured using the viable impactor showed a significantly lower efficiency only for particles in the 2.1–3.3 μm particle diameter interval.

Discussion

Two parameters are most important for filter performance: pressure drop and efficiency. The pressure drop is correlated to the energy required to move air through a filter bank. As dust loads on a filter, its pressure drop increases. Eventually, the resistance to airflow will be high enough that the blower in the AHU will no longer be able to provide the flow required to ventilate the building adequately. Figure 3 shows that the electrostatically charged synthetic filters operated at less than
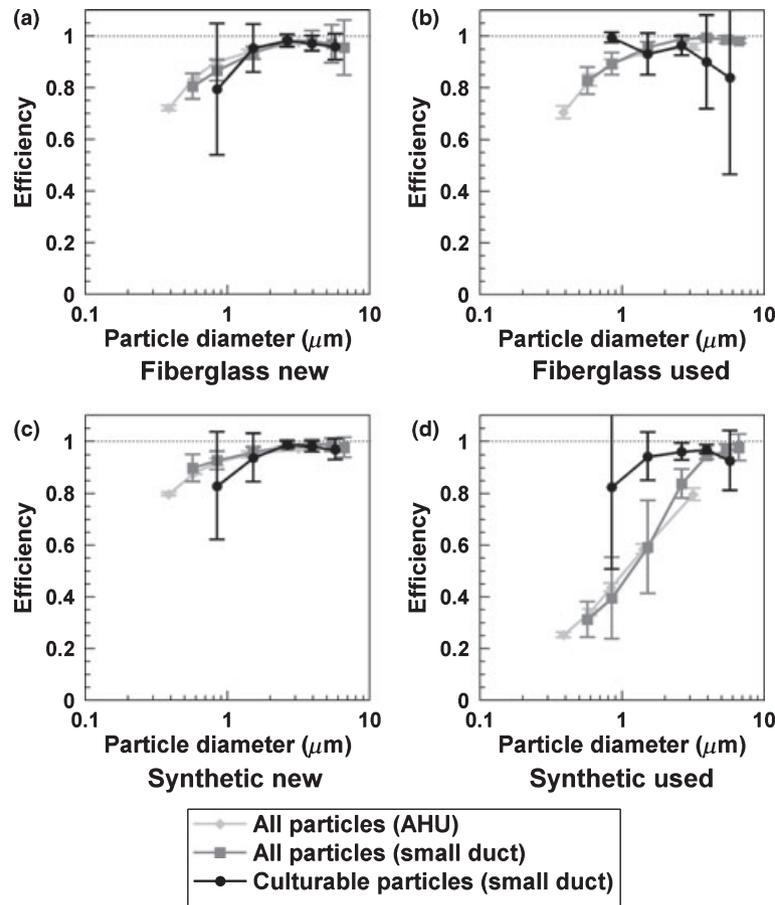
Fig. 6 Efficiency as a function of particle diameter as measured for all incoming particles in the hospital AHUs and the small duct apparatus and for culturable biological particles in the small duct apparatus for (a) a new fiberglass filter, (b) a fiberglass filter used in the hospital AHUs for 90 days, (c) a new electrostatically charged synthetic filter, and (d) a synthetic filter used in the hospital AHUs for 90 days. Data points representing mean efficiency at each particle diameter are connected by straight lines. Plotted diameters represent the geometric mean of the lower and upper diameter for size intervals on the instruments used. The particle diameters for measurements of all incoming particles are light scattering diameters whereas diameters for measurements of culturable biological particles are aerodynamic diameters. Error bars represent 95% confidence intervals for the mean efficiency

Table 3 *P*-values for two-sample *t*-tests with equal variances comparing the mean efficiency measurements for each test filter made using the Royco optical particle counter for all particles entering the small duct apparatus to the corresponding measurements for culturable particles made using the Andersen viable impactor. The particle diameters for measurements using the optical particle counter are light scattering diameters whereas the diameters for measurements of culturable biological particles are aerodynamic diameters

	Fiberglass		Synthetic	
Particle diameter interval (μm)	New	Used	New	Used
0.65–1.1	0.40	0.0042[a]	0.18	0.0035[a]
1.1–2.1	0.65	0.43	0.56	0.0008[a]
2.1–3.3	0.80	0.12	0.54	0.0006[a]
3.3–4.7	0.49	0.22	0.30	0.018[a]

[a]These comparisons are considered significant with $P < 0.05$.

