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Reductions in particulate matter concentrations resulting from air filtration: A randomized sham-controlled crossover study

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Abstract

One-hundred seventy-two households were recruited from regions with high outdoor air pollution (Fresno and Riverside, CA) to participate in a randomized, sham-controlled, cross-over study to determine the effectiveness of high-efficiency air filtration to reduce indoor particle exposures. In 129 households, stand-alone HEPA air cleaners were placed in a bedroom and in the main living area. In 43 households, high-efficiency MERV 16 filters were installed in central forced-air heating and cooling systems and the participating households were asked to run the system on a clean-air cycle for 15 min per hour. Participating households that completed the study received true air filtration for a year and sham air filtration for a year. Air pollution samples were collected at approximately 6-month intervals, with two measurements in each of the sham and true filtration periods. One week indoor and outdoor time-integrated samples were collected for measurement of $PM_{2.5}$, PM_{10}, and ultrafine particulate matter (UFP) measured as $PM_{0.2}$. Reflectance measurements were also made on the $PM_{2.5}$ filters to estimate black carbon. True filtration significantly improved indoor air quality, with a 48% reduction in the geometric

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AUTHOR CONTRIBUTIONS

Deborah H. Bennett was involved in conceptualization, funding acquisition, and supervision for study, and wrote much of the original draft. Rebecca E. Moran was involved in project administration and supervision of study staff, assisted with project methodology, and wrote portions of the original draft. Paula Krakowiak conducted formal statistical analysis and wrote parts of the original draft. Daniel J. Tancredi assisted with study conceptualization, developed statistical analysis plan, and provided guidance to Dr. Krakowiak who conducted the analysis. Nicholas J. Kenyon assisted with study conceptualization, and reviewed and edited the manuscript. Jeffery Williams provided valuable feedback throughout the study, and reviewed and edited the manuscript. William J. Fisk assisted with study conceptualization and methodologies, provided valuable insights throughout study, and reviewed and edited the manuscript.

CONFLICT OF INTEREST

The authors have no conflicts of interest.

SUPPORTING INFORMATION

Additional supporting information may be found in the online version of the article at the publisher's website.

mean indoor $PM_{0.2}$ and $PM_{2.5}$ concentrations, and a 31% reduction in PM_{10}. Geometric mean concentrations of indoor/outdoor reflectance values, indicating fraction of particles of outdoor origin remaining indoors, decreased by 77%. Improvements in particle concentrations were greater with continuously operating stand-alone air cleaners than with intermittent central system filtration. Keeping windows closed and increased utilization of the filtration systems further improved indoor air quality.

Keywords

central system filtration; indoor air quality; $PM_{2.5}$; stand-alone air cleaners; ultrafine particles

1 | INTRODUCTION

Particulate matter (PM) and other air pollutants have long been known to cause adverse respiratory health effects, including increased asthma symptoms,[1–6] as well as reduced lung function in healthy children.[7–9] As people spend approximately two-thirds of their time indoors at home,[10,11] indoor home levels of air pollution have an impact on health.

Pollutant indoors result from outdoor air pollutants infiltrating into the indoor environment and contributions from indoor pollutant sources.[12,13] As outdoor PM crosses the building envelope (shell) and enters the home, a portion of the PM is removed through deposition in the building shell.[14] Concentrations of outdoor particles are further reduced through particle filtration and deposition in the indoors.[15,16] The fraction of PM of outdoor origin remaining suspended in indoor air is referred to as the infiltration factor.[14,17,18] PM is also emitted by indoor sources such as cooking, candles, and resuspension.[19] The efficiency of removal through filtration can be improved either by increasing the efficiency of the filters used, or by increasing the volume of air filtered. For an air filtration system to have a significant impact on the particle concentration, the ratio of the flow rate through the filter to the volume of the home should be similar in magnitude to the air exchange rate of the home.

Stand-alone air cleaners have been shown to reduce indoor particle concentrations in several studies.[20–26] Studies have noted that small stand-alone air cleaners will often lack a sufficient clean-air delivery rate to substantially reduce indoor particle concentrations, except in small areas, such as a bedroom with a closed door.[27,28] High-efficiency filters installed in the central system[29] have also been shown to reduce PM concentrations[30,31] and are also predicted to reduce concentrations in model simulations.[32–34] More detailed simulation studies have predicted varying effectiveness based on factors such as the leakiness of the home and the duration the system fan is running.[35] Cost estimates of filtering air in a home through upgrading the filters, assuming the systems run for a long enough period to significantly filter the air, found the associated cost dependent on the efficiency of the fan and whether the climate was more temperate or extreme, influencing the time the central system would run without heating or cooling.[30,34] Studies have found that the time the central system ran varies by climate zone, with smaller time-average flow rates in mild climates, and in the mildest California climates, months could pass without any operation of forced-air systems.[36–39]

In this paper, we determine the extent to which the use of high-efficiency central system filtration and high-efficiency stand-alone air cleaners reduce indoor concentrations of $PM_{0.2}$, $PM_{2.5}$, and PM_{10} in California homes. This was accomplished in two ways: first by comparing indoor pollutant concentrations between periods with true and sham filtration, and second, by comparing indoor/outdoor (I/O) ratios of pollutant concentrations between the true filtration and sham periods. Factors influencing the reduction in concentration through filtration are also evaluated.

2 | METHODS

2.1 | Study overview

Non-smoking homes in regions with high outdoor air pollution were enrolled in a sham-controlled, cross-over study to evaluate the effectiveness of high-efficiency filtration of indoor air to reduce concentrations of PM. One intervention group had the existing air intake grills for the central forced-air heating and cooling systems removed and new ones installed to enable the installation of a high-efficiency filter. The other intervention group had high-efficiency stand-alone air cleaners placed in a child's bedroom and in the main living area. The protocol called for providing true air filtration for a year and sham filtration for a year, allowing estimation of the improvements in indoor air quality related to the improved air filtration. Participants were randomized to begin with either true or sham filtration. HEPA filters were used in the stand-alone air cleaners, and MERV 16 filters were used in the central system. Stand-alone air cleaners also contained material for removal of ozone and volatile organic compounds (VOCs). To minimize air exchange with the outdoors, we asked participants to keep windows and doors closed while they were in the study. More details on many of the methods used in the study are shown in the Appendix S1.

2.2 | Study recruitment

Two study populations were recruited: one in the greater Fresno, CA area, and one in the greater Riverside, CA area. These two cities ranked in the top 5 for ozone pollution and in the top 10 for short-term particulate matter pollution in the United States.[40] Approximately two-thirds of participants were recruited from the Fresno area and one-third from the Riverside area.

