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Biological and Metal Contaminants in HVAC Filter Dust

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ABSTRACT

Recently, the interaction between particles retained on HVAC filters and indoor air quality has gained more attention due to their possible relationship to irritation, health outcomes, and odors. This paper focuses on microbial contaminants and metals captured on HVAC filters in nine residential and light-commercial buildings. Culturable fungi and bacteria populations captured in the dust were quantified using standard spread plate methods and heavy metal (Pb, As, Cd) concentrations were determined by atomic absorption spectroscopy. Culturable fungal and fungal spore concentrations ranged from 10^4 to 10^6 and from 10^2 to 10^3 CFU/g, respectively, while culturable bacteria and bacterial spore concentrations ranged from 10^5–10^7 and 10^3–10^5 CFU/g, respectively. Microbial concentrations were consistent across filters having different efficiencies with median concentrations within one order of magnitude. Heavy metal concentrations were as high as 29 µg/g for lead, 6 µg/g for cadmium, and 7 µg/g for arsenic. Variations observed in the metal concentrations between different dust samples may be due to particle size differences related to different filter efficiencies and indoor sources. This investigation provides insight into possible metal sources and concentrations of biological and heavy metal contaminants present in indoor environments.

INTRODUCTION

Indoor air quality researchers typically focus their attention on biological, chemical and particulate contamination of indoor environments and the health effects and discomfort that these contaminants may cause. Indoor environmental investigations typically rely on short-term sampling techniques that provide only a snapshot of contaminant concentrations in the indoor environment at the time of sampling. HVAC filter dust is a potential resource that has received less attention and may enhance our understanding of indoor occupant exposure. Filters are typically in place for extended periods of time and have the potential to serve as long-term samplers of the indoor environment. Furthermore, HVAC filter dust can be collected with minimal effort and analyzed for a broad range of contaminants. This paper focuses on bacteria, fungi, and heavy metals captured on HVAC filters and investigates how these parameters vary with filter and building characteristics.

Several studies have measured the concentration of bacteria and fungi in indoor environments, especially in air and settled dust (e.g., Bouillard *et al.*, 2005; Dales *et al.*, 1997; Verhoeff and Burge, 1997). However, the reported concentrations are difficult to compare because they vary considerably depending on sampling technique and sampling location, among other factors. An alternative approach for investigating air and settled dust would be to analyze the dust that collects on HVAC filters. A recent study has suggested that HVAC dust may provide an integrated measure of airborne contamination levels in an indoor environment (Tringe et al., 2008). HVAC filters are able to retain biological particles and microorganisms can survive, accumulate, and, under certain conditions, multiply on HVAC filters (Farnsworth *et al.*, 2006; Foarde and Hanley, 2001; Kemp *et al.*, 1995; Kemp *et al.*, 2001; Moritz *et al.*, 2001; Simmons and Crow, 1995). In addition, a number of studies suggest a relationship between Sick Building Syndrome (SBS) symptoms and the presence of microorganisms on filters (e.g., Schleibinger and Ruden, 1999). Several researchers have also studied heavy metal concentrations in house dust and the correlation with potential indoor and outdoor sources and particle size distributions (Al-Rajhi *et al.*,

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1996; Chattopadhyay *et al.*, 2003; Decker *et al.*, 2002; Kim *et al.*, 1998; Tong, 1998). Despite these efforts, we are not aware of any research that utilizes HVAC filters as samplers to characterize metal concentration levels indoors or that examined the influence of HVAC systems and potential sources on metal concentrations found on the HVAC dust.

While both microbial populations and metals found indoors have been studied, the relationship between their presence in HVAC filter dust and critical characteristics of both the particular HVAC system and the building remains unclear. This research compares the contaminant levels found in HVAC filters with different filter efficiencies and provides insight into potential sources of contamination. This investigation is part of a broader evaluation of the utility of using filters as samplers for the indoor environment.

METHODOLOGY

Eight residential and one commercial building in Austin, Texas were selected for this investigation. These sites represent a sample of convenience and not a random sample. To characterize the sites considered, data was collected regarding the year the buildings were built, number of occupants, past or current presence of smokers, proximity to major highways, presence of attached garage, filter location, and conditioned volume. Two sets of HVAC filters were collected from each site, approximately three months apart. All filters were stored in a 4º C (39 ºF) environmental chamber maintained at a relative humidity (RH) of approximately 70% until the analyses were performed within a few weeks following collection.

