Environmental Research 138 (2015) 93–100

Contents lists available at ScienceDirect

Environmental Research

journal homepage: www.elsevier.com/locate/envres

Indoor particulate matter in rural, wood stove heated homes

Erin O. Semmens [a,*], Curtis W. Noonan [a], Ryan W. Allen [b], Emily C. Weiler [a], Tony J. Ward [a]

[a] Department of Biomedical and Pharmaceutical Sciences, Center for Environmental Health Sciences, 32 Campus Drive, The University of Montana, Missoula, MT 59812, USA

[b] Faculty of Health Sciences, 8888 University Drive, Simon Fraser University, Burnaby, BC, Canada V5A 1S6

ARTICLE INFO

Article history:
Received 18 October 2014
Received in revised form
1 February 2015
Accepted 3 February 2015
Available online 19 February 2015

Keywords:
Particulate matter
Biomass combustion
Wood stove
Indoor air quality
Infiltration efficiency

ABSTRACT

Ambient particulate matter (PM) exposures have adverse impacts on public health, but research evaluating indoor PM concentrations in rural homes in the United States using wood as fuel for heating is limited. Our objectives were to characterize indoor PM mass and particle number concentrations (PNCs), quantify infiltration of outdoor PM into the indoor environment, and investigate potential predictors of concentrations and infiltration in 96 homes in the northwestern US and Alaska using wood stoves as the primary source of heating. During two forty-eight hour sampling periods during the pre-intervention winter of a randomized trial, we assessed PM mass (<2.5 μm) and PNCs (particles/cm^3) in 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). Daily mean (sd) $PM_{2.5}$ concentrations were 28.8 (28.5) μg/m^3 during the first sampling period and 29.1 (30.1) μg/m^3 during the second period. In repeated measures analyses, household income was inversely associated with $PM_{2.5}$ and smaller size fraction PNCs, in particular. Time of day was a significant predictor of indoor and outdoor $PM_{2.5}$ concentrations, and infiltration efficiency was relatively low (F_{inf} (sd)=0.27 (0.20)). Our findings demonstrate relatively high mean PM concentrations in these wood burning homes and suggest potential targets for interventions for improving indoor air quality and health in rural settings.

1. Introduction

The health effects associated with exposure to particulate matter less than 2.5 μm in aerodynamic diameter ($PM_{2.5}$) are well known. To date, much of this research has focused on investigating the effects of ambient exposures in urban areas dominated by industrial and vehicular sources of $PM_{2.5}$. However, emissions from biomass combustion generated from heating of homes are a major source of $PM_{2.5}$ in rural areas of the United States (US).

In many areas of the US, wood stoves are used for home heating with over 11 million homes reporting use of wood as either a primary or secondary heating fuel (U.S. Energy Information Administration, 2009). Over 80% of these wood stoves are old and inefficient (Air Quality Management Work Group, 2005), often generating $PM_{2.5}$ concentrations *indoors* that exceed health based standards such as the US Environmental Protection Agency (US EPA) 24-h National Ambient Air Quality Standard (NAAQS) of 35 micrograms/meter^3 (μg/m^3) (US EPA, 2011) or the corresponding World Health Organization (WHO) standard of 25 μg/m^3 (WHO, 2006). The setting for the study described here is a randomized controlled trial designed to assess the efficacy of in-home interventions in improving indoor air quality and respiratory health in asthmatic children living in wood stove homes in the rural, western US and Alaska. Although recent calls to improve indoor air quality assessment in the developing world have been made (Clark et al., 2013), comparatively little emphasis has been placed on indoor $PM_{2.5}$ concentrations in wood stove homes in the US, a necessary initial step in improving our understanding of the risks to public health posed by these common residential exposure sources and in developing strategies for their mitigation (Barn, 2014).

Our objectives were to: characterize indoor particulate matter (PM) concentrations and infiltration of PM from outdoor sources in homes using wood stoves as the primary source of heating and examine the relationship between particle mass and count concentrations. Further, we evaluated various wood stove burning practices, activities in the home (e.g. opening of windows), socioeconomic factors (e.g. household income), and home characteristics (e.g. home type, size, and presence of pets) as potential predictors of PM concentrations and infiltration within these wood-burning homes.

* Corresponding author. Fax: +1 406 243 2807.
E-mail addresses: erin.semmens@umontana.edu (E.O. Semmens), curtis.noonan@umontana.edu (C.W. Noonan), allenr@sfu.ca (R.W. Allen), emily.weiler@umontana.edu (E.C. Weiler), tony.ward@umontana.edu (T.J. Ward).

http://dx.doi.org/10.1016/j.envres.2015.02.005
0013-9351/

2. Materials and methods

2.1. Study setting

The Asthma Randomized Trial of Indoor Wood Smoke (ARTIS) provided the setting in which we evaluated $PM_{2.5}$ and particle number concentrations (PNCs) in homes containing wood stoves located in rural areas of Montana, Idaho, and Alaska. The methods utilized in the parent study have been described in detail elsewhere (Noonan and Ward, 2012). Briefly, during the initial winter of enrollment in the study, participation involved pre-intervention residential indoor air sampling and collection of data on multiple biomarkers including inflammatory cytokines in exhaled breath condensate and urinary cotinine and respiratory health endpoints such as the Pediatric Asthma Quality of Life Questionnaire (PAQLQ) (Juniper et al., 1996) in children with asthma. Interventions designed to improve indoor air quality (installation of improved wood stoves or air filtration units) were implemented during the fall followed by a repetition of exposure and health outcome assessment during the following winter. We present here findings based on the pre-intervention winter exposure assessments. The efficacy of wood stove changeouts and air filtration units in reducing indoor $PM_{2.5}$ concentrations in ARTIS homes will be presented in a separate manuscript.

