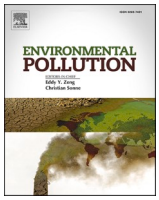
Environmental Pollution 297 (2022) 118756

Contents lists available at ScienceDirect

Environmental Pollution

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



A pilot study characterizing tetrachloroethylene exposure with exhaled breath in an impacted community☆,☆☆

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ARTICLE INFO

Keywords:
Exhaled breath
Tetrachloroethylene
Superfund site
Vapor intrusion
Community exposure
Community-engaged research

ABSTRACT

Martinsville, Indiana overlays four groundwater contamination plumes, including a U.S. Environmental Protection Agency (EPA)-designated Superfund site. The primary contaminants are tetrachloroethylene (PCE), trichloroethylene (TCE), and other volatile organic compounds (VOCs). Martinsville represents many similar communities facing the challenge of groundwater and soil contamination and vapor intrusion, where residents are often frustrated by the lack of help in understanding and addressing the problem. The objective of this study was to evaluate PCE in exhaled breath to identify and quantify exposure to PCE and to explore the extent and level of PCE exposure among community residents. We measured chlorinated VOCs in exhaled breath samples from 38 healthy individuals who lived either in a contamination area or outside any plume area. We also measured VOCs in indoor air and tap water samples collected from 10 homes. PCE was detected in all exhaled breath samples (mean: 6.6 μg/m^3; range: 1.9–44 μg/m^3) and tap water samples (mean: 0.74 μg/L; range: 0.39–0.92 μg/L). PCE was detected in six of nine (66%) homes with air concentrations ranging from 1.6 to 70 μg/m^3, exceeding the EPA action level of 42 μg/m^3. We did not detect TCE or any other chlorinated VOCs in these samples. PCE exposure occurred among individuals living on the EPA Superfund site, as well as among those living on other plume sites and those living outside any known plumes. Preventive measures should focus on identifying highly exposed groups and reducing their exposures, followed by addressing moderately elevated exposures in the community. Our results demonstrated that PCE in exhaled breath can be used as an effective tool in community engaged environmental health research to evaluate the extent and level of community exposure, increase awareness, and promote residents' participation in research and site cleanup decision-making.

1. Introduction

Tetrachloroethylene (PCE) is an industrial solvent widely used in dry cleaning, metal degreasing and the aerospace industry (Agency for Toxic Substances and Disease Registry (ATSDR) 2019a). Due to poor waste management, it has been found in at least 949 of the 1854 Superfund sites designated by the U.S. Environmental Protection Agency (EPA) and many unlisted hazardous waste sites (Agency for Toxic Substances and Disease Registry (ATSDR) 2019b), threatening the health of nearby communities. PCE is a known neurotoxicant. High levels of exposure affect the central nervous system, causing changes in mood, visuospatial memory, attention, and reaction time (Cichocki et al., 2016; Guyton et al., 2014). These effects were mostly observed among workers exposed to high concentrations of PCE in the workplace (Altmann et al., 1995; Cavalleri et al., 1994; Echeverria et al., 1995). Exposures to PCE have also been linked with liver and kidney abnormalities, immunological impairments, reproductive effects, and cancer (Agency for Toxic Substances and Disease Registry (ATSDR) 2019a). Evidence of these associations are primarily from occupational exposures and animal studies, with limited data from individuals residing in the close vicinity

☆ This paper has been recommended for acceptance by Wen Chen.☆☆ The authors declare they have no actual or potential competing financial interests.

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https://doi.org/10.1016/j.envpol.2021.118756
Received 25 September 2021; Received in revised form 22 December 2021; Accepted 25 December 2021
Available online 27 December 2021

to dry-cleaning operations (Ma et al., 2009; McDermott et al., 2005; Schreiber et al., 2002). As a ubiquitous, legacy contaminant, there is widespread community exposure to PCE in the U.S. and worldwide (Folkes et al., 2009; Forand et al., 2012; Johnston and Gibson, 2014), which has significant public health relevance but has not been well studied (Agency for Toxic Substances and Disease Registry (ATSDR) 2019a). This is partly due to the nature of the community exposure, which is low-level, continuous, long-term, multi-media, multi-pathway, and often in conjunction with other chlorinated volatile organic compounds (VOCs), including PCE's degradation products.

Contaminated groundwater and soil are often the major sources of exposure to PCE and other VOCs among impacted communities. Groundwater contamination can affect drinking water if the municipal water for a community is sourced from a contaminated well field. Indoor air, on the other hand, can be contaminated through vapor intrusion, which is the migration of chemical vapors from subsurface into buildings, a process similar to the transport of radon into houses. Vapor intrusion of chlorinated VOCs is a common issue at soil or groundwater contamination sites across the nation and is one of most frequently encountered and difficult contamination challenges to address in the Midwest (Ma et al., 2020). Many studies have focused on measuring contaminants in environmental media and investigating mechanisms of transport and transformation of the contaminants (Eklund et al., 2018; Eklund and Simon, 2007; Folkes et al., 2009; Johnston and Gibson, 2013, 2014; U.S. Environmental Protection Agency, 2012). These approaches, while essential to inform site investigations and remediation practices, leave the precise nature of human exposure and related public health impacts unmeasured. Meanwhile, the multi-media exposure scenario poses substantial challenges to assessing community members' exposure to PCE.