Characterization of Sites and Filters

The filters were categorized according to the minimum efficiency reporting value (MERV) as determined by ASHRAE Standard 52.2 (ASHRAE, 2007) and reported by the manufacturers. The sample included seven low-efficiency filters (MERV <5), seven mid-efficiency filters (MERV 5-8) and four high-efficiency filters (MERV 9-14). Filter pressure drop measurements were performed at filter installation and removal using an Energy Conservatory DG700 digital manometer, and the mean value of these two measurements characterized the mean filter pressure drop. Mean flow rates across each filter in fan-only mode were measured using an Energy Conservatory True Flow Plate. By monitoring the HVAC systems two or three times during the cooling season for 24 hours approximately every month, we measured the cooling duty cycle, which is an estimate of the fraction of time that the HVAC system is running during the cooling season. In addition, during the monitoring events, the temperature and RH in the HVAC system return plenum were also recorded. To estimate the mass accumulated on each filter, we subtracted the mean weight of three unused filters from the weight of the used filter using a balance (Sartorius B310S). Table 1 summarizes the instruments used during the investigation.

Microbial and Metal Analyses

Two samples of dust from each filter were acquired by shaking and scraping the dust material off the filters. The samples were subsequently analyzed for microbial and heavy metal concentrations. The enumeration of culturable bacteria and fungi was completed using the standard spread plate method 9215C (APHA, 1998). The microorganisms present in the HVAC filter dust were transferred into a phosphate buffer solution (PBS, 8 g/L NaCl, 0.2 g/L KCl, 1.44 g/L Na_2HPO_4, and 0.24 g/L KH_2PO_4) by sonication and vortexing for 10 minutes each. For bacterial enumeration, a 0.1 ml aliquot of PBS was plated on R_2A agar plates containing 0.04% cycloheximide. For fungal determinations, a 0.1 ml aliquot of PBS was plated on Sabouraud Dextrose Agar (SDA) plates containing 0.01% chloramphenicol. Bacterial plates were incubated for 3-7 days at 30 °C (86 ºF), while fungal plates were incubated for 7-14 days at room temperature (approximately 23 °C/73 ºF). After incubation, the number of bacterial and fungal colonies formed was counted and the results were used to estimate the microbial concentration in the dust, expressed as colony forming unit (CFU) g^{-1} dust. The analysis was performed three times for each dilution and the average number of colonies formed was recorded. The ability of the microorganisms to form spores was also tested by pasteurizing an aliquot of the samples for 15 minutes at 75º C (167 ºF) and then plating the samples as described above. Any colonies that formed were assumed to have originated from spores and to represent the spore-forming fraction of the population.

Heavy metal concentrations in the HVAC filter dust were determined by atomic absorption spectroscopy (Perkin Elmer AAnalyst 600). Dust samples were digested via the microwave-assisted digestion method 3030K (APHA, 1998). This method consists of a nitric acid digestion under controlled pressure and temperature conditions that facilitate the transfer of the metals present in the particles into the liquid extract. The liquid extract from each sample was analyzed for selected

Table 1. Summary of Instrumentation

Measurement	Manufacturer	Model	Accuracy
Temperature	Onset	Hobo U10	±0.4°C (0.7°F)
Relative humidity	Onset	Hobo U10	±3.5%
Pressure drop	Energy Conservatory	DG 700	±1% or 0.2 Pa (0.0008 IWC)
Air flow	Energy Conservatory	True Flow Plate	±7%
Weight	Sartorius	Balance B310S	±0.001 g

heavy metals (Pb, As, Cd) according to method 3111B (APHA, 1998). To ensure the accuracy of the measurements, reagent blanks and periodic calibration checks were also analyzed.

A nonparametric statistical method, the Wilcoxon Rank-Sum Test, which does not assume any specific distribution of the data, was applied to compare and identify dissimilarities between the different data groups. When comparing the different data groups, a significance level of 0.1 was assumed owing to the small sample size and the conservative nature of this statistical test.

RESULTS AND DISCUSSION

Table 2 characterizes the nine sites and the presence of likely sources of contamination. Site 9 was the one light commercial building included in the study. All the sites were relatively close to major highways and five sites had attached garages. Sites 2, 3, 4, and 9 were attached to other dwellings. Four sites had the filter located at the unit, while five were located at the return register. In Sites 3 and 9, multiple filters were present. Cooling duty cycles of the sites ranged from 9 to 34%. There were no smokers occupying any of the sites, although Site 2 had smokers in the past. Sites 3 and 4 were located in the same residence with two separate and independent HVAC systems for different floors of the residence. The sites summarized in Table 2 represent a range of HVAC systems and operating characteristics for this region of the country.

