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Seasonal variation in indoor air quality from a field study investigating the impact of ventilation rates on the health of asthmatic children in Québec City

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SUMMARY
This paper describes the results obtained in 115 homes during a randomized intervention study investigating the impact of ventilation rates on indoor air quality (IAQ) and the respiratory health of asthmatic children in Québec City, Canada. Ventilation interventions were conducted in half the homes determined to be under ventilated in order to increase the air exchange rate in the heating season to above 0.30 h^{-1}. The majority of the homes (85%) did not meet our nominal ventilation goal of 0.30 h^{-1} and the average air exchange rate measured in winter was a factor of 2.8 smaller than in summer. The concentrations of the aldehydes, NO_2 and O_3 were all higher in summer while most hydrocarbons, aromatics, halocarbons and alcohols were higher in winter. On average, most homes met Health Canada's guideline for an 8-hr exposure of formaldehyde of 50 µg m^{-3} in winter but not in summer despite the higher observed air exchange rates.

IMPLICATIONS
On average, the homes in this study met Health Canada's formaldehyde exposure guideline during the heating season but exceeded it during the non-heating season despite the occurence of significantly higher air exchange rates. These results suggest that increased ventilation on its own may not suffice to reduce the concentration of formaldehyde in indoor environments.

KEYWORDS
indoor air quality, field study, air exchange rate, seasonal variation, intervention

INTRODUCTION

This paper describes the preliminary results obtained from a randomized intervention study investigating the impact of ventilation rates on indoor air quality (IAQ) and the respiratory health of asthmatic children in Québec City, Canada. The objective of this study was to determine whether increased ventilation will lead to a corresponding decrease in the number of asthmatic symptoms in children, to correlate ventilation rates with IAQ, and to support research for determining health-based ventilation rates.

The first phase of the field study involved three residential home visits (two during the heating season and one in summer) where a number of IAQ relevant chemical, biological and physical parameters were measured over a 6 to 8 day period. A series of questionnaires capturing information related to housing characteristics and occupant behavior were also administered during the residential home visits. This paper focuses on the preliminary IAQ parameters and ventilation measurements in 115 homes in the first phase of the study.

In the second phase, any home consistently meeting a minimum ventilation rate of 0.30 air exchanges per hour or more was excluded from further study. Of the 115 homes involved in the study, 85 were eligible for the intervention. All remaining homes, with consistently low or sporadically low measured ventilation rates, were randomly divided into two groups. One group of homes (n=43), had their ventilation rates increased by a combination of: installation of a heat recovery ventilator; modification of the existing ventilation system; and/or modification of occupant behavior. The other group (n=42), did not have any modifications done to the ventilation rate and served as a control group.

The monitoring in the second phase (ongoing) after the intervention is identical to the first phase and will be used to assess the effectiveness of the intervention on improving the indoor air quality and respiratory health

METHODS

The average air exchange rates (AER) measured in the child's bedroom over a 6 to 8 day period were determined using the perfluorocarbon tracer (PFT) technique developed by the Tracer Technology Group at Brookhaven National Laboratory (Dietz and Cote, 1982). Three PFT emitters were placed throughout the house (except for the child's bedroom), while two capillary adsorption tubes, used to sample the PFT, were placed in the child's bedroom and in the living room. Analysis of triplicate CATS, placed side by side, showed a standard deviation of less than 6% in the measured air exchange rate. The average difference between simultaneously measured air exchange rates in the child's bedroom and the living room was found to be 17% for 110 different homes. This is based on 139 sets of measurements from the living room and child's bed room after the outlier measurements were removed. In all cases, the homes were treated as a single zone. The AER was also measured over a 4-5 hour period in the child's bedroom using SF_6 tracer gas decay according to the ASTM test method E 741-00 (ASTM, 1997) using an Innova 1312 or 1412 photoaccoustic field gas monitor. Building air tightness was measured using a Minneapolis Blower Door^{TM} from The Energy Conservatory equipped with a DG-700 pressure and flow gauge and the data was analyze with the TECTITE Airtightness Test Analysis Software. The blower door test was conducted according to the ASTM E 779-03 test method (ASTM, 2003).

Formaldehyde was measured in the child's bedroom over a 6 to 8 day period using duplicate Waters Sep-Pak ® ExPosure cartridges as a passive sampler. The cartridges were subsequently analyzed for formaldehyde using high performance liquid chromatography (HPLC) according the ASTM test method D 5197-03 (ASTM, 2006). Ozone (O_3) and nitrogen dioxide (NO_2) were sampled using passive sampler badges produced by Ogawa & Company, which use coated filters to trap O_3 or NO_2. A detailed extraction and analysis protocol for the O_3 and NO_2 impregnated filter pads can be obtained from Ogawa & Company (Ogawa, 2011). The concentration of NO_2 (0.32 ppb detection limit for a 7 day exposure) was determined on a Spectro UV-Vis Double Beam UVD-3500 spectrophotometer at a wavelength of 545 nm. The concentration of O_3 (0.39 ppb detection limit for a 7 day exposure) was determined by ion chromatography using a Dionex KS-1000 ion chromatograph using an IonPac ® AS 22 column (Ogawa, 2011). The relative humidity and temperature were measured with an Onset HOBO U12-013 data logger and the CO_2 concentration was measured with a Vaisala GMW21 CO_2 sensor. The CO_2 concentrations displayed in Table 1 are the 24-hour average over the 6 to 8 day measurement period.