Previous studies indicated that measuring PCE in blood, urine, or exhaled air, or measuring trichloroacetic acid (a metabolite of PCE) in the blood or urine, are useful methods to identify and quantify exposure to PCE. While PCE in blood is a commonly used biomarker, exhaled breath sampling is non-invasive, relatively simple and causes less discomfort to the participants (Agency for Toxic Substances and Disease Registry (ATSDR) 2019a). Approximately 97–99% of PCE total intake is eliminated unmetabolized into the expired air with an elimination half-life of several days (Chiu et al., 2006; Chiu and Ginsberg, 2011; Fernandez et al., 1976; Gordon et al., 1967). Thus, PCE in exhaled breath closely represents a person's recent exposure from multiple exposure routes. PCE in exhaled breath has been measured in occupational exposure studies (McKernan et al., 2008; Monster et al., 1983; Scheepers et al., 2019) and in assessing residential exposure among those living in the vicinity of dry-clean operations (Storm et al., 2011) or having dry-cleaned clothes (Thomas et al., 1991). It was also used in the 1980s to measure individuals' total exposure and resulting body burden of carcinogenic chemicals, including PCE, in several U.S. cities (Wallace et al., 1986; Wallace, 1986; Wallace et al., 1987). Thus, this approach has been demonstrated to produce meaningful exposure data, but not to characterize residents' exposure to PCE among communities living near or on hazardous waste sites.

Martinsville, Indiana represents many similar communities facing the challenge of PCE exposures from contaminated groundwater, soil, and indoor air. The city overlays four groundwater contamination sites (also called "plumes"), including a EPA-designated Superfund site, the Pike and Mulberry Streets PCE Plume. The total size of the groundwater contamination is over 60 acres, all located in the same aquifer. The primary contaminants are PCE, trichloroethylene (TCE), and other VOCs such as vinyl chloride, methyl ethyl ketone, toluene, acetone, and 1,4-dioxane. Most investigations have focused on measuring the concentrations of contaminants in the environment (e.g., in groundwater, soil, indoor air, and sub-slab air) to delineate the contamination sites and inform remedial plans. No communication mechanisms were established to effectively disseminate information to residents. Many community members are not aware of the contamination, but those who are aware are deeply concerned about the exposure and the potential health impacts.

We conducted this pilot study in 2019–2020 in response to concerns raised by the community. The aim of the project was to investigate the feasibility of using exhaled breath analysis to characterize human exposure to PCE and other chlorinated VOCs among Martinsville community residents. We collected samples of exhaled breath, residential indoor air, and municipal tap water to explore the level and extent of PCE exposure in the community. To our best knowledge, it was the first study using PCE in exhaled breath as a measure to evaluate exposure to chlorinated VOCs in a community that is located on contamination sites.

2. Methods

2.1. Study Location and participants

Martinsville is a community of about 11,000 people located in central Indiana. In 2002, the City of Martinsville Water Utility (MWU), which provided drinking water to about 15,000 people, detected PCE in one of the source water wells. The potentially responsible parties included a commercial and institutional dry cleaning and laundry company that operated from 1986 to 1991. While a carbon filtration system has been in place since 2005 to protect the municipal drinking water supply, other exposure pathways have not been investigated until recently. The Indiana Department of Environmental Management (IDEM) carried out a cleaning called "removal action" from 2004 to 2008. The EPA placed the site on the Superfund National Priorities List (NPL) in May 2013, due to the continued increase of PCE concentrations in the groundwater at the site. The EPA site investigation conducted from 2016 to 2017 concluded that human exposure was not under control, mainly due to potential exposure through inhalation of indoor air contaminated via vapor intrusion and consumption of water from contaminated private wells. Three other known groundwater contamination sites are O'Neil, Twig, and Harman-Becker plumes, which are under investigation and remediation supervised by the IDEM and managed by consulting firms (August Mack Environmental, 2019; McKinney and Evans, 2019; CBRE Inc, 2018; Wilcox Environmental Engineering Inc, 2019). The level and extent of human exposure related to these sites had not yet been investigated by any personal exposure measures such as personal air samples or biological monitoring.

Information gathered from a community advisory board established in 2019 indicated a broad spectrum of awareness about the contamination in the community. While many residents know little about the contamination, those who do know are deeply worried about the exposure and believe their health has been impacted, with concerns about cancer, diabetes, hypertension, autoimmune diseases, drug abuse, mental health, and other health conditions (Martinsville Indiana Superfund Site Association, 2016; U.S. Environmental Protection Agency (EPA) 2019). In this pilot study, we recruited 39 healthy non-smokers from the community. These participants were from 26 residences located in different areas of the city (Table 1), some on plumes and some outside any of the known plumes. Study procedures and methods were approved by the Institutional Review Board (IRB) at Purdue University. Participants completed informed consent and assent documents prior to being enrolled.

2.2. Sample collection

We collected samples in December 2019 and January 2020. We asked participants to remove chemicals such as recently dry-cleaned clothes, paint, glues, brake and wood cleaners, spot removers, and suede protectors, from their homes at least 24 h prior to the sample collection. Exhaled breath samples were collected according to NIOSH Method 3704 (precision 11.5%, accuracy 22.5%) (National Institute for Occupational Safety and Health, 1998) with slight modifications, using Tedlar bags (249-01-PP, USA) in a clean environment on a Sunday

Table 1
Characteristics of study population.