Table 3 summarizes the characteristics of the 18 HVAC filters, two from each site, that were evaluated during the project. The mean pressure drop across the filter, ΔP, and the mean volumetric airflow through the HVAC system, Q, were obtained by averaging the values obtained at installation and at removal. For a few filters, we were not able to measure the filter pressure and supply plenum pressure (required for the flow measurement) at filter installation, so the measurements collected at the time of filter removal are reported. For Filter 2 of Site 2, the value reported represents the observation acquired at installation. The mean temperature and RH observed at the HVAC return plenum during the monitoring events are also reported. These values do not represents mean levels during the period the filters were in place, but only what was observed during the monitoring visits.

For some filters, the days in service was not known, because it was the filter the homeowner had in place when we started the investigation. For seven filters it was possible to estimate the mass accumulated over the service life because these filters were weighed before use. As expected, we observed a correlation between filter efficiency and particle mass accumulated on the filter. The mean mass accumulated on the low-efficiency and mid-efficiency filters was 1.7 and 4.0 g, respectively. There may also be a correlation between the mass of particles accumulated on filters and the presence of carpet in the house. The mean mass accumulated on the filters from the sites with and without carpet was 3.9 and 0.8 g, respectively. Carpets tend to accumulate more dust than bare floors because they are harder to clean than other types of floor. As a consequence, particle resuspension from carpet is expected to be greater than from other floor surfaces (Yoon and Brimblecombe, 2000). As demonstrated by Corsi *et al.* (2008), resuspension of PM_{10} is much larger than $PM_{2.5}$ suggesting that even the low MERV filters can retain many of the larger particles from vacuuming activities.

Figure 1 presents the mean culturable microbial concentrations in the HVAC filter dust from the nine sites investigated, expressed as CFU/g dust. Since two filters were collected and analyzed from each site, 18 total samples are represented in Figure 1 and the mean value for each site is shown. For each site, the left bar indicates the culturable concentration of bacteria while the right bar represents the

Table 2. Site Characteristics

Site #	Year Built	Number of Occupants	Proximity to Highway, km (miles)	Attached Garage	Carpet	Filter Location	Conditioned Volume, m^3 (ft^3)	Cooling Duty Cycle, %
1	1975	2	1.0 (0.62)	Yes	No	Unit	422 (14,900)	14
2	1973	2	0.6 (0.37)	Yes	Yes	Unit	309 (10,900)	16
3	1998	1	0.2 (0.12)	Yes	No	Register[2]	114 (4,020)	9
4	1998	1	0.2 (0.12)	Yes	Yes	Register	227 (8,010)	27
5	1949	2	1.8 (1.12)	No	No	Register	276 (9,740)	32
6	1941	4	1.1 (0.68)	No	Yes	Register	324 (11,400)	29
7	Late 70s[1]	4	0.6 (0.37)	No	Yes	Unit	259 (9,140)	34
8	1984	3	0.5 (0.31)	Yes	Yes	Unit	308 (10,900)	15
9	1995	3	0.2 (0.12)	No	Yes	Register[3]	656 (23,200)	19

[1]Estimated based on neighborhood and nearby homes.
[2]Three filters in different return grilles were present at this site.
[3]Two filters in different return grilles were present at this site.

Table 3. Filter Characteristics

Site	Filter	Filter Efficiency	Pressure Drop ΔP, Pa (IWC)	Air flow Q, m^3/h (cfm)	Temperature, °C (°F)	RH, %	Days in Service	Mass on Filter, g
1	1	Low	22±0.2 (0.088±0.0008)	1710±120 (1010±71)	24.7±0.50 (76.5±33)	70.8±4.1	88	
	2	Mid	50±0.5 (0.20±0.002)	1670±120 (981±69)			95	
2	1	Low		1280±90 (754±53)				
	2	Low	58±0.6 (0.23±0.002)	1780±130 (1050±74)[1]	26.6±0.83 (79.8±34)	66.7±3.7	95	4.5±0.002
3	1	High	37±0.4 (0.15±0.002)	1420±100 (837±59)	25.5±0.77 (78.0±33)	62.4±4.5	85	
	2	Mid	33±0.3 (0.13±0.001)	1450±100 (851±59)			99	1.3±0.002
4	1	Low	64±0.6 (0.26±0.002)[2]	941±66 (554±39)[2]				0.3±0.002
	2	High	54±0.5 (0.22±0.002)	1000±70 (589±41)	26.1±0.87 (78.9±34)	58.4±3.5	85	
5	1	Mid	78±0.8 (0.31±0.003)[2]	1990±140 (1170±82)				
	2	Low	59±0.6 (0.24±0.002)	1940±140 (1140±80)	24.4±1.9 (75.9±35)	63.0±5.9	87	0.3±0.002
6	1	High	89±0.9 (0.36±0.004)[2]	1800±130 (1060±74)[2]				
	2	Mid	92±0.9 (0.37±0.004)	1660±120 (975±68)	24.8±1.3 (76.6±34)	58.9±5.0	90	4.2±0.002
7	1	Low	49±0.5 (0.20±0.002)	1300±91 (763±54)	26.0±0.30 (78.8±33)	60.1±2.9	87	
	2	Mid	81±0.8 (0.32±0.003)	1140±79 (669±46)			92	4.1±0.002
8	1	Mid	48±0.5 (0.19±0.002)[2]	1150±80 (676±47)[2]				
	2	Low	27±0.3 (0.11±0.001)	1200±84 (705±49)	24.7±1.3 (76.5±34)	52.5±3.9	88	
9	1	High	76±0.8 (0.30±0.003)[2]	2730±190 (1610±110)				
	2	Mid	81±0.8 (0.32±0.003)	2790±200(1640±120)	24.0±1.6 (75.2±35)	54.2±5.3	82	6.5±0.002

