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Coarse particulate matter and airborne endotoxin within wood stove homes

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Abstract

Emissions from indoor biomass burning are a major public health concern in developing areas of the world. Less is known about indoor air quality, particularly airborne endotoxin, in homes burning biomass fuel in residential wood stoves in higher income countries. A filter-based sampler was used to evaluate wintertime indoor coarse particulate matter (PM_{10-2.5}) and airborne endotoxin (EU/m³, EU/mg) concentrations in 50 homes using wood stoves as their primary source of heat in western Montana. We investigated number of residents, number of pets, dampness (humidity), and frequency of wood stove usage as potential predictors of indoor airborne endotoxin concentrations. Two 48-h sampling events per home revealed a mean winter PM_{10-2.5} concentration ($\pm$ s.d.) of 12.9 ($\pm$ 8.6) μ g/m³, while PM_{2.5} concentrations averaged 32.3 ($\pm$ 32.6) μ g/m³. Endotoxin concentrations measured from PM_{10-2.5} filter samples were 9.2 ($\pm$ 12.4) EU/m³ and 1010 ($\pm$ 1524) EU/mg. PM_{10-2.5} and PM_{2.5} were significantly correlated in wood stove homes (r = 0.36, P < 0.05). The presence of pets in the homes was associated with PM_{10-2.5} but not with endotoxin concentrations. Importantly, none of the other measured home characteristics was a strong predictor of airborne endotoxin, including frequency of residential wood stove usage.

Keywords

Indoor; Pollution; Particulate matter; Coarse fraction; Endotoxin; Biomass combustion

Introduction

It is well known that cookstoves are a significant source of indoor air pollution in many developing areas throughout the world. Studies have shown that particles <10 μ m (PM₁₀) can be elevated in homes that use biomass fuel, with indoor concentrations approximately 10–70 times above ambient concentrations observed in some of the world's most polluted cities (Salvi and Barnes, 2010). Globally, less focus has been placed on understanding the

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Supporting Information

Additional Supporting Information may be found in the online version of this article

biomass combustion exposures associated with domestic heating. Wood burning has been found to be a significant source of ambient particulate matter (PM) in rural areas of Scandinavia, New Zealand, Canada and the Northwest United States, including the northern Rocky Mountains of western Montana (Larson and Koenig, 1994; Maykut et al., 2003; McGowan et al., 2002; NERI, 2005; Noonan and Ward, 2007; Noonan et al., 2012b; Schumpert et al., 2006; Ward and Lange, 2010; Ward et al., 2006), in some cases accounting for up to 90% of ambient fine particles (PM_{2.5}) (McGowan et al., 2002). Importantly, indoor air quality can be impacted by wood stove use. Elevated short- and long-term PM_{2.5} concentrations generated from wood burning (Noonan et al., 2012a; Ward et al., 2008, 2011) frequently are much higher than those observed in the ambient environment and often higher than the 24-h ambient standard established by the U.S. Environmental Protection Agency (EPA) of 35 µg/m³.

As people spend the majority of their time indoors (Klepeis et al., 2001), it is important to understand indoor exposures to hazardous pollutants such as PM₁₀ and PM_{2.5}. PM₁₀ and PM_{2.5} can penetrate into the thoracic and lower airways and are known to cause a variety of adverse health effects (Brunekreef and Forsberg, 2005). The coarse size fraction, consisting of particles with an average aerodynamic diameter of <10 µm and >2.5 µm (PM_{10-2.5}), has arisen as a new class of interest because, unlike PM₁₀, it is not as strongly correlated with PM_{2.5} (Tager et al., 2010). PM_{10-2.5} has been shown to cause a more significant pulmonary inflammatory response than PM_{2.5} in an animal model (Tong et al., 2010) as well as increased inflammatory potential in multiple respiratory cell lines (Gualtieri et al., 2010; Oeder et al., 2012). Coarse particles captured during wildfire activity have shown more proinflammatory and oxidative stress potential on an equal-dose basis than fine particles (Wegesser et al., 2010). This inflammatory potential may be linked to the biological components of PM_{10-2.5}, as biological inactivation of the coarse fraction significantly attenuates inflammatory effects in healthy humans (Alexis et al., 2006).

