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Reduction of personal PM_{2.5} exposure via indoor air filtration systems in Detroit: an intervention study

Melissa M. Maestas¹, Robert D. Brook², Rosemary A. Ziemba³, Fengyao Li¹, Ryan C. Crane¹, Zachary M. Klaver¹, Robert L. Bard², Catherine A. Spino⁴, Sara D. Adar⁴, Masako Morishita¹

¹Exposure Science Lab, Family Medicine, College of Human Medicine, Michigan State University, East Lansing, MI, USA

²Division of Cardiovascular Medicine, University of Michigan, Ann Arbor, MI, USA

³Community Health Nursing, Ann Arbor, MI, USA

⁴School of Public Health, University of Michigan, Ann Arbor, MI, USA

Abstract

The adverse health effects of fine particulate matter (PM < 2.5 µm in diameter [PM_{2.5}]) air pollution are well-documented. There is a growing body of evidence that high-efficiency particulate arrestance (HEPA) filtration can reduce indoor PM_{2.5} concentrations and deliver some health benefits via the reduction of exposure to PM. However, few studies have tested the ability of portable air filtration systems to lower overall *personal-level* PM_{2.5} exposures. The Reducing Air Pollution in Detroit Intervention Study (RAPIDS) was designed to evaluate cardiovascular health benefits and personal PM_{2.5} exposure reductions via indoor portable air filtration systems among senior citizens in Detroit, Michigan. We evaluated the utility of two commercially available high-efficiency (HE: true-HEPA) and low-efficiency (LE: HEPA-type) indoor air filtration to reduce indoor PM_{2.5} concentrations and personal PM_{2.5} exposures for 40 participants in a double-blinded randomized crossover intervention. Each participant was subjected to three intervention scenarios: HE, LE, or no filter (control) of three consecutive days each, during which personal, indoor, and outdoor PM_{2.5} concentrations were measured daily. For mean indoor PM_{2.5} concentrations, we observed 60 and 52% reductions using HE and LE filters, respectively, relative to no filtration. Personal PM_{2.5} exposures were reduced by 53 and 31% using HE and LE filters, respectively, when compared with the control scenario. To our knowledge, this is the first indoor air filtration intervention study to examine the effectiveness of both HE and LE filters in reducing *personal* PM_{2.5} exposures.

Keywords

Personal exposure; particulate matter; inhalation exposure

Masako Morishita, tomoko@msu.edu.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Introduction

The detrimental effects of ambient fine particulate matter ($PM < 2.5 \mu m$ in diameter [$PM_{2.5}$]) on cardiovascular (CV) health are well-documented [1–4]. As such, both the American Heart Association and European Society of Cardiology have recognized ambient $PM_{2.5}$ as a major CV risk factor [5], presenting an urgent need to utilize methods of exposure reduction beyond governmental policies in order to protect human health.

There is a growing body of evidence that high-efficiency particulate arrestance (HEPA) filtration can reduce indoor $PM_{2.5}$ concentrations and deliver CV health benefits via the reduction of exposure to PM [6–12]. Given that people spend over 88% of their time indoors [13], interventions targeted at reducing indoor $PM_{2.5}$ concentrations could be a practical means of reducing overall personal $PM_{2.5}$ exposure. However, the CV health benefit results to date are mixed [13–15]. Moreover, to our knowledge, no study has quantified how the use of indoor air filtration reduced overall personal $PM_{2.5}$ exposure during interventions (e.g., [6–12]), which may be contributing to the mixed CV health results.

Studies of $PM_{2.5}$ health effects have historically relied on outdoor [1–3] or indoor [6–12] measurements and assumptions that those measurements can serve as a proxy for personal exposure. However, many studies have found that personal exposure concentrations are higher than either indoor or outdoor concentrations [16–18], and the literature is conflicted regarding which of these exposure measurements is most relevant to health effects. Taken together, there is a need for further research to assess personal $PM_{2.5}$ exposure separately from indoor $PM_{2.5}$ concentration.

Reducing Air Pollution in Detroit Intervention Study (RAPIDS) was designed to investigate the effectiveness of air filtration at reducing personal-level exposures to $PM_{2.5}$ and mitigating related CV health effects among older adults in a prototypical US urban location. The first objective of this study was to evaluate the use of portable indoor air filtration units as a practical means for reducing personal $PM_{2.5}$ exposures, and in this paper we present how effectively commercially available high-efficiency (HE: true-HEPA) and low-efficiency (LE: HEPA-type) air filtration technologies can reduce indoor $PM_{2.5}$ concentrations and personal exposure to $PM_{2.5}$.