[1]Only initial measurement
[2]Only final measurement

culturable fungal concentration. The height of each bar indicates the mean culturable concentration and originated from the counts of the microbes with the ability to form colonies on the specific agar plates described in the Methodology section. The bottom section of each bar represents the spore forming fraction of the population, which is the fraction of the viable microbial concentration able to survive the pasteurization treatment. Only the error bars for the total height of the columns are shown in the figure and the bars on the lower portions were of similar magnitude.

The culturable bacterial concentrations were consistently greater than the fungal concentrations for the nine sites investigated. The bacterial concentrations ranged from 10^5 to 10^7 CFU/g while the bacterial spore concentrations were typically two orders of magnitude lower, ranging from 10^3 to 10^5 CFU/g. The mean concentration across the sites was 1.4×10^7 CFU/g for bacteria and 1.2×10^5 CFU/g for bacteria spores. Culturable fungal concentrations were consistently lower than bacteria levels and varied in the 10^4 -10^6 CFU/g range. Fungal spore concentrations were typically the lowest of all four categories and varied in the 10^2 - 10^3 CFU/g range. The mean concentration across the sites for fungi and fungal spores was 1.1×10^6 and 1.4×10^3 CFU/g, respectively. To put these microbial concentrations in context, these values are similar to those observed in soil for both bacteria and fungi (Lovell *et al.*, 1995; Toro *et al.*, 1997).

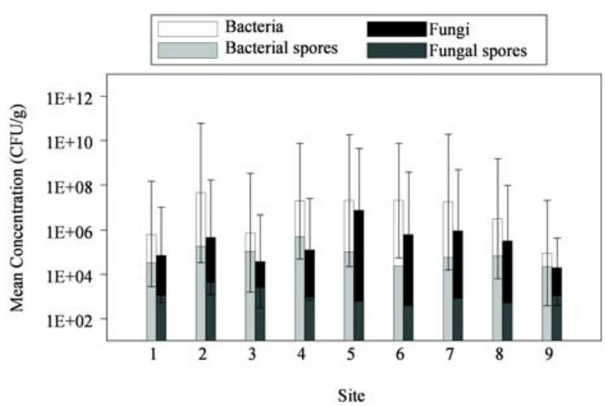

Figure 1 *Mean microbial concentrations in HVAC filter dust.*

The culturable bacterial and fungal concentrations observed in the current study are slightly higher than the values reported in the literature for settled dust (Bouillard *et al.*, 2005; Chew *et al.*, 2003). This difference may be attributable to the HVAC airflows that deliver airborne microbes and nutrients to HVAC filters. Many studies have suggested that microbial contamination of HVAC filters occurs because filters collect sufficient organic material and nutrients to support microbial growth (Burge, 1987; Kemp *et al.*, 2001; Pejtersen, 1996). Kemp *et al.* (1995) also observed enhanced fungal growth when additional nutrients were delivered to HVAC filters. The culturable microbial concentrations encountered in this study suggest that HVAC filters in residential buildings in a humid environment like central Texas during the cooling season represent a hospitable environment for microbial proliferation.

The microbial concentrations measured in this study represent only the culturable fraction of the microbial population able to grow on the specific media utilized. Toivola *et al.* (2002) estimated that only 1% of the microbial population indoors is culturable and molecular based tools offer the promise of being able to detect a much greater fraction of the microbial community, not just the culturable fraction. However, the extraction of DNA directly from HVAC filter dust cake is particularly challenging and, as reported by Ramakrishnan *et al.* (2006), the use of standard commercial DNA extraction kits often generates inconsistent results. Nevertheless, the authors are currently investigating these techniques and their applicability to further characterize microbial populations on HVAC filters.

