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Levels and Sources of Volatile Organic Compounds in Homes of Children with Asthma

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Abstract

Many volatile organic compounds (VOCs) are classified as known or possible carcinogens, irritants and toxicants, and VOC exposure has been associated with the onset and exacerbation of asthma. This study characterizes VOC levels in 126 homes of children with asthma in Detroit, Michigan, USA. The total target VOC concentration ranged from 14 to 2,274 $\mu\text{g}/\text{m}^3$ (mean = 150 $\mu\text{g}/\text{m}^3$; median = 91 $\mu\text{g}/\text{m}^3$); 56 VOCs were quantified; and *d*-limonene, toluene, *p*, *m*-xylene and ethyl acetate had the highest concentrations. Based on the potential for adverse health effects, priority VOCs included naphthalene, benzene, 1,4-dichlorobenzene, isopropylbenzene, ethylbenzene, styrene, chloroform, 1,2-dichloroethane, tetrachloroethene and trichloroethylene. Concentrations varied mostly due to between-residence and seasonal variation. Identified emission sources included cigarette smoking, solvent-related emissions, renovations, household products and pesticides. The effect of nearby traffic on indoor VOC levels was not distinguished. While concentrations in the Detroit homes were lower than levels found in other North American studies, many homes had elevated VOC levels, including compounds that are known health hazards. Thus, the identification and control of VOC sources is important and prudent, especially for vulnerable individuals. Actions and policies to reduce VOC exposures, e.g., sales restrictions, improved product labeling and consumer education, are recommended.

Keywords

Indoor; volatile organic compounds (VOCs); exposure; risk; asthma

1 Introduction

Many volatile organic compounds (VOCs) are classified as known or possible human carcinogens, irritants and toxicants (U.S. EPA 2012). In addition, several studies have linked VOC exposure with asthma exacerbation in children, although the evidence has been judged inadequate or insufficient (National Research Council 2000). These studies include a cross-

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sectional survey in Sweden of children's exposure (ages 13 to 14 years, n=627) to VOC levels in schools (Smedje et al. 1997); a case-control study in Australia of children (aged 6 months to 3 years; 88 cases; 104 controls) implicating benzene, toluene and dichlorobenzene (Rumchev et al. 2004); a cross-sectional study in Buffalo, New York of children (ages 1 to 17 years; n=3008) using self-reported indoor chemical odors (Lin et al. 2008); and a case-control study (33 cases, 40 controls) in Korea (Hwang et al. 2011). As an example of a study with contrasting results, a case-control analysis of children (ages 9 to 11 years; 193 cases; 223 controls) in the United Kingdom found no relationship between total VOC levels and persistent wheeze (Venn et al. 2003). Other indoor and environmental factors known to trigger asthma symptoms include temperature, humidity, mold, allergens and other air pollutants (Mendell 2007; Weichenthal et al. 2007; Sly et al. 2011).

Most exposure to VOCs occurs indoors, a result of numerous indoor emission sources, low ventilation rates, and the length of time spent indoors, especially in homes. Important VOC sources include cleaning products, tobacco smoke, cooking, heating appliances, VOC outgassing (from furniture, floor and wall coverings, and other building products), paints, glues, polishes, waxes, pesticides, personal care products, and the migration of emissions from attached garages (Wieslander et al. 1997; Wallace 2001; Batterman et al. 2006b; Batterman et al. 2007; Schlink et al. 2010; Dunagan et al. 2011). Indoor concentrations can be affected by air exchange rates (AERs), building renovations, house age and size, door and window opening, and outdoor VOC levels (Brown et al. 1994; Weisel 2005; Jia et al. 2008b; Jo and Sohn 2009; Breen et al. 2010).

The objective of this study is to characterize VOC levels in living rooms and bedrooms of a large group of children with asthma living in Detroit, Michigan, USA. We examine the spatial and temporal variability in the homes of these children over multiple seasons, evaluate factors that may affect VOC concentrations, and identify culpable sources. Results are compared to several other recent studies.

2 Materials and Methods

2.1 Participant recruitment and study design

Families in Detroit, Michigan with a child ages 6 to 12 years having symptoms or medication use consistent with persistent asthma were recruited as part of an intervention study examining ways to reduce triggers of asthma in the home by the use of air filters and air conditioners (ACs). The study used a community-based participatory research approach. Recruitment used questionnaires distributed to caregivers at schools, community fairs, and other venues (Parker et al. 2008), and ultimately a total of 126 households were recruited following informed consent and other procedures approved by our community-based steering committee and the University of Michigan Institutional Review Board. Families entered the study on a rolling basis between March 2009 and February 2010, and the field study was concluded in September 2010. Households were randomized to a control group receiving only community health worker (CHW) home education visits (n=37); the "standard" intervention group receiving a standalone filter (Whispure 510, Whirlpool Corporation, Benton Harbor, MI) installed in the child's bedroom and the CHW visits (n=47); and an "enhanced" intervention group receiving the filter, the CHW visits, and a

room AC (FAA062P7A, Frigidaire Augusta, GA) also installed in the child's bedroom (n=42).

A total of 356 visits to the households were conducted for environmental assessments, of which 325 were considered to yield valid VOC data. Six to 10 homes were typically visited each week. Most visits occurred in spring and summer seasons (105, 102, 65, and 53 visits occurred in spring, summer, fall and winter, respectively; Supplemental Table S1). Most (90%) households had valid visits in at least two seasons (13, 38, 66 and 9 homes had 1, 2, 3 and 4 visits, respectively). Visits included physical/chemical measurements (described below), inspection of building characteristics (documenting the type of structure, house/room size, heating and cooling systems, etc.), health measurements, and surveys administered to the child's primary caregiver (to be reported elsewhere) on health, demographic and personal factors (education, race, etc.) and indoor activities (e.g., smoking, cooking and cleaning practices). Building features, AERs, particulate matter concentrations, filter use, and characteristics of the study homes and population have been previously reported (Du et al. 2011; Batterman et al. 2012a; Batterman et al. 2013). This paper reports on the over 1,300 VOC samples collected in the study homes during the study.

2.2 Sample collection and analysis

VOCs were measured as integrated 7-day samples using tube-type passive samplers (thermal desorption tubes, stainless steel, 10 cm × 4 mm id; Scientific Instrument Services, Inc., Ringoes, NJ, USA) packed with 160 mg of Tenax GR and 70 mg of Carbosieve SIII adsorbents. Duplicate samplers were deployed in the child's bedroom along with continuous monitors for temperature and relative humidity (T/RH). A third VOC sampler (and sometimes a fourth as a duplicate) was placed in the main living area, along with a second T/RH monitor. A field blank was also deployed on each visit.

The protocols and performance of the sampling and analysis methods are described elsewhere (Batterman et al., 2002; Jia et al., 2006; Peng and Batterman, 2000). In brief, each sample was spiked with 2 µL of the internal standard (containing 1 ng/µL each of fluorobenzene and pbromofluorobenzene), and analyzed using a short-path thermal desorption/cryofocusing system (Scientific Instrument Services, Inc., Ringoes, NJ, USA) and gas chromatography/mass spectrometry (GC 5973/ MS 6890, Agilent, Palo Alto, CA, USA) for over 100 target compounds including alkane, aromatic, terpenoid, halogenated, and phenolic compounds. VOC targets also included two tobacco smoke (ETS) tracers: 2,5-dimethylfuran (DMF) and 3-ethenylpyridine (3-EP) (Charles et al. 2008). ETS is very likely present if these tracers are detected, although some false positives are possible (burnt food and coffee roasting can contain DMF) (Wang et al. 1983; Powrie et al. 1986). Method detection limits (MDLs) were determined for each VOC as the standard deviation of 7 replicate low concentration measurements, using standard solutions spiked into the thermal desorption tubes, multiplied by 3.14 (Peng and Batterman, 2000).

AERs were measured using two perfluorocarbon tracers (PFTs), hexafluorobenzene and octafluorotoluene that are inert and do not exist naturally (Batterman et al. 2006a). These compounds were measured with high sensitivity. Emitters were individually calibrated, periodically checked, and re-filled as needed. AERs for the house's living area and child's

sleeping area, and interzonal flows between these areas have been reported elsewhere (Du et al. 2012).