Materials and methods

Intervention

In this randomized double-blind crossover intervention study, we placed two portable air filtration units (model HAP424, Holmes, Boca Raton, FL, USA) in the bedroom and main living space of each participant's residence for three separate intervention periods, each consisting of 3 days. Each of these intervention periods was separated by a washout period of at least 1 week. Each participant served as their own control, and no two subjects from the same residence participated simultaneously. During each intervention period, participants were exposed to three scenarios in random order: unfiltered air (no filter installed in filtration unit), LE ("HEPA-type" filter, model HAPF30D-U2, Holmes, Boca Raton, FL, USA), and HE ("True-HEPA" filter, model HAPF300D-U2, Holmes, Boca Raton, FL,

USA). Participants were blinded as to which filter type was installed in the filtration units in each scenario. The “HEPA-type” filter removes 99% of particles at 2 microns in size, while the “true-HEPA” filter removes 99.97% of particles at 0.3 microns in size. All air cleaners exhibited similar noise (average of 46 decibels at 6 feet) and identical outward appearance regardless of filtration status. The average energy consumption for a single-filtration unit was ~2 kWh over a 24-h period. This filter system has a certified Clean Air Delivery Rate (CADR) of 98 ft³/min. Individual residences utilized the same floor plan (~515 sq ft) and were equipped with hydronic baseboard heaters (i.e., no central forced-air heating system), and window air conditioning units that provide minimal air filtration. This study was conducted May through November of each year from 2014–2016.

Subjects

This study enrolled 40 participants from a government-subsidized low-income senior-citizen residential facility in Midtown Detroit, Michigan. The participants were non-smokers, not on supplementary oxygen, and ranged in age from 48–88 (mean of 67). Each morning of the interventions, a short survey was verbally administered to participants regarding their activities over the preceding 24 h. Subjects were asked if they left their apartment and, if so, for how long. If the subjects answered with a range for how long they were away from their apartment (e.g., 2–3 h), then the mid-point of the range (e.g., 2.5 h) was used when calculating the average overall subjects. Subjects were asked whether and for how long they opened their living room and/or bedroom windows. The survey also included questions about their means of transportation and whether or not they did any cooking.

This study was approved by the Institutional Review Board of the University of Michigan. Written informed consent was obtained from all subjects during a screening visit. This study has been registered at [ClinicalTrials.gov](https://clinicaltrials.gov) ().

Exposure assessment

Twenty-four hours of daily personal, indoor, and outdoor PM_{2.5} concentrations were measured during each 3-day intervention period. To assess personal exposure, participants carried a battery-powered particulate monitor (model personal DataRAM™ pDR-1500 Aerosol Monitor, Thermo Environmental Instruments Inc, Franklin, MA, USA). The pDR provided both real-time and 10-minute-averaged PM_{2.5} concentration data (“pDR data”), and also collected PM_{2.5} on a 37-mm Teflon filter. The integrated 24-h personal PM_{2.5} concentrations were then determined gravimetrically from the filters, and are reported as “personal PM_{2.5} data” throughout this paper. Correlation of the integrated “pDR data” and the filter-based personal data was $R^2 = 0.69$ ($N = 296$). We excluded pDR data and personal PM_{2.5} data for which the pDR was operating < 10 h in any 24-h period. The personal PM_{2.5} data were replaced by half the method detection limit if the concentration was below the detection limit.

Indoor PM_{2.5} samples were collected onto Teflon filter media using a custom-built pump system and Teflon-coated aluminum cyclone sample inlets at a nominal flow rate of 16.7L/min as determined via calibrated rotameters (Matheson Inc., Montgomeryville, PA, USA). The 24-h daily indoor concentration was then determined gravimetrically.

Outdoor PM_{2.5} samples were collected using a sequential air sampler (Partisol-Plus Model 2025, Rupprecht and Patashnick, Inc., Albany, NY, USA) located on the roof of a 3-story building 125 m from the study site. Outdoor PM_{2.5} was collected on 47-mm Teflon filters for subsequent gravimetric analysis. The indoor sampling systems have been used in several previous studies; a comparison with a commercially available outdoor sampling system has been previously documented [19].

