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Reducing indoor air pollutants with air filtration units in wood stove homes

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Abstract

Background: Biomass burning has been shown to be a major source of poor indoor air quality (IAQ) in developing and higher income countries across the world. Specifically, wood burning for cooking and heating contributes to high indoor concentrations of fine (particles with aerodynamic diameters $<2.5 \mu\text{m}$; $\text{PM}_{2.5}$) and coarse (particles with aerodynamic diameters $<10 \mu\text{m}$ and $>2.5 \mu\text{m}$; PMc) particulate matter. Endotoxin, predominantly found within the coarse fraction of airborne particulate matter, is associated with proinflammatory effects and adverse outcomes among susceptible populations. The aim of this study was to assess the efficacy of air filter interventions in reducing indoor $\text{PM}_{2.5}$, PMc , and PMc -associated endotoxin concentrations in homes using a wood stove for primary heating.

Results: Homes ($n=48$) were randomized to receive in-room air filtration units with either a high efficiency filter (i.e. active) or a lower efficiency fiberglass filter (i.e., placebo). The active filter intervention showed a 66% reduction in indoor $\text{PM}_{2.5}$ concentrations (95% CI: 42.2% to 79.7% reduction) relative to the placebo intervention. Both the active and the placebo filters were effective in substantially reducing indoor concentrations of PMc (63.3% and 40.6% average reduction for active and placebo filters, respectively) and PMc -associated endotoxin concentrations (91.8% and 80.4% average reductions, respectively).

Conclusions: These findings support the use of high efficiency air filtration units for reducing indoor $\text{PM}_{2.5}$ in homes using a wood stove for primary heating. We also discovered that using lower efficiency, lower cost filter alternatives can be effective for reducing PMc and airborne endotoxin in homes burning biomass fuel.

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Graphical abstract

Keywords

biomass; particulate matter; endotoxin; coarse; air filter; residential

1. Introduction

Exposure to particulate matter is known to exacerbate existing respiratory conditions (van Berlo et al., 2012) with size fraction playing an important role in the toxicity of the particles (Tong et al., 2010). Epidemiological evidence indicates that coarse particulate matter (particles with aerodynamic diameters $<10\ \mu\text{m}$ and $>2.5\ \mu\text{m}$; PM_c) has an acute effect on respiratory health, particularly among susceptible populations (Brunekreef and Forsberg, 2005). Further, the biological component of the coarse fraction including endotoxin, a component of the cell wall of Gram-negative bacteria, has long been known to trigger asthma symptoms (van Berlo et al., 2012) and severity in children (Liu, 2004).

People spend a majority of their time indoors, averaging 86–87% of time for the general population and 89–90% for children (Klepeis, 2001). The home environment is ideal for health-based interventions because it can be altered with fewer resources and fewer barriers than the outdoor environment. It has been estimated that for every dollar spent on home-based multicomponent interventions designed to reduce asthma morbidity, the monetary value of the resulting benefits, such as averted medical costs, was \$5.30 – \$14.00 (Nurmagambetov et al., 2011). Air filters have been shown to significantly reduce breathing problems, asthma symptoms and allergy attacks (Eick and Richardson, 2011; Fisk, 2013; Johnson et al., 2009; McDonald et al., 2002). These results are likely achieved because air filters can reduce exposure to asthma triggers such as airborne pet allergen (van der Heide et al., 1999) and particulate matter.

In reducing concentrations of indoor PM, two in-room air cleaner technologies are typically utilized: systems that operate on the principle of electrostatic precipitation, and air cleaners using filtration technologies. Both systems are widely available, economical, and simple to use. As it has been estimated that 4.8 million susceptible individuals live in homes with significant exposures to residential wood smoke (Noonan et al., 2015), evaluating interventions that reduce these indoor exposures is important when considering the potential corresponding improvements to human health. To this end, our team has evaluated high efficiency air filtration technologies in wood burning homes, and have observed consistent

reductions (~60%) in indoor wood smoke PM across multiple locations (Hart et al., 2011a; Ward et al., 2015). We have not, however, investigated the impact of lower efficiency filtration units on reductions in PM, or how filtration influences changes in indoor, airborne endotoxin.

