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Efficacy of interventions targeting household air pollution from residential wood stoves

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Abstract

Wood is commonly used for residential heating, but there are limited evidence-based interventions for reducing wood smoke exposures in the indoor environment. The Asthma Randomized Trial of Indoor Wood Smoke (ARTIS) study was designed to assess the efficacy of residential interventions to reduce indoor PM exposure from wood stoves. As part of a three arm randomized placebo-controlled trial, two household-level interventions were evaluated: wood stove changeouts and air filtration units. Exposure outcomes included indoor measures such as continuous $PM_{2.5}$, particle counts, and carbon monoxide.

Median indoor $PM_{2.5}$ concentration was 17.5 μg/m^3 in wood burning homes prior to interventions. No significant reductions in $PM_{2.5}$ concentrations were observed in the 40 homes receiving the placebo filter intervention. Sixteen homes received the wood stove changeout and showed no significant changes in $PM_{2.5}$ or particle counts. $PM_{2.5}$ concentrations were reduced by 68% in the filter intervention homes. Relative to placebo, air filtration unit homes had an overall $PM_{2.5}$ reduction of 63% (95% CI: 47%−75%). Relative to the wood stove changeout, the filtration unit intervention was more efficacious and less expensive, yet compliance issues indicated a need for evaluation of additional strategies for improving indoor air quality in homes using wood stoves.

Keywords

$PM_{2.5}$; wood stoves; household air pollution

Introduction

Throughout the United States, wood stoves are the most intensively utilized type of residential space heater, with over 11 million homes using wood as either a primary or secondary heating source.[1] The use of wood stoves in rural areas is facilitated by limited alternatives to burning wood due to the lack of existing natural gas pipelines. Wood is also an economical choice when considering the elevated costs of heating oil and other fossil

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fuels. With an average annual usage of 2,100 hours per device, more than 80% of existing wood stoves are old and inefficient models.[2]

Several studies have determined that residential wood stoves are a significant source of ambient $PM_{2.5}$ throughout the winter months.[3, 4] This is especially true in rural areas of western Montana and Fairbanks (AK), two areas in which our study (described below) was carried out. Chemical Mass Balance $PM_{2.5}$ source apportionment modeling has identified wood smoke contributions between 56–77% of the ambient wintertime $PM_{2.5}$ in multiple communities throughout western Montana.[5] Similar modeling in Fairbanks revealed that 60–80% of the ambient $PM_{2.5}$ came from residential wood combustion, depending on year and sampling location.[6]

Wood stoves can also contribute to elevated concentrations of household air pollution. Mean $PM_{2.5}$ concentrations within wood burning homes have been reported from 12.8 to 54.0 $\mu g/m^3$.[7, 8, 9, 10] In a study conducted in western Montana, many of the wood stove homes investigated had 24-hour $PM_{2.5}$ average concentrations that exceeded the current Environmental Protection Agency (EPA) $PM_{2.5}$ 24-hour National Ambient Air Quality Standard (NAAQS) of 35 $\mu g/m^3$.[11] Although there are currently no indoor $PM_{2.5}$ standards in the US, these indoor exposures are of particular concern, as most people spend the majority of their time indoors, as much as 95% in some areas.[12]

Globally, household air pollution has a major impact on human health. The primary source of premature mortality and years of healthy life lost attributable to household air pollution from solid fuels is chronic respiratory and cardiovascular diseases in adults and lower respiratory tract infections in children.[13] Recent studies support the urgent need for interventions designed to reduce respiratory morbidity and mortality through improvement of indoor air quality.[11, 14, 15, 16] Importantly, residential wood stoves are a modifiable source of household air pollution. This suggests that cost-effective and sustainable strategies can be implemented that reduce exposures to wood smoke-related $PM_{2.5}$ among people living within these homes, with the overall goal of improving human health.

In this study, we evaluated the impact of two interventions (wood stove changeouts and indoor air filtration units) targeting indoor residential wood smoke. Wood stove changeouts are defined as the replacement of older model (high emission) wood stoves with improved technology, low-emission stoves. The filtration intervention included the installation of stand-alone air filtration units within wood-burning homes. Here, we present the findings from this study, providing an evaluation of these high (wood stove changeout) and moderate (air filtration unit) cost strategies for reducing in-home wood smoke PM.

Methods

As previously detailed in Noonan and Ward (2012)[17], the Asthma Randomized Trial of Indoor Wood Smoke (ARTIS) provided the setting in which we evaluated changes in household air pollution within wood burning homes. ARTIS is a three-arm randomized placebo-controlled intervention trial with two treatment arms (wood stove changeouts and air filtration). The intervention trials were conducted within the homes of asthmatic children that used older model wood stoves as the primary source of heating. Homes with tobacco smoking residents were excluded. Figure 1 provides an overview of the ARTIS study, including intervention arms.

Indoor air sampling took place within wood burning households during consecutive pre- and post-intervention winter periods (typically November 1 through March 15). During both winter periods, the exposure sampling episodes consisted of two, 48-hour continuous $PM_{2.5}$ measurements as well as particle counts for several PM size fractions. Carbon monoxide, temperature, and relative humidity were also continuously measured. The first cohort of homes was enrolled during the winter of 2008–2009 with the final cohort completing post-intervention sampling during the winter of 2012–2013.

The ARTIS study took place in semi-urban to very rural areas of the northern Rocky Mountains (Montana and Idaho) and Fairbanks (AK), locations where residential wood combustion is a major source of ambient $PM_{2.5}$ and a primary source of home heating throughout the winter months. Specifically, intervention based studies were conducted in the following regions: 1) a 100-mile radius surrounding Missoula in western Montana; 2) the Nez Perce Indian Reservation in Idaho; 3) Butte, MT; and 4) Fairbanks, Alaska. The western Montana (WMT) study area was further separated into three groups according to the years in which homes were enrolled in the study.

Interventions

Wood Stove Changeout.

Older model wood stoves were changed out and replaced with EPA-certified wood stoves. The new stoves were all certified as low-emission according to EPA standards (produces only 2 to 5 grams of smoke per hour). EPA-certified wood stoves were purchased and installed by certified technicians within the western Montana study areas. In some cases, new hearth pads and venting packages were provided to the residences to meet code. Following installation, a contracted wood stove expert conducted specific training on best burn practices within the home, and verified the successful installation of the new stoves. Note that this was not a fuel switching intervention as pellet, natural gas, propane, etc. stoves were not provided as changeout options. The new stoves were installed during the fall (following the pre-intervention winter) prior to the start of the post-intervention winter. Prior to enrollment of the final cohort of homes, this intervention arm was discontinued as an interim analysis indicated the wood stove changeouts were not efficacious in reducing indoor $PM_{2.5}$.[18]

Air Filtration Unit.