A major biological component of PM_{10-2.5} is endotoxin (Liu, 2004). Endotoxins, lipopolysaccharides derived from the outer membrane of Gram-negative bacteria, have long been recognized to cause both immediate and sustained airflow obstruction in asthmatics (Liu, 2004). A temporo-spatial analysis detected ambient endotoxin in the coarse fraction at concentrations 10-fold higher than found in PM_{2.5} (Heinrich et al., 2003), and this relationship exists in both indoor and outdoor environments (Menetrez et al., 2009). A recent study conducted in Nepal and Malawi measured airborne endotoxin concentrations in homes burning biomass fuel at orders of magnitude higher than those found in homes in developed countries (Semple et al., 2010). A similar study found wood-burning homes in Scotland and Ireland had higher airborne endotoxin concentrations than homes burning coal, peat, or using gas cooking (Semple et al., 2011). However, the frequency of stove loading and stoking was not accounted for in that study.

Here, we present results from a two-winter study that measured indoor PM_{2.5}, PM_{10-2.5}, and airborne endotoxin concentrations within 50 wood stove homes throughout western Montana, evaluating home characteristics previously identified as predictors of endotoxin. These characteristics include dampness/moisture sources (Park et al., 2001; Sordillo et al., 2011), presence of pets (Park et al., 2001; Sordillo et al., 2011; Thorne et al., 2009), and

number of people living in the home (Singh et al., 2011; Thorne et al., 2009). We also collected novel data relevant to wood stove usage and ambient weather conditions, both of which could potentially influence indoor biomass smoke exposures.

Methods

Description of parent study

Asthma Randomized Trial of Indoor Wood Smoke (ARTIS) is an intervention-based study aimed at improving the quality of life of asthmatic children living in wood stove homes by reducing in-home $PM_{2.5}$ exposures. The ARTIS study involves four separate 48-h sampling visits per household over two consecutive winters (a baseline winter and post-intervention winter) (Noonan and Ward, 2012). The use of a non-EPA certified (older model) wood stove as the primary heating source in the home was required for inclusion in the study. In this manuscript, we present baseline (i.e. pre-intervention) indoor air quality data collected over two winters (seven homes during November 2010–March 2011 and 43 homes during November 2011–March 2012) for homes within a 200-mile radius of Missoula, Montana.

Home characteristics data

At each sampling visit, homeowners reported descriptive characteristics of their residence, including number of pets (furry animals only, that is, dogs and cats) and square footage. Throughout the 48-h sampling event, the homeowners were asked to track wood stove usage, recording each time the wood stove was loaded or stoked. Ambient meteorological data including temperature, humidity, wind speed, and precipitation were collected for all sampling days from the weather station nearest to the respective homes. Mean distance (range) from homes to the nearest weather station was 16.8 miles (0.6–44.4 miles). Meteorological data were averaged across visits for each home.

Indoor sampling

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, if possible. In each sampling event, $PM_{2.5}$ was continuously measured with a DustTrak (TSI Inc., Shoreview, MN, USA). The DustTrak is an optical scattering instrument that measures PM in the airflow by measuring 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. During each sampling event, a DustTrak 8530 recorded 60-s averages of $PM_{2.5}$.

Optical mass measurements (such as those made by the DustTrak) are dependent upon particle size and material properties; therefore, custom calibrations are needed to improve the measurement accuracy when evaluating specific sources of combustion. In an effort to accurately present 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). In addition to the DustTraks, co-located Q-traks (TSI Inc.) were used to record 60-s

averages of indoor temperature and humidity (%rH). Data were downloaded from the DustTraks and Q-traks at the conclusion of each sampling event.

Coarse fraction concentrations commonly are calculated from separate PM_{10} and $PM_{2.5}$ measurements. In this study, direct measurements of $PM_{10-2.5}$ and $PM_{2.5}$ were collected using a filter-based CPEM developed by RTI International (Research Triangle Park, NC, USA). As previously described (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 PM_{10} PEM (MSP Corp., Shoreview, MN, USA). $PM_{10-2.5}$ is collected on two sequential 25-mm PTFE filters with polymethylpentene (PMP) support rings (thickness 3.0 μm ; Zefon International, Inc., Ocala, FL, USA), while $PM_{2.5}$ is collected on a final 37-mm PTFE filter with PMP support rings (thickness 2.0 μm ; Zefon International, Inc.). The CPEM utilizes a battery-operated pump to achieve a flow rate of 2 Lpm. Flow rates measured with a Drycal DC-Lite (BIOS International, Butler, NJ, USA) prior to and following each sampling event were averaged to calculate the sample volume. If necessary, pump flow was adjusted at deployment to achieve 2 Lpm. All data from multiple sampling events per home were averaged to produce one winter average per home.