The present study examined the efficacy of two classifications of air filters in the reduction of PM_{2.5}, PM_c, and endotoxin within homes using wood stoves for residential heating. Homes were randomized to receive high efficiency “active” or lower efficiency “placebo” filters that looked similar in order to blind participants to their intervention. “Active” filters had a Minimum Efficiency Reporting Value (MERV) rating of 13, meeting specifications for capturing >90% of particles 1–3 µm with a dust-spot efficiency of 80–90% with typical application in hospital laboratories while “placebo” filters had a MERV rating of 2 and are typically used to protect residential furnaces from the buildup of unwanted materials and are not commonly used for direct indoor air quality reasons (EPA, 2012).

2. Materials and Methods

2.1 Study Design

This study utilizes a subset of homes from the Asthma Randomized Trial of Indoor Wood Smoke (ARTIS) study. ARTIS is an intervention-based study designed to improve the quality of life of children with asthma living in wood stove homes by reducing in-home levels of PM_{2.5} (Noonan and Ward, 2012). Use of a non-EPA certified, older model wood stove as the primary heating source in the home was required for inclusion in the ARTIS study. The ARTIS study involved four separate 48-hour sampling visits over two consecutive winters - a baseline winter and post-intervention winter. After baseline sampling was completed homes were randomized into three treatment arms: 1) homes receiving an active, in-room filtration unit, 2) homes receiving a placebo in-room air filtration unit, and 3) homes receiving a new high-efficiency wood stove to replace their older model. Interim analysis showed that the wood stove changeouts were not efficacious in reducing indoor PM_{2.5} (Ward et al., 2015). As a result, this intervention arm was discontinued and homes assigned to the wood stove changeout were excluded from the results presented here. The active air filter and placebo air filter are designed to appear similar to household members, thereby blinding them to treatment status. This single-blind control arm was an essential feature of a randomized controlled trial evaluating asthma health outcomes.

In this study we present baseline and post-intervention measures from a subset of 48 homes. Indoor PM_c and endotoxin levels were collected for baseline and post-intervention winters. Among these, 25 homes were assigned to the active filtration arm and 23 homes were assigned to the placebo arm. During each of two winters (baseline and post-intervention), exposure sampling consisted of two 48-hour monitoring events. At each sampling event homeowners reported descriptive characteristics of their residence, including number of full-time residents (adults and children), number of pets (furry animals only, i.e., dogs and cats) and square footage.

As previously described (Noonan and Ward, 2012), following the baseline winter all homes received two in-room stand alone air filtration units. One large (20 ft x 18 ft) air filtration

unit (Filtrete Ultra Clean Air Purifiers, 3M, St. Paul, MN, USA) designed for a 360 ft² space was placed in the same room as the wood stove, typically the main living room. Within the child's bedroom, an in-room air filtration unit designed for 170 ft² was placed. Participants were instructed to operate the units on the "high" setting throughout the duration of the winter. Homes were randomly assigned filters with a MERV value of 13 or 2 for installation in the air filtration units, with a higher MERV indicating higher efficiency. Units were taped closed to ensure there was no human interference with the filters.

To assess compliance with continuous usage, each air filtration unit was fitted with a data logging kilowatt meter (KWM). The KWM monitored on/off status and logged the amount of kilowatt-hours used by the filtration units. Laboratory tests of the air filtration units determined a predicted kilowatt-hour usage of 3.13 per day for the large units and 1.90 per day for the small units running continuously on "high". KWM values were recorded at each sampling visit, and this value was divided by the predicted value to estimate filter use compliance.