Within each randomly assigned home, a Filtrete Ultra Clean Air Purifier (3M, St. Paul, MN) was placed in the same room as the wood stove (20 ft x 18 ft). In addition, a smaller Filtrete unit (17 ft × 10 ft) was placed in the child’s bedroom. These units are rated by their ability to provide an equivalent amount of contaminant free air into the space, and have a Clean Air Delivery Rate (CADR) of 112. The filters in these units are approximately 85% efficient at removing 0.2 μm particles (cigarette smoke size particles) and over 95% efficient at removing 3 µm particles. The units were operated on the “high” setting throughout the duration of the intervention winter period. Filters were replaced approximately once per month to maximize collection efficiency. Kilowatt meters attached to each unit measured the amount of usage. Kilowatt hour readings were recorded up to four times during the post-intervention winter, with percent compliance for each home estimated by dividing the observed kilowatt hours used by the expected usage. The expected kilowatt hour usage for the large filtration unit (room size of 20 ft x 18 ft) was determined in the laboratory while operating on the “high” setting.

Air Filtration Unit - Placebo Intervention.

Similar to the Air Filtration Unit intervention, a larger Filtrete unit (for room size 20 ft x 18 ft) was placed in the same room as the wood stove, and a smaller unit (17 ft × 10 ft) was placed in the child’s bedroom. Instead of a high efficiency filter, the units were fitted with placebo filters. The placebo filters used in the Filtrete devices were manufactured at the University of Montana using a porous filter media. These units were also run on the “high” setting with placebo filters changed out monthly. Compliance was assessed with the kilowatt meters as above. Upon completion of the study, placebo-assigned homes were provided with the appropriate filters to restore the air cleaning functionality of the unit.

Sampling Program

During each 48-hour sampling event during both the pre- and post-intervention winters, three air samplers were deployed within the home. A DustTrak 8520/8530 (TSI, Shoreview, MN) was used to continuously measure $PM_{2.5}$ mass throughout the 48-hour sampling events. Due to the sensitivity of measurements obtained from optical scatter instruments to particle size and material properties and thus combustion sources, we applied a wood smoke-specific correction factor of 1.65 to all indoor DustTrak $PM_{2.5}$ measurements.[19] Second, a Lighthouse 3016-IAQ particle counter (Lighthouse Worldwide Solutions, Fremont, CA) was used to continuously measure particle counts within six size fractions (0.30–0.49, 0.50–0.99, 1.00–2.49, 2.5–5.0, 5.0–10.0, 10.0+ µm). Together, the 0.30–0.49, 0.50–0.99, and 1.00–2.49 µm fractions comprised the “fine” fraction, and the 2.5–5.0 and 5.0–10.0 the “coarse.” Particle number concentrations (PNCs) are reported as the number of particles per cm^3. Finally, a Q-Trak (TSI, Shoreview, MN) was used to continuously measure carbon monoxide, carbon dioxide, temperature and relative humidity. During each sampling event, these monitors were co-located and placed approximately 3–5 feet off the ground within the same room as the wood stove. Field personnel were trained to put the samplers at the same locations within the home for each sampling event across both winters. To standardize the height of sampling inlets, we provided our own tables to set the equipment on during each sampling event.

All samplers had 60-second recording intervals, and were zero calibrated prior to each sampling event. Since we observed significant temporal variability in $PM_{2.5}$ concentrations throughout a 24-hour period in this study,[10] daily averages were included in the calculation of 48-hour averages only when they were generated from data that were at least 80% complete to ensure that the averages were representative of concentrations experienced during the entire sampling events. Instrument malfunctions (e.g., flow errors) or power failures were the primary reasons for sampling events with less than 100% air sampling data capture.

Prior to sampling, demographics and home characteristics surveys were completed by participants. These surveys documented information such as household income, education, type/age/size of home, and age of wood stove. We asked the household residents to use an activity log to record specific activities that occurred within the home during the 48-hour sampling periods. Specifically, activities recorded included cooking and cleaning activities, traditional or cultural burning, and other activities that may have contributed to increased PM levels (e.g., burning incense or candles or opening of windows or doors). During each sampling episode, a wood burning record was also utilized to track frequency/amount of burning, including the number of times that the wood stove was loaded/stoked, burn intensity (none or light, average or heavy), source of wood (harvest or purchase) and approximate age of wood (less than one year, one year, or two years or more).

Statistical analyses

We calculated the median and range of indoor air concentrations of PM and CO for the pre-intervention winter and reported these for each ARTIS site. The pre- and post-intervention winter median and range of $PM_{2.5}$ concentrations and PNCs also are reported by intervention group. Linear mixed models account for the dependence of repeated measures of indoor air quality in the same home and were used to evaluate whether pre- to post-intervention changes in indoor air quality concentrations differed significantly by intervention. Each indoor air quality metric was evaluated separately in statistical analyses. As this study was a randomized controlled trial, which, by design, should result in a balance of both measured and unmeasured potentially confounding factors in each intervention arm, primary models followed the principle of intent-to-treat and included only winter (pre- or post-intervention) as a time-dependent variable, intervention group assignment as a time-independent three-level indicator variable, and a multiplicative interaction term containing winter and intervention group. $PM_{2.5}$ and CO concentrations and PNCs were skewed and log-transformed in analyses. Thus, results are reported as the percent change in geometric mean PM concentration from the pre- to the post-intervention winter for each intervention group and as the relative percent change (95% CI), compared to the placebo arm, in analyses of intervention efficacy. All statistical analyses were conducted using SAS v9.3 (Cary, NC) and STATA v9 (College Station, TX).

Sensitivity analyses

Despite the randomized design of the study, it is possible that an unequal distribution of potentially confounding factors between intervention arms occurred. To evaluate whether confounding contributed to observed results, we performed analyses adjusted for socioeconomic factors (household income and education), burning practices (none/light or average/heavy burning intensity, the length of time wood was seasoned before burning (less than one year/one year/two or more years), and cords of wood burned), home activities (presence of any burning in addition to wood stove use and opening of doors/windows), home characteristics (house versus apartment/mobile home/duplex), and meteorological variables (temperature, humidity, and precipitation). Socioeconomic measures were included in analyses as time-independent, 3-level indicator variables. All other covariates were included as time-dependent, indicator variables with the exception of cords of wood burned and meteorological information, which were included as continuous data in analyses. Potential confounding was assessed by adding each covariate into the primary model separately and examining the degree to which statistical significance and the magnitude of the coefficient for the winter*intervention group interaction changed. In addition, we assessed the impact on results of including all potential confounders in the primary model at once.

We also examined the impact of filtration unit compliance on efficacy of the filtration unit in reducing PM concentrations. These analyses were restricted to homes assigned to the active filtration unit (n = 34) and placebo (n = 37) arms of the randomized trial with information on kilowatt hour usage. Linear mixed models including terms for winter, filtration unit compliance, and a multiplicative interaction term containing winter and compliance were used to evaluate dependence of PM reduction on compliance with recommended usage of the filtration unit. Analyses were performed separately for homes assigned to the active filtration and placebo arms. Compliance was divided into tertiles (< 68 %, 68–89 %, and > 89 % compliant) based on the mean percent compliance estimated during the post-intervention winter.