Households with children, ages 6–12 years, with self-reported doctor-diagnosed asthma, were enrolled in the study. Inclusion criteria were developed for the symptom pattern of their asthma. Additional inclusion criteria were that the family speak either Spanish or English, not be expecting to move for the next 2 years, and be willing to run an air cleaner continually, or, if using the central system filtration, be willing to run the system 15 min per hour. There must not be any smokers living in the home, and the home must not have existing high-efficiency filtration. Participants in homes where windows were open at least 8 h a day in the cold season, November through March, were excluded.

Flyers were distributed in the community to describe the study and provide contact information. Potential participants were then screened for eligibility, and those who were eligible and interested enrolled. This study was reviewed, approved, and overseen by the

UC Davis institutional review board (IRB). Participants were informed that they would have both periods of true and periods of sham filtration during the study. The study also examined impacts on asthma exacerbation and was registered as a clinical trial.

2.3 | Central system filtration

In many of the homes equipped with a suitable, ducted heating, ventilation, and air-conditioning (HVAC or central) system, a whole-home central forced-air filtration system from the IQAir Company was used. The air cleaning system was designed to attach to the central filtration return-air intake where it replaced the existing return-air grille, see Figure 1. To be in this group, homes needed to have a working central forced-air system with a fan-only mode, be willing to operate their system for 15 min of every hour, and the system must be compatible with the installation of the intake filter and study thermostat.

The study's forced-air cleaning system filter holder was installed over the space where the traditional filter had been installed, and provided space for a 2 inch thick air filter that was both slightly longer and slightly wider than the existing filter, with the increased length and width varying slightly based on the difference between existing filter size (which varies between homes) and the size of the filter holder that would cover the space. The filter utilized a high-performance media with a combination of mechanical and electrostatic filter properties. The media was pleated tightly with hot melt separators. The larger dimensions and increased depth combined with mini-pleat design of the filter resulted in approximately double the filter media surface area. The filter efficiency rating was MERV 16, which indicated a minimum composite particle removal efficiency of 95% or better for particles 0.3 to 1.0 microns in size and a pressure drop that was similar to a typical 1 MERV 8 filter (see Appendix S1). The supplier estimated the filter life for the planned run time to be approximately 6 months.

For the control portion of the central system intervention study, IQAir produced a special "sham" filter that had a similar physical appearance to the "real" filter used for the intervention portion of the study, but had a lower-efficiency rating of MERV 4, which reflected the performance of most common residential central system filters.

A thermostat was installed that would run the fan for a portion of every hour regardless of heating or cooling needs, designated as a "clean-air" cycle. Thermostats were set to run on a clean-air cycle by study staff for either 15 or 20 min of every hour. More information on the filters and thermostats used can be found in the Appendix S1.

2.4 | Stand-alone air cleaners

For homes not equipped with suitable central systems, we selected stand-alone air cleaners from IQAir (Figure 1). Two models were used for this study, which varied in width and airflow only (large: 35 × 10 × 32 inches and small: 17.5 × 10 × 32 inches). Both air cleaners were designed to provide high particle filtration efficiency and clean large volumes of air while operating at low sound levels (48 dB(A) @ 400 cfm for the larger unit, and 49 dB(A) @ 240 cfm for the smaller unit). The air cleaners contained a particle and gas-phase filter element that incorporated true HEPA filter media to achieve a total system efficiency of greater than 99% for ultrafine and fine particles (0.01–10 μm), and a 1 cm thick activated carbon bed to reduce ozone and VOCs.

Each home with stand-alone air cleaning received two stand-alone air cleaners: one for the child's bedroom and one for the living room. The larger air cleaner was preferred whenever space allowed because it provided the highest air cleaning performance to noise ratio. The stand-alone air cleaners were operated and controlled via an electronic control panel. The air cleaner in the main living area was set with an air flow of 300 cfm (with a sound level of 42 dB(A) for the large air cleaner), and the cleaner in the child's bedroom was set at a flow of 175 cfm (with a sound level of 33 dB(A) for the large air cleaner and 42 dB(A) for the small air cleaner). Occasionally, participants requested a lower fan speed, yielding a lower air flow rate.

For sham operation, the air cleaners were equipped with a special "sham" filter that had similar physical appearance to the "real" filter used for the intervention portion of the study, but incorporated a solid panel hidden between the particle filtration media and the carbon bed. This blocked airflow through the filter. Special vents were opened on the back of the air cleaner to bypass the filter and draw in air. During true operation, the vents were covered on the inside by a clear plastic foil, thereby maintaining the same outward appearance of the air cleaner for both study periods. This effectively turned the air cleaner into a room fan, with similar airflow and noise level as in the true mode (Figure 1E).

2.5 | Recording filtration usage

The amount of time that the stand-alone units or central system operated was automatically recorded. Participants were asked to run the stand-alone unit all the time and to not change the flow rate. However, participants sometimes turned units off or changed the flow rate. Each stand-alone air cleaner recorded the total number of hours operated and the total airflow on a computer memory device. From this, we determined that the fraction of time the stand-alone air cleaner had run since the last visit. The central forced-air filtration system included a pressure sensor and a microchip to record the pressure difference across the filter every 5 min, indicating if the central system was operating.

Calculations were made to determine whether the participants were complying with the specified protocol for running their stand-alone air cleaners or central systems. Participants were requested to always run the air cleaners and asked to run them at a specified flow rate; therefore, compliance was the ratio of the average volumetric flow rate through the two air cleaners over the sampling week to the flow rate we asked participants to use of 475 CFM, calculated for both the sampling week and the 6-month period between visits. Because this study was imbedded into a 2-year health study, we were able to evaluate the use of the air cleaners over a longer period of time than would have been possible if the study had been designed strictly as a study focusing on air concentrations. For homes with high-efficiency filtration in central forced-air systems, the fraction of time the system fan was running as compared to the desired 20 min per hour was calculated, presented for the sampling week and for the 3-month period prior to each visit. Participants were categorized as to whether the compliance ratio was above 90%, between 75% and 90%, between 50% and 75%, between 25% and 50%, and below 25%.

2.6 | Air quality measurements

For each home, integrated one-week air pollution samples were collected at 6, 12, 18, and 24 months, with two measurements in each of the sham and true periods. Measurements were conducted outdoors, when there was a safe place for the sampler, and indoors, with indoor samplers being placed in the main living area. $PM_{0.2}$, $PM_{0.2–2.5}$, and $PM_{2.5–10}$ were measured in the main living area using a cascade impactor with the $PM_{0.2}$ mass collected on a 37 mm Teflon filter and the $PM_{0.2–2.5}$ and $PM_{2.5–10}$ mass collected on a polyurethane foam (PUF) substrate.[41–4 3] Additionally, $PM_{2.5}$ samples were collected using an impaction-based PEM for $PM_{2.5}$ designed for 1.8 LPM flow with particles collected on a 37 mm Teflon filter.[44] Black carbon (BC) is commonly used as marker for outdoor particles, associated with incomplete combustion of fossil fuels and having few indoor sources.[45] Indoor and outdoor black carbon levels were measured using an EEL43 M Smoke Stain Reflectometer (Diffusion Systems Ltd.), and transformed into an absorption coefficient according to ISO 9835[46,47] on the $PM_{2.5}$ filters. Concentrations were also measured before the air cleaners were installed, referred to as pre-intervention samples, with results presented in the Appendix S1.

