Reductions in Residential Wood Smoke Concentrations and Infiltration Efficiency using Electrostatic Air Cleaner Interventions

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SUMMARY
Residential woodsmoke (RWS) has received increasing attention as an important source of ambient particulate matter ($PM_{2.5}$) that negatively impacts air quality and health. An investigation of the impact of ambient RWS emissions on indoor air quality was conducted in 32 residences, together with an evaluation of the effectiveness of electrostatic air cleaners (ESAC) at reducing indoor $PM_{2.5}$ concentrations. Monitoring was conducted for 3 days in total. On day 1 the woodstove operated as usual with no ESAC. On days 2 and 3 the woodstove was not in operation. The ESAC was randomly chosen to operate in "filtration" or "placebo filtration" mode on day 2 and then switched on day 3. Twenty-one homes had valid infiltration efficiency estimates on the two days when indoor woodstoves were not in use. Average infiltration efficiencies were reduced from 0.49 (Std Dev = 0.29) to 0.29 (Std Dev = 0.20) when the air cleaner was in operation.

IMPLICATIONS
Residential wood smoke is known to adversely affect respiratory health and also contains several carcinogenic compounds. This study demonstrates that electrostatic air cleaners are an inexpensive method of reducing indoor $PM_{2.5}$ potentially resulting from wood smoke emissions from outdoor sources.

KEYWORDS
Indoor air pollution, $PM_{2.5}$, wood burning emissions, recursive model, wood smoke tracer.

INTRODUCTION
Residential wood smoke (RWS) has received increasing attention as an important source of ambient particulate matter ($PM_{2.5}$) that negatively impacts air quality and respiratory health (Naeher et al, 2007). It is therefore desirable to reduce emissions and human exposure to wood smoke emissions in indoor environments where people spend the majority of their time.

There is some evidence of wood smoke exposure occurring inside homes where wood burning appliances (WBA) are present (Allen et al, 2009). Allen et al, (2009), Barn et al, (2008) and Ward et al, 2008 identified that approximately 30% of indoor $PM_{2.5}$ in communities impacted by RWS is contributed by outdoor RWS entering the home. In addition to the infiltration of outdoor wood smoke, indoor air quality can potentially also be impacted by “leakage” from indoor WBA directly into the indoor environment (Allen et al, 2009).

A small number of studies have identified air cleaners as an inexpensive method of reducing indoor $PM_{2.5}$ (Skulberg et al, 2005). A recent study noted improved vascular function in adults after use of indoor HEPA filters (Brauner et al, 2008) and other studies have reported decreased respiratory/allergy symptoms with indoor air cleaner use (van der Heide et al, 1999; Sublett et al, 2010; Skulberg et al, 2005).

Indoor and outdoor WBA, e.g. stoves, wall insert fire places, furnaces and outdoor wood boilers, are widely used for space and water heating and to a lesser extent cooking in the wintertime in the Annapolis Valley, rural Nova Scotia, Canada. The Annapolis Valley’s topography is conducive to trapping emissions especially during thermal inversions (typically 2 to 5 severe inversions per winter) leading to elevated mean 24-hr $PM_{2.5}$ concentrations greater than 20 $\mu g\ m^{-3}$ (Gibson, 2010). Current government air pollution surveillance monitoring does not extend to the communities on the Annapolis Valley floor. These factors, along with the need to understand the impact of ambient RWS emissions upon indoor air quality, were the main reasons for conducting this research.

METHODS

Between December 2009 – April 2010 Health Canada and Dalhousie University conducted a study of ambient and indoor air quality in the Annapolis Valley, Nova Scotia (Gibson et al, 2011). Thirty-two homes were monitored for three consecutive days each, with two homes monitored per week. Indoor monitoring equipment was placed on the main floor (typically the living room). Outdoor monitoring equipment was located in the backyard, several meters away from the home. All monitors were located at breathing height (1.5m). On day 1, participants used their indoor woodstove and/or basement wood furnace as normal, allowing a baseline of indoor air quality to be determined. On the second day, the indoor woodstove/wood furnace was not operated; however, outdoor wood boilers (where present) were allowed to remain in operation over the 3-days. An ESAC was placed on the opposite side of the room in relation to the monitors and was randomly assigned to operate in “filtration” or “placebo filtration” mode (internal filter replaced with placebo filter). On the third day, the woodstove/wood furnace remained inactive and the ESAC was in the opposite mode to the previous day. Two technicians visited the home daily to change out the monitoring equipment and administer questionnaires. Approval was obtained from Health Canada and Dalhousie University Research Ethics Boards to conduct the study.