	Location			
	Superfund site[a]	Other Plumes	Outside Plumes	Total
Households				
N (%)	12 (46%)	11 (42%)	3 (12%)	26
Indoor air sample	Yes (n = 10)	No	No	
Tap water sample	Yes (n = 10)	No	No	
Participants				
N (%)	24 (61%)	12 (31%) (O'Neil 6, Twigg 4, Harman-Becker 2)	3 (8%)	39[b]
Exhaled Breath Sample (Valid)	Yes (n = 24)	Yes (n = 12)	Yes (n = 3)	39[b]
Gender				
Male, n (%)	15 (38%)	4 (10%)	1 (3%)	20
Female, n (%)	9 (23%)	8 (21%)	2 (5%)	19
Age		Median Age (Range)		
Adults, n (%)	35 (90%)	45 (18–70) years		
Children, n (%)	4 (10%)	13 (12–15) years		

Note.
[a] 12 households were located on the Superfund site. Residential air and tap water samples were collected from 10 of these households, from which there were 22 participants. We did not collect matching residential or tap water samples from the households of other two participants living on the Superfund site, and we did not collect residential air or tap water samples outside the Superfund site.
[b] We collected 39 valid exhaled breath samples from 38 of 39 study participants, as we were not able to collect a valid exhaled breath sample from a participant due to sampling device malfunctions; meanwhile, we collected a repeat exhaled breath sample from a participant to confirm an observed high PCE concentration.

morning to represent participants' exposure from the residential environment. We asked participants to breathe normally for 5 min and then to take a deep breath, hold it for 10 s, exhale half their breath (self--determined) into the air and then exhale the last half of their held breath into a Tedlar bag through a polypropylene disposable mouthpiece connected to the bag. Approximately 1 L of exhaled air was collected. Samples were shipped under cold conditions (<4 °C) and analyzed within 48 h of collection. We collected residential indoor air and tap water samples at 10 homes located on the Superfund site. We collected the indoor air samples (24 h) preceding the collection of the exhaled breath samples to match the exposure window, using SUMMA or SilcoCan canisters that were pre-certified, following the EPA standard method. We collected tap water samples from the kitchen faucet, using glass vials filled to the top to avoid sample loss. Tap water at these homes was connected to the city municipal water system. No well water was collected. We sent the exhaled breath, indoor air, and water samples to a commercial laboratory (Microbac Laboratories, Inc., Merrillville, IN, USA) for analysis. Indoor air and tap water samples were analyzed within 4 days of collection. One repeat exhaled breath sample was collected from a participant to confirm an observed high PCE concentration. One exhaled breath sample and one indoor air sample were void due to sampling device malfunctions. In total, we collected 39 valid exhaled breath samples from 38 participants and 9 indoor air and 10 tap water samples from 10 homes.

2.3. Sample analysis

We analyzed samples following the EPA Air Method, Toxic Organics-15 (TO-15) (U.S. Environmental Protection Agency (EPA) 1999). To ensure the integrity of samples throughout the process, we followed quality assurance and quality control procedures. Targeted analytes included 1,1,1-trichloroethane (CAS# 71-55-6), 1,1,2,2-tetrachloroethane (CAS# 79-34-5), 1,1,2-trichloroethane (CAS# 79-00-5), 1,1-dichloroethane (CAS# 75-34-3), 1,1-dichloroethene (CAS# 75-35-4), 1,2-dichloroethane (CAS# 107-06-2), cis-1,2-dichloroethene (CAS# 156-59-2), PCE (CAS# 127-18-4), trans-1,2-dichloroethene (CAS# 156-60-5), TCE (CAS# 79-01-6), and vinyl chloride (CAS# 75-01-4). The detection limits in the air, breath, and water samples were 0.26 μg/m^3 and 0.26 μg/L for PCE and 0.17 μg/m^3 and 0.26 μg/L for TCE.

2.4. Data analysis

We performed descriptive analysis on contaminant concentrations in exhaled breath, indoor air, and tap water samples. Concentrations reported as lower than the limit of detections (LODs) were assigned a value of LOD/ $\sqrt{2}$ in subsequent analyses (Liu et al., 2011). To compare group means, we used analysis of variance (ANOVA). To estimate associations of natural log-transformed PCE concentrations among 21 breath, 9 indoor air and 10 water samples from 10 homes, we used SAS PROC MIXED with a random intercept for home to account for clustering of individuals within homes. We defined statistical significance as $p < 0.05$. To perform these analyses, we used Microsoft Office 365 Excel Spreadsheet, Minitab statistical software (version 14, Minitab Inc., USA), and SAS (version 9.4, SAS Institute, USA).

3. Results

3.1. Study participant characteristics

Thirty-nine participants from 26 households enrolled in the study; some families had two or more members participating in the study. Twenty-four of the participants lived on or near the Superfund site (the Pike & Mulberry Streets PCE Plume Martinsville, IN), 12 lived on other plumes (six on O'Neil, four on Twigg, two on Harman-Becker), and three lived outside any plumes (Table 1). Half of the participants were female, 90% were adults, and all children were at least 12 years old at the time of the study. All participants were healthy non-cigarette smokers.