2.7 | Home characteristics and window usage

A questionnaire and home-walkthrough inspection were utilized to obtain information about the home environment, including heating and air-conditioning systems, gas appliance use, mold and water damage, flooring, age of home, square footage of home, and distance to roadway. Participants filled out a diary that included specific pollutant sources that occurred during the sampling week such as smoking in the home, wood or candle burning, cooking activities, and cleaning product use. Also included was whether windows were left open for more than 2 h each day.

2.8 | Data analysis

The primary analysis compared the values of the indoor particle concentrations between the periods having true filtration and having sham filtration using generalized linear mixed-effects (GLMM) regression models. This regression strategy accounts for important features of the longitudinal study, including the need to account for time-varying confounders, especially seasonal effects, and partial follow-up from subjects not completing the study. PM measurements had an approximate log-normal distribution and so they were natural log transformed and modeled using mixed-effects linear regression models. Independent variables include time-varying binary indicator variables for whether air cleaners or central filtration and binary indicators for true vs. sham filtration.

Random effects were used to account for residual within-household correlation in the vector of repeatedly measured outcomes. The effects of each intervention were assessed by the intervention-specific adjusted mean difference in outcomes in true vs. sham filtration periods. In addition, between-intervention comparisons of true vs. sham filtration contrasts were estimated to compare the effectiveness of interventions. Additional fixed-effects specified prior to model fitting are included to adjust statistically for study stratum identifiers, covariates and/or mediators, or modifiers of intervention effects.

The base model for these analyses included two main effect terms, filtration type (sham vs. true) and filtration system (air cleaner vs. central), an interaction term (filtration type × filtration system), and covariates (season and city), with household ID as the random variable. The outcome variables were log-transformed indoor $PM_{0.2}$, $PM_{2.5}$, $PM_{0.2–2.5}$, PM_{10}, and $PM_{2.5–10}$. Model results are calculated as adjusted mean differences (β coefficients) and 95% confidence intervals (CI). When the differences (β) are back-transformed (by applying the inverse natural log transformation, exp[β]), the adjusted mean differences (sham minus true) can be interpreted as adjusted geometric mean (sham:true) ratios or, for pairwise contrasts of adjusted mean differences, as ratios of adjusted geometric mean ratios. For ease of interpretation, we report percent reduction in geometric mean concentrations due to using true filtration, by using the transformation $100 \times [1 - \exp(-\beta)]$.

To assess whether intervention effects were modified by candidate effect modifiers, a series of models based on the core model were fitted, one effect modifier at a time. For each candidate effect modifier, interaction terms were added to allow estimated intervention effects to vary according to the value of the candidate effect modifier. Nested likelihood ratio tests were used to assess whether the model with effect modification provides statistically significant improvements in model fit, compared to the core model. We considered age of home, filtration utilization during the sampling week, window opening during the sampling week, outdoor PM concentrations, and distance to roadway.

Interaction terms with p values less than 0.20 were considered broadly significant. Associations between the filtration status (or another exposure) and indoor air pollution measurements were further evaluated and described at the various levels of any moderating factors identified as broadly significant based on this definition. For pairwise comparisons at a particular level of the moderating factor (or combination of factors), p values greater than 0.05 but less than 0.20 were described as approaching significance or marginally significant whereas p values less than 0.05 indicated statistical significance at the α = 0.05 level. Given the low statistical power in analyses with interaction terms (especially those containing 3-way interaction terms), the usual statistical significance thresholds were slackened. Trading off a higher type-1 error rate in exchange for a lower type-2 error rate is commonly done when evaluating interaction terms, given the low statistical power available for such analyses. Despite this loosened definition of significance, all results with p values greater than 0.05 should be interpreted with caution. Additional details on the analysis are presented in the Appendix S1.

3 | RESULTS

3.1 | Study participation

A total of 172 households were recruited into the study. Twenty-three percent of the households earned less than $23 000 annually, and another 20% came from households that earned between $23 000 and $46 000. While there was a good representation in the lower income brackets, there was still a significant portion that came from households that had higher incomes (37% from households with earning above $70 000). Twenty percent of the households had a member with a 4-year college degree, while another 20% had a member with a graduate degree. There was significant diversity based on race and ethnicity, which we report here as the race of the child/children participating in the asthma study with summary statistics calculated on a per household basis, with 47% identifying their child as Hispanic, 33% as white, 11% as black or African American, and 5% as mixed race. More details are shown in Table S2. The majority of homes were detached houses (80%), and the age of the homes was distributed over time. The homes tended to have gas stoves (71%) and central cooling (78%). We note that the majority of homes utilizing stand-alone air cleaners also had central heating and cooling.

There were several criteria that homes had to meet to be able to install filtration through the central system. We conducted inspections of the central system for the first 146 homes during the enrollment visit to determine whether the home could have central system filtration installed. Of these, 29%, or 43 homes, had a central system installed. The reasons for not being able to install the central system are included in the Appendix S1. We ceased installing central system filtration partway through the study due to some study thermostats not operating properly (see Appendix S1). The majority of the homes had a single return-air intake and a single thermostat (30 homes). However, some homes had two return-air intakes and either a thermostat for both intakes or separate thermostats for each intake (13 homes).

Of the 172 homes, 129 had stand-alone air cleaners installed, and 103 (80%) completed the study. Of the 43 homes with a central system installed, 33 (77%) completed the study. However, of the 43 with the central system installed, 9 (21%) asked to be switched from central filtration to stand-alone cleaners, either due to an incompatibility of the thermostat with their system or because they found the thermostat difficult to use (see Appendix S1). During data analysis, for homes that switched from central filtration to stand-alone air cleaners, concentrations measured with true filtration were analyzed based on the type of filtration actually in the home at the time of the measurement. All but one of the households that switched completed the study. A CONSORT-Statement flow chart for participation and completion is shown in the Appendix S1.

3.2 | Utilization of air filtration

The majority of homes operated the air cleaners at least 90% of the desired time both during the sampling week (Figure 2A) and during the time between visits (Figure 2B). Compliance was greater during the 1-week sampling period. For homes with high-efficiency filtration in central forced-air systems, the fraction of time the system fan was operated as compared to the desired time is presented for the sampling week in Figure 2C and for the 3-month period prior to each visit in Figure 2D. The difference in compliance between the sampling week and the three months prior appears to be greater for homes utilizing filtration through the central system as compared to the homes with stand-alone air cleaners. This is likely because homes had to keep the thermostat in the clean-air mode, and frequently, thermostats appear to have been taken out of clean-air mode, either intentionally or inadvertently.