Quality assurance (QA) measures taken to ensure reproducibility and data quality included the use of standard operating protocols, collection and analysis of blanks at each visit, quarterly calibrations, and duplicate samples. Blank field samples showed little if any contamination. MDLs for individual VOCs ranged from 0.02 to 1.8 $\mu\text{g}/\text{m}^3$, depending on the compound. Duplicate samples had precisions below 20% in most cases, thus, most analyses averaged duplicates. Overall measurement uncertainty was considered to be low, and the sampling and analytical methods were appropriate for the indoor application.

2.3 Data analysis

Description statistics were computed for each VOC and home (average of multiple visits), including the detection frequency (DF; fraction of observations exceeding the MDL). We checked for outliers in the 13 homes that had only one valid visit, and whether statistics fell within the expected range. To further ensure that results were representative, we restricted the analysis to those homes that had valid measurements in at least 2 and 3 seasons, and repeated the descriptive analysis. To understand sources of variation, random effect models were used to apportion the variance of each VOC's concentration to four sources: between-residence variability; within residence variability (i.e., living room and bedroom); season (variance between seasonal visits); and measurement uncertainty (variance between replicates) (Jia et al. 2012). Apportionments were performed individually for the 35 VOCs with DF above 50%. (Apportionments with low DF may not be reliable.) Because this analysis assumes normality, log-transformed data was used for this analysis. (VOC concentrations were approximately lognormally distributed.)

As mentioned, the presence of ETS was determined by the detection of the DMF and 3-EP tracers, as well as survey responses regarding indoor smoking. Group differences in VOC levels were compared using Kruskal-Wallis (K-W) tests with $\alpha = 0.05$ to examine effects of season, AER, temperature, traffic measures, and other variables. The effect of vehicle traffic within 100 and 300 m buffers of each home on benzene and ΣBTEX (sum of benzene, toluene, ethylbenzene, and xylene) levels was investigated using generalized linear models that used quartiles of vehicle-miles-traveled per day within each buffer as a potential explanatory variable.

Potential VOC sources and associations among VOCs were identified using factor analyses and varimax rotations. Factors with eigenvalues exceeding 1 that included at least one variable with a loading over 0.3 were extracted. These analyses included those VOCs that had measurable levels ($>$ MDL) for at least 10% of the homes (40 target VOCs). Measurements below MDLs were set to one-half of MDL.

VOCs were prioritized based on screening level health risk estimates. The excess lifetime individual cancer risk for the i^{th} VOC was calculated as $\text{Risk}_i = \text{EC}_i \times \text{CSF}_i$ where EC_i = exposure concentration, estimated as the average indoor concentration ($\mu\text{g}/\text{m}^3$), and CSF_i = cancer slope factor (per $\mu\text{g}/\text{m}^3$). The non-cancer risk hazard quotient (HQ_i) was calculated as $\text{HQ}_i = \text{EC}_i / \text{RfC}_i$, where RfC_i = reference concentration ($\mu\text{g}/\text{m}^3$) relevant to adverse (non-

cancer) outcomes. CSF and RfC values were taken from the Integrated Risk Information System (IRIS) and, if unavailable, from the Initial Risk Screening Levels (IRSLs) used in Michigan's air toxic screening program (IARC 2012; MDEQ 2012; U.S. EPA 2012). (CSF, RfC and IRSL values and other information are listed in Supplemental Table S2.) The risk and HQ calculations represent screening level estimates that assume indoor measurements are representative of lifetime exposures, and that exposures outside the home, e.g., at school or work, are low or comparable to levels in homes. These assumptions are supported by many studies showing that indoor settings, particularly residences, are the dominant VOC microenvironment for most individuals (U.S. EPA 2011; Su et al. 2013), especially for children and the elderly who spend most of their time at home. This assumption may not apply to adults who spend less time at home, and particularly to those working in settings with high VOC exposure.

Descriptive and factor analyses used SPSS 17 (IBM Corp., Somers, NY, USA). The traffic analysis used PROC GLM, and the variance component analyses used PROC NESTED, both in SAS (v9.1.3, SAS Institute, Cary, NC, USA). Data and results were organized using Microsoft Excel (Microsoft, Seattle, WA, USA).

3 Results and Discussion

3.1 Indoor concentrations

A total 56 VOCs were detected in the 126 homes, which were distributed across the more populated areas of Detroit (Figure 1). 35 compounds were detected in at least half of the homes (Table 1). The household average total target VOC (Σ VOC) concentration was 150 $\mu\text{g}/\text{m}^3$ (median of 91 $\mu\text{g}/\text{m}^3$). Concentrations varied considerably among households, from 14 to 2,274 $\mu\text{g}/\text{m}^3$, and distributions were strongly right-skewed. VOCs with the highest average concentrations included aromatics (benzene, toluene, and xylenes), alkanes ($n\text{-C}_{7-13}$ and methyl cyclohexane), terpenes (d -limonene and α -pinene), and tetrachloroethene. No VOC differed significantly among the three intervention groups, thus subsequent analyses use pooled data.

Because the sample was unbalanced with respect to number of visits made to each home, we checked to whether the group of homes with fewer visits (13 homes had 1 visit) was representative. In this subset, the VOC data showed no outliers, and means and other statistics were within the seasonal range of the larger sample. Analyses restricted to the 75 households that had valid measurements during at least three seasons (Supplemental Table S3) also showed results very similar to those obtained using all of the household data (Table 1). For example, most 25th, 50th and 75th percentile concentrations were within a few percent, and means were within 25% (and usually much closer) with the exceptions of 1,2,3-trimethyl benzene (37% higher), 1,4-dichlorobenzene (64% lower), ethyl acetate (34% higher) and ethyl methacrylate (31% lower).

Many VOCs were found in all or nearly all homes, including d -limonene and α -pinene, which are constituents of cleaning products, air fresheners and fragrances (Nazaroff and Weschler 2004; Aronson et al. 2007), and toluene and other aromatics, which are in household products, paints, adhesives, synthetic fragrances, evaporated fuel, vehicle

emissions, and many other products. Ethyl acetate, detected in 71% of visits, exceeded 10 $\mu\text{g}/\text{m}^3$ in 20 households (16%); this VOC is used in nail polish remover, glue and other products (U.S. National Library of Medicine 2012). Naphthalene and 1,4-dichlorobenzene, two VOCs used as pest repellents and deodorants, were found at very high levels in a few homes (e.g., the highest household levels were 556 and 4,249 $\mu\text{g}/\text{m}^3$, respectively, which occurred in different homes); such high levels likely result from inappropriate use of these products (Jia and Batterman 2010; Batterman et al. 2012a; Chin et al. 2013).

Comparison to other studies—Although concentrations of several VOCs in a number of houses appeared elevated, VOC levels measured in other North American studies tend to be higher. Figure 2 contrasts results with four other relevant studies. The Three Cities Study (TCS) used 1-week samples in living rooms ($n=161$ houses) measured in 2005 and 2006 in three southeast Michigan cities: Dearborn, a densely populated and industrialized city, in many ways similar to Detroit; Ypsilanti, a more urban and commercial city; and Ann Arbor, a largely suburban and affluent community (Jia et al. 2008a). The Mechanistic Indicators of Childhood Asthma Study (MICAS) collected 7-day samples (participant-deployed) in Detroit homes of children (ages 9 to 13 years, $n=41$) with and without asthma in November and December, 2006 (Johnson et al. 2009; Johnson et al. 2010). The Windsor, Ontario (Canada) Exposure Assessment Study (WOEAS) (Health Canada 2006), was conducted just south of Detroit in non-smoking homes with asthmatic children (aged 9–12 years, $n=47$) in summer and winter of 2006. In WOEAS, caregivers were not occupationally exposed, and 5-day samples collected in summer and winter results were averaged. The fourth study is a compilation of 77 reports examining residences in the US and countries with similar lifestyles from 1995–2010 (Logue et al. 2011). While there is significant variability within each study, median concentrations of benzene and d-limonene levels among the studies were similar; 1,4-dichlorobenzene levels varied widely (probably dependent on occupant use of deodorant and pesticide products (Chin et al. 2013); and toluene levels were lowest in the present study.