Results

Pre-Intervention Home Characteristics

In total, 98 homes were randomized following the pre-intervention winter periods, with 90% (i.e. 88 homes) completing post-intervention sampling. Importantly, homes lost to follow-up were not significantly different compared to homes that completed the randomized trial with respect to intervention assignment or pre-intervention indoor $PM_{2.5}$ concentrations, socioeconomic characteristics, or burning practices (data not shown). One reason for discontinuing participation in ARTIS was moving to another residence (n=2), while other homes simply chose not to continue with the post-intervention sampling program (n=8). The vast majority of daily $PM_{2.5}$ sampling was 80% complete in all intervention groups. Homes assigned to the placebo, wood stove changeout, and filter intervention arms had 80% complete $PM_{2.5}$ data for 99% (297 of the 301 days), 100% (130 of 130 days), and 98% (300 of 306 days) of the attempted sampling days, respectively. The mean percentage of sufficiently complete days per home did not vary significantly by treatment group (i.e., mean of 7, 8, and 7 days for the placebo, wood stove changeout, and filter arms, respectively).

Table 1 presents the information collected at the baseline visit of the pre-intervention winter for each of the 98 homes across all study areas (western Montana, Nez Perce Indian Reservation, Butte, and Fairbanks), overall and by intervention group. Thirty nine percent of the participating childs' caregivers (i.e., parent or guardian) reported annual household incomes of $50,000 or more, 43% had a college degree, and 72% lived in a house compared to a mobile home, duplex/apartment, or other. The wood stove changeout arm included a higher percentage of homes with annual household income less than $29,999 per year and a lower percentage of homes in which the caregiver's highest reported education level was a college degree. In addition, an average of 2.5 (1.3) children resided within the homes.

As a criteria for participation in the study, each home used a wood stove as its primary source of heat. The wood stoves within the homes were an average of just over 20 years old (data not shown). Sixty-four percent (64%) of homes reported harvesting their own wood compared to 36% that reported purchasing their wood. Residents across all study areas reported burning, on average, 5.1 (2.4) cords of wood during the pre-intervention winter (data not shown).

Sixty-one percent of the homes seasoned their wood for at least one year before burning. The majority of residents (74%) reported that wood stove usage was "average to heavy" during the sampling events. The filtration unit arms, both active and placebo, were more likely to season wood for at least two years prior to burning and less likely to report average to heavy intensity burning or opening a door or window during the sampling period. Mean indoor temperatures across all intervention arms were consistent (21.9–22.3 °C). Fairbanks homes had the lowest average indoor relative humidity (21.8 (7.7) %), while the Nez Perce homes had the highest average indoor relative humidity (39.1 (7.9) %) (data not shown).

Pre-Intervention $PM_{2.5}$ Concentrations

In Table 2, summary PM concentrations for the pre-intervention winter sampling periods are reported for each study area. Across all study areas, the highest median indoor $PM_{2.5}$ concentrations during the pre-intervention winter were measured in the second cohort of western Montana (WMT 2) homes (23.9 (range: 7.9, 129.3) $\mu g/m^3$, Table 2). We were also interested in documenting the highest $PM_{2.5}$ concentrations measured during each of the sampling events. Similar to the median indoor $PM_{2.5}$ concentrations, the median of the highest concentrations observed during the pre-intervention winter, (presented as $PM_{2.5}$ max in Table 2), was observed in WMT 2 residences, with the median maximum exceeding 700 $\mu g/m^3$.

Pre-Intervention Particle Count Concentrations

As presented in Table 2, results from sampling for particle counts showed that there were more particles in the 0.3–0.49 and 0.5–0.99 size fractions compared to the larger size fractions (1.0–2.49 and coarse fractions). Particles in the largest size fraction (10.0+) had the lowest concentrations compared to the other size fractions (results not shown). Wood smoke particles typically exhibit a peak in the size distribution between 0.15 and 0.4 μm.[20] Thus, the smaller particle size fractions observed within the homes were consistent with a wood stove combustion source. No consistent patterns in PNCs were observed by study site, although the first two cohorts of western Montana homes generally had the highest median concentrations of the smallest size fraction PNCs.

Pre-Intervention Carbon Monoxide Concentrations

Pre-intervention average carbon monoxide concentrations were low in the western Montana, Nez Perce, and Fairbanks homes, with median concentrations ranging between 0.1 and 0.6 ppm (**see** Table 2). Pre-intervention winter carbon monoxide levels in the Butte (n=8) homes were more elevated, with a median of 6.5 ppm (range: 0, 13.5). Note that the post-intervention median for this study area was 0.9 (range: 0, 1.0).

Intervention efficacy

Placebo Filter - Control—Air filtration units outfitted with placebo filters were used in this study as our control. In total, these placebo units were placed in 40 homes across each of the study areas. As seen in Table 3, using linear mixed model analyses we observed a non-significant 9% (95% CI: −19%, 30%) reduction in $PM_{2.5}$ concentrations as measured by the DustTrak. Consistent with results of analyses examining the influence of the placebo filter on $PM_{2.5}$ mass concentrations, a non-significant 27% (95% CI: −19%, 54%) reduction in "fine" fraction PNCs (0.30–0.49 µm, 0.50–0.99 µm, and 1.00–2.49 µm) was also observed. A much greater and significant reduction in "coarse" fraction particles was observed in the placebo arm, with the post-intervention concentration 57% (95% CI: 25%, 76%) lower than the pre-intervention concentration. Socioeconomic factors, burning practices, home activities, home characteristics, and meteorological variables do not explain this association as significant reductions in coarse fraction particles persisted even after adjustment for these covariates (data not shown). The placebo was not expected to influence, and did not affect, carbon monoxide concentrations.

Wood Stove Changeout—Sixteen homes were assigned to the wood stove changeout intervention prior to discontinuation of this intervention arm. Among these, the median of the pre-intervention winter average $PM_{2.5}$ concentrations was 40.7 (range: 8.7, 86.8) $\mu g/m^3$ (**see** Table 3). The median of the average concentrations measured during the winter following the installation of the EPA-certified wood stove was 32.4 (range: 6.1, 138.4) $\mu g/m^3$. As displayed in Table 3, no significant changes in $PM_{2.5}$ or PNCs of any size were observed in the wood stove changeout arm in primary or multivariable adjusted analyses. Relative to the placebo arm, CO concentrations were reduced an additional 87% (95% CI: 33%, 97%) in the wood stove change out arm.

Filtration Unit—Following discontinuation of the wood stove changeout arm, all homes in the WMT 3 group were assigned to either the filtration unit intervention or the placebo intervention, resulting in a total of 42 homes assigned to this arm. As shown in Table 3, using the DustTrak measurements the median of the pre-intervention winter average $PM_{2.5}$ concentrations was 17.1 (range: 6.1, 163.1) $\mu g/m^3$, and the median of the post-intervention winter average $PM_{2.5}$ concentrations was 6.5 (range: 0.7, 65.6) $\mu g/m^3$. Geometric mean $PM_{2.5}$ concentrations were reduced by 69% (95% CI: 59%, 76%), while $PM_{2.5}$ spikes were reduced by 54% (95% CI: 29%, 70%).