Recruitment and enrollment of subjects occurred as described previously (Noonan and Ward, 2012). To be eligible, homes had to utilize an older model wood stove as a primary heating source as well as have a child between 7 and 17 years of age with asthma who was expected to reside in the home for the next 2 years. In this context, older model wood stoves include those devices that are fueled by wood, and do not have modern control features focused on emission reduction. Homes with smoking residents were excluded. The first cohort of homes was enrolled for the winter of 2008–2009 with the final group completing pre-intervention sampling during the winter of 2011–2012. Parents or guardians of child participants provided signed permission, and assent was documented among children prior to participating in the study. The study was approved by the Institutional Review Board at the University of Montana.

2.2. Indoor and outdoor air exposure assessment

PM air sampling instruments were placed approximately 5 feet off of the ground in the living or common room (which usually contained the wood stove) of participating homes. In addition, outdoor $PM_{2.5}$ sampling occurred outside the home using a DustTrak 8520 housed in a portable DustTrak Environmental Enclosure 8535 (TSI Inc., Shoreview, MN, USA), which enabled it to operate during cold temperatures. Indoor $PM_{2.5}$ concentrations were assessed using either a DustTrak 8520 or 8530, the primary model deployed for indoor monitoring during later years of the study. PM concentrations were assessed continuously and recorded as 1-min averages throughout each of two 48-h sampling periods that occurred during the pre-intervention winter. The DustTrak measures $PM_{2.5}$ concentrations by calculating the forward scattering of an infrared diode laser beam in the airflow. Each instrument was zero calibrated prior to each sampling event. Calibration and field maintenance of the device was performed as described previously (McNamara et al., 2013). 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 and outdoor $PM_{2.5}$ concentrations (McNamara et al., 2011). PNCs were assessed using a Lighthouse 3016-IAQ particle counter (Lighthouse Worldwide Solutions, Fremont, CA) that continuously measured 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).

Summary PM concentrations over each 48-h sampling period are reported. For $PM_{2.5}$, we also calculated the percentage of homes with 48-h averages exceeding WHO and US EPA health-based 24-h ambient air quality guidelines (WHO, 2006) and standards (US EPA, 2011). We included only those averages that were generated from data that was at least 80% complete to ensure that the averages were representative of concentrations experienced during the entire sampling event. Temporal patterns over the course of each sampling event also were evaluated. Six four-hour time periods (10 pm–2 am, 2–6 am, 6–10 am, 10 am–2 pm, 2–6 pm, and 6–10 pm) were chosen a priori and were expected to correspond approximately to times when the residents of participating homes would be sleeping (10 pm–6 am), at home and actively using their wood stoves (6–10 am and 6–10 pm), or not at home (10 am–6 pm).

2.3. Covariate ascertainment

QTRAKs (TSI Inc.), co-located with the DustTraks and particle counters, were used to record 1-min averages of indoor temperature and humidity throughout the sampling periods. In addition, adult residents reported the usage of the wood stove during each sampling event including the number of times that the wood stove was loaded/stoked, burn intensity (none, light, average, or heavy), source of wood, and approximate age of wood. We also ascertained the occurrence of activities in the home that are potential predictors of elevated $PM_{2.5}$ concentrations (i.e. cooking, cleaning, pets, etc.). Demographic and home characteristics data also were captured from an adult resident. We expected that home characteristics such as square footage would not change throughout the study. Thus, we used data from the most recent visit or from a subsequent visit when home characteristics information was missing for a particular visit since no participants moved between visits during the pre-intervention winter. Meteorological data including temperature, relative humidity, precipitation, and wind speed were obtained from the Western Regional Climate Center (2013) and averaged over the first, second, and third calendar days of each sampling event. Lastly, during each sampling event (with the exception of the first year of the study), household caregivers recorded the times that the child was actually in the home during the scheduled sampling events to more accurately quantify in-home exposure for the child.

2.4. Infiltration estimation

Infiltration efficiency (F_{inf}) is defined as the fraction of the outdoor concentration that penetrates indoors and remains suspended. It depends on particle penetration and deposition, as well as the air exchange rate, and in the absence of indoor sources F_{inf} is equal to the indoor–outdoor concentration ratio. Continuous indoor and outdoor $PM_{2.5}$ sampling during each of two 48-h winter visits was exploited to quantify F_{inf} in homes using a well-validated recursive model approach (Allen et al., 2003, 2007). Hourly indoor and outdoor concentration averages were calculated from 1-min averages, and any hourly average generated from less than thirty minutes of data was excluded. The recursive modeling approach used here involves a censoring algorithm that identifies indoor source periods as those during which indoor concentrations increase without a corresponding increase outdoors. We excluded homes in which the 25th percentile indoor measurement exceeded the 75th percentile outdoor measurement, because these situations represent either a constant indoor source or instrument calibration problems, both of which prevent the recursive model from being applied (Allen et al., 2003). F_{inf} was set