Table 4 *P*-values for two-sample *t*-tests with equal variances comparing the mean efficiency measurements for the used test filters made using either the Royco optical particle counter for all particles entering the small duct apparatus or the Andersen viable impactor for culturable particles to the equivalent measurements for the corresponding new test filters. The particle diameters for measurements using the optical particle counter are light scattering diameters whereas the diameters for measurements of culturable biological particles are aerodynamic diameters

	Fiberglass		Synthetic	
Particle diameter interval (μm)	Optical particle counter	Viable impactor	Optical particle counter	Viable impactor
0.65–1.1	0.18	0.17	<0.0001[a]	0.97
1.1–2.1	0.079	0.63	0.0001[a]	0.92
2.1–3.3	0.25	0.24	<0.0001[a]	0.031[a]
3.3–4.7	0.43	0.21	0.0008[a]	0.26

[a]These comparisons are considered significant with $P < 0.05$.

50% of the adjusted pressure drop of the fiberglass filters throughout the 13-week test period in the hospital. Also, the adjusted pressure drop of the synthetic filters increased more slowly than the pressure drop of the fiberglass filters, although this difference could be related to the lower efficiency of the synthetic filters during most of the test period.

The lower pressure drop of the electrostatically charged synthetic filters is an important advantage

for HVAC system operation. AHUs with these synthetic filters are likely to require less electrical energy to operate than AHUs with the fiberglass filters. In addition, the electrostatically charged synthetic filters will require a substantially longer time to reach a pressure drop that is unacceptable for operating the fan in the unit. Furthermore, many buildings have AHUs in which more efficient fiberglass filters cannot be installed because blowers will no longer be able to supply sufficient air to ventilated spaces. Because of their lower pressure drop, electrostatically charged synthetic filters offer an option for achieving higher efficiency, at least initially, without limiting airflows.

Figures 4 and 5 show that the efficiency of the fiberglass filters mounted in the hospital AHUs and challenged with ambient particles changed little over the 13-week test period. However, the efficiency of the electrostatically charged synthetic filters declined substantially with use as they collected ambient particles. The decrease in efficiency for the filters made from charged synthetic fibers was most likely caused by shielding of charges on the fibers by dust collected on the filters. This result was consistent with the findings from past studies (Barrett and Rousseau, 1998; Raynor and Chae, 2003, 2004; Walsh and Stenhouse, 1998).

Air velocity through the filter media is an important factor affecting collection efficiency. During the first 5 weeks of testing in the hospital AHUs, the velocities of air passing through the filter banks in AHU #8 and AHU #12 were within 5% of one another. However, during the final 8 weeks, the average velocity for the charged synthetic filters was about 16% lower than the average velocity for the fiberglass filters. Although its effects should be small, the reduced velocity for the synthetic filters might have slightly enhanced the collection of particles smaller than 0.5 μm in diameter due to electrostatic and diffusion processes and slightly decreased collection of particles larger than 2 μm by the impaction mechanism.

When new, clean fiberglass and electrostatically charged synthetic filters and fiberglass and charged synthetic filters used for 13 weeks in the hospital AHUs were evaluated in the small test apparatus, Figure 6 shows that curves of efficiency vs. particles diameter measured for all ambient particles were similar to curves measured *in situ* in the hospital AHUs. An important difference between the tests in the hospital HVAC systems and the small duct system was the presence of pre-filters in the HVAC systems. This difference meant that more particles of larger diameter were available for sampling during tests in the small apparatus. However, the lack of a pre-filter does not appear to have affected results substantially.

Comparisons of efficiency curves in Figure 6 and the results of statistical analyses shown in Tables 3 and 4 show interesting trends. For both the fiberglass and electrostatically charged synthetic filters, Table 4 indicates that the culturable particle efficiency for the used filters did not exhibit a significant difference from the efficiency of the new filters with the exception of the 2.1–3.3 μm range for the synthetic filters for which the significantly different efficiencies were 98.9% (new) and 96.1% (used). On the other hand, the efficiency differences for the new and used synthetic filters measured for all particles using the optical particle counter were much larger and were significant for all particle size intervals evaluated. With the exception of used fiberglass filter in the 0.65–1.1 μm interval, Table 3 shows that the only statistically significant efficiency differences measured between the culturable particles and all incoming particles was for the used synthetic filter. Although the reason for the single significant difference in measurements for the used fiberglass filters is uncertain, the result may have been caused by the abnormally high number of CFUs counted upstream from the test filter in both of the measurements that helped comprise the 0.65–1.1 μm culturable particle efficiency for this filter.

Figure 6 compares efficiency as a function of light scattering diameter for measurements of all incoming particles to efficiency as a function of aerodynamic diameter for culturable particles. The density of culturable particles can be expected to be 1.0–1.5 g/cm^3 (Hinds, 1999). Thus, the geometric diameters for culturable particle efficiency readings would be slightly smaller than the diameters shown on the plot. In general, light scattering diameters can vary from −50% to +140% of the geometric diameters of particles an optical particle counter is measuring (Hinds, 1999). For the mixed ambient particles sampled in this study, the variance between light scattering and geometric diameter would be expected to be small. On the logarithmic scale for diameter shown in Figure 6, the effects of considering different types of particle diameter together should be minimal.