Table 3 also demonstrates efficacy of this intervention unit as, relative to homes assigned to the placebo arm, homes assigned to the air filtration unit experienced a 66% (95% CI: 50%, 77%) greater reduction in $PM_{2.5}$ concentrations from the pre- to post-intervention winter. Findings were not sensitive to adjustment for socioeconomic factors, burning practices, home activities, home characteristics, and meteorological variables. The percent reduction in $PM_{2.5}$ concentrations, relative to placebo, changed by only one percent when the potential confounders described above were included in analyses (data not shown). Strong and significant reductions in PNCs of all sizes were observed although these were significantly greater than those observed in the placebo arm only for the smallest two size fractions and all of the fine fraction PNCs combined.

Mean percent compliance in homes assigned to the active filtration unit was 78% (sd: 37%), which did not differ significantly from the compliance observed in homes assigned to the placebo arm (mean (sd): 79% (30%); P = 0.8). No significant interaction between winter and compliance was observed for homes in the filtration unit (P = 0.8) or placebo (P = 1.0) arms. $PM_{2.5}$ concentrations were significantly lower in active filtration unit homes during the post-intervention winter independent of tertile of compliance (Figure 2). Similar to our primary findings, no reductions were observed in any tertile of compliance for placebo homes (Figure 2). In addition, no significant dose-response in $PM_{2.5}$ reduction efficacy was observed by tertile of estimated compliance for either intervention arm (data not shown). Please note that an additional **Figure** is provided in the Supplemental section that presents the efficacy of the active filter and placebo filtration units in reducing non-transformed $PM_{2.5}$ concentrations, by tertile of compliance as determined by kilowatt hour usage.

Discussion

Household air pollution is a major contributor to global morbidity and mortality. An estimated 3.5 million deaths and 4.5% of disability-adjusted life-years worldwide in 2010 were attributed to household air pollution from the burning of solid fuels as reported in the Global Burden of Disease Study.[13] This disease attribution to household air pollution is based only on the proportion of households using solid fuels for cooking, predominantly in developing country settings. Nevertheless, in higher income countries the use of solid fuels, predominantly wood, for residential heating contributes substantially to ambient and household air pollution. Consideration of these sources may increase the global attribution of household air pollution to disability-adjusted life-years estimates. To address this environmental public health issue, our team evaluated two different intervention strategies targeting the reduction of indoor wood smoke PM, the replacement of old wood stoves with lower emission, “EPA-certified” wood stoves (wood stove changeout) and the installation of air filtration units.

Evaluation of Wood Stove Changeouts

This is the first study to evaluate the efficacy of replacing wood stoves used for residential heating in a randomized trial design. Our findings in the wood stove intervention arm were unexpected, as we observed no overall improvements in indoor $PM_{2.5}$ concentrations, relative to the placebo control, although CO concentrations were reduced.

Wood stove changeouts are a common strategy used by environmental agencies to address ambient air quality issues within residential wood burning communities. For example, a large-scale stove changeout campaign of over 1,100 homes in a small rural community resulted in a 27.6% reduction in winter period ambient $PM_{2.5}$.[9] In the same community engaging in the large-scale changeout campaign, observations in homes before and after stove replacement indicated overall 60–70% reductions in indoor $PM_{2.5}$ concentrations as measured by TSI DustTraks.[21] However, findings across these homes and over multiple years of observation were highly variable, and a subset of homes (24%) did not experience a reduction in $PM_{2.5}$ following changeout (Noonan et al., 2012a).[9] Similarly, in a wood stove changeout evaluation conducted in northern Idaho, sampling results showed that indoor air quality was improved in 10 of 16 homes, resulting in a 36% reduction in mean indoor $PM_{2.5}$ and a 60% reduction in $PM_{2.5}$ spikes. Still, five homes showed increased indoor $PM_{2.5}$ concentrations following the changeout.[8] Finally, a study by Allen et al. (2009)[7] did not find a consistent relationship between stove technology upgrades and indoor air quality improvements in homes where stoves were exchanged within 15 homes.

The highly variable outcomes of the above-mentioned studies and the failure of the current study to demonstrate efficacy for the stove changeout arm are not well understood or easily explained. One possible explanation for these variable findings is that residents are not operating their new stoves optimally, and therefore not maximizing the PM reduction capabilities of the new units. A previous study suggested that stove use training following installation could result in improved outcomes.[8] To address this finding, the homes assigned to the wood stove changeout intervention in the ARTIS study were provided with initial wood stove training by a stove expert when their stoves were replaced. Further evaluation of training or communication strategies for the delivery of this content may be required to improve efficacy.

While the wood stove changeout intervention was primarily dependent upon the introduction of improved technology, certain behavioral factors related to wood stove use may obscure any improvements in wood combustion efficiency. For example, the use of firewood that is not properly dried is known to be an important factor in smoke emissions regardless of the stove technology.[22] Our study did not address or monitor the use of proper wood fuels among participants (including moisture meter readings), but accounting for this and other stove use behavioral factors is essential for future evaluations of technology-based stove interventions.

Due to the multi-year observation periods of our study, it is also possible that temporally-varying factors, such as wintertime inversions, could have impacted our findings with respect to the wood stove changeout intervention. The placebo-controlled randomized design partially protects against this. Moreover, in sensitivity analyses our findings remained robust to considerations of socioeconomic factors, burning practices, home activities, home characteristics, and meteorological variables.

The costs associated with this intervention further argue against wood stove changeouts as an effective strategy for improving indoor air quality. In some of the residences participating in this study, new hearth pads and venting packages were required to meet code, adding additional expenses to the intervention. In total, the wood stove intervention averaged between $2,500–$4,500 per home, creating challenges for broadly implementing this strategy in rural, economically challenged communities.

Evaluation of Air Filtration Units

A key study design feature for evaluation of the air filtration unit intervention was that residents in this arm were blinded to intervention status with respect to the placebo arm (i.e., sham air filter). Results from the 42 homes assigned to this intervention showed that the air filtration unit resulted in a 69% exposure reduction in indoor $PM_{2.5}$ concentrations and reduced fine fraction PNCs in excess of 70%. These decreases were markedly and significantly greater than those observed in homes assigned to the placebo arm, in which $PM_{2.5}$ concentrations and combined fine fraction PNCs did not decline significantly. The air filter changes, described here in relative terms (i.e., percent change), also reflect meaningful changes in absolute terms with median $PM_{2.5}$ concentration changes from 17.1 $\mu g/m^3$ to 6.5 $\mu g/m^3$. Although these values are low compared to household air pollution observed in developing country settings with biomass cookstoves, recent integrated exposure response (IER) analyses indicate health benefits in this range. The lower end of the IER curves for ischemic heart disease, stroke and chronic obstructive pulmonary disease are based on studies of ambient air pollution and are weighed against a counterfactual concentration distribution, termed the theoretical minimum risk exposure distribution (TMRED).[23] As proposed by Lim et al (2012), the IER curves employed a counterfactual distribution with a lower bound of 5.8 $\mu g/m^3$ and an upper bound of 8.8 $\mu g/m^3$.[13] This range should not be interpreted as a level below which there is no health risk, but the median $PM_{2.5}$ concentrations in our air filtration arm shift to within this range from a pre-intervention level that exceeds U.S. and WHO annual ambient air quality standards.