Gravimetric analyses

The gravimetric analyses of $PM_{10-2.5}$ and $PM_{2.5}$ 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 h in an environmentally controlled weighing facility at The University of Montana. The facility was maintained at a temperature of $20-23 \pm 2^\circ C$ with relative humidity of $30-40 \pm 5\%$. 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., Fair-field, 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.

Endotoxin extraction and analyses

Filter extraction methods were optimized for endotoxin analyses using methods adapted from the study by Thorne (2000) and Spaan et al. (2007). For $PM_{10-2.5}$, the two sequential 25-mm Teflon filters were combined and extracted in 5 ml sterile, pyrogen-free water containing 0.05% Tween-20 for 1 h at room temperature with vigorous shaking. The extracts were then centrifuged at $1000 \times g$ for 15 min at room temperature, and 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 50 to 0.005 endotoxin units (EU)/ml. The absorbance in each well was measured at 405 nm every 30 s for 90 min (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 EU/m³ and EU/mg.

Statistical analyses

SAS v9.2 (SAS, Cary, NC, USA) was used to perform all statistical analyses. Pearson's correlation coefficients were estimated to investigate relationships between log-transformed air quality measurements assessed using different sampling instruments. In regression analyses, we used the natural log of PM_{10-2.5} and airborne endotoxin concentrations to satisfy model assumptions, which we assessed in plots of residuals. Results therefore are reported as the percent change in geometric mean PM_{10-2.5} and airborne endotoxin concentrations associated with various home characteristics. Multiple linear regression was used to examine these relationships in models adjusted for other home characteristics. Sensitivity analyses were performed to examine the impact on results after excluding a home with an average PM_{2.5} concentration approximately 63% higher than the next highest PM_{2.5} concentration (163.08 µg/m³ compared to next highest 101.94 µg/m³). In addition, we examined the relationship between home characteristics and indoor air concentrations first using only visit 1 measurements and then using only visit two measurements to compare the results by visit with those obtained in the primary analysis using averaging across visits.

Results

During the winters (November–March) of 2010–2011 and 2011–2012, 50 homes with wood stoves were sampled for a total of 100 48-h events. PM and endotoxin sampling results are summarized in Table 1, along with home characteristic and indoor/ambient meteorological information. Throughout the sampling program, the average (± s.d.) PM_{10-2.5} concentration in the homes was 12.9 (± 8.6) µg/m³. Endotoxin in PM_{2.5} was not detectable in 32% (*n* = 16) of the homes. Maximum endotoxin concentrations in PM_{2.5} were 2.9 EU/m³ and 73.8 EU/mg. The average (± s.d.) corrected PM_{2.5} concentration in the homes was 32.3 (± 32.6) µg/m³. The average (± s.d.) endotoxin concentration in PM_{10-2.5} was 9.2 (± 12.4) EU/m³ and 1010 (± 1524) EU/mg of PM_{10-2.5}. During the winter sampling months, the ambient temperature was −0.38 (± 3.02)°C, wind speed was 4.79 (± 2.04) mph, and precipitation was 0.12 (± 0.21) inches. Homes had an average of approximately 4 (± 1) residents and an average size of 1881 (± 986) square feet. Indoor humidity was on average less than half of ambient humidity (28.1 vs. 69.7 %rH, respectively).

Table 2 presents Pearson's correlation coefficients between log-transformed concentrations of PM_{2.5}, PM_{10-2.5}, and endotoxin within the wood stove homes (*n* = 50). DustTrak-measured PM_{2.5} and CPEM-measured PM_{2.5} were significantly, although only modestly, correlated (*r* = 0.29, *P* < 0.05), possibly due to the loss of volatile and semi-volatile compounds present in PM_{2.5} from the CPEM filters. The CPEM filters also collected very small masses of PM_{2.5} due to the low flow rate (2 l/min) and short sampling period (48 h),