Outside of North America, much higher VOC levels have been reported in homes of individuals with asthma (or with asthma-like symptoms). As examples, in Sweden, toluene averaged 120 $\mu\text{g}/\text{m}^3$ (range of 1 to 2,330 $\mu\text{g}/\text{m}^3$; $n=88$) in living rooms and bedrooms sampled in 1991 and 1992 (Norbäck et al. 1995); in Australia, median and maximum benzene concentrations were 20 and 82 $\mu\text{g}/\text{m}^3$, respectively, and toluene levels were 17 and 154 $\mu\text{g}/\text{m}^3$ in living rooms of children's homes (ages 6 months to 3 years, $n=88$) sampled in 1997 through 1999 (Rumchev et al. 2004); and in Korea, toluene, formaldehyde, *p,m*-xylene and ethylbenzene had geometric mean concentrations of 46, 31, 14 and 9.2 $\mu\text{g}/\text{m}^3$, respectively, in homes of children (ages 8 to 13 years, $n=33$) sampled in 2008 (Hwang et al. 2011). The Swedish, Australian and Korean studies show higher, and sometimes much higher, VOC levels than the present study and most of the North American studies.

Concentrations of VOCs measured in different studies can differ for many reasons. Levels in more recent studies (after 2000 or so) are often lower due to progress made in controlling indoor and outdoor emissions, as well as the reduction or elimination of indoor smoking (McCarthy et al. 2007; Su et al. 2011; Batterman et al. 2012a). Because outdoor VOC levels provide a 'floor,' indoor concentrations can be affected by urbanization, proximity to

industry, traffic and other emission sources, and meteorology. Regional differences in building design (including attached garages), building materials, and climate can influence both AERs and emissions. In comparison to most other North American studies, few Detroit homes have attached garages, eliminating a common source of BTEX and other fuel-related VOCs (Batterman et al. 2006c; Chin and Batterman 2012). The use of VOC-emitting products (air fresheners, scents, pesticides, etc.) can depend on social and cultural practices and jurisdictional controls. Finally, sampling and analytical methods can affect results, e.g., studies using short sampling periods and without seasonal averaging generally show greater variability, a result of temporal variability (described below).

3.2 Variation in VOC levels

The variance components analysis apportioned the variability in VOC concentrations to between-household variation ($49 \pm 11\%$ of the total variance), seasonal variation ($34 \pm 12\%$); within-household variation (between living rooms and bedrooms; $10 \pm 6\%$); and measurement variation (among replicates; $7 \pm 6\%$). While the apportionments varied by VOC (Figure 3, Supplemental Table S4), the largest source of variation was household-to-household differences, a result of the different VOC products used/stored in each house, variation in smoking and AERs, and other factors that varied by household. A few studies have reported large variation in VOC concentrations among households (Sexton et al. 2004; Zhu et al. 2005; Jia et al. 2012). As discussed below, however, seasonal variation was nearly as important as variation among household.

Seasonal variation—Overall, VOCs levels were highest in spring and fall, and lowest in summer and winter (Figure 4). Seasonal changes can be caused by many factors including the AER, which depend on the indoor-outdoor temperature difference, the presence and use of air conditioners, window opening, wind speed, age and condition of the house, and other factors (Breen et al. 2010; Du et al. 2012). In the Detroit homes, the AER in the living area averaged 1.02 ± 0.92 1/h (median = 0.80 1/h, n=277) and varied seasonally (K-W test, $p = 0.002$; median test, $p = 0.009$) (Table 2) (Du et al. 2012). The higher AERs observed in winter reflect large indoor-outdoor temperature differences and high wind speeds; in summer, temperature differences as well as opened windows also increase the AER. AERs are lower in other seasons (seen especially in spring) as windows are closed and the driving forces (primarily the temperature difference) are small (Breen et al. 2010). AERs were negatively correlated with VOC concentrations, especially for toluene, styrene, α -pinene and limonene (Spearman rank correlation coefficients from -0.3 to -0.4 ; Supplemental Table S5), as expected for VOCs with strong indoor sources (Haghighat and Huang 2003; Gilbert et al. 2008; Stocco et al. 2008; Lin et al. 2009).

Several studies have reported seasonal variation and similar trends in VOC levels as found in Detroit (Ilgen et al. 2001; Rehwagen et al. 2003; Schlink et al. 2010; Jia et al. 2012). Importantly, this variability means that measurements in multiple seasons are needed to estimate long-term VOC levels in households.

Within-house variation—Within-household variation was relatively small, based on the variance components analysis, and also based on relative absolute concentration differences

between the concentrations in living rooms and bedrooms, which showed a median difference of 30% across the 41 VOCs (range from 8 to 69%; n=279 pairs). The variation within a building depends on the degree of mixing, airflows and locations of VOC sources. Given that most (87%) Detroit homes had forced air heating/cooling systems, air is often well-mixed and within-home concentration gradients were small, especially when averaged over longer periods (1-week in the present case) (Batterman et al. 2007; Dodson et al. 2008). However, this conclusion is limited to differences between living rooms and bedrooms, which were selected as the locations where children spent most of their time. VOC levels may show greater differences in kitchens, bathrooms, and possibly other settings.

Temperature—Indoor temperatures averaged 22.5 ± 3.5 °C (median = 22.3 °C, n=227), varied seasonally (K-W test $p < 0.001$; median test, $p < 0.001$), and increased by 5 °C in summer compared to winter (Table 2). Concentrations of most VOCs were negatively correlated with indoor temperature ($-0.1 < r < -0.3$; Supplemental Table S5). AERs and indoor temperatures were positively (though weakly) correlated ($r=0.17$).

Environmental tobacco smoke—Based on ETS tracers (detected in 35 homes) and occupant surveys (positive responses in 37 homes), smoking may have occurred in 53 homes. Both indicators were positive in 19 homes. Homes with smoking during the sampling period are defined using the ETS tracers, which provided stronger evidence of smoking based on particulate matter (PM) concentrations (Batterman et al. 2012a). Homes with ETS detected during the sampling period had higher levels of benzene, tetrachloroethene, styrene, phenol, n-butylbenzene, naphthalene, 2-methylnaphthalene, 1-methylnaphthalene, and n-pentadecane, but lower levels of α -pinene (Supplemental Table S6). Most of these VOCs are found in cigarette smoke (Charles et al. 2007; Chambers et al. 2011). While the differences noted were statistically significant, concentration changes were small, e.g., median levels changed by only 10 to 20%.

While smoking and ETS have been associated with large increases in PM concentrations (Batterman et al. 2012), effects on VOC levels tend to be small. As examples: in Regina, Saskatchewan, Canada, benzene concentrations averaged $3.4 \mu\text{g}/\text{m}^3$ in homes with at least one smoker (n=31), compared to $2.5 \mu\text{g}/\text{m}^3$ (n=158) in non-smoking homes (Health Canada 2007); and in MICAS, homes with smokers had higher indoor/outdoor ratios of benzene, ethylbenzene and xylene (Johnson et al. 2010). Smoking causes larger differences when personal sampling is used (which gives exposures), as compared to area sampling used in the present (and most) studies (Edwards et al. 2001).

Other factors—Additional factors that have been associated with indoor VOC concentrations include the use and storage of certain household products, building renovations, attached garages, and vehicle emissions (Brown et al. 1994; Diez et al. 2000; Rumchev et al. 2004; Jia and Batterman 2010; Chin and Batterman 2012). Elevated concentrations ($>50 \mu\text{g}/\text{m}^3$) of *n*-alkanes (*n*-C₇₋₁₃) were found in 14 Detroit homes, which may indicate recent building renovation (Rumchev et al. 2004). In this study, only nine houses had an attached garage. Although the amount of traffic exposure varied considerably among homes, the amount of traffic within either 100 or 300 m buffers showed only weak and statistically insignificant effects on indoor benzene and ΣBTEX levels (using

correlations and GLMs). The ability to discern the influence of outdoor VOC levels and sources on indoor concentrations is limited since many indoor sources emit the same compounds, e.g., the BTEX compounds associated with vehicle exhaust and gasoline (Chin and Batterman 2012) are also found in ETS, paints, adhesives, solvents, oils and incense (Diez et al. 2000; Charles et al. 2007; Alexopoulos and Bakeas 2011). Similarly, identifying sources by VOC profiles is rarely definitive, as further discussed in Section 3.3.