Although the placebo intervention served its function in serving as a control for the $PM_{2.5}$ reduction intervention, both the active filter and the placebo filter treatment arms saw significant reductions in coarse fraction PNCs. These findings were likely the result of the porous nature of the placebo filter material being efficient at “scrubbing” out the larger sized particles, while allowing the smaller particles to pass through the material. This translates as both a study strength and a potential study limitation. As a strength, any health outcomes associated with the air filtration arm could be interpreted as likely due to the treatment effect on reduced $PM_{2.5}$ as the coarse fraction PM was equally impacted by the air filtration and placebo arms. As a potential study limitation, an intent-to-treat analysis would not show efficacy for any health measures that are impacted by change in this larger coarse fraction PM. Exploration of changes in such measures that are responsive to changes in both $PM_{2.5}$ and coarse fraction PM would require exposure-response analysis.

The use of air filtration units to reduce indoor PM is not a unique strategy for addressing household air pollution. Previously, two randomized controlled trials have reported on the efficacy of air filtration units in reducing in-home PM. Reisman et al. (1990)[24] reported a 73% reduction in total suspended particulates due to air filter usage and found modest improvements in total symptoms among the air filtration treatment group. A second, more recent randomized controlled trial reporting on PM levels demonstrated a 39% reduction in PM10 among homes using air filtration units.[25] Comparable to our homes, Hart et al. (2011)[26] showed that when using an air filtration unit within a wood-burning home, particle count concentrations were reduced by 61–85%, with similar reductions observed in particle mass concentrations. The results from Hart et al. were replicated in a study conducted by Wheeler et al. (2014)[27], where an air filtration unit was used in wood burning homes in Nova Scotia, Canada to reduce indoor $PM_{2.5}$ by 52%. Finally, crossover studies in rural British Colombia communities impacted by residential wood combustion demonstrated the efficacy of air filtration units for reducing indoor $PM_{2.5}$ in both homes with and without wood stoves.[28, 29]

In our study, we observed compliance issues that resulted in less than optimal usage of the air filtration units within the homes. These compliance issues were primarily centered around concerns about the noise of the filtration units, as well as concerns about the electrical costs of running the units on the high setting for the entire winter period. When considering compliance, an important question is determining what the overall percent PM reductions are at different levels of usage. We observed that the filtration unit was highly efficacious in significantly reducing $PM_{2.5}$, even within homes in the lowest tertile (i.e. less than 68%) of compliance (**see** Figure 2). In this study, we were not able to evaluate the long-term compliance after households had completed their participation, but concerns about sustainable effectiveness of this strategy are worthy of further investigation.

Conclusions

Wood stove changeouts are typically employed as a community-level strategy to lower ambient $PM_{2.5}$ concentrations during cold temperature periods. Several studies, including this one, have shown equivocal impacts on household air quality following stove technology upgrades. The overall variability in results coupled with the costs of replacement of an old wood stove ($2,500–$4,500 per home) may preclude this intervention from being broadly implemented in rural, economically challenged communities. The use of an air filtration unit within wood burning homes in this study showed an overall 69% reduction in indoor $PM_{2.5}$ concentrations and a 75% reduction in the particle count concentration of the smallest size fraction measured in this study (0.3–0.49 μm), a size range representative of the known size distribution of wood smoke.[20] Indoor air quality improvements associated with this intervention were robust to differences in usage compliance although overall compliance in this study was fairly high during the period evaluated. However, the effectiveness of filtration units as a broad-scale strategy to address household air pollution (from residential wood stoves) in impacted communities may be limited by economic considerations (costs of the unit (~$200), yearly filter replacement (~$100), and energy usage (~$100–$200/year)) and long-term compliance issues for which little data are available.

Health agencies and clinical practitioners recognize the importance of identifying sustainable, cost-effective interventions that improve quality of life of residents. In looking at next steps, education to the homeowner on best burn practices could be an inexpensive and sustainable strategy to reduce wood smoke exposures within the homes. Importantly, training on best-burn practices was not conducted in this study. Despite the promotion of best burn practices by various tribal, local, state, and federal agencies, such strategies have rarely been formally and rigorously tested in regionally and culturally distinct settings. Demonstration of effective education-based interventions may also inform strategies to supplement the current global effort to introduce improved cookstove technologies.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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References

1. U.S. Department of Energy (USDOE). Table HC6.7. Space heating in U.S. homes, by census region, Washington, DC, 2009.
2. Air Quality Management Work Group (AQMWG). Recommendations to the Clean Air Act Advisory Committee: Phase I and Next Steps Washington, DC, 2005.
3. Larson T, Gould T, Simpson C, Liu LJ, Claiborn C, Lewtas J. Source apportionment of indoor, outdoor, and personal $PM_{2.5}$ in Seattle, Washington, using positive matrix factorization. J Air Waste Manag Assoc 2004; 54(9): 1175–1187. [PubMed: 15468670]
4. Naeher LP, Brauer M, Lipsett M, Zelikoff JT, Simpson CD, Koenig JQ, et al. Woodsmoke health effects: a review. Inhal Toxicol 2007; 19: 67–106.
5. Ward T, Lange T. The impact of wood smoke on ambient $PM_{2.5}$ in northern Rocky Mountain valley communities. Environ Pollut 2010; 158: 723–729. [PubMed: 19897293]
6. Ward TJ, Trost B, Conner J, Flanagan J, Jayanty RKM. $PM_{2.5}$ source apportionment in a subarctic airshed - Fairbanks, Alaska. Aero Air Qual Res 2012; 12: 536–543.
7. Allen R, Leckie S, Millar G, Brauer M. The impact of wood stove technology upgrades on indoor residential air quality. Atmos Env 2009; 43: 5908–5915
8. Ward T, Boulafentis J, Simpson J, Hester C, Moliga T, Warden K et al. Lessons learned from a woodstove changeout on the Nez Perce Reservation. Sci Total Environ 2011; 409(4): 664–670. [PubMed: 21144555]
9. Noonan CW, Navidi W, Sheppard L, Palmer CP, Bergauff M, Hooper K et al. Residential indoor $PM_{2.5}$ in wood stove homes: follow-up of the Libby changeout program. Indoor Air 2012a; 22(6): 492–500. [PubMed: 22607315]
10. Semmens EO, Noonan CW, Allen RW, Weiler EC, Ward TJ. Indoor particulate matter in rural, wood stove heated homes. Environ Res 2015; 138C: 93–100. 10.1016/j.envres.2015.02.005.
11. Noonan CW, Ward TJ, Navidi W, Sheppard L. A rural community intervention targeting biomass combustion sources: effects on air quality and reporting of children’s respiratory outcomes. Occ Environ Med 2012b; 69: 354–360.
12. Jenkins P, Phillips T, Mulberg J, Hui S. Activity patterns of Californians: use of and proximity to indoor pollutant sources. Atmos Res 1992; 26A: 2141–2148.
13. Lim SS, Vos T, Flaxman AD, Danaei G, Shibuya K, Adair-Rohani H et al. A comparative risk assessment of burden of disease and injury attributable to 67 risk factors and risk factor clusters in 21 regions, 1990–2010: a systematic analysis for the Global Burden of Disease Study 2010. Lancet 2012; 380(9859): 2224–2260. [PubMed: 23245609]
14. Torres-Duque C, Maldonado D, Perez-Padilla R, Ezzati M, Viegi G. Biomass fuels and respiratory diseases: a review of the evidence. Proc Am Thorac Soc 2008; 5(5): 577–590. [PubMed: 18625750]
15. Diette GB, Accinelli RA, Balmes JR, Buist AS, Checkley W, Garbe P et al. Obstructive lung disease and exposure to burning biomass fuel in the indoor environment. Global Heart 2012; 7(3): 265–270. [PubMed: 23139916]
16. Sood A Indoor fuel exposure and the lung in both developing and developed countries: an update. Clin. Chest Med 2012; 33(4): 649–665. [PubMed: 23153607]
17. Noonan CW, Ward TJ. Asthma randomized trial of indoor wood smoke (ARTIS): Rationale and methods. Contemp Clin Trials 2012; 33: 1080–1087. [PubMed: 22735495]