resulting in reduced precision in the measurements as homes with low $PM_{2.5}$ concentrations were within the sensitivity of the scale. Therefore, due to the DustTrak's optimized design for $PM_{2.5}$ sampling and the development of our wood smoke-specific DustTrak correction factor (McNamara et al., 2011), only corrected DustTrak values were used for further $PM_{2.5}$ analyses. As presented in Table 2, $PM_{2.5}$ (as measured by the DustTrak) was significantly correlated with $PM_{10-2.5}$ ($r = 0.36$, $P < 0.05$). Measures of airborne endotoxin concentrations in the coarse fraction (EU/m³ and EU/mg) were correlated strongly with each other ($r = 0.76$, $P < 0.0001$) and endotoxin as measured in EU/m³, but not EU/mg was significantly correlated with $PM_{10-2.5}$ mass concentrations.

Table 3 presents linear regression results (95% confidence interval) describing the relationship between home characteristics and $PM_{10-2.5}$ and airborne endotoxin concentrations in crude analyses and analyses adjusted for number of residents, number of pets, times loaded/stoked, square footage, ambient temperature, indoor humidity, and DustTrak $PM_{2.5}$. Number of pets was significantly associated with $PM_{10-2.5}$ concentrations with each additional pet in the home associated with an estimated approximately 20% increase in $PM_{10-2.5}$ concentrations in crude (95% CI: 3%, 44%) and adjusted (95% CI: 0%, 42%) analyses. A 500 ft² increase in home size was significantly associated with an 8% (95% CI: 15%, 1%) decrease in $PM_{10-2.5}$ concentration. The point estimate was similar in analyses adjusted for other home characteristics, but the association did not remain statistically significant. A 10 $\mu\text{g}/\text{m}^3$ elevation in $PM_{2.5}$ was significantly associated with a 3% increase in $PM_{10-2.5}$ although this association did not persist after adjustment for other home characteristics. The number of times the stove was loaded/stoked was not associated with $PM_{10-2.5}$ concentrations or either measurement of airborne endotoxin. The magnitude of each association was weakened slightly in adjusted analyses. Wood stoves were in use in the vast majority of homes during our sampling events. However, we should note that one home reported no burning activity during the sampling periods and had an average of 6.7 $\mu\text{g}/\text{m}^3$ $PM_{10-2.5}$, 0.18 EU/m³ and 53.2 EU/mg of $PM_{10-2.5}$ (results not shown).

Findings from sensitivity analyses were consistent with results from our primary analyses. Excluding the home with the highest $PM_{2.5}$ concentration from our analyses had little impact on the results. To determine whether averaging across visits affected results, all variables were investigated for associations with air sampling data using only the first visit and again using only the second visit of each winter, and results were similar (data not shown).

Discussion

Several factors have been identified as predictors of indoor endotoxin concentrations. Larger numbers of residents and/or pets in the home may stir up, or resuspend, particulate matter due to increased activity. Higher number of residents has also been found to be significantly associated with increased endotoxin concentrations in dust samples in two large studies sampling 184 and 2552 homes, respectively (Singh et al., 2011; Thorne et al., 2009). An increase in residents in our study homes suggested an increase in the mean EU/m³ although these results were not statistically significant. Our smaller sample size compared with the larger studies described above limited our precision in describing associations. Another

important distinction between this study and prior studies was the choice of sample media for assessing endotoxin levels. Both of the larger studies used dust endotoxin as a surrogate of the airborne endotoxin directly evaluated in our study. Airborne endotoxin measured over 1.5 days has been determined to be a more direct measure of exposure than the use of dust endotoxin (Horick et al., 2006). This is primarily due to dust endotoxin typically correlating poorly with airborne endotoxin levels (Mazique et al., 2011; Park et al., 2001). Despite the differences in sample media, our study suggests a similar relationship between number of residents and airborne endotoxin.

Number of pets has also been identified as a predictor of in-home endotoxin levels (Park et al., 2001; Sordillo et al., 2011; Thorne et al., 2009). Park et al. (2001) investigated presence of dogs in homes and found a 96% difference in airborne endotoxin in total suspended particulate between homes currently having a dog and homes that had never had a dog. Thorne et al. (2009) and Sordillo et al. (2011) evaluated number of pets and endotoxin in dust using presence/absence of dogs and cats. Our study collected data on all 'furry' animals currently living in the home (dogs, cats, guinea pigs, etc). Number of pets showed no relationship with both measurements of endotoxin in our study but was associated with PM_{10-2.5} concentrations.