Table 4 summarizes the median microbial concentrations observed on filters with different MERV ratings. Median microbial concentrations on HVAC filters were relatively consistent across filters with different removal efficiencies. The median concentrations were typically within one order of magnitude of each other and application of the Wilcoxon Rank-Sum Test to the data did not find any significant differences between filters with different MERV ratings. Despite this general similarity, high-efficiency filters had the lowest median microbial concentrations for bacteria, fungi and fungal spores. As reported by Waring and Siegel (2008), the particle mass that accumulates on HVAC filters strongly depends on their removal efficiency, and high-efficiency filters capture a greater mass of particles. Typical bacteria and fungi cell sizes vary from less than a micron to several microns, depending on the microbial species. Therefore, high-efficiency filters are more likely to retain an elevated number of microbial cells. A high-efficiency filter also captures more non-biological particles, potentially providing microorganisms with a greater amount of substrate and nutrients, and therefore promoting their growth. However, the presence of non-biological particles will also increase the mass captured on the filters and serve to diminish the measured microbial concentration because it is based on CFU per unit mass (both biotic and abiotic) of dust captured. This is one possible explanation for the decreased microbial concentrations observed on the dust captured in the high-efficiency filters.

Figure 2 summarizes the mean HVAC filter dust concentrations of lead, cadmium and arsenic for each site. Pb had consistently the greatest concentration in all the samples with values ranging from 5.4 to 28.6 μg/g dust. The median Pb concentration across all samples was 13.0 μg/g. HVAC filter dust concentrations for Cd and As were lower than Pb concentrations with values varying in the 0.5 - 6 and 0.8 - 7.3 μg/g ranges, respectively. The median concentrations of Cd and As across all the samples analyzed were 1.9 μg/g and 1.4 μg/g, respectively. The metal concentrations reported in the literature for indoor dust are similar to those reported here for HVAC filter dust and are typically in the μg/g range, with Pb and Zn concentrations that tend to be higher than the other metals and can reach the mg/g range (Al-Rajhi *et al.*, 1996; Lisiewicz *et al.*, 2000; Turner *et al.*, 2006).

Sites 5, 6 and 7 had higher Pb concentrations than the rest of the sample. None of the three sites had attached garages or is located adjacent to a major highway, suggesting that leaded gasoline is not the major source of indoor lead. Sites 5 and 6 were the oldest sites investigated and we hypothesize that the elevated Pb concentration was derived from leaded paint, still in use when the residences were built. Several researchers (Chattopadhyay *et al.*, 2003; Kim *et al.*, 1998; Tong, 1998) provide evidence for this hypothesis. There was uncertainty about the age of Site 7, the other site with an elevated Pb concentration although it was located in a neighborhood constructed in the 1970s and was likely to have contained leaded paint. Site 3, the newest residence investigated had the lowest Pb concentration again supporting the hypothesis that leaded paint is an important contributor to indoor lead levels. A correlation between the age of a property and Pb levels in settled dust has also been observed by other researchers (Adgate *et al.*, 1998; Kim *et al.*, 1998; Tong, 1998). However this correlation is not entirely consistent throughout our study; for instance, Site 4, which is also a new residence, had a higher Pb concentration than several older sites in the study so other factors may be important. At a given site, our data suggests that a correlation between the Pb, Cd and As metal concentrations may exist, as suggested by Sites 5, 6, and 7. In these sites, the concentrations of the three metals analyzed are all above the median values observed in this study suggesting a common source, or coincident sources, of metal contamination.

Table 5 summarizes the median concentrations of Pb, Cd and As in HVAC filter dust collected on filters with different removal efficiencies. The median metal concentrations for the high-efficiency and low-efficiency filters were always the lowest and the greatest, respectively. For Pb and, especially, As, the concentrations in the high-efficiency filters were significantly lower than those in the low-efficiency filters. As described above, high-efficiency filters retain a greater fraction of small particles than low-efficiency filters. On the other hand, low-efficiency filter dust has a greater proportion of larger particles than high-efficiency filter dust. Therefore, the data suggest that large particle size fractions may have greater metal concentrations than small particle size fractions. This observation is in accordance with the findings of Al-Rajhi *et al.* (1996). However, another study (Lisiewicz *et al.*, 2000) detected higher metal concentrations in fine particles than in larger particles. General conclusions are difficult to draw because of the limited number of sites