The volatile organic compounds were sampled on Perkin Elmer stainless steel ATD Passive samplers containing a Tenax TA 60/80 sorbent. Duplicate passive samplers were left in the child's bedroom for a period of 6 to 8 days. The VOCs were then desorbed from the tubes with a flow of helium using a Gerstel TDS 3 thermal desorption system and focused on a cooled inlet at -90 C°. The thermal desorber temperature ramp was 60 C° min^{-1} until 300 C° followed by a 5 min hold time. The compounds were then separated and detected on an Agilent 6890 GC-MSD operating in scan mode from m/z 35 to 300. The GC was equipped with a 30 m x 250 μm i.d. Supelco SPB-624 column and the temperature program was 35 C° for 5 min followed by a 6 C° min^{-1} temperature ramp to 230 C°.

Particulate matter was measured (heating season only) using a Grimm 1.108 particle counter and a TSI P-Track ultrafine particle counter for 4 to 5 hours during in the child's bedroom for the first day of the 6 to 8 measurement period. Airborne mould spores were measured using a Staplex model MAS-2 two-stage microbial air sampler for 5 minutes during each of the visits in the heating season in the child's bedroom, living room and the basement. The spores were collected onto both dichloran 18% glycerol (DG-18) and malt extract agar (MEA) covered petri dishes. Settling mould spores were collected for 4 to 5 hours in the child's bedroom onto both MEA and DG-18 covered petri dishes. Both the airborne and settling mould spore samples were incubated at 25 ºC for 7 days then analyzed visually with a microscope to obtain a colony count. Allergen samples in dust were collected from the child's mattress and carpet, if present in the child's bedroom, using a Philips Topomatic T518 vacuum cleaner equipped with a Dustream™ collector from Indoor Biotechnologies. The dust samples were then analyzed by Aerotech Laboratories for dust mite (Der p 1, Der f 1), cat (Fel d 1) and dog (Can f 1) allergens using an enzyme-linked immunosorbent assay (ELISA).

Prior to conducting the individual ventilation intervention the precise prescription was modeled for several homes computationally and physically in NRC's purpose built Indoor Air Research Laboratory (IARL). The computational fluid dynamics (CFD) calculations were performed using Fluent and were conducted to optimize the geometry and initial placement of any supply and return air vents in the child's bedroom that would be required during the installation of a heat recovery ventilator. The results of the computational models were then validated physically in a 1:1 scale model of the child's bedroom in the IARL. Measurements of SF_6 tracers gases, register flow rate, surface temperature, air temperature and velocity profiles throughout the model bedroom were compared to those predicted with the CFD modeling. Good agreement was obtained between the computational and physical modeling. In most cases, the placement of a circular air supply register, supplying fresh air from the HRV, located at the center of the child's bedroom provided better ventilation than placement near the door or along the wall.

RESULTS

Table 1. Summary of the seasonal concentrations of selected IAQ parameters measured in the child's bedroom during the winter/fall and summers (AER = air exchange rate, DL = detection limit, n = number of seasonal measurements)

Parameter	Summer (arithmetic mean)	Winter/Fall (arithmetic mean)
SF_6 AER (h^{-1})	NA	0.31 (n = 214)
PFT AER (h^{-1})	0.96 (n=94)	0.34 (n = 220)
Relative Humidity (%)	48.7 (n=114)	46.3 (n=224)
Temperature (ºC)	22.7 (n=108)	20.0 (n=135)
CO_2 (ppm, 24-hr average)	884 (n=110)	1024 (n=203)
NO_2 (ppb)	2.6 (n=114)	2.1 (n=216)
O_3 (ppb)	1.1 (n=115, n<DL=22)	0.4 (n=219, n<DL=190)
Formaldehyde (µg m^{-3})	59.8 (n=115)	37.6 (n=225)
Benzene (µg m^{-3})	5.2 (n=115)	6.2 (n=219, n<DL=2)
Toluene (µg m^{-3})	41.3 (n=115, n<DL=1)	47.3 (n=219)
Hexanal (µg m^{-3})	37.8 (n=115, n<DL=2)	25.9 (n=214)
Dichloromethane (µg m^{-3})	3.3 (n=50, n<DL=65)	5.1 (n=148, n<DL=71)
Tetrachloroethylene (µg m^{-3})	4.7 (n=89, n<DL=26)	6.1 (n=192, n<DL=27)
α-pinene (µg m^{-3})	18.5 (n=115)	17.7 (n=219)