A unique aspect of our study was the focus on homes using biomass combustion for heating and the inclusion of wood stove usage data. Loading and stoking of a wood stove are important events to document because a plume of smoke can enter the indoor air when the stove's door is opened. The number of times the wood stove was loaded/stoked was not associated with PM_{10-2.5} concentrations or either measurement of airborne endotoxin. Residents of homes in this study opened their stove doors an average of approximately 10 times during the 48-h visits, with a range of 0–36 times (Table 1). In two similar studies, homes that contained non-EPA certified wood stoves had an average of five loading/stoking events over their sampling period of 24–48 h (Noonan et al., 2012a; Ward et al., 2011).

Evaluating indoor air quality based on square footage of the home gave us some intriguing results. Our homes ranged from 420 to 4500 square feet with a mean ($\pm$ s.d.) of 1881 ($\pm$ 986) square feet. A 500 ft² increase in home size was significantly associated with an 8% decrease in PM_{10-2.5} concentration in unadjusted analyses, although this relationship was not significant when adjusted for other home characteristics. This finding is likely influenced by many factors. It is possible that the smaller homes, typically mobile homes in our study, may not be as well ventilated or insulated as the larger, newer homes in our study. Portable classrooms, constructed similar to mobile homes, have shown low ventilation rates (Shendell et al., 2004). As a result, the smaller homes may be experiencing greater re-infiltration of emitted particles. Conversely, particles in smaller volumes (smaller homes) are not dispersed as efficiently as larger volume spaces (such as larger homes) leading to higher concentrations in smaller homes. The discrepancy in insulation may also necessitate less wood burning per volume to maintain a comfortable indoor temperature in the larger homes. Further studies are needed to validate these theories.

Ambient temperature and indoor humidity were not significantly correlated with any of the indoor air quality values reported here. Dampness/moisture sources have been identified as

predictors of in-home endotoxin (Park et al., 2001; Sordillo et al., 2011), but these studies investigated dampness qualitatively by survey data on humidifier use, report of water damage, visible mold, use of central air, and living in an apartment. A recent review emphasized that there is a lack of standardized and validated exposure assessment methods for microbial components in indoor air, with most studies using either trained fieldworkers or dust sampling to investigate moisture sources (Tischer and Heinrich, 2013). However, the continuous measurement of relative humidity in homes has been used in health studies. One study with indoor continuous relative humidity levels similar to ours [mean: 29.1% ($\pm$ 5.0)] concluded that a 1% increase in relative humidity was associated with an increased risk of lower respiratory tract infections among young Inuit children in Canada (Kovesi et al., 2007). We evaluated continuous relative humidity data and did not find indoor humidity to be a significant predictor of airborne endotoxin. We are unaware of any studies that have investigated the relationship between the field identification of dampness/moisture sources and real-time indoor relative humidity in wood stove homes. Until this relationship is established, we are not confident that our data go against the paradigm of dampness/moisture sources being a large predictor of indoor endotoxin.

Our sampling regimen allowed for simultaneous measurements of indoor temperature, humidity, PM_{2.5}, and PM_{10-2.5}. Although our study focuses on reporting coarse fraction concentrations, it is notable that overall 48-h average (*corrected*) PM_{2.5} levels were similar to the EPA's health-based 24-h ambient air quality standard of 35 $\mu\text{g}/\text{m}^3$. In addition, 16 (32%) sampled homes had winter PM_{2.5} averages above this concentration. These concentrations were consistent with previous studies conducted by our team in Libby, Montana. Two residential studies focused on 16 and 21 homes with older model wood stoves measured average ($\pm$ s.d.) PM_{2.5} concentrations of 51.2 ($\pm$ 32.0) $\mu\text{g}/\text{m}^3$ and 45.0 ($\pm$ 33.0) $\mu\text{g}/\text{m}^3$, respectively (Noonan et al., 2012a; Ward et al., 2008). If the correction factor was applied to the Libby residential studies as it was in this study, the average PM_{2.5} concentrations measured in our study homes would be very similar (31.03 and 27.27 $\mu\text{g}/\text{m}^3$ in Libby vs. 32.3 $\mu\text{g}/\text{m}^3$ in our study) (Noonan et al., 2012a; Ward et al., 2008).