Measurement uncertainty—As noted, measurement variation was small, averaging only $8 \pm 12\%$. Measurement variation increased for VOCs with low detection frequencies, e.g., 1-methylnaphthalene, 2-methylnaphthalene, n-hexadecane and phenol.

3.3 Source identification using factor analysis

Factor analyses using the long term (multiseason) averages at the homes ($n=126$) resolved 11 factors, a large number. Frequently, several VOCs were present in multiple factors, indicating multiple sources or effects on that VOC (demonstrated in the loading matrix, Supplemental Table S7). Factor 1 contained mostly aromatics (BTEX, trimethylbenzenes, etc.), and likely represents solvents emissions (pens, inks, coatings, paint, perfume, adhesives and varnish) and vehicle-related emissions. Factor 2 contained C_{12-16} n-alkanes, and likely reflects oil and diesel engine exhaust. Factor 3 with *d*-limonene, phenol and α -pinene reflects the use of household products, fragrances, air fresheners and building materials. Factor 4 included $C_{9,10,12}$ n-alkanes, which are constituents of oils, lubricants and solvents. The remaining factors explained from 3.1 to 4.8% of the total variance. Factor 5 (cyclohexane, n-heptane, methyl cyclohexane) may indicate paints, adhesives and solvents. Factor 6 (ethyl acetate, 2-hexanone, tetrachloroethene) may reflect glues, nail polish removers, solvents and paints. Factor 7 (chloroform) likely reflects disinfection byproducts associated with water use. Factor 8 (1,2-dichloroethane, 1,4-dichlorobenzene) includes degreasers, paint remover and moth crystals. Factor 9 (C_{11-12} n-alkanes and tetrachloroethene) may reflect solvents. Factor 10 (3-EP) represents ETS sources. Lastly, factor 11 (1,4-dichlorobenzene, naphthalene) are the pest repellents discussed earlier.

Factor analyses based on the seasonal visits ($n=325$) resolved 10 factors (Supplemental Table S8). In this case, ETS was not resolved (the detection frequency of 3-EP was only 8%). Analyses performed for each season might better identify sources that vary by season, and can separate periods (e.g., summer) when children are more likely to be home. However, most results of seasonally-stratified analyses were comparable to that for household averages, e.g., again, 10 factors were identified, and the first four or five factors explained over half of the total variance with similar VOC sources (Supplemental Tables S9–S12).

3.4 Risk-based rankings

Ten of the target VOCs have been identified as possible or known carcinogens (Supplemental Table S3). Of these, household-average concentrations of six VOCs exceeded an individual excess lifetime cancer risk level of 10^{-5} in some or many homes (73, 68, 40, 29, 17 and 2 homes for naphthalene, benzene, 1,4-dichlorobenzene, chloroform, 1,2-dichloroethane, and isopropylbenzene, respectively), and all ten VOCs exceeded the 10^{-6}

level (exceeded in 126, 126, 124, 126, 126, 41, 17, 10, 4, and 3 homes for naphthalene, benzene, 1,4-dichlorobenzene, chloroform, 1,2-dichloroethane, isopropylbenzene, ethylbenzene, styrene, trichloroethylene, and tetrachloroethene, respectively) (Figure 5). 1,4-dichlorobenzene and naphthalene presented the highest risks, which reached 10^{-2} in one home and 10^{-3} in 10 homes. Benzene risk exceeded a risk level of 10^{-4} in two homes, and 10^{-5} in half ($n=68$) of the homes, based on the lower limit of slope factor range (1.3–4.5 $\mu\text{g}/\text{m}^3$ for a 10^{-5} risk) (U.S. EPA 2012). Another known carcinogen, chloroform, exceeded a risk level of 10^{-5} in 31 homes and 10^{-4} in one home. The probable human carcinogen 1, 2-dichloroethane, exceeded a risk level of 10^{-5} in 16 homes. Isopropylbenzene exceeded risks of 10^{-5} in two homes.

Based on 75th percentile concentrations, the risk ranking of the ten carcinogenic VOCs is 1,4-dichlorobenzene > naphthalene > benzene > (chloroform) > (1,2-dichloroethane) > isopropylbenzene > ethylbenzene > styrene > (tetrachloroethene) > (trichloroethylene). In this ranking, VOCs in parentheses have a detection frequency below 50%, and thus reflect some uncertainty regarding the robustness of this ranking.

Hazard quotients (HQ) for chronic non-cancer health effects exceeded one in 21 homes for naphthalene (maximum HQ=67), and in 2 homes for 1,4-dichlorobenzene (maximum HQ=3). Concentrations of other VOCs were far below reference concentrations, indicating that non-cancer health effects are unlikely.

Calculations of excess health risks have been used to prioritize VOCs in several studies. A recent review identified seven VOCs (acetaldehyde, acrolein, benzene, 1,3-butadiene, 1,4-dichlorobenzene, formaldehyde, naphthalene) as priority indoor air pollutants (Logue et al. 2011). Three VOCs (formaldehyde, benzene, naphthalene) were identified as priorities in European homes (Koistinen et al. 2008). WHO identified five priority VOCs (benzene, styrene, toluene, trichloroethylene and tetrachloroethene) (WHO 2000). The VOCs identified in these rankings are similar to those in the Detroit homes.

VOCs that can pose health risks arise from many indoor and outdoor sources. Identifying and controlling VOC sources is important and prudent, particularly for vulnerable individuals. Individuals can minimize exposure by eliminating or minimizing use of VOC-emitting products (e.g., air fresheners), choosing VOC-free or low-VOC consumer products, minimizing migration indoors of VOCs from attached garages and outdoor sources, and using ventilation and other controls when VOCs are used indoors. Policies that can reduce exposure include sales bans and restrictions on toxic chemicals, improved labeling, building and ventilation standards, and consumer education.

3.5 Study strengths and limitations

This study characterized VOC concentrations in a large sample of Detroit homes with asthmatic children using measurements repeated in multiple seasons. Sampling used a one-week sampling period, and included VOC measurements in both living rooms and bedrooms, as well as blanks, replicates and other means to ensure quality results. In addition, AERs and other variables were measured to help to interpret results. We recognize several limitations. Target VOCs did not include very volatile compounds, e.g., aldehydes

and carbonyls. Only homes of asthmatic children in Detroit were sampled, and results may not be applicable to other homes. While home inspections were conducted, not all sources that might emit VOCs were noted. Outdoor VOC concentrations were not measured. Both VOC and AER measurements were time averaged, and short-term effects (hourly to daily) were not characterized. Because a single location was monitored in each room, we do not have direct information on within-room variation in VOC levels; however, this is unlikely to be significant for the 1-week averaging period given the small between-room differences observed. The factor analysis provides only tentative identification of sources. The risk estimates, which used available measurements and recommended parameters, are screening level estimates of excess risk that assume that VOC measurements are representative of long-term exposure, and they do not account for exposures in environments outside the home, time budgets, and mixture effects. While we used robust statistical tests, repeated measures, and a large sample size, many results are VOC-specific, and some may be affected by interactions, outliers, sampling schedules, or other factors that could not be identified, in part due to sample size limitations. Most of these limitations result from cost and logistical factors. Lastly, the study design does not permit a direct investigation of whether short- or long-term VOC levels are associated with asthma.