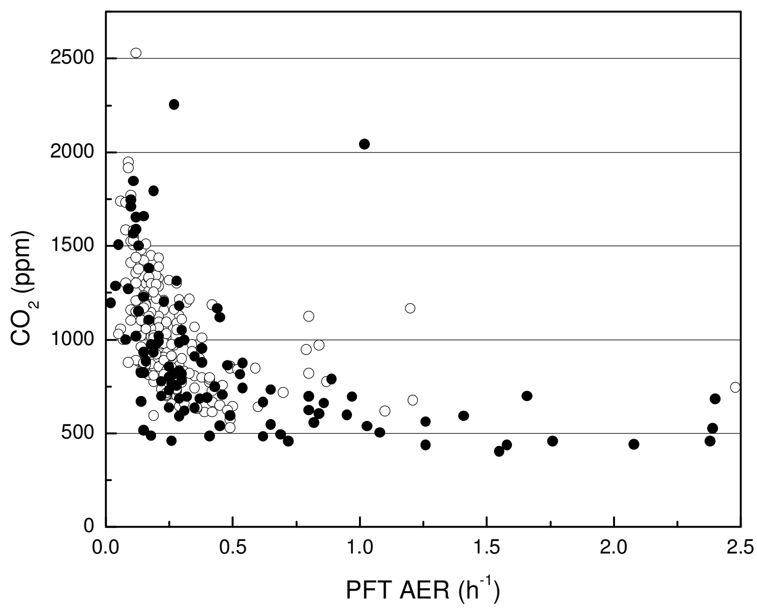

Figure 1. Relationship between the average CO_2 concentrations (ppm, 24-hr average) measured in the child's bedroom and the PFT derived air exchange rate (h^{-1}) in winter/fall (open circle) and summer (solid circle).

DISCUSSION

From Table 1 it can be seen that the arithmetic mean of the air exchange rates measured during the winter/fall season with both the PFT and SF_6 methods were similar. However, for individual measurements, there was some disagreement between the air exchange rate obtained with both techniques, with the SF_6 method tending to give a slightly higher air exchange rate for a given visit. Since air infiltration is weather dependent, this variation was to be expected (Sherman, 1998). Due to the shorter integration time for the SF_6 method (4 to 5 hours), it can be easily influenced by the occupant's behavior or anomalous conditions present during the measurement period. The PFT results, with a 6 to 8 day measurement period, should be considered more representative of the average air exchange rate encountered in the home; thus, these values were used to make associations between the air exchange rates and the IAQ parameters. The PFT air exchange rates measured in this study were slightly higher than those measured by Gilbert *et al.* where 80% of the homes in Québec City (n = 96) had an air exchange rate below 0.23 h^{-1}.

From Table 1 there is a clear seasonal variability in the measured relative humidity, O_3, and volatile organic compounds. With the exception of the aldehydes, NO_2 and O_3 all the chemicals had higher concentrations in winter/fall. The mean winter/fall NO_2 concentration of 2.1 ppb observed in this study was lower than the mean value of 5.0 ppb (n = 96) reported by Gilbert *et al.* (Gilbert *et al.*, 2006) measured in Québec City during January and April 2005.

Generally, for the VOC compound classes measured in this study the concentrations were higher in winter/fall than summer less the aldehydes for which the case was the reverse. The cause for the higher concentrations observed in winter/fall is likely due to the lower air exchange rates which lead to a slower removal of the pollutants from the indoor environment. For example, in Figure 1, it can be seen qualitatively that there is an inverse relationship between the CO_2 concentration measured in the child's bedroom and the air exchange rate measured in both summer and winter/fall. The CO_2 concentration decreases as the air exchange rate increase up to about ~0.5 air exchanges per hour after which the CO_2 concentration seems to be independent of the air exchange rate. It should be noted that the CO_2 measurements presented in Table 1 and Figure 1 are the 24-hr averages over the 6 to 8 day measurement period as we did not have any information regarding the time of occupancy in the child's bedroom.

On average, the formaldehyde concentrations observed in heating season would have satisfied Health Canada's exposure guideline (Health Canada, 2006) of 50 $\mu g\ m^{-3}$ for an 8-hr exposure but not during the summer. As formaldehyde is emitted in the home by a variety of off-gassing sources (Gilbert *et al.*, 2008) its concentration is expected to be higher in homes that have lower air exchange rates, which is more often the case in winter and fall. During the summer, however, average formaldehyde concentrations were higher (statistically significant at the 99.9% confidence level as obtained from the student's t-test) than in winter/fall despite the higher average air exchange rates. A possible explanation could be that the increased temperature and relative humidity in summer would promote the release of formaldehyde from hydrolysis reactions and off-gassing from construction materials and consumer products.

CONCLUSIONS

Our preliminary results indicate that there is a marked seasonal dependence of the air exchange rates and some of the measured IAQ parameters. Most of the pollutants were found to have higher concentrations in winter or fall, with the exception of the aldehydes, NO_2 and O_3. Our data for the pre-intervention phase study indicates that on average the homes do not meet our nominal ventilation rate goal of 0.30 air exchanges per hour for residential buildings. Based on the PFT measurements, 85% of the homes do not achieve this ventilation rate during the winter/fall period.

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