2.2 Data Collection

2.2.1 Indoor Air Sampling—The 48 wood burning homes participating in this study were located in the following regions: 1) a 100-mile radius surrounding Missoula in western montana; 2) the Nez Perce Indian Reservation in Idaho; 3) Butte, Montana; and 4) Fairbanks, Alaska. Indoor air sampling took place during consecutive baseline and post-intervention winter periods (typically November 1 through March 15). Samplers were collocated in each home in the common living area on a table 3–5 feet off the ground and across the room from the wood stove. At each sampling event, a DustTrak 8530 (TSI Inc., Shoreview, MN, USA) measured 60-second averaged PM_{2.5} concentrations for the duration of the 48-hour sample period. The DustTrak is an optical scattering instrument that measures PM in the airflow by determining the extent of forward scattering of an infrared diode laser beam. The device is factory calibrated to the respirable fraction of standard ISO 12103–1, A1 test dust (formerly Arizona Test Dust). DustTraks were zeroed and the impaction plate was cleaned and greased/oiled as necessary prior to each sampling event.

Optical mass measurements are dependent upon particle size and material properties. Therefore, custom calibrations are needed to improve the measurement accuracy when evaluating specific sources of combustion. To accurately characterize wood smoke-related PM_{2.5} concentrations, all DustTrak PM_{2.5} measurements presented in this manuscript were corrected to an indoor wood smoke-specific correction factor of 1.65 developed by our research group (McNamara et al., 2011) and previously used in reporting results from the ARTIS study (McNamara et al., 2013; Ward et al., 2015).

Direct measurements of PM_c were collected using a Teflon filter-based coarse particle environmental monitor (CPEM) developed by RTI International (Research Triangle Park, NC, USA). As previously described (McNamara et al., 2013; Thornburg et al., 2009; Williams et al., 2009) the CPEM is a series of three separation stages designed to be inserted into the MSP Model 200 PM10 PEM air sampler (MSP Corp., Shoreview, MN, USA). PM_c is collected on two sequential 25 mm PTFE filters with polymethylpentene (PMP) support rings (thickness 3.0 µm; Zefon International, Inc., Ocala, FL, USA). The CPEM utilizes a

battery-operated pump to achieve a flow rate of 2.0 L/min. Flow rates were measured with a Drycal DC-Lite (BIOS International, Butler, NJ, USA) prior to and following each sampling event, and the rates were averaged to calculate the sample volume. If necessary, pump flow was adjusted at deployment to achieve 2.0 L/min. All data from multiple sampling events per home within a given winter were averaged to produce one winter average per home.

2.2.2 Gravimetric Analyses—The gravimetric analyses of PM₁₀ CPEM filters were conducted according to previously described guidelines (Lawless and Rodes, 1999) and modified for optimal conditions for teflon filters (Menetrez et al., 2009). Prior to sampling, each filter was placed into individually labeled sterile polystyrene AnalySlide containers (Pall Corp., Ann Arbor, MI, USA) and allowed to equilibrate for 24–48 hours in an environmentally controlled weighing facility at the University of Montana. The facility was maintained at a temperature of 20–23 °C ± 2 °C with relative humidity of 30–40% ± 5%. Humidity was maintained using an 8-gallon Kenmore Whole House humidifier (model 758.15408). Static was controlled using a grounded anti-static floor mat (ComfortKing USA, Inc., Fairfield, NJ, USA) as well as a radioactive neutralizer (Thermo Fisher Scientific Inc., Waltham, MA, USA). Filters were weighed prior to and after each sampling event with a calibrated MT5 microbalance (Mettler-Toledo LLC, Columbus, OH, USA). Multiple laboratory blanks were within the repeatability of the scale (0.8 µg). A minimum of 10% field blanks was included in all analyses.