3.2. Exhaled breath

PCE was detected in 39 (100%) exhaled breath samples collected from 38 participants, with the concentrations ranging from 1.9 to 44 μg/m^3 (Table 2). We did not detect TCE or any other chlorinated VOCs in any exhaled breath samples. Because one exhaled breath sample had a substantially higher PCE concentration (44 μg/m^3) than the other exhaled breath samples, we collected a second exhaled breath sample from that participant, who lived on the Superfund site, which yielded a PCE concentration of 30 μg/m^3. The average PCE concentration of these two samples was used in the subsequent analyses. The arithmetic mean (AM) and the median of the PCE concentrations in the exhaled breath samples was 5.8 and 4.4 μg/m^3, respectively. There was no significant difference in breath sample PCE concentrations between females (n =

Table 2
PCE concentrations in residential indoor air, tap water, and exhaled breath.

	Indoor Air (μg/m^3)	Tap Water (μg/L)	Exhaled Breath (μg/m^3)
Sample collected, N	9	10	39
#Sample > LOD[a]	6	10	39
#Sample > LOQ[b]	2	none	34
Arithmetic mean (range)	9.1[c] (<0.26–70)	0.74 (0.39–0.92)	6.6 (1.9–44)
Median	1.7[c]	0.83	4.5
Standard Deviation	27.7[c]	0.19	7.9

Note.
[a] LOD (limit of detection) for PCE: < 0.26 μg/m^3 in indoor air; < 0.26 μg/L in water; < 0.26 μg/m^3 in breath.
[b] LOQ (limit of quantification) for PCE: 3.4 μg/m^3 in indoor air; 1.0 μg/L in water; 3.4 μg/m^3 in exhaled breath.
[c] Results lower than LOD were imputed as the LOD/ $\sqrt{2}$.

19) and males (n = 20, $p = 0.83$), or between children (n = 4) and adults (n = 35, $p = 0.24$). When comparing the PCE concentrations in the exhaled breath samples from participants living on the Superfund site (n = 24) with those from participants living outside the Superfund site (n = 15), we also found no significant difference in PCE concentration ($p = 0.75$) (Fig. 1). The PCE concentrations among breath samples from participants living outside the Superfund site had greater variation (a wider interquartile range) compared to breath samples from the participants living on the Superfund site. Furthermore, we also detected PCE in exhaled breath samples collected from the three residents who lived outside any of the plume areas. PCE concentrations in the exhaled breath samples from 35 residents living inside the plume areas had an AM and a median of 6.8 and 4.5 μg/m^3, and PCE concentrations in the exhaled breath samples from three residents living outside the plume areas had an AM and a median of 3.9 and 3.8 μg/m^3 (Fig. 2). These numbers suggest there is PCE exposure occurring in the community beyond the Superfund site. We did not detect TCE or any other chlorinated VOCs in any exhaled breath samples.

3.3. Residential indoor air and municipal water

We collected 24 h integrated indoor air samples from ten homes located in the Superfund site. PCE was detected in six of nine valid samples (66%). The AM of values above LOD was 13.5 μg/m^3, with a median of 2.3 μg/m^3 and a standard deviation (SD) of 27.7 μg/m^3 (Table 2). Notably, PCE concentration in one home reached 70 μg/m^3, exceeding the EPA removal action level of 42 μg/m^3 for chronic exposures in residential air (Georgia Department of Public Health, 2016; The Office of Environmental Health Hazard Assessment, 2019). The highest PCE concentrations were found in two exhaled breath samples from the single resident of this home (44 and 30 μg/m^3). Meanwhile, PCE was detected in 10 (100%) of the tap water samples, with an AM of 0.74 μg/L, a range of 0.39–0.92 μg/L, and a SD of 0.19 μg/L, indicating a narrow distribution of the concentrations. The results were semi-quantifiable, as the detection limit for PCE in water is 0.26 μg/L and the quantification limit is 1.0 μg/L. The EPA drinking water standard, the Maximum Contaminant Level (MCL), for PCE is 5 μg/L. None of these homes were on private wells and the tap water was connected to the municipal water system. We did not detect TCE or any other chlorinated VOCs in any of these samples.

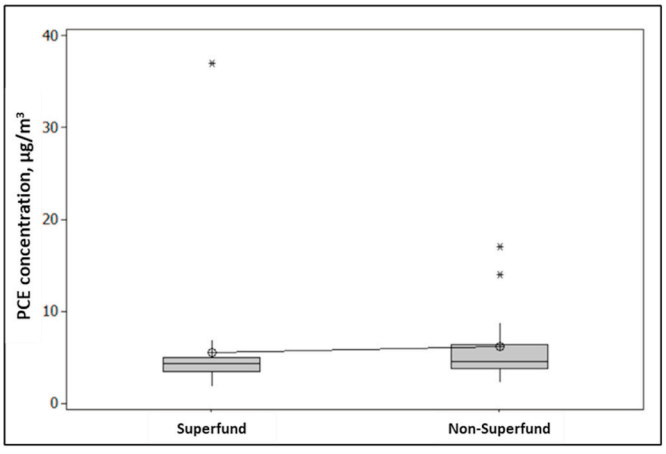

Fig. 1. The PCE concentration (μg/m^3) in exhaled breath samples from subjects living on vs. off the Superfund site ($p = 0.75$). The sample size is n = 23 exhaled breath samples from 23 participants living on the Superfund site (after excluding one invalid exhaled breath sample and taking the average of the repeated samples collected from the same participant) and n = 15 from 15 participants living outside the Superfund site (including three residents living outside any plume areas).