3.3 | Air quality measurements

Almost all of the participants still participating in the study had air pollution samples collected at the 6-, 12-, and 18-month visits, with the percentage of homes having samples collected ranging from 94% to 99%. For logistical reasons, 32 households enrolled for the full duration of the study did not have an air sample collected at the final visit. All of these visits were for the sham filtration configuration. Pre-intervention air concentrations, measured prior to the filters being installed to establish baseline PM levels in the homes, were substituted for the missing final sham visit measurements (see Appendix S1). Due to both participants dropping out of the study and missed visits, of the 172 households initially enrolled, 92% had air samples collected at 6 months, 83% had samples collected at 12 months, and 75% at 18 months. Households with partial data were included in the analysis. Some early measurements of PEM $PM_{2.5}$ and CI $PM_{0.2}$ were eliminated from the data analysis due to a problem that resulted from a faulty o-ring, affecting 21% of the 6-month samples. None of the pre-intervention samples that were substituted for 24-month values were affected by this problem, as those were participants that were enrolled later in the study (enrollment occurred over approximately 9 months). The median percent difference on blanks collected after replacing the o-ring was 4.3% ($n = 31$) for PEM $PM_{2.5}$ samples and 8.4% ($N = 35$) for the cascade impactor (CI) $PM_{0.2}$ samples. The median percent difference throughout the study was 3.6% ($n = 42$) for CI $PM_{0.2–2.5}$ samples and 6.1% ($n = 42$) for CI $PM_{2.5–10}$ samples.

Histograms of the distribution of $PM_{0.2}$, $PM_{0.2–2.5}$, $PM_{2.5,}$ and PM_{10} during true and sham periods can be seen in Figure 3A–D, respectively, indicating that the distributions of indoor PM concentrations were lower during the true period. Table 1 presents the geometric means calculated within the regression model of PM concentrations for all size fractions, I/O ratios for select size fractions, and I/O reflectance values for $PM_{2.5}$ for all true and sham periods. Clear reductions are apparent with true filtration, with $PM_{2.5}$ concentrations of 6.64 μg/m^3 [95% CI on GM reduction: 6.08, 7.25] during sham reduced to 3.46 μg/m^3 [3.11, 3.84] during true filtration. Reductions are also seen in the I/O ratios (Table 2). The geometric mean (GM) PM 2.5 I/O ratios in sham and true filtration were 0.71 [95% CI: 0.64, 0.78] and 0.35 [0.32, 0.40], respectively (Table 3). The geometric mean (GM) reflectance I/O ratios, indicative of outdoor sources of particles, in sham and true filtration were 0.45 [0.38, 0.54] and 0.10 [0.07, 0.14], respectively. Summary statistics of measured concentrations are available in the Appendix S1.

Indoor PM concentrations for all size fractions were significantly higher during sham compared with true filtration periods (Table 3). Looking at the values from Table 1, it is clear that the differences are greater for the smaller size fractions with a 48% [95% CI: 42%–53%] drop in GM concentration for $PM_{0.2}$ as compared to 31% [26%–36%] drop in GM concentration for PM_{10}.

Having the intervention through a stand-alone air cleaner as opposed to the central system revealed significantly greater improvements in air quality for all size fractions (Table 3). For example, for $PM_{0.2}$, there was a 34% [21%–46%] decrease in the concentration with central filtration as compared to a 52% [46%–57%] decrease with stand-alone air cleaners. This was a statistically significantly comparison in $PM_{0.2}$ for the stand-alone air cleaner vs. central system ratio in adjusted true vs. sham geometric mean ratios (0.73 [0.59, 0.91]), indicating that air cleaners resulted in 27% better true vs. sham GM ratios. There were significantly greater reductions in PM concentrations with the stand-alone air cleaners compared to the central systems for all size fractions. Indoor concentrations were significantly lower during true compared with sham filtration with the air cleaners for all size fractions. For central system filtration, reductions were significant for all size fractions except for $PM_{2.5–10}$. The trend of greater reductions for smaller size fractions observed in all homes was mirrored in the homes with central system filtration and in the homes with stand-alone air cleaners.

Outdoor particle levels were compared to determine whether they differed between true and sham periods. Outdoor levels were slightly lower in sham than in true filtration but the difference did not reach statistical significance (See Appendix S1). As outdoor particle levels were higher during true periods, this would act to reduce the calculated absolute indoor PM reductions by the air cleaners.

To account for the impact of varying outdoor concentrations on indoor levels, analyses were also conducted on log-transformed I/O ratios for $PM_{0.2}$, $PM_{2.5}$, and PM_{10}. The I/O ratios during the sham period were significantly higher compared with the true filtration period, with greater differences for smaller size fractions, $PM_{0.2}$ (49% [42%–55%]) and PM2.5 (50% [43%–56%]) as compared to PM_{10} (34% [27%–39%]) (Table 4). As with the indoor concentrations, I/O ratios were lower during true filtration in homes with stand-alone air cleaners than in homes with filtration using the central system, ranging from 23% to 29% larger reductions, with statistically significant differences in the ratio of ratios for $PM_{0.2}$ (0.71 [0.54–0.94]) and PM_{10} (0.76 [0.61–0.94]), but not reaching statistical significance for $PM_{2.5}$ (0.77 [0.57–1.06], $p = 0.11$) (Table 4).

The reflectance I/O ratios were 4.34 times higher in sham than in true filtration, which corresponds to an estimated reduction of 77% [95% CI: 68%–84%], $p < 0.0001$. In contrast to the PM results, there was not a statistically significant difference in the percent reduction of the I/O reflectance due to true vs. sham filtration between homes that had stand-alone air cleaners vs. central system filtration. I/O reflectance was only slightly lower in stand-alone air cleaner homes than with central systems, indicating that improvements in air quality of outdoor origin with true filtration did not vary much by the type of home filtration system (See Appendix S1).

3.4 | Moderator analysis

3.4.1 | Window opening—The frequency of windows open was considered as a moderator. Participants indicated on a diary if the windows were open for more than 2 h each day. A greater portion of the population opened windows during spring as compared to other seasons, with a median of 3 days per week with open windows in spring, as compared to 0 for winter and 1 for both summer and fall. Twenty-three percent of the population indicated that they had open windows 6–7 days per week in all, or all but one sampling diary. Thirty-four percent of the homes generally kept their windows shut (see Appendix S1).

Analysis for moderators that influenced the sham vs. true filtration found that differences in indoor air pollution were influenced by window usage. In Table 5, we express reductions in geometric mean indoor PM concentrations due to true (relative to sham) filtration in subgroups defined by window usages, as well as pairwise comparisons of true:sham geometric mean ratios among subgroups defined by level of the window usage variable.