2.2.3 Endotoxin Extraction and Analyses—Filter extraction methods were optimized for endotoxin analyses using methods adapted from Thorne et al. (Thorne et al., 2009) and Spaan et al. (Spaan et al., 2007), as previously described (McNamara et al., 2013). The two sequential PM₁₀ 25 mm teflon filters were combined and extracted in 5 mL sterile, pyrogen-free water containing 0.05% Tween-20 for one hour at room temperature with vigorous shaking. The extracts were centrifuged at 1,000-x g for 15 minutes at room temperature. Supernatants were transferred into sterile, endotoxin-free conicals (Greiner Bio-One North America Inc., Monroe, NC, USA). Extracts were diluted 50-fold with pyrogen-free water prior to endotoxin analysis to counteract enhanced yields due to Tween interference (Spaan et al., 2008). Samples were analyzed for endotoxin using a kinetic chromogenic Limulus amoebocyte lysate (LAL) assay (Endosafe Endochrome-K; Charles River Laboratories Inc., Charleston, SC, USA). Lyophilized standard endotoxin, chromogenic substrate, and LAL preparations were reconstituted using pyrogen-free water. A 12-point standard curve was generated, ranging from 0.005 to 50 endotoxin units (EU)/mL. The absorbance in each well was measured at 405 nm every 30 seconds for 90 minutes (Thorne, 2000). Samples with nondetectable endotoxin levels were assigned a value of two-thirds the limit of detection (LOD) of the assay (Spaan et al., 2008). Final endotoxin results are presented as both endotoxin units per cubic meter air (EU/m³) and EU per milligram PM mass (EU/mg).

2.3 Statistical Analyses

Forty-eight ARTIS homes that had CPEM sampling and 80% complete DustTrak data from at least one visit per winter were included in the statistical analyses. Potential differences by intervention assignment in baseline demographic characteristics and indoor air quality

measures were assessed using Fisher's exact and Mann-Whitney tests as appropriate. Modification of baseline to post-intervention changes in indoor air quality by intervention assignment was evaluated using generalized estimating equations (GEE) to account for repeated measurements within the same home. Endotoxin and PM concentrations were skewed; therefore, these measures were log-transformed results reported as the percent change (95% CI) in geometric mean concentrations. Primary analyses were not adjusted.

Multiple sensitivity analyses were performed. Robustness of findings to adjustment for demographic and home characteristics was examined. Specifically, we first evaluated the impact on results of inclusion of each demographic and home characteristic separately in the primary model. Next, we investigated modification of baseline to post-intervention changes in indoor air quality by intervention assignment in analyses fully adjusted for all demographic and home characteristics reported in Table 1. In addition, as described previously (Ward et al., 2015), we evaluated the impact of filtration unit compliance on efficacy of the filtration intervention in improving various measures of IAQ. These analyses were restricted to the 41 homes with kilowatt hour usage information. We examined the impact on results of the inclusion of compliance as a potentially confounding factor. We also evaluated effect modification by compliance and utilized GEE models that included terms for intervention assignment, winter, and mean compliance (continuous), and multiplicative interaction terms containing intervention*winter, intervention*compliance, winter*compliance, and a term containing all three variables to investigate the importance of compliance on observed results. STATA version 9.2 (College Station, TX, USA) was used for all statistical analyses.

3. Results

Overall, repeated measures in 23 placebo homes and 25 active filter homes contributed to a total of 167 observations. Entry to the study was staggered across two winters. Baseline (pre-intervention) sampling occurred during the winter of 2010–2011 for five homes and during the winter of 2011–2012 for forty-three homes (Table 1). Demographic and home characteristics are presented in Table 1. The small sample size in the first cohort of homes included in the analyses described here precluded us from examining between-site differences in these characteristics. Baseline demographic characteristics and winter concentrations of IAQ measures did not differ significantly by intervention assignment (Table 1).