3.4. Associations between PCE in exhaled breath and in indoor air and tap water

Associations of PCE concentrations in exhaled breath samples from 21 residents of the 10 homes where water samples and 9 homes where indoor air samples were collected adjusted for clustering of residents within homes. A doubling of PCE in indoor air resulted in a 46% (95% CI = 39, 54; p = 0.02) increase in exhaled breath PCE and a doubling of PCE in water resulted in a 58% (95% CI = 17, 200; p = 0.49) increase in exhaled breath PCE. However, given that the measured PCE concentrations in the water samples were lower than the LOQ for PCE in water, the association for PCE in tap water and exhaled breath samples may be less accurate than that for indoor air and exhaled breath samples.

4. Discussion

We measured chlorinated VOCs in 39 exhaled breath samples collected from 38 residents and in residential indoor air and tap water samples collected from 10 homes located in the EPA Superfund site in Martinsville, Indiana. The breath samples came from 35 individuals who lived in one of four groundwater contamination areas and from three individuals who lived outside the plume areas. PCE was detected in all 39 (100%) exhaled breath samples (AM: 6.6 μg/m^3; range: 1.9–44 μg/m^3) and in six of nine (66%) homes, with indoor air concentrations in those six ranging from 1.6 to 70 μg/m^3 (LOD: 0.26 μg/m^3). PCE was detected in 10 (100%) tap water samples (AM: 0.74 μg/L; range: 0.39–0.92 μg/L). We did not detect TCE or any other chlorinated VOCs in any of these samples.

PCE in exhaled breath was measured in dry cleaning workers, industrial workers, and those living or working in the vicinity of dry cleaning shops (Dias et al., 2017; McKernan et al., 2008; Scheepers et al., 2019; Schreiber et al., 2002; Solet et al., 1990; Storm et al., 2011). It has also been measured to evaluate exposures to VOCs among general population or diseased children (Delfino et al., 2003; Wallace et al., 1986; Wallace, 1986; Wallace et al., 1987). Concentrations reported in these studies are summarized in Table 3, along with the results of the current study. Occupationally exposed groups or those living or working close to dry cleaners generally had much higher PCE concentrations in the exhaled breath than general public. The results of our study appear to be slightly higher than what recently reported in general population (Delfino et al., 2003; Storm et al., 2011), but lower than residents sharing the building with dry cleaning shops. The EPA Total Exposure Assessment Methodology (TEAM) Study conducted in 1979–1985 reported higher means which could due to higher population background at the time or differences in sample collection and analysis methods (Wallace et al., 1986; Wallace, 1986; Wallace et al., 1987). We recently tested PCE in exhaled breath among university controls and PCE was only detected in one of four participants (data not presented). Our measurements of PCE in exhaled breath samples collected from Martinsville residents indicated that some individuals living in the community were experiencing higher exposure than others were. We measured concentrations over 30 μg/m^3 for one resident, who lived in the home with the highest indoor air concentration of 70 μg/m^3. Exhaled breath samples also indicated that elevated exposure was not an issue pertaining only to those living on the Superfund site, as we observed no significant difference in PCE concentrations in exhaled breath between residents living on or off the Superfund site. Therefore, PCE in exhaled breath can potentially be used in the community to identify resident groups with high, with elevated but not high, and with low exposures. Exposure reduction strategies should be developed accordingly.

There are several considerations to discuss here regarding indoor air PCE concentrations and the relationship between PCE concentrations in exhaled breath and indoor air. First, despite the small sample size, our indoor air data produced a distribution of PCE concentrations that is quite similar to that of the EPA's indoor air data collected in Martinsville