With its unique setting (wood stove homes), the use of a filter-based sampler to measure airborne endotoxin directly as opposed to the use of surrogate dust endotoxin, and the analysis of home characteristics as well as meteorological data, our study has a number of strengths. Several study limitations should be considered when attempting to generalize our findings. The lack of a standardized protocol for endotoxin sampling and analysis is the main challenge in comparing our quantitative results to the limited literature on indoor air quality in homes burning biomass fuel in developed countries. Many methodological factors can influence the measured concentration of endotoxin in a sample, such as filter type, extraction solution, extract storage, and assay solution (Spaan et al., 2007, 2008). A study in Ireland and Scotland monitored several airborne pollutants in homes using biomass fuel and found EU/ m^3 concentrations similar to those reported here, although they were investigating endotoxin in PM_{2.5} only (Semple et al., 2011). Endotoxin concentrations in EU/ m^3 as well as EU/mg of particle collected were reported within the ranges of our results in a sampling methods comparison study, but particle size selection and presence of biomass burning in the homes were not indicated (Frankel et al., 2012). We could not identify the partial

contribution of spike events due to wood stove loading/stoking activity to the 48-h averages (as can be done with continuous data) because the CPEMs are filter-based samplers. Finally, although our study is the first to use CPEMs in wood stove homes, our in-home coarse fraction concentrations were comparable to those reported by the other published studies to-date that deployed the CPEM [our study: $12.9 (\pm 8.6 \mu\text{g}/\text{m}^3)$ vs. $12.8 (\pm 18.5 \mu\text{g}/\text{m}^3)$ in homes (Williams et al., 2009) vs. $11.6 (\pm 8.5 \mu\text{g}/\text{m}^3)$ during personal monitoring (Williams et al., 2012)].

Concluding statement

This study is the first to describe coarse fraction particulate matter and airborne endotoxin in wood stove homes using a state-of-the-art filter-based sampler. Home characteristics and ambient weather conditions were evaluated for their influence on pollutant levels although only number of pets was associated with $\text{PM}_{10-2.5}$ concentrations in the homes. Our study shows a relationship between number of residents and airborne endotoxin, consistent with previous literature establishing this relationship with dust endotoxin. After application of an indoor wood smoke-specific correction factor, levels of $\text{PM}_{2.5}$ were slightly below the EPA 24-h standard of $35 \mu\text{g}/\text{m}^3$. $\text{PM}_{10-2.5}$ and $\text{PM}_{2.5}$ were significantly correlated in the homes, presenting a challenge for future health effects research in distinguishing the separate health effects of $\text{PM}_{10-2.5}$ and $\text{PM}_{2.5}$ in wood stove homes. Airborne endotoxin in the coarse fraction may be a unique exposure of interest in health effect studies with people living in wood stove homes as both measurements of airborne endotoxin (EU/m^3 and EU/mg) showed no correlation with $\text{PM}_{2.5}$ (as measured with a DustTrak) or $\text{PM}_{10-2.5}$ concentrations.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Practical Implications

Indoor air quality can be adversely affected by biomass burning in developing as well as higher income countries. This study is the first to evaluate the impact of wood stove usage on indoor coarse fraction concentrations and airborne endotoxin. In homes containing wood stoves, wintertime concentrations of $PM_{10-2.5}$ and airborne endotoxin were not associated with loading/stoking activities, number of residents, or indoor humidity. The number of pets in the home significantly predicted $PM_{10-2.5}$ concentrations but not airborne endotoxin. Unlike previous studies in nonwood stove homes, $PM_{10-2.5}$ and $PM_{2.5}$ were correlated in these homes. Overall, home characteristics and wood stove usage did not explain the variability in $PM_{10-2.5}$ or airborne endotoxin concentrations in these homes.

Table 1Home characteristics, air sampling, and meteorological results from all homes ($n = 50$)