4 Conclusions

A total of 56 VOCs were detected in the 126 homes sampled of children with asthma living in Detroit, Michigan, and 35 VOCs were found in at least half of the homes. The predominant compounds included aromatics, alkanes, terpenes and tetrachloroethene. Although many compounds were detected, concentrations were generally lower than levels reported in other recent studies in North America. The analysis of temporal and spatial variability indicates the need to obtain repeated measurements in multiple seasons to characterize indoor levels; this is generally more important than sampling in multiple locations within a home. Emission sources, identified using tracers, high concentrations of several VOCs, and factor analysis, included cigarette smoking, vehicle related emissions, renovation, solvents, household product and pesticides. As expected, concentrations were negatively associated with air exchange rates, indicating the significance of indoor sources. VOCs posing cancer risks that exceed guideline levels in many homes included naphthalene, benzene, 1,4-dichlorobenzene, isopropylbenzene, ethylbenzene and styrene; a small number of homes had high risks due to chloroform, 1,2-dichloroethane, tetrachloroethene and trichloroethylene. High levels of naphthalene and 1,4-dichlorobenzene, associated with non-cancer effects in humans, were found in a subset of residences.

This study provides information regarding VOC exposures of a vulnerable population, children with asthma. While evidence supporting the role of VOC exposure in asthma exacerbation is limited, this study identifies VOCs and emission sources that might pose hazards, and thus can help to facilitate actions and policies to decrease exposure and reduce possible triggers of asthma.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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6 References

- Alexopoulos, EC.; Bakeas, EB. Benzene: Environmental Exposure. Elsevier; Burlington: 2011.
- Aronson DB, Bosch S, Gray DA, Howard PH, Guiney PD. A comparative human health risk assessment of p-dichlorobenzene-based toilet rimblock products versus fragrance/surfactant-based alternatives. *J. Toxic. Environ. Health, Part B.* 2007; 10(7):467–526.
- Batterman S, Du L, Mentz G, Mukherjee B, Parker E, Godwin C, Chin JY, O'Toole A, Robins T, Rowe Z, Lewis T. Particulate matter concentrations in residences: an intervention study evaluating stand-alone filters and air conditioners. *Indoor air.* 2012a; 22(3):235–252. [PubMed: 22145709]
- Batterman S, Du L, Parker E, Robins T, Lewis T, Mukherjee B, Ramirez E, Rowe Z, Brakefield-Caldwell W. Use of Free-standing Filters in an Asthma Intervention Study. *Air Qual. Atmos. Health.* 2013 In press.
- Batterman S, Hatzivasilis G, Jia C. Concentrations and emissions of gasoline and other vapors from residential vehicle garages. *Atmos. Environ.* 2006c; 40(10):1828–1844.
- Batterman S, Jia C, Godwin C, Hatzivasilis G. A dominant source of VOC exposure: Attached garages. *Epidemiology.* 2006b; 17(6):S350–S350.
- Batterman S, Jia C, Hatzivasilis G. Migration of volatile organic compounds from attached garages to residences: a major exposure source. *Environ Res.* 2007; 104(2):224–240. [PubMed: 17350611]
- Batterman S, Jia C, Hatzivasilis G, Godwin C. Simultaneous measurement of ventilation using tracer gas techniques and VOC concentrations in homes, garages and vehicles. *J. Environ. Monitor.* 2006a; 8(2):249–256.
- Breen MS, Breen M, Williams RW, Schultz BD. Predicting Residential Air Exchange Rates from Questionnaires and Meteorology: Model Evaluation in Central North Carolina. *Environ. Sci. Technol.* 2010; 44(24):9349–9356. [PubMed: 21069949]
- Brown SK, Sim MR, Abramson MJ, Gray CN. Concentrations of Volatile Organic Compounds in Indoor Air – A Review. *Indoor air.* 1994; 4(2):123–134.
- Chambers DM, Ocariz JM, McGuirk MF, Blount BC. Impact of cigarette smoking on Volatile Organic Compound (VOC) blood levels in the U.S. Population: NHANES 2003–2004. *Environ Int.* 2011; 37(8):1321–1328. [PubMed: 21703688]
- Charles SM, Batterman SA, Jia C. Composition and emissions of VOCs in main- and side-stream smoke of research cigarettes. *Atmos. Environ.* 2007; 41(26):5371–5384.
- Charles SM, Jia C, Batterman SA, Godwin C. VOC and Particulate Emissions from Commercial Cigarettes: Analysis of 2,5-DMF as an ETS Tracer. *Environ. Sci. Technol.* 2008; 42(4):1324–1331. [PubMed: 18351112]
- Chin J-Y, Batterman SA. VOC composition of current motor vehicle fuels and vapors, and collinearity analyses for receptor modeling. *Chemosphere.* 2012; 86(9):951–958. [PubMed: 22154341]
- Chin JY, Godwin C, Jia C, Robins T, Lewis T, Parker E, Max P, Batterman S. Concentrations and risks of p-dichlorobenzene in indoor and outdoor air. *Indoor air.* 2013; 23(1):40–49. [PubMed: 22725685]
- Diez U, Kroeßner T, Rehwagen M, Richter M, Wetzig H, Schulz R, Borte M, Metzner G, Krumbiegel P, Herbarth O, Diez. Effects of indoor painting and smoking on airway symptoms in atopy risk

- children in the first year of life results of the LARS-study. *Int. J. Hygiene Environ. Health*. 2000; 203(1):23–28.
- Dodson RE, Levy JI, Spengler JD, Shine JP, Bennett DH. Influence of basements, garages, and common hallways on indoor residential volatile organic compound concentrations. *Atmos. Environ*. 2008; 42(7):1569–1581.
- Du L, Batterman S, Godwin C, Chin J-Y, Parker E, Breen M, Brakefield W, Robins T, Lewis T. Air change rates and interzonal flows in residences, and the need for multi-zone models for exposure and health analyses. *Int J Environ Res Public Health*. 2012; 9(12):4639–4662. [PubMed: 23235286]
- Du L, Batterman S, Parker E, Godwin C, Chin J-Y, O'Toole A, Robins T, Brakefield-Caldwell W, Lewis T. Particle concentrations and effectiveness of free-standing air filters in bedrooms of children with asthma in Detroit, Michigan. *Build. Environ*. 2011; 46(11):2303–2313. [PubMed: 21874085]
- Dunagan SC, Dodson RE, Rudel RA, Brody JG. Toxics use reduction in the home: lessons learned from household exposure studies. *J. Cleaner Prod*. 2011; 19(5):438–444.
- Edwards RD, Jurvelin J, Saarela K, Jantunen M. VOC concentrations measured in personal samples and residential indoor, outdoor and workplace microenvironments in EXPOLIS-Helsinki, Finland. *Atmos. Environ*. 2001; 35(27):4531–4543.
- Gilbert NL, Guay M, Gauvin D, Dietz RN, Chan CC, Lévesque B. Air change rate and concentration of formaldehyde in residential indoor air. *Atmos. Environ*. 2008; 42(10):2424–2428.
- Haghighat F, Huang H. Integrated IAQ model for prediction of VOC emissions from building material. *Build. Environ*. 2003; 38(8):1007–1017.
- Health Canada. Windsor Ontario Exposure Assessment Study: VOC Sampling Data Summary (2005–6). Ottawa, Ontario, Canada: 2006. http://publications.gc.ca/collections/collection_2012/sc-hc/H128-1-10-618-eng.pdf?
- Health Canada. Regina Indoor Air Quality Study: VOC Sampling Data Summary. Ottawa, Ontario, Canada: 2007. available on http://publications.gc.ca/collections/collection_2012/sc-hc/H128-1-10-617-eng.pdf?
- Hwang G, Yoon C, Choi J. A Case-Control Study: Exposure Assessment of VOCs and Formaldehyde for Asthma in Children. *Aerosol Air Qual. Res*. 2011; 11(7):908–914.
- IARC. Agents classified by the IARC monographs. 2012. Available from <http://monographs.iarc.fr/ENG/Classification/index.php>
- Ilgen E, Levsen K, Angerer J, Schneider P, Heinrich J, Wichmann HE. Aromatic hydrocarbons in the atmospheric environment – Part II: univariate and multivariate analysis and case studies of indoor concentrations. *Atmos. Environ*. 2001; 35(7):1253–1264.
- Jia C, Batterman S, Godwin C. VOCs in industrial, urban and suburban neighborhoods-Part 1: Indoor and outdoor concentrations, variation, and risk drivers. *Atmos. Environ*. 2008a; 42(9):2083–2100.
- Jia C, Batterman S, Godwin C. VOCs in industrial, urban and suburban neighborhoods-Part 2: Factors affecting indoor and outdoor concentrations. *Atmos. Environ*. 2008b; 42(9):2101–2116.
- Jia C, Batterman SA, Relyea GE. Variability of indoor and outdoor VOC measurements: An analysis using variance components. *Environ. Pollut*. 2012; 169:152–159. [PubMed: 21995872]
- Jia CR, Batterman S. A Critical Review of Naphthalene Sources and Exposures Relevant to Indoor and Outdoor Air. *Int. J. Environ. Res. Public Health*. 2010; 7(7):2903–2939. [PubMed: 20717549]
- Jo W-J, Sohn J-Y. The effect of environmental and structural factors on indoor air quality of apartments in Korea. *Build. Environ*. 2009; 44(9):1794–1802.
- Johnson M, Hudgens E, Williams R, Andrews G, Neas L, Gallagher J, Ozkaynak H. A participant-based approach to indoor/outdoor air monitoring in community health studies. *J. Exp. Sci. Environ. Epidemiol*. 2009; 19(5):492(410).
- Johnson MM, Williams R, Fan Z, Lin L, Hudgens E, Gallagher J, Vette A, Neas L, Özkaynak H. Participant-based monitoring of indoor and outdoor nitrogen dioxide, volatile organic compounds, and polycyclic aromatic hydrocarbons among MICA-Air households. *Atmos. Environ*. 2010; 44(38):4927–4936.