The magnitude of the reductions in indoor geometric mean $PM_{0.2}$ concentrations due to true filtration was greater in homes that opened windows less frequently, and this trend was observed in homes with stand-alone air cleaners as well as central filtration systems. In homes with stand-alone air cleaners, the reduction in indoor $PM_{0.2}$ concentrations due to true filtration was greater in homes that rarely (53% [46%–60%], $p < 0.0001$) or sometimes opened windows (56% [43%–66%], $p < 0.0001$) than in homes that always opened windows (42% [29%–54%], $p < 0.0001$). When expressed as true vs. sham geometric mean ratios, the ratio of these geometric mean ratios approaches statistical significance (0.81, 95% CI: 0.62, 1.07, $p = 0.14$), suggesting that more effective filtration is achieved when windows are opened less frequently. A similar trend was observed in homes with central filtration although the mean differences between sham and true filtration were smaller. Results for indoor $PM_{2.5}$ concentrations also revealed numerically greater reductions during true vs. sham filtration when windows were rarely vs. always open. The difference in improvement approached significance for stand-alone air cleaner homes but not central system homes, though it did trend in the expected direction. It should be noted that the subset of homes with central filtration systems was smaller than homes with air cleaners, therefore, affecting the power to detect significant differences in this analysis.

The influence of moderators was also evaluated for the reflectance I/O ratios, with the frequency of opening windows significantly modifying the effect of sham vs. true filtration. Reflectance I/O ratios were reduced to a greater extent by true (vs. sham) filtration in homes that rarely opened windows (82% [95% CI: 71%–89%], $p < 0.0001$), compared to homes that always opened windows (41% [9%–62%], $p = 0.02$), with the rarely vs always open ratio of true:sham geometric mean ratios reaching statistically significance (0.31 [0.16, 0.58], $p < 0.001$). Homes that sometimes opened windows had reductions (41% [9%–62%], $p < 0.0001$) comparable to homes that rarely opened windows.

3.4.2 | Home characteristics—The age of the home was another moderating factor for the relationship between filtration status and indoor particle levels. The age of the home was divided into two categories: homes built before 1977 and homes build in 1977 or later. In response to the energy crisis in the 1970s, homes built in 1977 or later tend to have lower air exchange rates than older homes; thus, it was anticipated that filtration would be more effective in newer homes. Approximately 40% of the homes were built before 1977. In homes with stand-alone air cleaners, the observed trend was for greater reductions in geometric mean PM levels from true vs. sham filtration in homes built in 1977 or later as compared to homes built before 1977 (Table 5), although the differences only reached significance for $PM_{0.2–2.5}$ (0.80 [0.70, 1.00], $p = 0.05$) (See Appendix S1). In contrast, among homes with central filtration, the difference between true and sham was greater in the older homes, which was not expected, but only reached significance for $PM_{2.5}$ (0.63 [0.40, 0.96], $p = 0.03$).

3.4.3 | System usage—When evaluating the percentage of system usage as a moderator, in homes with central filtration, geometric mean indoor $PM_{2.5}$ concentrations were reduced on average by 32% [16%, 46%] during true compared with sham filtration when the hypothetical home ran their filtration system 100% of the amount of time asked (ie, use ratio = 1, or a runtime percentage of 33%, given that time asked for central filtration was 20 min per hour, on average) (Table 5). By comparison, in hypothetical homes that ran their central filtration system 75% of the amount of time asked (ie, use ratio = 0.75, or a relative runtime of 15 min per hour [25%]), the reduction in log geometric mean levels of $PM_{2.5}$ was 27% [6%, 43%] ($p < 0.0001$), less than the 32% had the system run the protocol-specified time. The ratio of the true:sham adjusted geometric mean ratios for indoor $PM_{2.5}$ concentrations in hypothetical homes that ran their filtration system 75% vs. 100% of the time asked was marginally significant (0.92 [0.84, 1.01], $p = 0.09$). Similar results were found in homes with stand-alone air cleaners, although for these the time asked was 60 min per hour (ie, always). These findings indicate that using the intervention more yielded better PM reductions.

4 | DISCUSSION

4.1 | Overall findings

High-efficiency filtration had a clear positive impact on indoor concentrations of particulate matter. Concentrations for all size fractions, $PM_{0.2}$, $PM_{2.5}$, PM_{10}, $PM_{0.2–2.5,}$ and $PM_{2.5–10}$ as well as I/O ratios of $PM_{0.2}$, $PM_{2.5}$, PM_{10} and reflectance measured on $PM_{2.5}$ filters were significantly lower with true filtration than sham filtration for homes with stand-alone cleaners. The percent decrease in the geometric mean of the indoor concentration from sham to true was the same for $PM_{0.2}$ and $PM_{2.5}$, and slightly lower for PM_{10}, driven by a small reduction in $PM_{2.5–10}$. The observed differences are likely due to several factors. Smaller particles ($PM_{2.5}$) have a lower deposition velocity than larger particles ($PM_{2.5–10}$), and thus a longer residence time in indoor air. The high-efficiency filtration removes particles in both size fractions, but the relative change in the total particle removal rate (via filtration, deposition, and air exchange) is greater for smaller particles. The reductions in I/O BC were the greatest. Cox et al.[26] measured $PM_{2.5}$, ultrafine particles, and BC in 43 homes with and without stand-alone air cleaners. They also found that BC was more effectively removed with filtration than $PM_{2.5}$.

For homes with filtration through the central system, PM concentrations were significantly lower with true vs. sham for all size fractions except $PM_{2.5–10}$. The sham central filters were MERV 4 and primarily removed this size fraction, and thus, it is not surprising that there is not a difference between sham and true filtration for this size fraction. The mean difference between indoor concentrations measured with sham filtration and indoor concentrations measured with true filtration was significantly greater for all size fractions for homes with stand-alone air cleaners as compared to those with central system filtration. Comparing the percent decrease in indoor concentrations from sham to true conditions between central filtration and stand-alone air cleaners, the percent decrease is approximately 20% greater for air cleaners across all size fractions (eg, 52% vs. 34% for $PM_{0.2}$, 36% vs. 16% for PM_{10}). Similarly, Zhang et al.[31] measured reduction of $PM_{2.5}$ in 20 homes in Canada with MERV 8, MERV 11, and MERV 14 filters, and found lower than estimated reductions from filtration installed in the central system.

Reductions in I/O ratios were also greater with stand-alone air cleaners than central filtration for all size fractions, with differences being statistically significant for I/O $PM_{0.2}$ and I/O

PM_{10}. Both the indoor concentrations and I/O ratios were lower with air cleaners than with central system filtration, although only for $PM_{0.2}$ were the indoor concentrations and I/O ratio statistically significantly lower.

These results clearly indicate that indoor air quality is improved with high-efficiency filtration and the improvements were greater with stand-alone air cleaners than with central filtration. Airflows through the central system were measured in 30 of the 43 homes with filtration through the central system, and this, along with home area, an assumed ceiling height of 8 feet (not measured), and use time was used to calculate the ratio of the volume of air filtered to the volume of the home. The volume of air filtered relative to the volume of the home was found to be greater with central system filtration as opposed to air cleaners, so this was not the cause of the difference. One of the two stand-alone air cleaners was located in the room where air samples were obtained, and so this room may have had the lowest particle concentration in the house. This would result in stand-alone air cleaners appearing to be more effective than central system filtration.