Continuous, near real-time (1-min integration) $PM_{2.5}$ mass concentrations were measured inside and outside each home simultaneously using DustTraks (Model 8520) operating at a flow rate of 1.7 l/min. Harvard Impactors (HI) (37 mm 2 μm pore size, ring supported PTFE filters) and Thermo ChemCombs (47 mm Pre-fired Quartz filters) were used to collect 24-hr $PM_{2.5}$ samples inside and outside each home. HI and ChemCombs operated at a flow rate of 10 l/min using SKC Inc. Leyland Legacy pumps with flow rate checks performed pre and post sampling using a TSI 4140 digital mass flow meter. A flow rate of ± 20% was deemed acceptable. Pre and post sample gravimetric measurements of the 37 mm PTFE filters was conducted in accordance with USEPA quality assurance guidelines (USEPA, 1998). The 47 mm quartz filters were analyzed for Levoglucosan, a woodsmoke chemical marker (Ward et al, 2008). Air exchange rates (AER) were measured inside the home by the perflurocarbon tracer (PFT) technique (Dietz et al, 1986). Four PFT emitters were deployed on day 1 and taken down at the end of sampling on day 3. A daily capillary adsorption tube (CAT) was used as the receptor for the PFT tracer gas. For each home, the air exchange rate, expressed as air changes per hour (ACH), was calculated by dividing the air exchange rate by the measured house volume. A 3M Filtrete™ was used in the ESAC assessment. A Davis Vantage Pro II weather station (Davis Instruments Corp. Hayward, California 94545 USA) was deployed outside each home, which recorded temperature (T), pressure (mb) and relative humidity (RH) at 15-min intervals. Indoor T and RH were recorded at 1-min intervals using a YesTek monitor (Model 206 Falcon).

Each participant completed two different questionnaires to identify sources of exposure within the home and factors that may influence concentrations of air pollutants. Daily questionnaires were given to the participants for recording home activities such as: cleaning, cooking, use of candles/incense, opening of windows and quantity of wood burned in the stove, furnace or boiler. A technician-administered questionnaire was used to obtain information on housing characteristics such as: primary and secondary heating sources, age and type of home, presence of a garage, location of wood stores and types of ventilation systems. The technicians ensured there were no omissions in the questionnaires and noted any local sources of air pollution such as wood boilers.

All data analyses were completed using SAS v. 9.2. (SAS Institute Inc, NC, USA) and SigmaPlot v. 11 (Systat Software Inc, IL, USA). Continuous $PM_{2.5}$ Dustrak data were corrected to their gravimetric equivalent by using the $PM_{2.5}$ HI data. The measurements were compared using the reduced major axis (RMA) regression on the 83 and 88 days of valid outdoor and indoor measurements, respectively. Details regarding RMA regression are described in Heal et al, (2000). The corrected continuous $PM_{2.5}$ data was stratified by home id and experimental day. Total contribution of levoglucosan to indoor $PM_{2.5}$ was determined by dividing the Levoglucosan concentrations by the $PM_{2.5}$ concentration for the same time period. A Wilcoxon signed rank test was performed on the indoor, outdoor and Levoglucosan/$PM_{2.5}$ ratio measurements for each day as well as between days to assess any significant differences between locations and days.

The contribution of ambient PM to indoor levels is dependent on the infiltration efficiency (F_{inf}), which is the proportion of ambient PM that penetrates indoors and remains suspended. F_{inf} is governed by the penetration efficiency (P), air exchange rate (AER), and decay rate (k) and is shown in Eq (1):

$$F_{inf} = (P \times AER)/(AER + k) \qquad (1)$$

the F_{inf} estimates for each day in each home were calculated using a recursive mass balance model (RM) and indoor source censoring algorithm applied to the continuous $PM_{2.5}$ data (Allen et al, 2003).

RESULTS

Of the 32 study homes, only fifteen had valid data available for all three days of measurements. This was primarily due to power failures and an inadequate sample size for the recursive model after censoring out indoor $PM_{2.5}$ sources such as those resulting from cooking. There were twenty-one homes where data were available when the air cleaner intervention took place. Housing characteristics for all homes are presented in Table 1. The majority of homes included in the study used wood, or a combination of wood and oil or wood and electricity as a primary heating fuel (n=24). The size of the homes ranged from <200 to 350 m^2 with only 7 homes having attached garages.

Previously, DustTraks have been assessed for precision and bias (Wallace et al, 2010) by running them side by side to determine precision-corrected bias. Relative to other DustTraks, the bias-corrected mean precision was 6% (Std Dev 3%; range 3–10%) and precision was approximately 10%. Using the RMA regression method it was found that the outdoor DustTraks overestimated the $PM_{2.5}$ concentrations by 3.23x with an R^2 of 0.82 while the indoor DustTraks overestimated by 2.97x with an R^2 of 0.96.