18. Semmens E, Noonan C, Ward T, Hester C. Are indoor air filters a sustainable intervention for reducing indoor particulate exposures? Epidemiology 2012; 23(5S): S638.
19. McNamara ML, Noonan CW, Ward TJ. Correction factor for continuous monitoring of wood smoke fine particulate matter. Aero Air Qual Res 2011; 11: 315–322.
20. Hays MD, Geron CD, Linna KJ, Smith ND, Schauer JJ. Speciation of gas-phase and fine particle emissions from burning of foliar fuels. Environ Sci Technol 2002; 36: 2281–2295. [PubMed: 12075778]
21. Ward TJ, Palmer C, Bergauff M, Hooper K, Noonan CW. Results of a residential indoor $PM_{2.5}$ sampling program before and after a wood- stove changeout. Indoor Air 2008; 18: 408–415. [PubMed: 18665872]
22. U.S. Environmental Protection Agency (US EPA). Consumers - best burn practices Available: http://www.epa.gov/burnwise/bestburn.html [accessed January 10, 2012].
23. Burnett RT, Pope CA, III, Ezzati M, Olives C, Lim SS, Mehta S, Shin HH, Singh G, Hubbell B, Brauer M, Anderson HR, Smith KR, Balmes JR, Bruce NG, Kan H, Laden F, Prüss-Ustün A, Turner MC, Gapstur SM, Diver WR, and Cohen A. An integrated risk function for estimating the global burden of disease attributable to ambient fine particulate matter exposure. Environ Health Perspect 2014; 122:397–403. [PubMed: 24518036]
24. Reisman RE, Mauriello PM, Davis GB, Georgitis JW, DeMasi JM. A double-blind study of the effectiveness of a high-efficiency particulate air (HEPA) filter in the treatment of patients with perennial allergic rhinitis and asthma. J Allergy Clin Immunol 1990; 85: 1050–7. [PubMed: 2191991]
25. Eggleston PA, Butz A, Rand C, Curtin-Brosnan J, Kanchanaraksa S, Swartz L, et al. Home environmental intervention in inner-city asthma: a randomized controlled clinical trial. Ann Allergy Asthma Immunol 2005; 95: 518–24. [PubMed: 16400889]
26. Hart JF, Ward TJ, Spear TM, Rossi RJ, Holland NN, Loushin BG. Evaluating the effectiveness of a commercial portable air purifier in homes with wood burning stoves: a preliminary study. J Environ Public Health 2011; 2011: 1–7.
27. Wheeler AJ, Gibson MD, MacNeill M, Ward TJ, Wallace LA, Kuchta J, et al. Impacts of air cleaners on indoor air quality in residences impacted by wood smoke, Environ Sci Technol 2014; 48: 12157–12163. [PubMed: 25247985]
28. Allen R, Carlsten C, Karlen B, Leckie S, van Eeden S, Vedal S et al. An air filter intervention study of endothelial function among healthy adults in a woodsmoke-impacted community. Am J Respir Crit Care Med 2011; 183(9): 1222–1230. [PubMed: 21257787]
29. Barn P, Larson T, Noullett M, Kennedy S, Copes R, Brauer M. Infiltration of forest fire and residential wood smoke: An evaluation of air cleaner effectiveness. J Expo Sci Environ Epi 2008; 18: 503–511.

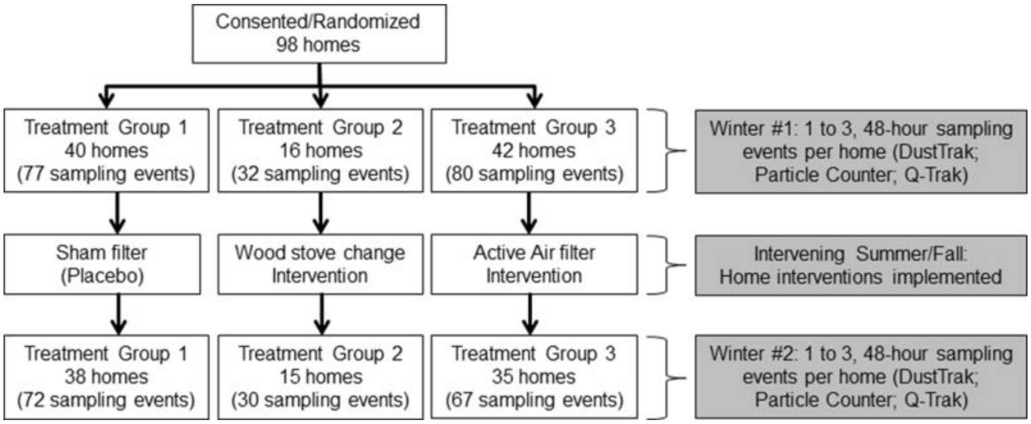

Figure 1.

Overview of ARTIS program intervention arms.