Indoor air quality measures at baseline and post-intervention are presented in Supplemental Table 1. As with previous observations in wood stove homes (McNamara et al., 2013; Noonan et al., 2012; Ward et al., 2011), the average measured baseline PM_{2.5} concentrations in the 48 homes varied widely (Supplemental Table 1). Median (range) baseline PM_{2.5} concentrations were 15.7 (6.1–163.1) µg/m³ in active filter homes and 19.8 (6.0–101.9) µg/m³ in placebo filter homes. Median (range) baseline PM_c concentrations were 9.9 (3.3–36.8) µg/m³ and 10.8 (3.5–46.2) µg/m³ in the active filter and placebo filter homes, respectively. Median baseline endotoxin concentrations, presented in endotoxin units per cubic meter air (EU/m³) and EU per milligram PM mass (EU/mg), appeared higher in the

placebo filter homes although, as reported in Table 1, these differences were not statistically significant.

In the 25 homes that received the active filter, $PM_{2.5}$ concentrations were significantly reduced (Table 2). Smaller size particle ($PM_{2.5}$) concentrations did not change significantly from the baseline to post-intervention winter in homes assigned to the placebo intervention. Relative to placebo, filter homes experienced a 65.7% (95% CI: 42.2%, 79.7%) greater reduction in $PM_{2.5}$ concentrations. In addition, airborne endotoxin and PMc were significantly reduced in the active filter homes. However, these reductions of the larger sized particles (PMc) and associated endotoxin were not significantly greater than those observed in homes assigned to the placebo intervention, as placebo filters also significantly reduced both measures of airborne endotoxin (EU/m³ and EU/mg of PMc) and PMc mass concentrations.

In sensitivity analyses, intervention efficacy was evaluated after adjustment for each characteristic in Table 1. Results of these secondary analyses showed that inclusion of socioeconomic and home characteristics variables in analyses had no effect on overall findings. In particular, the impact of multivariate adjustment for demographic and home characteristics on baseline to post-intervention percent change in IAQ measures is shown in Table 2. In all cases, effects were attenuated; however, intervention assignment continued to have no effect on change in PMc or endotoxin concentrations. The efficacy of the filter intervention in reducing $PM_{2.5}$ concentrations persisted with the filter associated with 59.9% (95% CI: 34.2, 75.6) reductions, relative to placebo.

In the homes included in the analyses presented here, we observed a mean of 72% (standard deviation: 34%) compliance with recommended filter usage. Mean compliance did not differ by intervention assignment ($P = 0.58$). This is lower in magnitude than the nearly 80% compliance observed in all homes in the ARTIS study (Ward et al., 2015). Adjustment for compliance had little impact on the magnitude of the reductions observed for endotoxin or PM (results not shown). As observed previously, the impact of intervention assignment on PMc and $PM_{2.5}$ was not modified by compliance (P for the intervention assignment * winter * compliance interaction term = 0.14 and 0.30 for PMc and $PM_{2.5}$, respectively). In contrast, mean compliance did significantly influence the efficacy of the interventions on reduction of endotoxin concentrations from the baseline to post-intervention winter (EU/m³, P for interaction = 0.002; EU/mg, $P = 0.014$). Unexpectedly, a one percentage point increase in compliance was associated with 5.5% (95% CI: 1.9%, 9.2%) higher EU/m³ from the pre- to post-intervention winter for the filter relative to the placebo (Table 3). In other words, the active filter performed no better relative to placebo at higher levels of user compliance. Similar results were observed for EU/mg (5.5% increase; 95% CI: 1.1%, 10.1%). The efficacy of the placebo in reducing endotoxin concentrations increased substantially as compliance increased. A 40.0% (95% CI: -204.3, 88.2) reduction in EU/m³ was observed at 25% compliance, and a 78.4% (95% CI: 39.5, 92.3) reduction was observed at 75% compliance (Table 3). Similar improvements with compliance were not observed in the filter arm.