Table 4. Median Microbial Concentrations in HVAC Filter Dust for Filters with Different Efficiencies

Filter MERV	Bacteria	Bacterial Spores	Fungi	Fungal Spores
	CFU/g			
Low	$6\times10^6\pm6\times10^5$	$5\times10^4\pm9\times10^3$	$4\times10^5\pm7\times10^4$	$1\times10^3\pm1\times10^3$
Mid	$9\times10^5\pm2\times10^5$	$7\times10^4\pm7\times10^3$	$6\times10^5\pm1\times10^5$	$8\times10^2\pm1\times10^3$
High	$3\times10^5\pm6\times10^4$	$7\times10^4\pm3\times10^3$	$1\times10^5\pm9\times10^4$	$6\times10^2\pm7\times10^2$

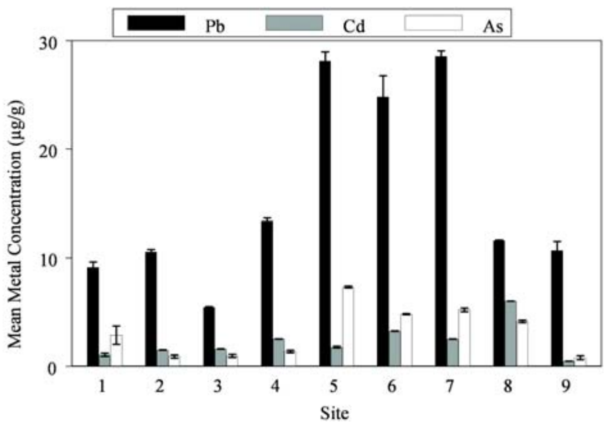

Figure 2 *Metal concentrations in HVAC filter dust.*

investigated in the current study and because the filters with different efficiencies were not uniformly distributed throughout the sites and, therefore, some biases due to potential site-specific sources are possible. Furthermore, different metal sources, both indoor and outdoor, may have a significant influence on the metal concentration distribution for particles of different sizes. In our study, Cd concentrations were extremely uniform across filters with different efficiencies and the Cd concentrations detected were comparable to values reported in the literature for settled dust (Jaradat *et al.*, 2004; Momani *et al.*, 2002; Turner *et al.*, 2006). The concentration of As in the low-efficiency filters was greater than those for the mid- and high-efficiency filters, suggesting that the As concentrations in the larger particle size fractions could be particularly elevated. Decker *et al.* (2002) associated elevated indoor dust levels of arsenic with pressure-treated wood.

Table 6 summarizes the mass of metals collected on the HVAC filters, calculated as the metal concentration multiplied by the mass of dust collected on the seven filters where the dust mass was measured. Filter 2 at Site 6 appears to be highly contaminated with all three metals. Metal mass seems to have similar trends for the three metals and it is unusual for a site to have a low concentration of one element and an elevated concentration of another one. Table 7 summarizes the median metal mass on filters with low and mid efficiencies. Mid-efficiency filters collected a higher mass of all three metals analyzed. Filter efficiency data obtained from ASHRAE Standard 52.2 (ASHRAE, 2007) indicates that mid-efficiency filters capture approximately two to three times as many 3.0–10.0 µm particles than the low-efficiency filters. Similar (or even stronger) trends in capture efficiency are also expected for smaller particles and, this difference in removal efficiency could explain the different quantities of metals retained on the filters.

There are several parameters that may play a significant role in the application of HVAC filters as samplers and could potentially represent confounding factors in data interpretation. Further investigation is required to understand the influence of size-resolved filter efficiency, indoor mixing conditions, HVAC system run time, microbial growth and decay in filter dust, and particle-size dependence of the contaminants of interest. Once the impact of these factors is better delineated, HVAC filters may become a useful, widely-available sampling tool that can be collected with minimal effort and analyzed for a broad spectrum of contaminants.

CONCLUSION

We measured microbial and metal concentrations in HVAC filter dust collected from nine sites. We detected culturable bacterial and fungal concentrations in the 10^5 - 10^7 and 10^4 - 10^6 CFU/g ranges, respectively. Spore concentrations represented a smaller fraction, typically two to three orders of magnitude lower than the total concentrations. The microbial concentrations in the filter dust were slightly higher than settled dust concentrations reported in the literature and are in the same range as those reported for soil. These results indicate that HVAC filters in humid environments such as central Texas represent a hospitable environment for microbial proliferation. Microbial concentrations on filters with different removal efficiencies were relatively similar, typically within one order of magnitude. Mean Pb concentrations in the HVAC filter dust were particularly elevated with mean values as high as 29 µg/g, while Cd and As concentrations were on the order of a few µg/g. A possible correlation between the age of the site and the Pb concentration was observed suggesting that leaded paint is a possible source of indoor Pb dust. Differences in heavy metal concentrations were observed between buildings and filters, suggesting that several factors including the influence of filter