- Koistinen K, Kotzias D, Kephelopoulous S, Schlitt C, Carrer P, Jantunen M, Kirchner S, McLaughlin J, Møhlhave L, Fernandes EO, Seifert B. The INDEX project: executive summary of a European Union project on indoor air pollutants. *Allergy*. 2008; 63(7):810–819. [PubMed: 18588546]
- Lin C-C, Yu K-P, Zhao P, Whei-May Lee G. Evaluation of impact factors on VOC emissions and concentrations from wooden flooring based on chamber tests. *Build. Environ*. 2009; 44(3):525–533.
- Lin S, Gomez MI, Hwang S-A, Munsie JP, Fitzgerald EF. Self-Reported Home Environmental Risk Factors for Childhood Asthma: A Cross-Sectional Study of Children in Buffalo, New York. *J. Asthma*. 2008; 45(4):325–332. [PubMed: 18446598]
- Logue JM, McKone TE, Sherman MH, Singer BC. Hazard assessment of chemical air contaminants measured in residences. *Indoor air*. 2011; 21(2):92–109. [PubMed: 21392118]
- McCarthy MC, Hafner HR, Chinkin LR, Charrier JG. Temporal variability of selected air toxics in the United States. *Atmos. Environ*. 2007; 41(34):7180–7194.
- MDEQ. Michigan Air Toxic Program, Screening Level List. Michigan Department of Environmental Quality; Michigan: 2012.
- Mendell MJ. Indoor residential chemical emissions as risk factors for respiratory and allergic effects in children: a review. *Indoor air*. 2007; 17(4):259–277. [PubMed: 17661923]
- National Research Council. *Clearing the Air: Asthma and Indoor Air Exposures*. The National Academies Press; Washington, DC: 2000.
- Nazaroff WW, Weschler CJ. Cleaning products and air fresheners: exposure to primary and secondary air pollutants. *Atmos. Environ*. 2004; 38(18):2841–2865.
- Norbäck D, Björnsson E, Janson C, Widström J, Boman G. Asthmatic symptoms and volatile organic compounds, formaldehyde, and carbon dioxide in dwellings. *Occup. Environ. Med*. 1995; 52(6): 388–395. [PubMed: 7627316]
- Parker EA, Israel BA, Robins TG, Mentz G, Lin X, Brakefield-Caldwell W, Ramirez E, Edgren KK, Salinas M, Lewis TC. Evaluation of community action against asthma: A community health worker intervention to improve children's asthma-related health by reducing household environmental triggers for asthma. *Health Educ. Behav*. 2008; 35(3):376–395. [PubMed: 17761540]
- Powrie WD, Wu CH, Molund VP. Browning reaction systems as sources of mutagens and antimutagens. *Environ. Health Persp*. 1986; 67:47–54.
- Rehwagen M, Schlink U, Herbarth O. Seasonal cycle of VOCs in apartments. *Indoor air*. 2003; 13(3): 283–291. [PubMed: 12950592]
- Rumchev K, Spickett J, Bulsara M, Phillips M, Stick S. Association of domestic exposure to volatile organic compounds with asthma in young children. *Thorax*. 2004; 59(9):746–751. [PubMed: 15333849]
- Schlink U, Thiem A, Kohajda T, Richter M, Strebek K. Quantile regression of indoor air concentrations of volatile organic compounds (VOC). *Sci.Total Environ*. 2010; 408(18):3840–3851. [PubMed: 20053420]
- Sexton K, Adgate JL, Ramachandran G, Pratt GC, Mongin SJ, Stock TH, Morandi MT. Comparison of personal, indoor, and outdoor exposures to hazardous air pollutants in three urban communities. *Environ. Sci. Technol*. 2004; 38(2):423–430. [PubMed: 14750716]
- Sly, PD.; Kusel, M.; Franklin, P.; Holt, PG. *Environmental Factors in Children's Asthma and Respiratory Effects*. Elsevier; Burlington: 2011.
- Smedje G, Norback D, Edling C. Asthma among secondary schoolchildren in relation to the school environment. *Clin. Exp. Allergy*. 1997; 27(11):1270–1278. [PubMed: 9420130]
- Stocco C, MacNeill M, Wang D, Xu X, Guay M, Brook J, Wheeler AJ. Predicting personal exposure of Windsor, Ontario residents to volatile organic compounds using indoor measurements and survey data. *Atmos. Environ*. 2008; 42(23):5905–5912.
- Su F-C, Mukherjee B, Batterman S. Trends of VOC exposures among a nationally representative sample: Analysis of the NHANES 1988 through 2004 data sets. *Atmos. Environ*. 2011; 45(28): 4858–4867.

- Su F-C, Mukherjee B, Batterman S. Determinants of personal, indoor and outdoor VOC concentrations: An analysis of the RIOPA data. *Environ. Res.* 2013; 126(0):192–203. [PubMed: 24034784]
- U.S. EPA. An Introduction to Indoor Air Quality: Volatile Organic Compounds (VOCs). US Environmental Protection Agency; Washington, DC: 2011. Available from: <http://www.epa.gov/iaq/voc.html>
- U.S. EPA. Integrated Risk Information System Database for Risk Assessment. US Environmental Protection Agency; Washington, DC: 2012. <http://www.epa.gov/iris/> [accessed on October 25, 2012]
- U.S. National Library of Medicine. National Library of Medicine Hazardous Substances Data Bank Database- Ethyl acetate. Bethesda, MD: 2012. <http://toxnet.nlm.nih.gov/cgi-bin/sis/htmlgen?HSDB> [Access on December 2012]
- Venn AJ, Cooper M, Antoniak M, Laughlin C, Britton J, Lewis SA. Effects of volatile organic compounds, damp, and other environmental exposures in the home on wheezing illness in children. *Thorax.* 2003; 58(11):955–960. [PubMed: 14586048]
- Wallace LA. Human exposure to volatile organic pollutants: Implications for indoor air studies. *Annu. Rev. Energ. Env.* 2001; 26:269–301.
- Wang TH, Shanfield H, Zlatkis A. Analysis of trace volatile organic compounds in coffee by headspace concentration and gas chromatography-mass spectrometry. *Chromatographia.* 1983; 17(8):411–417.
- Weichenthal S, Dufresne A, Infante-Rivard C. Review: Indoor Nitrogen Dioxide and VOC Exposures: Summary of Evidence for an Association with Childhood Asthma and a Case for the Inclusion of Indoor Ultrafine Particle Measures in Future Studies. *Indoor Built Environ.* 2007; 16(5):387–399.
- Weisel, CP.; Zhang, J.; Turpin, BJ.; Morandi, MT.; Colome, S.; Stock, TH.; Spektor, DM. Relationships of Indoor, Outdoor, and Personal Air (RIOPA): Part I. Collection Methods and Descriptive Analyses. Health Effects Institute; 2005. <http://pubs.healtheffects.org/view.php?id=31>
- WHO. Air Quality Guidelines for Europe. second ed. 2000.
- Wieslander G, Norback D, Bjornsson E, Janson C, Boman G. Asthma and the indoor environment: The significance of emission of formaldehyde and volatile organic compounds from newly painted indoor surfaces. *Int. Arch. Occup. Environ. Health.* 1997; 69(2):115–124. [PubMed: 9001918]
- Zhu J, Newhook R, Marro L, Chan CC. Selected Volatile Organic Compounds in Residential Air in the City of Ottawa, Canada. *Environ. Sci. Technol.* 2005; 39(11):3964–3971. [PubMed: 15984771]