4.2 | Interaction analysis

The interaction analysis results primarily corresponded to what was anticipated. There was a greater reduction in the indoor concentration with true filtration when windows were rarely open as opposed to frequently open, with the differences in concentrations between the two window opening conditions being most pronounced for $PM_{0.2}$. Closing windows decreases the air exchange rate of the home, and thus, the effective filtration rate is increased relative to the rate of particle entry, increasing the particle concentration reductions from cleaning. Newer homes typically have lower air exchange rates than older homes, and thus, a greater effectiveness of cleaning was anticipated with newer homes. There was greater reduction in indoor concentrations among newer homes than older homes with air cleaners. In homes with central system filtration, the trend was in the unexpected direction, with older homes having a greater reduction with true filtration than sham filtration. With the available data, it could not be determined why this was the case.

The more air filtered, the lower the expected indoor particle concentrations. The utilization value was a statistically significant interaction term for all three particle size fractions considered, $PM_{0.2}$, $PM_{2.5}$, and $PM_{0.2–2.5}$. Given the fact that there was little variability in the utilization of the filtration systems between homes, this factor clearly had a strong influence.

4.3 | Strengths and limitations

The study had many strengths, primarily because of the large study population allowing for comparison between stand-alone and central systems, as well as the analysis of mediation. Seventy-eight percent of the participants completed the study even though it was long, with many interactions.

Installing filtration through the central system added significant complexity to the study and did not reduce indoor particle concentrations as much as stand-alone air cleaners. The solution used to refit existing central systems was to install a larger filter holder over the existing air intake. A significant portion of the homes evaluated could not physically accommodate the larger filter holder. In order to provide a comparable duration of filtration to the stand-alone air cleaners, a new thermostat needed to be installed that could run a clean-air cycle. However, some homes could not have the new thermostat installed, for varying reasons.

While some household members were adept at learning to use new technology, some individuals found it difficult to use a programmable thermostat and preferred their old, simple ones that involved just setting the temperature. An additional problem with the thermostat was that participants could turn the clean-air cycle off, either intentionally or accidentally. The impact of this was seen in the slightly lower compliance with the protocol for central filtration than for stand-alone air cleaners, with approximately 70% of the population using the central system at least 75% of the requested time vs. approximately 80% of the population with stand-alone cleaners having at least 75% of the requested volumetric flow rate. Adoption of programmable thermostats may be a problem for wider adoption of central system filtration, although this concern should diminish over time as a greater fraction of the population becomes more adept with technology in general and programmable thermostats specifically.

Compliance with air cleaner utilization was higher during the sampling week than during the 6-month periods between study weeks, likely due to adjustments made by study personnel at the beginning of the week, coupled with participants being less likely to change settings when they knew study staff would be returning soon. In the Batterman et al.[48] study, participants had periods of time with more frequent visits from study staff, and they also found that filtration system use was greater during these periods of more contact with study staff, with use decreasing as the time since contact with staff increased.

A third concern with running filtration through the central system was the expense. A number of households requested greater reimbursements than were calculated based on average fan power. While requesting households generally submitted electricity bills that did show greater electricity use, it could not be determined if increased electricity use was due to the increased run time of the fan, the increased run time in combination with potentially running the air conditioning more due to the programmable thermostat failures, or an increase in electricity use unrelated to the central system. There is considerable variability in fan power requirements. Another increased cost of running of the fan more was added wear and tear on the central system, requiring more often repairs. Singer et al.[30] also pointed to importance of using more efficient fans when the central system is going to be run for longer periods of time. Finally, another potential cost is that in hot times of the year, if ducting is in an uncooled attic, running the clean-air cycle may require the air-conditioner to run for a longer period to meet cooling needs.

The stand-alone air cleaners were easy to utilize in the study. Participants generally did not object to where they were placed in the home, and they generally ran them utilizing the recommended airflow. Participants were reimbursed for electricity use, with decreased reimbursement if there was only little use of the air cleaner.

The study findings suggest that the most promising applications of high-efficiency central system filtration are in new construction in regions with high heating and cooling demands.

Central systems in this study were run for a greater fraction of time than typically needed in areas with mild weather.[39] In new construction, the application would be in homes with systems specifically designed to accommodate high MERV filters, and fans designed to run cost-efficiently. Alavy et al.[34] conducted simulation studies finding that high-efficiency HVAC filters would be most efficient in areas with longer system runtimes.

5 | CONCLUSIONS

- Stand-alone air cleaners and high-efficiency filtration with central heating and cooling systems reduced indoor concentrations of $PM_{0.2}$ and $PM_{2.5}$ by approximately 50% and reduced indoor PM_{10} by approximately 30%. Indoor concentrations of particles with outdoor air origin were also reduced by approximately 77%. Stand-alone air cleaners tended to reduce the measured indoor particle concentrations more that enhanced central system filtration, although the larger measured reductions in particles with stand-alone air filters might have been a consequence of measuring particles in one of the rooms with a stand-alone filter.
- Filtration systems were more effective in reducing particle concentrations in homes with limited window opening and in homes with increased filtration system operation.
- In many of the study homes, enhanced central system filtration was impractical to implement.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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DATA AVAILABILITY STATEMENT

The data for this paper are not publically available.

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Practical Implications

Both stand-alone air cleaners and high-efficiency filters installed in a central system reduce indoor particulate matter concentrations across multiple size fractions. Keeping windows closed and increasing airflow through the filtration system resulted in greater improvements in indoor air quality. Using stand-alone air cleaners may be more practical in older homes.

FIGURE 1.

(A) Central system return grille (B) the grille with filter installed and (C) the central system filtration system mounted to the return intake. Please note that while these pictures show a system mounted to a wall, homes in the study typically had the system mounted to the ceiling. (D) The large IQAir stand-alone air cleaner used in the study. (E) Diagram showing backside of air cleaner, and the locations of grilles utilized in converting to sham mode