Sample handling, processing, and analysis took place in Class 100 ultraclean rooms at the Michigan State University Exposure Science Laboratory and at the University of Michigan Air Quality Laboratory. Gravimetric determinations were made using a microbalance (MT-5, Mettler Toledo, Columbus, OH, USA) in a temperature/humidity-controlled environment as described in the Federal Reference Method [20].

Statistical analysis

We used the Friedman test [21, 22] with modifications to accommodate repeated measures [23] and missing observations [24] to evaluate distributional differences in observations among the various intervention scenarios. We also examined the average concentration of PM_{2.5} for the three days of an intervention, transformed it using a base-10 logarithm to account for the right-skewed nature of the data, and then used repeated measures analysis of variance (rANOVA) with missing data filled in according to the method described by Zar, 1999 [23] to evaluate distributional differences in observations among the various intervention scenarios. The rANOVA test is the parametric analog of the Friedman test [22]. If the rANOVA test was significant, then post hoc comparisons were done using the two-sample *t* test with Bonferroni correction [22] on the average concentration of the 3 days during an intervention transformed using a base-10 logarithm.

The Spearman rank correlation coefficients [25] were calculated among indoor, personal, and outdoor PM_{2.5} concentrations for data corresponding to each intervention scenario. The Spearman rank correlation was used because it is robust to outliers in the data [25].

PDR data were used to examine diurnal variation in personal PM_{2.5} exposure. The Kruskal–Wallis test [21] was used to test for differences in the distributions of pDR data among the intervention scenarios for each hour of the day. Statistical analyses were performed with MatLab software (Release R2016b; The MathWorks, Inc., Natick, MA, USA).

Results

Forty participants were recruited from a low-income senior-citizen residential facility in Midtown Detroit, Michigan. All participants' apartments had the same one-bedroom floor plan. With 40 participants, there were 120 possible person-days of PM_{2.5} measurements, and averaging each person's available data within an intervention week allowed for 40 possible person-weeks of PM_{2.5} measurements (Table 1). The missing data were due to subjects' partial participation and equipment failure.

Activity survey results indicated that on average, participants were in their apartments 89% of the time during interventions (278 surveys had a quantifiable answer). Window usage was

common, with participants reporting an open bedroom window on 71% of reported intervention days (yes/no question) and an open living room window on 66% of intervention days.

Figure 1 shows that mean indoor PM_{2.5} concentrations were reduced by 60 and 52% using HE and LE filters, respectively, compared with the control scenario. Table 2 shows the mean and standard deviation of the indoor, personal, and outdoor PM_{2.5} concentrations under each scenario, and shows the results of both the generalized Friedman and rANOVA tests indicating that there were differences among the distributions of indoor PM_{2.5} for the intervention scenarios with a significance level <0.05. A post hoc pairwise comparison test indicated significant differences ($P < 0.001$) in control versus HE, and control versus LE, but not in HE versus LE.

Boxplots for personal PM_{2.5} exposures are shown in Fig. 2, and Table 2 shows that personal PM_{2.5} exposures were reduced by 53 and 31% using HE and LE filters, respectively compared with the control scenario. As shown in Table 2, the results of the Friedman and rANOVA tests show that the distributions of personal PM_{2.5} for each scenario is different from each of the others. The overall mean (standard deviation) outdoor PM_{2.5} concentration for the study is 9.3 µg/m³ (4.1 µg/m³), and it did not show any significant difference among the intervention scenarios.

Spearman correlations between indoor, personal, and outdoor PM_{2.5} concentrations are shown in Table 3. As expected, the correlation was not significant between outdoor and either indoor or personal exposure during no filtration. The correlation between indoor and personal exposure during no filtration was significant, but the Spearman correlation was only 0.62.

The indoor PM_{2.5} concentration data under control scenarios was tested for temporal distributional differences among the 3 days within an intervention. Results of the Friedman test indicate that the indoor control PM_{2.5} concentration is unrelated to day (P -value = 0.592). The rANOVA test of the base-10 logarithm of indoor control PM_{2.5} concentration is also non-significant (P -value = 0.339). The indoor LE filtration data also has no difference in distribution among the three intervention days with a P -value for the Friedman test of 0.187 and a P -value for the rANOVA test of 0.054. Similarly, indoor HE filtration PM_{2.5} concentration is unrelated to intervention day with a Friedman P -value of 0.613 and an rANOVA P -value of 0.757. Summary statistics by day of intervention are given in Table 4.