4. Discussion

Homes burning biomass fuel, such as dung and charcoal commonly used in some developing countries, have airborne endotoxin concentrations orders of magnitude higher than concentrations measured in developed countries (Semple et al., 2010). Globally, household air pollution is one of the top four contributors to mortality (Lim et al., 2012). It is estimated that within the United States alone, there are approximately 4.8 million susceptible individuals that live in homes with residential wood stoves, leading to exposures to indoor wood smoke-derived PM and associated endotoxin for this population (Noonan et al., 2015). The results presented here provide a novel approach to reducing exposure to in-home biomass smoke, specifically PM_c and airborne endotoxin, through the use of simple, low-cost filter units.

Filter interventions have a cost-effective advantage over other intervention strategies targeting indoor particulate matter and endotoxin. Intensive repair of moisture damage has been shown to reduce the capacity of indoor particulate matter to induce inflammatory responses *in vitro* (Roponen et al., 2013), but addressing predictors of indoor endotoxin, such as dampness/moisture sources (Park et al., 2001; Sordillo et al., 2011), can be costly and labor-intensive. We found ‘placebo’ filter units with a low MERV rating reduced airborne endotoxin concentrations as effectively as higher cost, professional-grade air filters. Both measures of endotoxin within the coarse fraction were reduced in absolute concentration (EU/m³ $p < 0.01$, EU/mg $p < 0.10$) and percent change (EU/m³ $p < 0.05$, EU/mg $p < 0.10$) following the implementation of the placebo filter unit (Table 2). PM_c concentrations were also significantly reduced following the placebo intervention (mean absolute change $p < 0.05$). While moisture remediation would still be necessary if it were the only source of the airborne endotoxin, our results show exposure to biomass-associated endotoxin can be effectively reduced with low-cost filter units.

The active filters were extremely efficient in reducing in-home concentrations of PM_{2.5} relative to the placebo filters (Table 2). In a previous studies where pre/post PM_{2.5} measurements were conducted, these units have been shown to reduce indoor PM_{2.5} in wood stove homes by 68%–76% (Hart et al., 2011b; Ward et al., 2015). Both fine and coarse particulate matter were also significantly reduced in a different randomized trial investigating the use of high efficiency air cleaners in combination with health coaches in reducing secondhand smoke exposure in inner-city homes of children with asthma (Butz et al., 2011). While our low-cost filter units were efficient at reducing PM_c and airborne endotoxin, our results support the continued use of high-efficiency filter units (MERV of 13) to reduce indoor PM_{2.5}.

An intervention strategy commonly promoted for homes containing wood stoves is the exchange of older model wood stoves for improved technology stoves with high combustion efficiencies (i.e. wood stove changeout programs). This can be an expensive intervention (≈US\$2,500–US\$4,500 per home) and our group and others have shown that wood stove exchange programs have variable and inconsistent impacts on indoor PM_{2.5} (Allen et al., 2009; Noonan et al., 2012; Ward et al., 2015). These wood stove exchange studies did not evaluate the impact on endotoxin. One study found that a wood stove technology upgrade

failed to yield lower concentrations of indoor coarse fraction particle count concentrations following the exchange. Specifically, pre-intervention concentrations had a median (range) of 0.3 (0.1–2.2) particles/cm³ while post-intervention concentrations had a median (range) of 0.3 (0.1–1.6) particles cm³ (Ward et al., 2015).

Long term effectiveness of air filter units as an intervention strategy may be dependent upon household behavior and reductions in compliance due to perceptions of noise and operating costs. A recent study involving a stand-alone air filter intervention found that filter use was variable across the study population and declined over the study duration (Batterman et al., 2012). Our group has recently demonstrated that the efficacy of air filters in reducing PM_{2.5} is quite robust, even when there are departures from continuous usage compliance (Ward et al., 2015). The subset of homes presented here had a 72% mean compliance with recommended filter usage. The active filter performed significantly better than the placebo filter at reducing airborne endotoxin concentrations at 25% and 50% compliance, but at 75% compliance the statistical significance of that interaction was diminished (Table 3). This significant interaction was not found between compliance and PM_{2.5} and PMc reductions. Although the data collected here cannot substantiate this claim, it is reasonable to envision the interaction between compliance and endotoxin reduction may be reflective of placebo filters becoming dirty and densely packed with airborne materials during heavy use. These filters may then act as traps for larger particles, including airborne endotoxin, while smaller particles were able to pass through. It is not clear, however, why these heavy use placebo filters would serve as a trap for endotoxin whereas this pattern of placebo filter useage and particle reduction was not evident for PMc.