Practical implications

Total target VOC concentrations in the Detroit homes ranged from 14 to 2,274 $\mu\text{g}/\text{m}^3$, generally lower than found in earlier studies. However, a subset of houses had elevated concentrations, and levels of 1,4-dichlorobenzene, naphthalene and benzene reached levels commensurate with excess individual cancer risks of 10^{-2} , 10^{-3} and 10^{-4} , respectively. VOC concentrations varied mostly due to between-residence and season effects. The most important sources included cigarette smoking, vehicle-related emissions, building renovation, solvents, household products and pesticides.

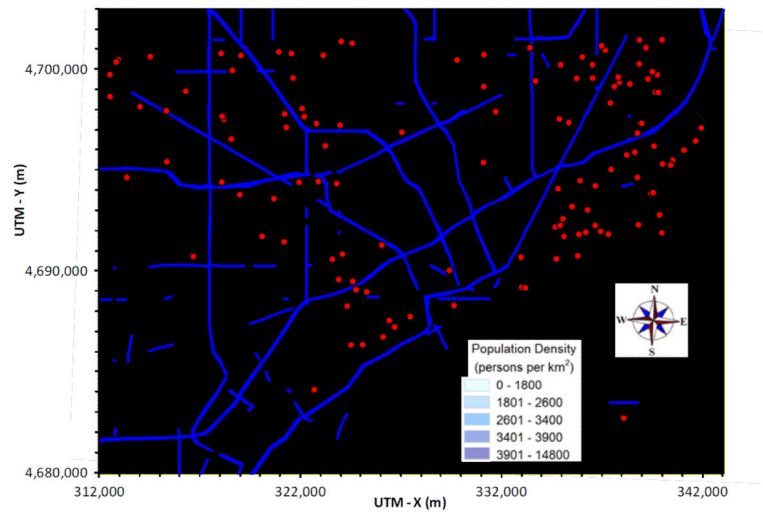


Figure 1. Locations of the 126 study homes (red dots) in Detroit, along with major roads and the population density. The area of the orange circle around each home is proportional to the vehicle-kilometers-driven (VKT) per day within a 100 m buffer of the home.

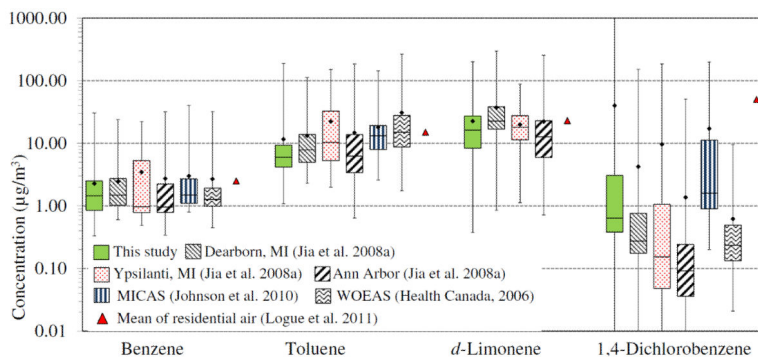


Figure 2. VOC concentrations in this study compared to results from the 3 city study in southeast Michigan (Jia et al. 2008a); Canada (Health Canada; 2006), Detroit (Johnson et al. 2010), and a meta-study (Logue et al. 2011). Box plots show minimum, maximum, 25th, 50th and 75th percentile concentration; points show means.



Figure 3. Variance components for indoor VOCs with detection frequencies above 50% (35 VOCs) showing fraction of variance attributable to four sources: between-residence, between-season, within-residence, and measurement precision. Based on based on 325 visits with valid data from 126 homes.

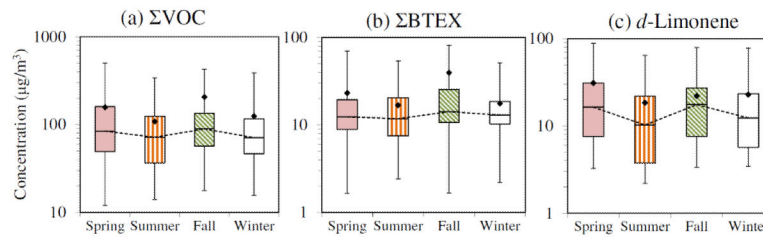


Figure 4. Season average concentrations for Σ VOCs, Σ BTEX and *d*-limonene. Sample sizes were 105, 102, 65 and 53 for spring, summer, fall and winter, respectively. Plots show 10th, 25th, 50th, 75th and 90th percentile concentrations; points show means.

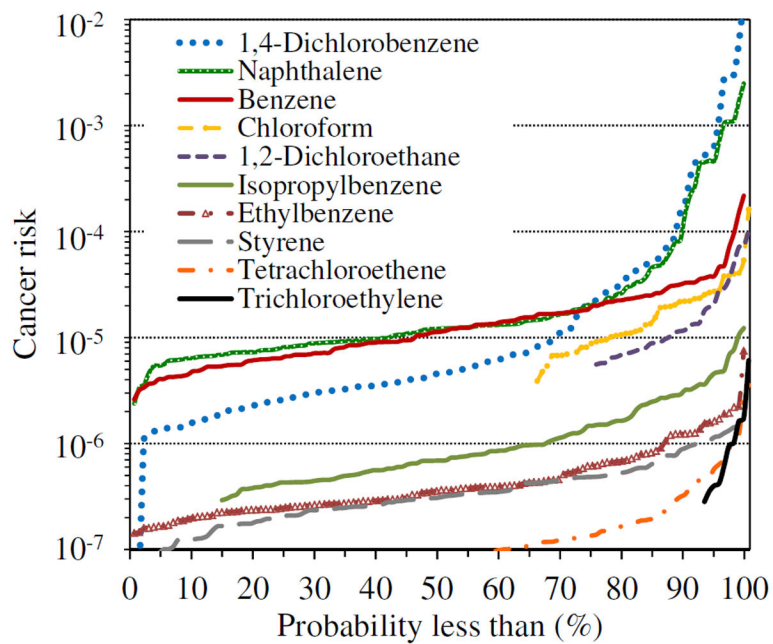


Figure 5. Distribution of cancer risks for selected VOCs in Detroit homes (n=126). Lines may start at high probabilities (not 0) as VOC concentrations in some homes fell below method detection limits (MDLs).

VOC concentrations ($\mu\text{g}/\text{m}^3$) by household average ($n=126$), except 'Max event' which shows highest household average in a single visit based on 325 visits.