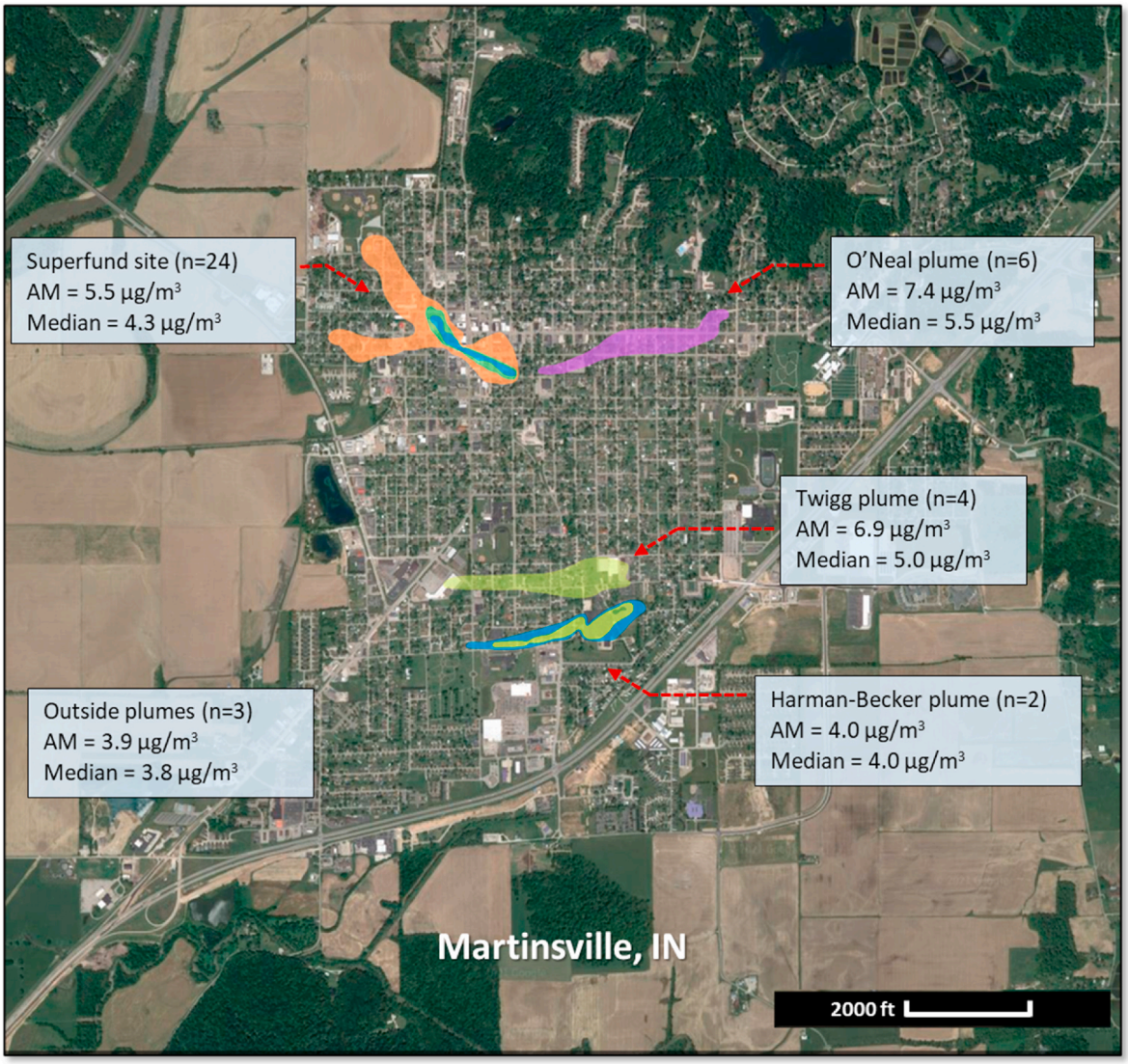

Fig. 2. Number of participants from each plume area and results of PCE in exhaled breath, in μg/m^3. AM: arithmetic mean.

residences during 2016–2017, as indicated by the cumulative distribution curves presented in Fig. 3. In this pilot study, we found that one of the nine homes tested (11%) had a PCE indoor air concentration above the EPA removal action level of 42 μg/m^3 for residential indoor air chronic exposures. Among the thirty-three residential properties tested by the EPA along the footprint of the Superfund site, the EPA found two homes that had PCE indoor air concentrations of 164 and 239 μg/m^3(single measurements), far exceeding the EPA removal action level.

Second, our exhaled breath PCE measurements from residents in the Superfund site were positively and significantly associated with PCE in residential air samples, suggesting that vapor intrusion may be an important exposure pathway in this community. Moreover, the cumulative distribution of PCE in exhaled breath in this study is also similar to that of the indoor air concentration from the EPA investigation (Fig. 3). The latter indicated that about 30% of tested homes had PCE concentrations in indoor air exceeding 3.8 μg/m^3, a Cancer Risk Evaluation Guide (CREG) value derived by the ATSDR. CREG is an estimated contaminant concentration at which exposure will cause no more than one excess case of cancer in a million persons exposed over their lifetime and thus indicates an acceptable level of risk for cancer (Agency for Toxic Substances and Disease Registry (ATSDR) 2019c). Assuming that our exhaled breath measurements are correlated with the indoor air PCE concentration in the community beyond the Superfund site, we estimate that Martinsville residents are exposed to PCE at levels ranging from low (<3.8 μg/m^3) to moderately elevated (between 3.8 μg/m^3 and 42 μg/m^3) and highly exposed (≥42 μg/m^3). The exact extent of the exposure needs to be determined in further investigations.

Third, it is important to note that indoor sources of PCE exposure are common and include, but are not limited to, freshly dry-cleaned clothes and consumer products such as some paint and spot removers, brake and wood cleaners, glues, and suede protectors. Without confirmed exposure pathways, it is difficult to attribute PCE exposure to groundwater contamination or vapor intrusion, especially when the exposure levels are low. To put this in context, PCE has been reported in urban homes in the U.S. with seasonal averages of 0.4 μg/m^3 in spring and 3.5 μg/m^3 during winter (World Health Organization, 2010). Homes affected by vapor intrusion have been reported to have median levels of PCE in indoor air that ranged from undetectable to 8.4 μg/m^3 (U.S. Environmental Protection Agency (EPA) 2011). Using the ATSDR CREG of 3.8 μg/m^3 and the EPA removal action level of 42 μg/m^3 as operative exposure limits, we recommend that the priority of the preventive measures should be focused on identifying highly exposed residents/households in the community (e.g. with indoor PCE air concentration >42 μg/m^3), regardless of their proximity to a contamination site, and reducing their exposures. Moderately elevated exposures (e.g. with 3.8 μg/m^3 < indoor PCE air concentration <42 μg/m^3) should also be

Table 3
PCE in exhaled breath reported in our study and other studies (in μg/m^3).