This study had several notable strengths. First, these observations took place within a pre-post randomized design. Thus, the authors were able to evaluate changes in PM_{2.5}, PMc, and endotoxin resulting from the active filter intervention relative to a placebo intervention. The authors could also evaluate the pre-post efficacy of the placebo filters alone, which led to the notable results presented in this manuscript. The randomized design ensured similar distribution across treatment arms of factors known to be associated with IAQ (Table 1). The findings were robust to adjustment for these potential predictors of IAQ measures (Table 2). Second, household participants were blinded to intervention status, with the appearance and operating conditions of the placebo filter being identical to that of the active filter. Third, we measured airborne PMc-associated endotoxin in the homes. Previous studies typically used dust endotoxin as a surrogate of airborne endotoxin (Singh et al., 2011; Thorne et al., 2009). However, only weak correlations have been observed between dust and airborne endotoxin (Mazique et al., 2011; Park et al., 2001). Our 48-hour sampling methods are in line with previous studies that have shown airborne endotoxin measured over 1.5 days to be a more direct measure of exposure than the use of dust endotoxin (Horick et al., 2006), but this may depend on the exposure scenario being considered. A limitation of our study is that given the specific nature of our exposure scenario (i.e., wood stove homes during cold temperature periods), we are unable to generalize our findings to other residential or seasonal settings. However, our findings are directly applicable to many residents across the world where biomass burning is a common source of residential home heating.

5. Conclusions

To our knowledge, this is the first study to investigate the efficacy of air filtration on in-home levels of PMc-associated endotoxin, and the observation that a low efficiency fiberglass filter significantly reduced PMc and airborne endotoxin is a novel finding. In a larger context, this finding demonstrates that known respiratory irritants (including PMc and airborne endotoxin) can be efficiently reduced in wood stove homes with the use of inexpensive low efficiency filters. In the absence of well-tested effective replacement technologies for traditional biomass-burning cookstoves, any strategies for reducing this exposure in a cost-effective manner could impact the global disease burden attributed to household air pollution. Nevertheless, the use of air filtration devices for removal of smaller particles with known toxic properties such as PM_{2.5} will require the more expensive, high efficiency filters.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Highlights

- High and low efficiency filters are evaluated
- Fine particles are significantly reduced using high efficiency air filters
- Larger particles and airborne endotoxin are reduced with high and low efficiency filters
- Constant filter unit use not required for pollutant reduction

Table 1.

Selected characteristics of ARTIS wood stove homes receiving an active (n=25) or placebo (n=23) filtration unit.