Table 5. Median Metal Concentrations in the HVAC Filter Dust for Filters with Different Efficiencies

Filter MERV	Pb	Cd	As
	μg/g		
Low	18.5±0.79	2.00±0.062	4.61±0.24
Mid	12.9±0.54	1.64±0.035	1.89±0.32
High	7.49±0.44	1.54±0.027	0.912±0.22

Table 6. Metal Mass of HVAC Filters

Site	Filter	Filter Efficiency	Pb	Cd	As
			Amount of Metal, μg		
2	2	Low	11.8±1.6	9.09±0.69	2.30±2.4
3	2	Mid	3.48±0.18	0.882±0.045	1.57±0.66
4	1	Low	5.11±0.28	0.752±0.033	0.407±0.032
5	2	Low	8.51±0.81	0.470±0.079	3.18±0.14
6	2	Mid	192±33	22.6±1.1	37.4±2.0
7	2	Mid	53.0±0.92	3.80±0.064	14.5±0.29
9	2	Mid	36.7±8.7	1.51±0.031	3.47±0.35

Table 7. Median Metal Mass on HVAC Filters with Different Efficiencies

Filter MERV	Pb	Cd	As
	Amount of Metal, μg		
Low	8.51±0.81	0.752±0.079	2.30±0.14
Mid	44.9±4.8	2.66±0.055	8.96±0.51

efficiency, system run time and indoor contaminant distribution need more exploration before filters can be used as sampling devices.

REFERENCES

Adgate, J. L., R. D. Willis, T.J. Buckey, J.C. Chow, J.G. Watson, G.G. Rhoads, and P.J. Lioy 1998. Chemical mass balance source apportionment of lead in house dust. Environmental Science & Technology, 32, 108-114.

Al-Rajhi, M.A., M.R. Seaward, and A.S. Al-Aamer 1996. Metal levels in indoor and outdoor dust in Riyadh, Saudi Arabia. Environment International, 22, 315-324.

APHA, 1998. Standard Methods for the Examination of Water and Wastewater, 20th Edition, 1998. Prepared and published jointly with AWWA, WEF.

ASHRAE. 2007. ASHRAE Standard 52.2- 2007, Method of testing general ventilation air-cleaning devices for removal efficiency by particle size. Atlanta: American Society of Heating, Refrigerating and Air-conditioning Engineers, Inc.

Bouillard, L., O. Michel, M. Dramaix, and M. Devleeschouwen. 2005. Bacterial contamination of indoor air, surfaces and settled dust, and related dust endotoxin concentrations in healthy office buildings. Ann Agric Environ Med, 12, 187–192.

Burge, H.A. 1987. Approaches to the control of indoor microbial contamination. In: Practical Control of Indoor Air Problems. Proceedings of ASHRAE IAQ 87, 33–37.

Chattopadhyay, G., K.C. Lin, and A.J. Feitz. 2003. Household dust metal levels in the Sydney metropolitan area. Environmental Research, 93, 301-307.

Chew, G.L., C. Rogers, H.A. Burge, M.L. Muilenberg, and D.R. Gold. 2003. Dustborne and airborne fungal propagules represent a different spectrum of fungi with differing relations to home characteristics. Allergy, 58, 13-20.

Corsi, R.L., J.A. Siegel, and C. Chiang. 2008. Particle Resuspension During the Use of Vacuum Cleaners on Residential Carpet', Journal of Occupational and Environmental Hygiene, 5, 232–238.

Dales, R.E., D. Miller, and E. McMullen. 1997. Indoor air quality and health: Validity and determinants of reported home dampness and moulds. International Journal of Epidemiology, 26, 120-125.

Decker, P., B. Cohen, J.H. Butala, T. Gordon. 2002. Exposure to wood dust and heavy metals in workers using CCA pressure-treated wood. AIHAI, 63, 166-171.

Farnsworth, J.E., S.M. Goyal, S.W. Kim, T.H. Kuehn, P.C. Raynor, M.A. Ramakrishnan, S. Anantharaman, and W.H. Tang. 2006. Development of a method for bacteria and virus recovery from heating, ventilation, and air conditioning (HVAC) filters. Journal of Environmental Monitoring 8, 1006-1013.

Foarde, K.K., and J.T. Hanley. 2001. Determine the efficacy of antimicrobial treatments of fibrous air filters. ASHRAE Transactions, 107 (1), 156-170.