Figure 3 shows the diurnal variation of pDR PM_{2.5} concentration. There are differences in the distributions of pDR data among the intervention scenarios for each hour of the day using the Kruskal-Wallis test at a significance level of 0.05. While interventions produced significant personal PM_{2.5} exposure reductions at all hours, the reductions were greater during typical sleep hours (between 10 PM and 8 AM) as compared with waking hours: 46 and 62 % reductions during sleep hours were observed for LE and HE, respectively, compared with 34 and 42% reductions during waking hours.

Discussion

This crossover indoor air filtration intervention study showed that the use of commercially available HE or LE filters in portable air filtration units significantly decreased both indoor PM_{2.5} concentrations (60 and 52%, respectively) and personal PM_{2.5} exposure (53 and 31%, respectively) compared with no filtration. To our knowledge, this is the first indoor air filtration intervention study to examine the effectiveness of commercially available HE and LE portable air filters in reducing *personal*/PM_{2.5} exposure. The overall indoor PM_{2.5} reduction difference between HE and LE filtration was relatively small. While LE filters may be efficient for reducing indoor PM_{2.5} concentrations, further study is needed to investigate whether this difference in PM_{2.5} exposure reduction is relevant to CV health outcomes.

This study is also unique in that it was conducted for an elderly urban population without any activity restrictions during the interventions. Some indoor air filtration studies request that participants adhere to certain restrictions during the intervention, such as keeping windows closed, staying indoors [6, 8], or not cooking [6]. Such restrictions (and homes described as “tightly sealed”), however, only allow for an assessment of the likely maximum reduction of indoor PM_{2.5} (57–61% [6–8].) and assume that indoor PM_{2.5} concentrations are an adequate substitute for personal exposures. Yet, reductions of indoor PM_{2.5} concentrations have been shown to be smaller under real-world conditions where such restrictions are absent (40–55% [9–12]).

For indoor PM_{2.5}, the observed 60% reduction during HE filtration compared with control (no) filtration was consistent with previous studies including Spilak et al. [11], who observed a 54.5% reduction in indoor PM_{2.5} when using an HE filter compared with a sham filter; Weichenthal et al. [10], who observed a median decrease from 42.5 µg/m³ to 22.0 µg/m³ (48% reduction); and Wheeler et al. [26] who observed a 52% reduction in fine particles in homes which used wood-burning for heating. Chen et al. [6] and Allen et al. [7] also observed 57 and 60% reductions indoor PM_{2.5} concentrations, respectively.

Our study measured personal and outdoor PM_{2.5} concentrations in addition to indoor concentrations, in contrast to previous studies, which were limited to indoor [7, 11, 12] or in some cases, indoor and outdoor [6, 9, 10, 26] PM_{2.5} concentration measurements. All of our participants lived in one residential facility, and thus, many variables were controlled for, such as apartment floor plan and size, stove type (electric), and proximity to streets and industrial sources of PM_{2.5}. This is similar to the work of Chen et al. [6] who studied 35 participants living in 10 dorm rooms—with the key difference being that in the present study, no two subjects from the same residence participated simultaneously to avoid clustering.

Our study also showed that the correlation between indoor and personal (no filtration) concentration was only 0.62, indicating that indoor monitoring did not fully describe total personal PM_{2.5} exposure. This information highlights the importance of measuring both indoor concentration and personal exposure in this type of intervention study. However, given that our elderly subjects spent most of their time indoors (~89%) and that reductions

of the mean indoor and personal PM_{2.5} via HE were 60 and 53%, respectively, indoor monitoring may be a reasonable proxy for personal PM_{2.5} exposure for this particular population.

The unique continuous personal PM_{2.5} exposure data revealed that the largest reductions occurred during sleep hours. While this may be the result of confined filtration volume, closed windows/doors or a greater percentage of time being spent indoors at night than during the day, further investigation of the health benefits of air filtration during sleep hours is warranted. We also plan to examine the effectiveness of the portable air filtration systems for each individual apartment.