	Mean	s.d.	Minimum	Maximum
Home characteristics				
Number of residents	4.2	1.4	2	8
Number of pets	1.5	0.89	0	4
Times loaded/stoked	9.6	6.5	0	36
Square footage	1881	986	420	4500
Indoor air measurements				
PM _{10-2.5} ($\mu\text{g}/\text{m}^3$)	12.9	8.6	5.1	46.2
EU/ m^3	9.2	12.4	0.002	52.0
EU/mg	1010	1524	0.35	6918
PM _{2.5} ($\mu\text{g}/\text{m}^3$)	32.3	32.6	6.0	163
Temperature ($^{\circ}\text{C}$)	22.4	2.5	16.6	28.5
Humidity (%rH)	28.1	6.4	17.6	48.1
Ambient air measurements				
Temperature ($^{\circ}\text{C}$)	-0.38	3.02	-5.95	4.71
Humidity (%rH)	69.7	8.5	44.8	83.2
Windspeed (mph)	4.79	2.04	1.77	11.0
Total Precip. (in.)	0.12	0.21	0	0.81

s.d., standard deviation; %rH, percent relative humidity; mph, miles per hour; in., inches. PM_{2.5} corrected values from DustTrak only. EU/ m^3 and EU/mg in PM_{10-2.5}.

Pearson's correlation coefficients between log-transformed concentrations of PM_{2.5}, PM_{10-2.5}, and endotoxin within the wood stove homes ($n = 50$)

Table 2

	PM _{2.5} (DustTrak)	PM _{2.5} (CPEM)	PM _{10-2.5} (CPEM)	EU/m ³	EU/mg
PM _{2.5} (DustTrak)	1	0.29*	0.36*	0.10	0.01
PM _{2.5} (CPEM)	—	1	-0.10	0.11	0.32
PM _{10-2.5} (CPEM)	—	—	1	0.31*	-0.04
EU/m ³	—	—	—	1	0.76**
EU/mg	—	—	—	—	1

* $P < 0.05$.

** $P < 0.0001$.

EU/m³ and EU/mg in PM_{10-2.5}.

Table 3

Linear regression results (95% confidence intervals)^a describing the relationship between home characteristics and PM_{10-2.5} and airborne endotoxin concentrations $N = 50$

	PM _{10-2.5}		EU/m ³		EU/mg	
	Unadjusted	Adjusted ^b	Unadjusted	Adjusted ^b	Unadjusted	Adjusted ^b
Number of residents	0.98 (0.91, 1.14)	1.03 (0.92, 1.15)	1.16 (0.77, 1.73)	1.33 (0.85, 2.08)	1.11 (0.75, 1.64)	1.26 (0.81, 1.97)
Number of pets	1.22 (1.03, 1.44) [*]	1.19 (1.00, 1.42) [*]	1.28 (0.69, 2.32)	1.27 (0.64, 2.53)	1.09 (0.59, 2.01)	1.12 (0.56, 2.22)
Times loaded/stoked	1.01 (0.99, 1.04)	1.00 (0.98, 1.02)	1.00 (0.92, 1.10)	0.99 (0.90, 1.09)	0.99 (0.91, 1.07)	0.98 (0.90, 1.08)
Square footage ^c	0.92 (0.85, 0.99) [*]	0.95 (0.88, 1.04)	0.83 (0.63, 1.10)	0.83 (0.60, 1.16)	0.91 (0.69, 1.20)	0.89 (0.64, 1.23)
Ambient temperature (°F)	1.03 (0.97, 1.08)	1.00 (0.95, 1.06)	1.03 (0.85, 1.24)	1.03 (0.84, 1.26)	1.00 (0.83, 1.19)	1.01 (0.83, 1.24)
Indoor humidity (%rH)	1.02 (0.99, 1.04)	1.01 (0.99, 1.04)	0.96 (0.88, 1.05)	0.94 (0.85, 1.04)	0.95 (0.87, 1.03)	0.94 (0.85, 1.03)
DustTrak PM _{2.5} (µg/m ³) ^d	1.03 (1.00, 1.06) [*]	1.02 (0.99, 1.05)	1.03 (0.93, 1.14)	1.01 (0.89, 1.14)	1.00 (0.90, 1.10)	0.99 (0.88, 1.12)

All coefficients correspond to one unit increase in predictor variable unless otherwise noted. EU/m³ and EU/mg in PM_{10-2.5}.

^{*} $P < 0.05$.

^a Regression results and confidence intervals are reported as percent change in geometric mean PM_{10-2.5}, EU/m³, or EU/mg. For example, 0.96 (0.91, 1.14) signifies a 4% reduction in geometric mean (95% CI: -9%, 14%).

^b Analyses adjusted for number of residents, number of pets, times loaded/stoked, square footage, ambient temperature, indoor humidity, and DustTrak PM_{2.5}.

^c Results per 500 ft² increase.

^d Results per 10 µg/m³ increase.