Jaradat, Q. M., K. A. Momani, A. A. Jbarah, and A. Massadeh. 2004. Inorganic analysis of dust fall and office dust in an industrial area of Jordan. Environmental Research, 96, 139-144.

Kemp, S.J., T.H. Kuehn, D.Y. Pui, D. Vesley, and A.J. Streifel. 1995. Growth of microorganisms on HVAC filters under controlled temperature and humidity conditions. ASHRAE Transactions, 101 (1), 305-316.

Kemp, P.C., H.G. Neumeister-Kemp, G. Lysek, and F. Murray. 2001. Survival and growth of micro-organisms on air filtration media during initial loading. Atmospheric Environment, 35, 4739-4749.

Kim, K.W., J.H. Myung, J.S. Ahn, H.T. Chon. 1998. Heavy metal contamination in dusts and stream sediments in the Taejon area, Korea. Journal of Geochemical Exploration, 64, 409-419.

Lisiewicz, M., R. Heimburger, and J. Golimowski. 2000. Granulometry and the content of toxic and potentially toxic elements in vacuum-cleaner collected, indoor dusts of the city of Warsaw. Science of the Total Environment, 263, 69-78.

Lovell, R.D., Jarvis, S.C., Bardgett, R.D. 1995. Soil microbial biomass and activity in long-term grassland: effects of management changes. Soil Biol. Biochemistry, 27, 969-975.

Momani, K. A., Q. M. Jaradat, A. Q. Jbarah, I. F. Momani, A.A. Omari. 2002. Water soluble species and heavy metal contamination of the petroleum refinery area, Jordan. J. Environ. Monit. 4, 990–996.

Moritz, M., H. Peters, B. Nipko, and H. Ruden. 2001. Capability of air filters to retain airborne bacteria and molds in heating, ventilating and air-conditioning (HVAC) systems. Int. J. Hyg. Environ. Health, 203, 401-409.

Pejtersen, J. 1996. Sensory pollution and microbial contamination of ventilation filters. Indoor Air, 239–248.

Ramakrishnan, M.A., S. Anantharaman, S.W. Kim, N.J. Stankey, T.H. Kuehn, P.C. Raynor, and S.M. Goyal. 2007. Detection of airborne bacteria in HVAC filters by polymerase chain reaction. Abstracts from the American Association of Aerosol Research Annual Meeting, Minneapolis, MN, 2006.

Schleibinger, H., and H. Ruden. 1999. Air filters from HVAC systems as possible source of volatile organic compounds (VOC)–laboratory and fields assays. Atmospheric Environment, 33, 4571-4577.

Simmons, R.B., S.A. Crow. 1995. Fungal colonization of air filters for use in heating, ventilating and air conditioning (HVAC) systems. J. of Industrial Microbiology, 14, 41-45.

Tong, S.T. 1998. Indoor and outdoor household dust contamination in Cincinnati, Ohio, USA. Environmental Geochemistry and Health, 20, 123-133.

Toivola, M., S. Alm, T. Reponen, S. Kolari, and A. Nevalainen. 2002. Personal exposures and microenvironmental concentrations of particles and bioaerosols. Journal of Environmental Monitoring, 166-174.

Toro, M., Azcon, R., Barea, J. 1997. Improvement of arbuscular mycorrhiza development by inoculation of soil with phosphate-solubilizing rhizobacteria to improve rock phosphate bioavailability (^{32}P) and nutrient cycling. Applied and Environmental Microbiology, 63, 4408-4412.

Tringe, S., Zhang, T., Liu, X., Yu, Y., Lee, W., Yap, J., Yao, F., Suan, S., Ing, S., Haynes, M., F., Rohwer,Wei, C.,Tan, P., Bristow, J., Rubin, E., Ruan, Y., 2008. The airborne metagenome in an indoor urban environment. PLoS ONE 3(4): e1862.

Turner, A., and L. Simmonds. 2006. Elemental concentrations and metal bioaccessibility in UK household dust. Science of the Total Environment, 371, 74-81.

Verhoeff, A.P., and H.A. Burge. 1997. Health risk assessment of fungi in home environments. Annals of Allergy Asthma & Immunology, 78, 544-554.

Waring, M. S., and J. A. Siegel. 2008. Particle loading rates for HVAC filters, heat exchangers, and ducts. Indoor Air in press.

Yoon, Y. H., and P. Brimblecombe. 2000. Contribution of Dust at Floor Level to Particle Deposit within the Sainsbury Centre for Visual Arts. Studies in Conservation, 45, 127-137.