Table 1

	MDL	DF(%)	Mean	Std. Dev.	Min	25th	Median	75th	90th	95th	Max	Max event
Aromatics												
Benzene	0.06	100	2.27	3.25	0.33	0.85	1.45	2.50	4.14	4.89	27.93	71.59
Toluene	0.04	100	11.62	23.22	1.08	4.17	6.02	9.30	19.88	30.56	179.84	448.05
Ethylbenzene	0.03	100	1.72	2.29	0.43	0.75	1.08	1.85	3.71	4.85	22.47	59.16
p-Xylene,m-Xylene	0.04	100	6.34	10.01	1.39	2.48	3.29	6.34	13.71	19.98	98.48	260.36
o-Xylene	0.04	100	2.02	3.15	0.34	0.80	1.14	1.81	4.11	6.18	30.46	80.65
4-ethyl toluene	0.17	100	1.92	3.91	0.29	0.59	0.79	1.28	4.02	6.58	30.81	71.22
1,3,5-Trimethylbenzene	0.02	100	0.70	1.09	0.10	0.25	0.33	0.55	1.55	2.48	9.59	23.61
1,2,4-Trimethylbenzene	0.03	100	2.18	3.61	0.29	0.77	1.03	1.72	4.92	8.41	34.29	83.89
Naphthalene	0.09	100	7.88	25.93	0.19	0.65	0.97	1.64	9.34	37.60	200.58	556.24
1,2,3-trimethyl benzene	0.03	99	0.80	1.12	0.01	0.29	0.40	0.83	1.98	2.56	9.52	22.43
Styrene	0.04	98	0.70	0.54	0.02	0.35	0.53	0.82	1.51	1.92	2.72	6.46
2-ethyl toluene	0.02	98	0.74	1.43	0.01	0.25	0.34	0.54	1.44	2.46	12.51	21.24
p-Isopropyltoluene	0.02	98	1.58	1.65	0.01	0.69	1.09	1.71	2.95	4.86	10.75	17.94
1,4-Dichlorobenzene	0.02	98	40.01	212.41	0.01	0.38	0.64	3.06	23.86	88.15	2125.94	4249.23
n-Propylbenzene	0.02	98	0.52	0.97	0.01	0.18	0.25	0.38	1.06	1.82	7.88	16.48
2-methylnaphthalene	0.10	94	0.30	0.24	0.05	0.17	0.23	0.35	0.49	0.79	1.60	3.06
1-Methylnaphthalene	0.08	79	0.16	0.11	0.02	0.09	0.13	0.19	0.25	0.39	0.75	1.45
Isopropylbenzene	0.05	67	0.13	0.18	0.02	0.04	0.07	0.15	0.31	0.45	1.23	2.91
n-Butylbenzene	0.03	49	0.11	0.28	0.02	0.02	0.03	0.07	0.26	0.37	2.30	6.83
Chlorobenzene	0.05	7	0.03	0.03	0.02	0.02	0.02	0.02	0.02	0.08	0.35	0.67
2-Chlorotoluene	0.02	2	0.01	0.04	0.01	0.01	0.01	0.01	0.01	0.01	0.34	0.67
sec-Butylbenzene	0.03	2	0.02	0.04	0.01	0.01	0.01	0.01	0.01	0.01	0.36	0.73
1,2-Dichlorobenzene	0.02	2	0.01	0.05	0.01	0.01	0.01	0.01	0.01	0.01	0.51	1.52
Bromobenzene	0.06	2	0.03	0.01	0.03	0.03	0.03	0.03	0.03	0.03	0.16	0.43
1,2,4-Trichlorobenzene	0.07	1	0.04	0.04	0.03	0.03	0.03	0.03	0.03	0.03	0.43	0.63
Alkanes												

	MDL	DF(%)	Mean	Std. Dev.	Min	25th	Median	75th	90th	95th	Max	Max event
n-Heptane	0.06	100	4.77	15.49	0.35	1.13	1.85	3.53	6.42	12.33	167.73	498.68
n-Octane	0.07	100	1.52	1.56	0.32	0.72	1.10	1.81	2.62	3.24	13.59	35.77
n-Nonane	0.58	97	4.01	8.10	0.29	1.02	1.70	3.35	6.68	16.19	62.92	124.31
n-Decane	0.31	92	3.19	7.16	0.11	0.58	1.02	2.10	6.06	13.54	47.37	93.47
n-Undecane	0.07	99	2.04	6.36	0.04	0.34	0.53	1.08	2.85	6.71	56.38	161.77
n-Dodecane	0.07	99	1.20	2.25	0.04	0.41	0.57	1.08	2.18	3.35	16.96	48.51
n-Tridecane	0.13	97	1.86	3.35	0.06	0.36	0.80	1.55	3.43	9.80	20.18	54.15
n-Tetradecane	0.26	98	5.22	12.36	0.13	1.03	1.83	3.64	9.65	25.53	107.71	310.12
n-Pentadecane	0.19	97	2.02	3.58	0.09	0.55	0.97	1.81	4.57	7.16	25.51	73.49
n-Hexadecane	0.44	90	1.32	0.96	0.22	0.69	1.06	1.69	2.50	3.14	5.27	11.13
Methyl cyclohexane	0.02	99	1.48	3.58	0.01	0.30	0.60	1.15	2.14	4.53	31.99	95.42
Cyclohexane	0.59	53	1.41	2.57	0.20	0.36	0.62	1.19	2.27	7.55	16.40	48.18
Terpenes												
α -Pinene	0.03	99	4.44	7.23	0.01	1.26	1.84	4.22	9.15	16.65	44.46	82.98
d-Limonene	0.56	99	22.56	23.44	0.38	8.34	16.23	27.25	43.30	60.58	172.96	305.68
Halogenated												
Tetrachloroethene	0.09	91	0.71	1.66	0.05	0.15	0.26	0.53	1.35	2.39	13.70	21.80
Chloroform	0.16	35	0.36	0.74	0.08	0.08	0.08	0.39	0.96	1.22	7.07	14.05
1,2-Dichloroethane	0.39	13	0.34	0.51	0.18	0.20	0.20	0.21	0.48	1.01	3.93	7.68
Trichloroethylene	0.09	6	0.07	0.14	0.04	0.04	0.04	0.04	0.04	0.10	1.48	2.70
Methylene chloride	0.71	6	0.54	0.91	0.35	0.35	0.35	0.35	0.38	0.91	7.85	12.43
1,1,1-Trichloroethane	0.39	6	0.26	0.41	0.19	0.19	0.19	0.19	0.19	0.48	4.47	5.79
Dibromochloromethane	0.21	4	0.11	0.04	0.10	0.10	0.10	0.10	0.13	0.18	0.43	0.65
1,1,1,2-Tetrachloroethane	0.21	2	0.13	0.12	0.11	0.11	0.11	0.11	0.11	0.11	1.04	2.28
Bromodichloromethane	0.73	1	0.38	0.05	0.37	0.37	0.37	0.37	0.37	0.37	0.87	1.25
Ketones, ethers, others												
Ethyl acetate	1.64	71	7.34	15.57	0.51	1.47	3.13	6.90	12.96	24.79	117.38	345.52
2-Hexanone	0.38	13	0.52	1.47	0.19	0.19	0.19	0.19	0.64	1.60	12.40	5.82
Ethyl methacrylate	0.65	4	1.22	6.87	0.33	0.33	0.33	0.33	0.33	0.58	73.74	36.82
2-Butanone	0.38	3	0.43	1.50	0.19	0.19	0.19	0.19	0.19	0.19	13.09	2.77
Phenol	1.15	56	1.32	0.60	0.36	0.88	1.23	1.66	1.92	2.44	3.28	12.53

	MDL	DF(%)	Mean	Std. Dev.	Min	25th	Median	75th	90th	95th	Max	Max event
Tetrahydrofuran	1.85	6	1.05	0.78	0.27	0.93	0.93	0.93	0.93	2.58	6.73	1.25
3-Ethenylpyridine	0.38	10	0.24	0.16	0.10	0.19	0.19	0.19	0.38	0.57	1.48	86.00
2,5-Dimethyl furan	0.36	5	0.21	0.09	0.13	0.18	0.18	0.18	0.26	0.35	0.82	25.99
Σ VOC	-	-	150	233	14	53	91	161	249	442	2274	4520

MDL: Method detection limits; DF: Detection frequency;

Table 2

Air exchange rates (AER, h⁻¹) and indoor temperature (Temp, °C) in the living area by season.

	n	Mean	Std.Dev.	Median	Min	Max
AER (h ⁻¹)						
Spring	87	0.81	0.71	0.59	0.14	4.47
Summer	85	1.17	1.28	0.85	0.15	9.79
Fall	53	1.04	0.71	0.91	0.11	3.63
Winter	52	1.11	0.62	0.98	0.20	2.47
Temp (°C)						
Spring	87	21.4	2.6	21.7	14.1	27.9
Summer	85	25.4	2.6	25.7	19.0	29.9
Fall	53	21.7	2.8	21.7	15.6	31.3
Winter	52	20.3	3.6	19.9	12.7	31.6