	All homes (N=48)		Filter (N=25)		Placebo (N=23)		
	n	%	n	%	n	%	p-value
Demographic characteristics ^{a,b}							
Community, pre-intervention winter years							
Butte, 2010–11	5	10	3	12	2	9	0.71
Western Montana, 2011–12	43	90	22	88	21	91	
Household income							
Less than \$29,999	15	33	7	30	8	35	0.26
30,000 to 49,999	16	35	6	26	10	43	
\$50,000 or more	15	33	10	43	5	22	
Caregiver's education							
High school diploma, GED or less	16	35	6	26	10	43	0.31
Some college	12	26	8	35	4	17	
College degree	18	39	9	39	9	39	
Children in home, mean (SD)	2.4	1.2	2.3	1.1	2.5	1.3	0.53
Home characteristics ^{a,b}							
House	36	75	20	80	16	70	0.40
Square footage, mean (SD)	1946	1019	1955	989	1936	1073	0.95
Dog	36	75	19	76	17	74	0.87
Cat	26	54	14	61	12	48	0.37
Endotoxin							
EU/m ³ , mean (SD)	8.5	10.8	7.1	11.1	10.1	10.6	0.35
EU/mg, mean (SD)	951.8	1444.7	750.7	1221.9	1170.31	1653.6	0.32
Particle concentrations							
PM _{10–2.5} (µg/m ³), mean (SD)	12.9	8.9	11.9	7.4	14.1	10.4	0.40
PM _{2.5} (µg/m ³), mean (SD)	32.4	32.7	34.1	39.2	30.5	24.5	0.71

^aTwo homes were missing information on household income, caregiver education, and home square footage, and one was missing information on the number of children residing in the home.

^bResults are reported as the number and percentage of homes with a particular characteristic except where otherwise specified.

Table 2.

Efficacy of active filter intervention (n=25) relative to placebo intervention (n=23) in improving indoor air quality in wood stove homes.

	% change (95% CI) ^a	% change, relative to placebo (95%CI) ^a	% change, relative to placebo (95%CI) ^b
Endotoxin			
EU/m3			
filter	-91.8 (-97.3, -74.5)	-58.1 (-91.1, 96.9)	-43.6 (-87.6, 157.2)
placebo	-80.4 (-93.2, -43.6)	ref	ref
EU/mg			
filter	-90.2 (-97.3, -64.8)	-63.9 (-93.9, 114.1)	-42.3 (-90.5, 243.1)
placebo	-72.8 (-92.1, -5.8)	ref	ref
Particle concentrations			
PM10-2.5 (µg/m3)			
filter	-63.3 (-77, -41.5)	-38.2 (-67.3, 16.8)	-24.3 (-57.7, 35.5)
placebo	-40.6 (-61.5, -8.4)	ref	ref
PM2.5 (µg/m3)			
filter	-69.8 (-79, -56.6)	-65.7 (-79.7, -42.2)	-59.9 (-75.6, -34.2)
placebo	-11.9 (-39.5, 28.4)	ref	ref

Abbreviations: EU, endotoxin units; PM, particulate matter; CI, confidence interval.

^aUnadjusted analyses using generalized estimating equations evaluating modification of pre-to post-intervention changes in indoor air quality by treatment assignment. Endotoxin and PM concentrations were log-transformed, and results reported as the percent change (95% CI) in geometric mean concentrations.

^bFully adjusted analyses. Four homes were missing information on covariates and were excluded from multivariate analyses.

Table 3.

Reduction in endotoxin concentrations (percent change (95% CI)) by intervention assignment and level of compliance with filter usage recommendations. (n = 41)

	25% compliance	p-value ^b	50% compliance	p-value ^b	75% compliance	p-value ^b
EU/m ³						
filter	97.8 (90.1, 99.5)	0.003	94.9 (82.7, 98.5)	0.023	88.4 (65.3, 96.1)	0.420
placebo	40.0 (−204.3, 88.2)		64.0 (−13.8, 88.6)		78.4 (39.5, 92.3)	
EU/mg						
filter	97.3 (80.8, 99.6)	0.018	94.1 (73.1, 98.7)	0.054	87.3 (53.8, 96.5)	0.418
placebo	17.2 (−544.2, 89.3)		52.9 (−106.0, 89.2)		73.3 (6.9, 92.3)	

Abbreviations: EU, endotoxin units; CI, confidence interval.

^aEndotoxin concentrations were log-transformed and results reported as the percent change (95% CI) in geometric mean concentrations.

^bThe p-value indicating statistical significance of the interaction between intervention assignment and winter (i.e. whether the reduction in endotoxin concentration varies between filter and placebo arms).