Table 2 includes descriptive statistics for the indoor and outdoor continuous $PM_{2.5}$ data by each of the monitoring days, as well as air exchange rate, indoor/outdoor temperature and relative humidity data. During day 1 when the WBAs in the residences were operational, the mean indoor $PM_{2.5}$ concentrations were significantly higher than the outdoor $PM_{2.5}$ (8.7 vs 3.9 µg/m^3, Std Dev =17.9 vs 4.4) (p=0.024). When the woodstove was off and the air cleaner was in filtration mode, the indoor $PM_{2.5}$ concentrations were not significantly different than outdoor concentrations (2.4 µg/m^3, Std Dev =1.6 vs. 3.6 µg/m^3, Std Dev =3.6) (p=0.052). When the WBAs were not in use and the air cleaner was in "placebo filtration" mode, the indoor $PM_{2.5}$ concentrations (5.6 µg/m^3, Std Dev =5.7) and outdoor concentrations (3.3 µg/m^3, Std Dev =3.8) were significantly different (p=0.029). There were significant differences between days when comparing indoor concentrations between day 1 and filtration (p=<0.001) as well as between days with filtration vs. placebo filtration (p=<0.001). Outdoor concentrations were not significantly different between any of the days.

Mean infiltration estimates were 0.5 (Std Dev =0.28), 0.29 (Std Dev =0.20) and 0.49 (Std Dev =0.29) for day 1, filtration and placebo filtration respectively, as shown in Table 3. In the 21 homes with valid F_{inf} estimates on both days when indoor WBA were not used, a 45.1% (95% CI 30.1 – 60.1%) reduction in mean $PM_{2.5}$ F_{inf} estimates was seen.

The mean indoor contribution of the wood smoke marker levoglucosan on placebo filtration days was approximately 2.6%, which was significantly less than the mean outdoor contribution which was 10.2% (p=0.004). Finding levoglucosan indoors indicates the presence of wood smoke. It is therefore reasonable to assume that the presence of levoglucosan indoors when the air cleaner was in 'placebo filtration' mode can be attributed to outdoor wood smoke infiltrating indoors.

DISCUSSION

A recent study by Barn et al, 2008 among 19 homes in a wood smoke impacted community in British Columbia, Canada reported that mean indoor $PM_{2.5}$ concentrations were reduced from 5.8 to 3.9 µg/m^3, and mean F_{inf} estimates were reduced from 0.28 to 0.10, when a HEPA filter was used. These F_{inf} estimates are all lower than this winter residential study in the Annapolis Valley, NS. This can perhaps be explained by the fact that the Barn study was undertaken in a colder northern community where temperatures were on average -12°C compared to the Annapolis Valley with mean temperatures of only 0.9°C perhaps suggesting that the Barn homes were more insulated and hence had lower infiltration. Mean reductions in F_{inf} estimates associated with use of the ESAC in this study was comparable to that reported by Barn, despite the higher F_{inf} estimates in this study.

CONCLUSION

Our findings add to the body of evidence which support the use of air cleaners to reduce exposure to indoor $PM_{2.5}$ that results from wood smoke emissions. The consequent reductions in the levoglucosan concentrations also suggest that this is an effective method in reducing indoor concentrations to ambient generated RWS.

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Table 1: Housing Characteristics Influencing Indoor Air Quality

Category	Type	N(homes)	% of Total
Primary Wood-burning Appliance	Free Standing Wood stove	21	68
	Wall insert	3	10
	Pellet stove	1	3
	Wood furnace	3	10
	Free standing and Wall insert	1	3
	Wood furnace and Wall insert	1	3
	Outdoor Wood boiler	1	3
Days per week Wood burning appliance in use	5 to 7 days	28	91
	3 to 5 days	2	6
	1 to 2 days	1	3
Construction year	1945 and before	14	45
	1946 to 1960	3	10
	1961 to 1980	7	22
	1981 to 2000	4	13
	2001 or later	3	10

Table 2: Descriptive Statistics of Gravimetric Corrected DustTrak Data, AER, Temperature and RH by Sampling Day

Measurement	Day	Location	N	Mean	Std Dev	Min	Median	Max
$PM_{2.5}$ *[μg m^{-3}]*	1	Indoor	32	8.7	17.2	1.7	3.9	88.4
		Outdoor	30	3.9	4.4	0.1	2.7	19.8
	Filtration	Indoor	31	2.4	1.6	1.0	1.7	7.5
		Outdoor	29	3.6	3.6	0.4	2.4	19.7
	Placebo Filtration	Indoor	30	5.6	5.7	1.6	3.6	23.3
		Outdoor	32	3.3	3.8	0.2	2.0	18.6
AER *[Air exchanges/hr]*	All	Indoor	94	0.6	0.3	0.1	0.5	1.4
Temp (°C)	All	Indoor	95	20.6	2.1	15.5	20.6	24.7
		Outdoor	96	0.9	5.3	-14.2	1.3	11.3
RH (%)	All	Indoor	95	33.7	4.5	26.0	33.1	45.2
		Outdoor	96	82.0	11.5	41.9	85.8	96.5

Table 3: Summary of F_{inf} estimates and Air Cleaner Effectiveness

Day	N. of Obs	F_{inf} Mean (Std.Dev.)	F_{inf} Range	Air Cleaner Effectiveness Mean (Std. Dev.)	Range
1	24	0.50 (0.28)	1.14	-	-
Filtration	26	0.29 (0.20)	0.92	45.12 (33.05)	127.85
Placebo Filtration	24	0.49 (0.29)	1.40		

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