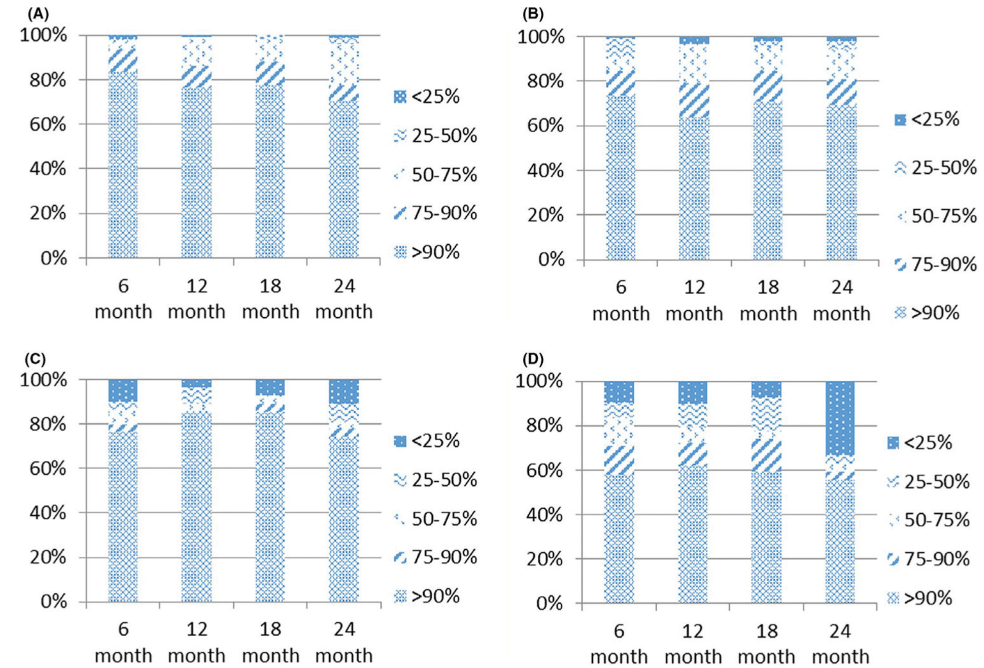

FIGURE 2.

(A) Fraction of the population that ran the air cleaners in their home at various percent values relative to the desired air flow rate over the sampling week. (B) Fraction of the population that ran the air cleaners in their home at various percent values relative to the desired air flow rate over approximately the 6 months between visits. (C) Fraction of the population that ran their central air system at various percent values relative to the desired air flow rate over the sampling week. (D) Fraction of the population that ran their central air system at various percent values relative to the desired air flow rate over approximately the 3 months prior to the visit

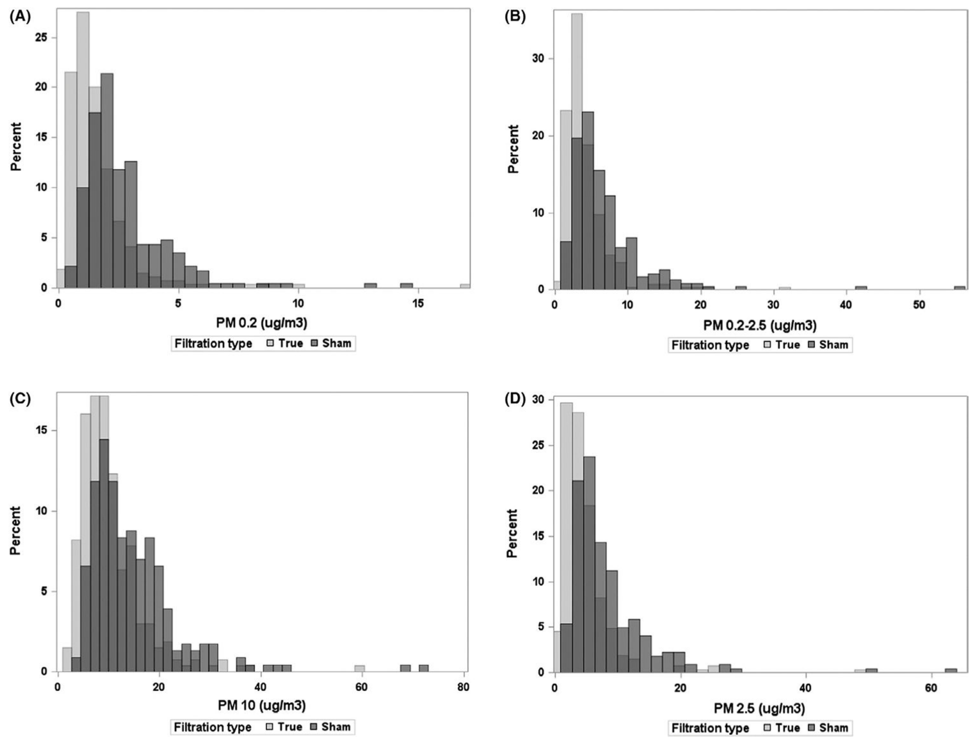

FIGURE 3.

Distribution of (A) $PM_{0.2}$ concentrations (μg/m^3), (B) $PM_{0.2}$ – $PM_{2.5}$ concentrations, (C) $PM_{2.5}$ concentrations (μg/m^3), and (D) PM_{10} concentrations (μg/m^3) true and sham periods. The overlap between the true and sham filtration distributions is indicated with the darker shading

TABLE 1

Geometric means (GM) of PM concentrations for each filtration type and filtration system

		$PM_{0.2}$		$PM_{2.5}$		PM_{10}		$PM_{0.2–2.5}$		$PM_{2.5–10}$	
Filtration type	**Filtration system**	**GM**	**95% CI**	**GM**	**95% CI**	**GM**	**95% CI**	**GM**	**95% CI**	**GM**	**95% CI**
Sham	All	2.31	2.12, 2.50	6.64	6.08, 7.25	12.68	11.74, 13.69	5.54	5.12, 6.00	4.35	3.97, 4.75
True	All	1.20	1.09, 1.33	3.46	3.11, 3.84	8.74	8.09, 9.45	3.30	3.03, 3.60	3.95	3.64, 4.28
Sham	Air cleaner	2.42	2.18, 2.67	6.96	6.27, 7.73	13.34	12.18, 14.62	5.69	5.17, 6.25	4.48	4.04, 4.97
True	Air cleaner	1.17	1.04, 1.30	3.39	3.01, 3.82	8.62	7.90, 9.41	3.19	2.90, 3.51	3.86	3.52, 4.23
Sham	Central	2.14	1.90, 2.41	6.25	5.40, 7.24	11.35	9.81, 13.12	5.16	4.42, 6.02	3.96	3.32, 4.74
True	Central	1.41	1.18, 1.68	3.92	3.13, 4.92	9.48	7.98, 11.27	3.84	3.17, 4.66	4.36	3.63, 5.23

Note: Geometric means shown are exponentiated predicted means from mixed-effects models of natural log-transformed outcomes.