One limitation of this study is that despite the proximity to highways and some industrial facilities, the outdoor PM_{2.5} at the study site (averaged over the study period) was below the National Ambient Air Quality Standard (NAAQS) of 12 µg/m³. However, indoor PM_{2.5} was higher than the NAAQS, indicating substantial indoor PM_{2.5} sources at the study site. Investigating outdoor and indoor PM_{2.5} components and sources is beyond the scope of this paper, and will be addressed in a future publication. Another limitation is the lack of other air pollution measurements such as particle number concentrations [27], which may have been useful given the proximity of our study site to highways. In any case, this study highlights that even in the NAAQS-compliant air pollution levels encountered in numerous urban settings, relatively inexpensive air filtration systems (at the time of the study, ~\$70 for a filtration unit and ~\$15–20 annually for air filters) may be an effective air pollution reduction tool.

In this crossover air filtration intervention study, we observed that indoor air filtration using either HE or LE filters measurably reduced both indoor PM_{2.5} concentrations and personal PM_{2.5} exposures. The reductions using HE filters were larger than for LE filters, and future work will need to elucidate whether this difference in PM_{2.5} exposure is biologically relevant to the CV system. While the utility of face masks for reducing personal exposure to PM_{2.5} has previously been demonstrated [28, 29], indoor air filtration is more practical for long-term and indoor usage. In highly polluted cities, the combination of in-home air filtration and masks for traveling outside the home should be investigated as a comprehensive intervention strategy [1].

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Fig. 1. Boxplot of indoor PM_{2.5} concentration (µg/m³) during each intervention scenario. The whiskers indicate the upper and lower deciles

Fig. 2. Boxplot of personal PM_{2.5} concentration (µg/m³) during each intervention scenario. The whiskers indicate the upper and lower deciles

Fig. 3. Diurnal variation of median pDR $PM_{2.5}$ concentration by intervention. The time point 0 represents data with time stamps between midnight and 1 AM

Table 1

Summary of sample size; for personal data, the first number indicates how many observations exist, while the number in parentheses indicates how many were used for the Friedman test

Variable	Control		LE		HE	
	Person-days	Person-weeks	Person-days	Person-weeks	Person-days	Person-weeks
Indoor	120	40	120	40	119	40
Personal	107 (104)	39	101 (98)	40	101 (99)	40
Outdoor	115	40	110	40	109	40

Summary of exposure data, presented as mean, (standard deviation), and [range]. The table shows *p*-values for both the Friedman test and repeated measures analysis of variance (rANOVA)

Table 2

Variable	Control	LE	HE	Friedman <i>P</i>	rANOVA <i>P</i>
Indoor PM _{2.5} µg·m ⁻³	17.5 (16.9) [4.1–117.5]	8.4 (5.4) [1.3–39.5]	7.0 (4.5) [1.1–30.8]	<0.001	<0.001
Personal PM _{2.5} µg·m ⁻³	15.7 (13.7) [2.1–91.6]	10.9 (9.6) [0.9–62.5]	7.4 (4.2) [0.9–19.1]	<0.001	<0.001
Outdoor PM _{2.5} µg·m ⁻³	9.0 (3.7) [2.5–21.2]	9.1 (4.0) [2.1–21.8]	9.7 (4.4) [2.1–21.8]	0.839	0.601

Table 3

Spearman correlations (ρ) between the various measures of PM_{2.5} for each intervention scenario. N indicates the number of pairs of data

Variable		Indoor			Personal		
		ρ	<i>P</i> -value	<i>N</i>	ρ	<i>P</i> -value	<i>N</i>
Control	Indoor	1		40			
	Personal	0.62	<0.001	39	1		39
	Outdoor	0.021	0.898	40	-0.14	0.383	39
LE	Indoor	1		40			
	Personal	0.68	<0.001	40	1		40
	Outdoor	0.35	0.026	40	0.24	0.142	40
HE	Indoor	1		40			
	Personal	0.59	<0.001	40	1		40
	Outdoor	0.35	0.027	40	0.012	0.941	40

Table 4Indoor PM_{2.5} mean, standard deviation (sd) and sample size (N) by intervention day

Variable	Day 1			Day 2			Day 3		
	Mean	SD	N	Mean	SD	N	Mean	SD	N
Control	19.0	22.5	40	14.7	11.1	40	18.8	15.5	40
LE	8.6	6.6	40	9.3	5.6	40	7.3	3.5	40
HE	7.3	4.3	40	6.8	4.2	40	6.9	5.1	39