Country Year of study	Subjects/comments	No. of subjects	Age (years)	Exhaled breath concentrations				Personal air sample, range or mean (SD)	Reference
				Mean (SD)	Minimum/ maximum	Measurable %	Method		
Brazil	Occupationally exposed individuals	25	21–65	325.0[a]	6.0/2635.0	100%	cold fiber solid phase microextraction	14–3205; Median = 599	Dias et al. (2017)
The Netherlands	Occupational exposure at a former dry cleaning shop	2	42–53	22.2 (8.0) pre-shift; 52.6 (15.5) post-shift (Participant A)	NR	100%	BioVOC sampler	1031 (499.3)[b]	Scheepers et al. (2019)
				26.0 (3.6) pre-shift; 63.6 (12.7) post-shift (Participant B)	NR				
USA,	New Jersey					93%	Using a specially-designed spirometer mounted in a van		Wallace et al. (1986)
1979–85	Fall 1981	300	7–85	13	NR/280			45	
	Summer 1982	110	7–85	10	NR			11	
	Winter 1983	49	7–85	11	NR			28	
	California								
	Los Angeles, Feb 1984	110	7–85	12	NR			16	
	Los Angeles, May 1984	24	7–85	9.1	NR			15	
	Contra Costa, June 1984	67	7–85	8.6	NR			5.6	
	North Carolina	23	7–85	3.9	NR	NR		3.3	Wallace et al. (1987)
	North Dakota	23	7–85	8.0	NR	NR		5.0	
USA	Dry cleaning workers	195	NR	52,800 in spring/fall[c]	NR	NR	12-L Saran gas bag	6782–935,937[c]	Solet et al. (1990)
				32,700 in winter[c]	NR	NR			
USA	living or working in vicinity of dry cleaners	17	6 - 60+	afternoon: 413 (164)	110–1000	NR	glass tube with shut-off valves at both ends	948 (640)	Schreiber et al. (2002)
				morning: 439 (166)	107–1125	NR		420 (174)	
USA	Asthmatic children	21	10–16	4.40 (10.77)	0.24/77.89	>75%	SUMMA canister	NR	Delfino et al. (2003)
USA	Dry cleaning workers	18	22–68	3460 pre-shift[c]	NR	NR	1-L sample collection bag	21,025[c]	McKernan et al. (2008)
				8210 post-shift[c]	NR	NR			
USA	living or working in vicinity of dry cleaners and controls								Storm et al. (2011)
	Adults, controls	44	20–55	4.6[d]	2.3–8.5[e]	NR	sorbent tube	2.9	
	Adults, low exposure	37	20–55	18.4[d]	9.6–28.0 [e]	NR		11.6	
	Adults, high exposure	12	20–55	141.4[d]	92.6–213.9[e]	NR		477.9	
	Children, control	49	5–14	3.7[d]	1.9–6.1[e]	NR		3.1	
	Children, low exposure	35	5–14	12.2[d]	5.2–25.4[e]	NR		12.4	
	Children, high exposure	9	5–14	159.5[d]	128.6–192.5[e]	NR		335.8	
USA	living in a community that is located on contamination sites	38	12-60+	6.6	1.9–44	100%	1 L sample collection bag	NR	Present study

[a] Median.
[b] Workplace air sample results.
[c] Converted, reported as *ppm*.
[d] Geometric mean.
[e] Percentile, 25th–75th.

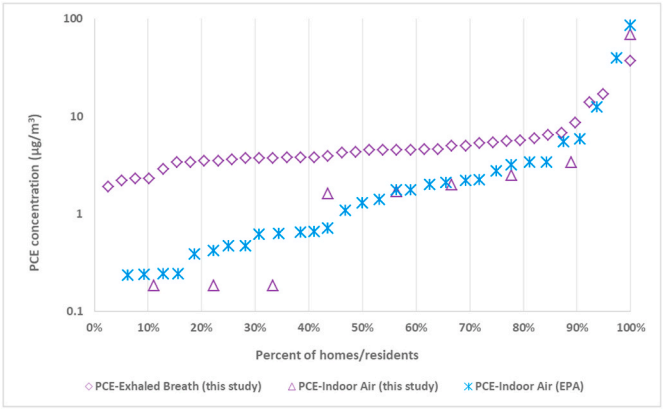

Fig. 3. Cumulative distributions of PCE concentrations in exhaled breath samples collected in this study (n = 38), in the indoor air collected in this study (n = 9), and in the indoor air collected in the EPA 2016–2017 site investigation (n = 33), in μg/m^3. Air samples with PCE concentrations less than the limit of detection (LOD) of 0.26 μg/m^3 were assigned 0.18 μg/m^3, which is LOD/ $\sqrt{2}$. PCE concentrations are averages if multiple samples were taken from a property or participant.

identified and addressed if resources are available.