TABLE 2

Geometric means (GM) of indoor/outdoor (I/O) ratios for selected size fractions and PM 2.5 reflectance values

		I/O $PM_{0.2}$		I/O $PM_{2.5}$		I/O PM_{10}		I/O reflectance	
Filtration type	**Filtration system**	**GM**	**95% CI**	**GM**	**95% CI**	**GM**	**95% CI**	**GM**	**95% CI**
Sham	All	0.75	0.69, 0.81	0.71	0.64, 0.78	0.55	0.51, 0.59	0.45	0.38, 0.54
True	All	0.38	0.35, 0.43	0.35	0.32, 0.40	0.37	0.34, 0.40	0.10	0.07, 0.14
Sham	Air cleaner	0.76	0.68, 0.84	0.72	0.64, 0.81	0.56	0.51, 0.62	0.44	0.36, 0.53
True	Air cleaner	0.36	0.32, 0.40	0.34	0.30, 0.38	0.35	0.32, 0.38	0.09	0.06, 0.13
Sham	Central	0.74	0.65, 0.84	0.70	0.60, 0.82	0.53	0.46, 0.60	0.50	0.34, 0.75
True	Central	0.48	0.39, 0.59	0.42	0.32, 0.55	0.43	0.35, 0.52	0.14	0.07, 0.30

TABLE 3

Percentage reduction in geometric mean indoor PM concentrations due to true (vs. sham) filtration and ratios of adjusted true:sham geometric mean ratios (GMR) for indoor PM concentrations for each size fraction for both the whole population and by intervention type

	$PM_{0.2}$			$PM_{2.5}$			PM_{10}			$PM_{0.2–2.5}$			$PM_{2.5–10}$		
	% reduction	**95% CI**	***p***	**% reduction**	**95% CI**	***p***	**% reduction**	**95% CI**	***p***	**% reduction**	**95% CI**	***p***	**% reduction**	**95% CI**	***p***
Overall	48	42, 53	<0.0001	48	42, 53	<0.0001	31	26,36	<0.0001	41	36,45	<0.0001	10	3, 15	0.003
AC	52	46, 57	<0.0001	51	46, 56	<0.0001	36	30,41	<0.0001	44	39, 49	<0.0001	14	8,20	<0.0001
CS	34	21,46	<0.0001	37	22,49	<0.0001	16	4,27	0.01	25	13,36	0.0003	*(11)* [a]	*3, (25)* [a]	0.14
	Ratio of ratios	**95% CI**	***p***	**Ratio of ratios**	**95% CI**	***p***	**Ratio of ratios**	**95% CI**	***p***	**Ratio of ratios**	**95% CI**	***p***	**Ratio of ratios**	**95% CI**	***p***
AC vs. CS ratio of true:sham GMRs	0.73	0.59, 0.91	0.01	0.78	0.37, 0.61	0.04	0.77	0.66, 0.90	0.002	0.76	0.63, 0.90	0.002	0.79	0.68, 0.90	<0.0001

Note: True vs. sham adjusted mean differences in natural log-transformed indoor PM concentrations estimated in mixed-effects linear regression models. When exponentiated, the difference represents a true:sham adjusted geometric mean ratio GMR, which can be expressed as a percentage reduction PR, using the transformation PR = 100 × (1 − GMR). For example, in the first column, percentage reductions of 52 and 34 percent are derived from geometric mean ratios of 0.48 and 0.66, respectively. The last row reports the AC vs. CS ratio of geometric mean ratios, with values below one indicating greater reductions due to AC compared to CS. AC indicates use of stand-alone air cleaners, and CS indicates enhanced central system air filtration.

[a] Italics font in parentheses indicates that there was actually an increase in the concentration and values should be interpreted as percent increase.

TABLE 4

Percentage reduction in geometric mean I/O PM ratios due to true (vs. sham) filtration and ratios of adjusted true:sham geometric mean ratios (GMR) for indoor PM concentrations for each size fraction for both the whole population and by intervention type

	I/O $PM_{0.2}$			**I/O $PM_{2.5}$**			**I/O PM_{10}**		
	% reduction	**95% CI**	***p***	**% reduction**	**95% CI**	***p***	**% reduction**	**95% CI**	***p***
Overall	49	42, 55	<0.0001	50	43, 56	<0.0001	34	27,39	<0.0001
AC	53	47, 59	<0.0001	54	48, 60	<0.0001	38	32,44	<0.0001
CS	34	16,48	0.001	41	21, 56	0.0004	18	0,33	0.04
	Ratio of ratios	**95% CI**	***p***	**Ratio of ratios**	**95% CI**	***p***	**Ratio of ratios**	**95% CI**	***p***
AC vs. CS ratio of true:sham GMRs	0.71	0.54, 0.94	0.02	0.77	0.57, 1.06	0.11	0.76	0.61, 0.94	0.01

TABLE 5

Percentage reduction in geometric mean indoor PM concentrations due to true (vs. sham) filtration and ratios of adjusted true:sham geometric mean ratios (GMR) for indoor PM concentrations for each size fraction intervention type and moderator

	$PM_{0.2}$			$PM_{2.5}$		
	% reduction	**95% CI**	***p***	**% reduction**	**95% CI**	***p***
Window always open, AC	42	29, 54	<0.0001	42	27, 54	<0.0001
Window sometimes open, AC	56	43, 66	<0.0001	53	38, 64	<0.0001
Window rarely open, AC	53	46, 60	<0.0001	53	45, 59	<0.0001
Window always open, CS	17	*(23)*[a], 45	0.35	30	*(12)*[a], 56	0.13
Window sometimes open, CS	41	11, 61	0.01	32	*(3)*[a], 55	0.07
Window rarely open, CS	39	26, 50	<0.0001	43	21, 59	0.001
Built before 1977, AC	49	39, 58	<0.0001	45	35, 54	<0.0001
Built 1977 or later, AC	53	46, 60	<0.0001	55	47, 62	<0.0001
Built before 1977, CS	41	24, 54	<0.0001	56	36, 69	<0.0001
Built 1977 or later, CS	31	12, 46	0.003	29	9, 44	0.01
Use ratio 0.75, AC	46	34, 55	<0.0001	44	31, 55	<0.0001
Use ratio 1.00, AC	52	47, 57	<0.0001	52	47, 57	<0.0001
Use ratio 0.75, CS	25	4, 42	0.02	27	6, 43	<0.0001
Use ratio 1.00, CS	31	16, 43	0.0004	32	16, 46	<0.0001
	Ratio of ratios	**95% CI**	***p***	**Ratio of ratios**	**95% CI**	***p***
AC: rarely vs. always open	0.81	0.62, 1.07	0.14	0.82	0.62, 1.08	0.15
CS: rarely vs. always open	0.73	0.47, 1.15	0.18	0.81	0.45, 1.43	0.47
AC: before 1977 vs. later 1977	1.09	0.86, 1.39	0.45	1.21	0.95, 1.54	0.12
CS: before 1977 vs. later 1977	0.86	0.61, 1.21	0.39	0.63	0.40, 0.96	0.03
AC: use ratio 1.00 vs. 0.75	0.88	0.73, 1.05	0.15	0.85	0.70, 1.03	0.10
CS: use ratio 1.00 vs. 0.75	0.93	0.84, 1.03	0.16	0.92	0.84, 1.01	0.09

[a] Italics font in parentheses indicates that there was actually an increase in the concentration and values should be interpreted as percent increase.