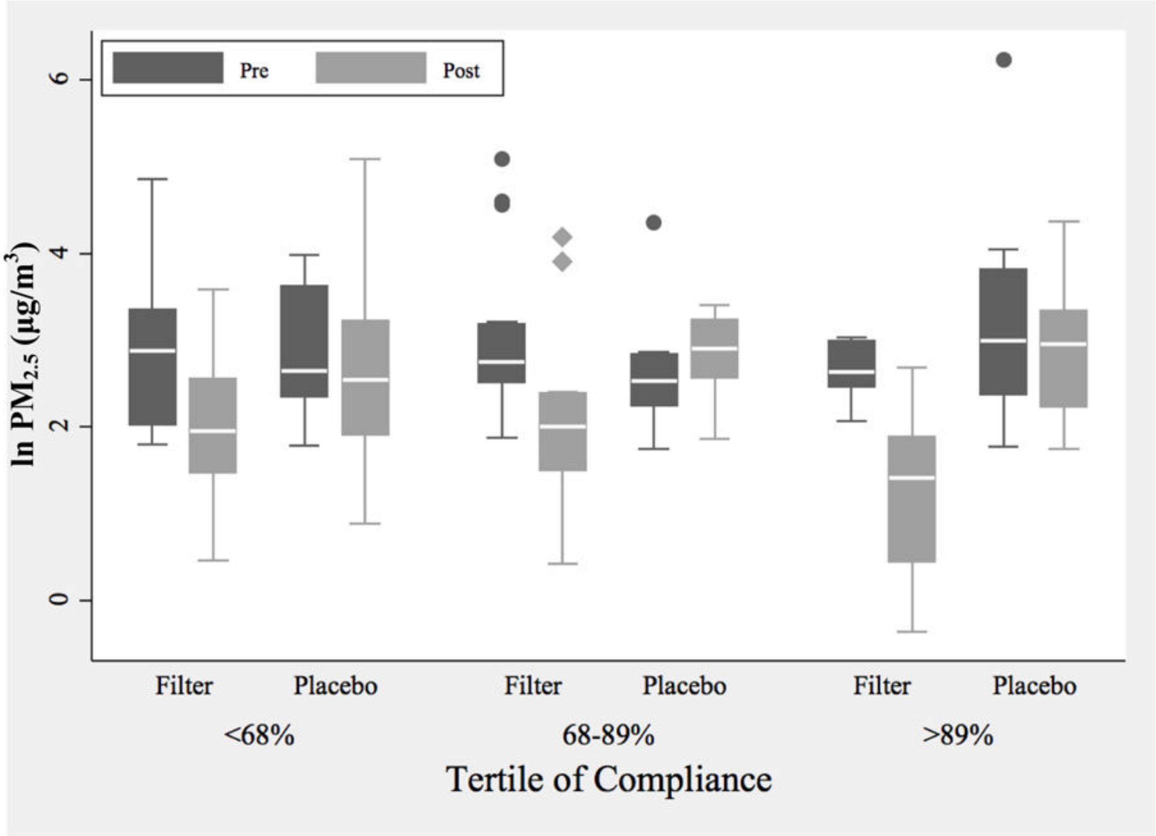

Figure 2.

Efficacy of the active filter (n = 34) and placebo (n = 37) filtration units in reducing natural log transformed $PM_{2.5}$ concentrations, by tertile of compliance as determined by kilowatt hour usage.

Table 1.

Selected characteristics of ARTIS homes during the baseline visit of the pre-intervention winter, overall and by treatment group.

	All homes (N=98)		Filter (N=42)		Woodstove changeout (N=16)		Placebo (N=40)	
	n	%	n	%	n	%	n	%
Demographic characteristics[a,b]								
Community, pre-intervention winter years								
WMT 1, 2008–09	12	12	4	10	4	25	4	10
WMT 2, 2009–10	21	21	8	19	6	38	7	18
Nez Perce, 2009–10	6	6	2	5	2	13	2	5
Butte, 2010–11	8	8	3	7	2	13	3	8
Fairbanks, 2010–11	8	8	3	7	2	13	3	8
WMT 3, 2011–12	43	44	22	52	0	0	21	53
Household income								
less than $29,999	29	32	12	33	7	47	10	26
30,000 to 49,999	26	29	9	25	2	13	15	38
$50,000 or more	35	39	15	42	6	40	14	36
Caregiver’s education								
High school diploma, GED or less	26	30	10	29	4	29	12	31
Some college	24	27	10	29	5	36	9	23
College degree	38	43	15	43	5	36	18	46
Children in home, mean(sd)	2.5	1.3	2.5	1.2	2.7	1.6	2.4	1.2
Wood, wood stove and usage								
Method of acquiring wood								
Harvest	57	64	24	62	9	64	24	67
Purchase	32	36	15	38	5	36	12	33
Wood age								
< 1 year	37	39	15	38	7	44	15	39
1 year	30	32	13	33	6	38	11	29
2 years+	27	29	12	30	3	19	12	32
Burn intensity								
None/light	25	26	12	29	2	14	11	28
Average/heavy	70	74	30	71	12	86	28	72
Activities in or near the home								
Burning (smoke, incense, candle, etc.)	30	31	12	29	6	38	12	30
Open door or window	32	33	11	26	8	50	13	33
Home characteristics								
House	70	72	32	76	9	56	29	74
Indoor temperature (° Celsius), mean (sd)	22.0	2.4	22.1	2.5	22.3	2.3	21.9	2.6
Indoor humidity (%rh), mean (sd)	28.1	8	28.2	6.9	28.3	9.2	27.9	8.7
Ambient meteorology								
Temperature (° Celsius), mean (sd)	−3.6	8.6	−2.8	9.3	−4.7	9.5	−4.0	7.8

	All homes (N=98)		Filter (N=42)		Woodstove changeout (N=16)		Placebo (N=40)	
	n	**%**	**n**	**%**	**n**	**%**	**n**	**%**
Humidity (% rh), mean (sd)	73.0	11.7	72.8	11.2	75.1	15.8	72.4	10.7
Precipitation (inches), mean(sd)	0.02	0.05	0.02	0.04	0.03	0.05	0.03	0.05

Abbreviation: WMT, western Montana.

[a] Seven homes were missing information on the number of children residing in the home. Information on the type of residence (e.g. house versus other) was missing for one home. N was equal to 85 and 86 for indoor temperature and indoor humidity, respectively. Two homes were missing ambient meteorology information.

[b] Results are reported as the number and percentage of homes with a particular characteristic except where otherwise specified.

Table 2.