The results in Figure 6 and Tables 3 and 4 suggest that the used synthetic filters collected culturable biological particles in the outdoor air with higher efficiency than ambient non-biological particles. Why might biological particles entering electrostatically charged synthetic filters not experience efficiency losses evident for the predominant non-biological particles? One hypothesis is that biological particles, at least those that grow when incubated at 25°C, carry much greater amounts of charge per particle than non-biological particles of the same size and that this greater charge might be sufficient to overcome the effect of charge-shielding by particles collected on the filter fibers. Mainelis et al. (2001, 2002) reported that recently generated biological particles carried higher levels of charge than recently generated non-biological particles. Although Mainelis et al. (2001) mentioned that these particles will become neutralized gradually over time in the ambient environment, the biological

particles sampled in this study may have been generated recently enough that they retained a higher level of charge than non-biological particles of the same size. The hypothesis that differences in the charge level of ambient biological and non-biological particles can lead to differences in filtration efficiency should be tested explicitly.

If the results for culturable particles can be substantiated in future studies, the findings may have important implications for the selection of HVAC filters. Although the electrostatically charged synthetic filters exhibited substantially lower pressure drop throughout testing, the efficiency of the synthetic filters for all particles declined substantially with use. Were biological particles to experience this reduced efficiency, these charged synthetic filters might not be an optimal choice for HVAC systems in healthcare facilities and buildings with increased risk of biological attack. However, the culturable particle efficiency results suggest the possibility that the electrostatically charged synthetic media may not experience an efficiency reduction for at least some biological particles. Thus, installation of synthetic filters with high MERV ratings may be an improvement for some applications in which pressure drop precludes installation of fiberglass filters with high MERV ratings.

Despite these possible implications, the limitations of the culturable particle efficiency measurements in this work must be noted. First, only a few sets of efficiency measurements were performed on each test filter. Because culturable particle efficiency measurements in this study were noisy, more measurements should be conducted to reduce error levels and provide higher confidence in the efficiency results. Second, most of the culturable particles collected in these ambient outdoor samples were probably fungal spores. Fungal spores, particularly *Aspergillus* spp., are important sources of airborne nosocomial infections during construction and renovation in and near healthcare facilities (Eickhoff, 1994). However, in healthcare settings and buildings with increased risk of biological attack, bacterial and viral particles may be of even greater concern. The extent to which the results for culturable particles in this work extend to all kinds of airborne microorganisms must be assessed before broad recommendations on the relative utility of fiberglass and synthetic filters can be made. Third, the organisms cultured on the wide-spectrum MEA collection medium used in this study may not be species that are infectious for humans and, therefore, may not be important for HVAC filters to collect. Fourth, little is known about the airborne transmission of potentially infectious agents (Roy and Milton, 2004). Even the particle sizes with which common airborne infectious agents are associated are unknown. This lack of fundamental knowledge regarding airborne infectious agents constrains recommendations regarding ventilation control measures.

Conclusions

The efficiency performance of synthetic filters carrying electrostatic charges and fiberglass filters without electrostatic charges was studied for 13 weeks in hospital HVAC systems. During this time, pressure drop across the filters was also evaluated. Additional measurements of collection efficiency for total particles and culturable biological particles were made in a small duct system.

When measured using all incoming particles, the charged synthetic filters showed a substantial decrease in efficiency with use for all particle diameters tested, ranging from 0.3 to 5.0 μm. The synthetic filter efficiency decreased for about 7 weeks before reaching a steady level that is likely close to the mechanical efficiency of the media. The efficiency of the fiberglass filters, on the other hand, remained steady with time. The most likely cause for the reduction in efficiency for the synthetic filters is shielding of electrostatic charges by collected dust. The pressure drop of the electrostatically charged synthetic filters adjusted to a standard velocity was less than 50% of the pressure drop for the fiberglass filters throughout the study.

Unlike the efficiency measured using all particles, the culturable particle collection efficiency for both the fiberglass and electrostatically charged synthetic media did not vary substantially between new and used filters. A potential reason for the differing observations for all particles and for culturable particles only is that biological particles may carry greater levels of charge per particle than non-biological particles of the same size. This greater charge might be sufficient to overcome the effect of charge-shielding by particles previously collected on fibers.

The observations of culturable particle efficiency for new and used filters in this study were limited in several ways and should be confirmed by additional research before firm recommendations on the relative merits of fiberglass and electrostatically charged synthetic filters are made. Within these limitations, the finding in this study that culturable particle efficiency remained steady with dust loading for the synthetic filters suggests the possibility that the synthetic filters may have a performance advantage over fiberglass filters due to reduced pressure drop if biological particles are the primary contaminants of concern. However, if both biological and non-biological particles are important, the choice of filter will more likely be based on a tradeoff between pressure drop and overall efficiency considerations.

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