The PCE concentrations we detected in the municipal tap water were well below the EPA drinking water MCL of 5 μg/L. They are in the range of semi-quantifiable, above the detection limit of 0.26 μg/L but below the quantification level of 1.0 μg/L. Data from MWU also indicate that post-treatment water meets the EPA drinking water standards for both PCE and TCE. Furthermore, our sample, although small, did not indicate a significant association between PCE in drinking water and in residents' exhaled breath. However, it is extremely challenging to develop a definitive public health message on whether the municipal water is safe to drink, since the EPA drinking water Maximum Contaminant Level Goal (MCLG) for PCE is zero. A MCLG is the level of a contaminant below which there is no known or expected health risk; this allows a margin of safety. As a result, many residents in Martinsville drink and cook with bottled water. In addition, due to the operation cost of the filtration system, the water rate for the municipal water has increased several times in the past years and will further increase in 2021–2022, putting the financial burden on the community. According to the EPA's Record of Decision, which explains the remediation plan for the clean-up of the Superfund site, the remedial operation will cover the cost of the filtration system once the remediation starts; however, this is not anticipated to be until 2023–2024. Using bottled water and bearing the cost of the filtration system have added a significant financial burden that has likely created environmental justice issues in the community, where 21.6% of the residents live in poverty (U.S. Environmental Protection Agency (EPA) 2019).

Martinsville represents many communities facing similar problems with groundwater and soil contamination from "legacy" contaminants – PCE has been detected in at least 949 of the 1854 EPA Superfund sites (Agency for Toxic Substances and Disease Registry (ATSDR) 2019b). Vapor intrusion of chlorinated VOCs is one of Indiana's most common and difficult challenges to address. Communities are often frustrated by the lack of help they receive in addressing and even understanding the problem. Meanwhile, little data have been published on personal exposure among residents in these communities. Site investigations at the state and potentially federal levels and subsequent remedial actions usually take decades, and residents are often continuously exposed during this lengthy process. According to the EPA, current human exposure on the Pike and Mulberry Streets PCE Plume Superfund site is "Not under Control," because unsafe human exposure is highly likely; but despite this, the participation rate in the tests conducted by the EPA has been low. Testing PCE in exhaled breath among residents is a unique tool that can help residents relate the contamination to their own and their family's exposures.

Our study results helped Martinsville residents understand that contamination could potentially affect everyone in the community, as PCE was detected in all 38 participants no matter where they lived. We disseminated our preliminary findings in a town hall meeting in Martinsville in February 2020 that was well attended by about 200 residents, news reporters, and local officials. Residents approached researchers expressing their willingness to participate in further projects. The research team and community partners formed a community advisory board to work together on grant proposals and interactions with local officials, the IDEM, and the EPA. We also facilitated the formation of the EPA community advisory group for the Pike and Mulberry Streets PCE Plume Superfund site as part of the Community Involvement Program that is required for the remediation process. Our experience demonstrates that using non-invasive approaches such as exhaled breath sampling in environmental health research can help increase community awareness about VOC contamination and thus increase residents' participation in the process of remedial decision-making by relating contaminations in the community to personal exposures.

We acknowledge the limitations of our study. Our results may not represent the true exposure distributions in the community due to the small sample size, and other factors may have contributed to the observed PCE concentrations in exhaled breath. The fact that we did not detect TCE or any other chlorinated VOCs in any samples might be due to the detection limits of the methods used in this study. Although PCE in exhaled breath can be more readily collected and measured than indoor air samples, which require pre-certified canisters and often take 24 h to collect, there are no exposure limits for PCE in exhaled breath with which to evaluate our results. Furthermore, our results cannot be directly compared with those of previous studies, as different methods were used to collect and analyze breath samples in those studies (McKernan et al., 2008; Scheepers et al., 2019; Storm et al., 2011; Wallace et al., 1986; Wallace, 1986; Wallace et al., 1987). Developing standard methods and field sampling protocols for measuring PCE and other VOCs in exhaled breath could help improve our knowledge on community exposure to these compounds and increase comparability between studies. Future studies should focus on identifying population background level of exposure and factors contributing to elevated exposure. In addition, incorporation of advanced technologies, such as a Proton Transfer Reaction Time-Of-Flight Mass Spectrometer (PTR-TOF-MS), would improve method sensitivity and data throughput.

5. Conclusion

Using exhaled breath samples, we measured PCE exposure among individuals living on the Martinsville EPA Superfund site, as well as among those living on other plume sites and those living outside any plumes. Preventive measures should focus on identifying highly exposed groups and reducing their exposures, followed by addressing moderately elevated exposures in the community if possible. Our results demonstrate that PCE in exhaled breath can be used as an effective tool in environmental health research to evaluate the extent and level of community exposure and promote community engagement in research and remedial decision-making.

Author statement

Sa Liu conceptualized the study. Thomas Edward Wallace contributed to the study design. Eileen Ziyao Yan, Sankalp Srisai Katta, Arteen Fazl Rasti, and Elizabeth Ann Aikins conducted the field research and performed preliminary analyses. Sa Liu wrote the initial manuscript. Jung Hyun Lee and Marwan Alajluoni performed statistical analysis and visualization. Wade Catt contributed to the conceptualization of the manuscript. Mary Ellen Turyk supervised statistical analysis and reviewed the manuscript. All authors edited the manuscript.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

We acknowledge Neeraja Balasubrahmaniam for assistance on sample collection, Deborah Corcoran for participant recruitment, and Juliet Minton for review and comments on the manuscript. The authors sincerely appreciate community residents for their participation in and support to the project. This research was funded by a Purdue University internal grant.

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