Site-specific summaries of indoor air quality measures in ARTIS homes during the pre-intervention winter.

indoor air quality measure[a]	**All** **2008–12 (n=98)** **median (range)**	**WMT 1** **2008–09 (n=12)** **median (range)**	**WMT 2** **2009–10 (n=21)** **median (range)**	**Nez Perce** **2009–10 (n=6)** **median (range)**	**Butte** **2010–11 (n=8)** **median (range)**	**Fairbanks** **2010–11 (n=8)** **median (range)**	**WMT 3** **2011–12 (n=43)** **median (range)**
$PM_{2.5}$ (μg/m^3)	17.5 (3.9, 508.2)	18.7 (7.6, 508.2)	23.9 (7.9, 129.3)	13.8 (12.5, 27.6)	17.1 (3.9, 101.9)	14.2 (5.7, 77.7)	17.4 (6, 163.1)
$PM_{2.5}$ max (μg/m^3)	400.6 (14.6, 18181.8)	348.2 (48.5, 18181.8)	739.4 (60, 9212.1)	391.5 (62.4, 763.6)	492.1 (14.6, 3781.8)	380.3 (67.3, 1739.4)	395.2 (30.9, 16424.2)
PNC (particles/cm^3)							
0.3–0.49 μm	40.5 (4.4, 275.2)	54.1 (21.2, 120.2)	51.1 (16.5, 198.9)	41.2 (37.3, 61.8)	30.8 (14.1, 275.2)	37.4 (13.3, 180.5)	33.6 (4.4, 162.3)
0.50–0.99 μm	5.2 (0.8, 34)	4.5 (3.6, 12.3)	5.6 (1.6, 30.9)	5.6 (4, 8)	6.4 (2, 24.9)	4.6 (1.8, 19.8)	5.3 (0.8, 34)
1.0–2.49 μm	0.6 (0.1, 4.3)	0.5 (0.3, 2.1)	0.6 (0.2, 3.9)	0.6 (0.4, 1.1)	1 (0.3, 3.5)	0.5 (0.2, 1.3)	0.7 (0.1, 4.3)
fine	48.3 (5.3, 303.6)	61.3 (26, 128.3)	58.7 (19.6, 214.8)	47.8 (41.7, 70.8)	37 (16.3, 303.6)	42.4 (15.5, 201.3)	38.4 (5.3, 181.2)
coarse	0.3 (0.1, 3.6)	0.3 (0.1, 0.8)	0.3 (0.1, 3.6)	0.5 (0.3, 1.1)	0.5 (0.2, 3.1)	0.2 (0.1, 0.4)	0.3 (0.1, 1.4)
CO (ppm)	0.1 (0, 13.5)	0.2 (0, 1.2)	0.3 (0, 1.7)	0.6 (0.5, 1.6)	6.5 (0, 13.5)	0.1 (0, 0.5)	0 (0, 1.1)

Abbreviations: WMT, western Montana; PNC, particle number concentration; ppm, parts per million.

[a] $PM_{2.5}$, PNC, and CO data were available for 98, 96, and 97 homes, respectively during the pre-intervention winter.

Table 3.

Treatment efficacy in reducing PM$_{2.5}$ and PNCs in ARTIS homes from the pre- to post-intervention winter.

	Pre-intervention winter[a]		**Post-intervention winter**[b]		**% change in geometric mean concentrations**[c]	**% change, relative to placebo (95%CI)**[c]
	N	**median (range)**	**N**	**median (range)**		
PM$_{2.5}$ (µg/m^3)						
filter	42	17.1 (6.1, 163.1)	35	6.5 (0.7, 65.6)	−69*	−66 (−77, −50)
wood stove[d]	16	40.7 (8.7, 86.8)	15	32.4 (6.1, 138.4)	−9	0 (−40, 65)
placebo	40	16.1 (3.9, 508.2)	38	16.9 (2.4, 163.2)	−9	ref
PM$_{2.5}$ max (µg/m^3)						
filter	42	370.6 (30.9, 16424.2)	35	193.9 (6.1, 3818.2)	−54*	−52 (−73, −14)
wood stove[d]	16	936.4 (48.5, 4539.4)	15	709.1 (23.0, 1921.2)	−30	−28 (−66, 56)
placebo	40	347.0 (14.6, 18181.8)	38	351.2 (26.1, 6363.6)	−3	ref
PNC (particles/cm^3)						
0.3−0.49 µm						
filter	40	35.9 (4.4, 179.6)	34	13.4 (0, 90.0)	−75*	−67 (−83, −33)
wood stove[d]	16	66.5 (18.2, 198.9)	15	71.2 (17.4, 247.5)	−4	29 (−47, 215)
placebo	40	38.2 (13.3, 275.2)	37	38.1 (0, 368.7)	−25	ref
0.50−0.99 µm						
filter	40	4.1 (0.8, 30.9)	34	1.7 (0, 14.9)	−75*	−62 (−84, −9)
wood stove[d]	16	8.5 (1.6, 24.1)	15	7.7 (2.2, 30.9)	−12	38 (−54, 315)
placebo	40	5.0 (1.8, 34.0)	37	4.9 (0, 39.9)	−36	ref
1.0−2.49 µm						
filter	40	0.6 (0.1, 4.3)	34	0.2 (0, 1.8)	−76*	−53 (−80, 7)
wood stove[d]	16	0.9 (0.3, 3.4)	15	0.6 (0.2, 3.6)	−15	64 (−44, 378)
placebo	40	0.5 (0.2, 3.9)	37	0.5 (0, 1.9)	−48*	ref
fine						
filter	40	40.6 (5.3, 192.3)	34	15.5 (0, 106.1)	−75*	−66 (−83, −31)
wood stove[d]	16	79.0 (20.4, 214.8)	15	82.6 (20.3, 279.0)	−5	29 (−47, 216)
placebo	40	43.8 (15.5, 303.6)	37	43.9 (0, 409.3)	−27	ref
coarse						
filter	40	0.3 (0.1, 1.5)	34	0.2 (0, 0.6)	−72*	−35 (−71, 46)
wood stove[d]	16	0.3 (0.1, 2.2)	15	0.3 (0.1, 1.6)	−19	91 (−33, 447)
placebo	40	0.3 (0.1, 3.6)	37	0.2 (0, 1.9)	−57*	ref
CO (ppm)						
filter	41	0.1 (0, 13.5)	35	0.3 (0, 1.2)	78	−13 (−75, 200)

	Pre-intervention winter[a]		Post-intervention winter[b]		% change in geometric mean concentrations[c]	% change, relative to placebo (95%CI)[c]
	N	median (range)	N	median (range)		
wood stove[d]	16	0.6 (0, 6.5)	15	0 (0, 1.1)	−76 *	−87 (−97, −33)
placebo	40	0.1 (0, 6.5)	38	0.2 (0, 1.6)	55	ref

*$P < 0.05$.

[a] $PM_{2.5}$, PNC, and CO data were available for 98, 96, and 97 homes, respectively during the pre-intervention winter.

[b] $PM_{2.5}$, PNC, and CO data were available for 88, 86, and 88 homes, respectively during the post-intervention winter.

[c] Linear mixed model analyses evaluating modification of pre- to post-intervention changes in indoor air quality by treatment assignment. $PM_{2.5}$, PNCs, and CO were log-transformed, and results reported as the percent change in geometric mean concentrations.

[d] Wood stove refers to the wood stove changeout intervention arm, which was discontinued prior to enrollment of the final cohort of homes due to a lack of efficacy in reducing indoor $PM_{2.5}$ concentrations.