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Human exposure to volatile organic compounds: a comparison of organic vapor monitoring badge levels with blood levels

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Abstract We undertook a study in Albany, New York, to investigate whether volatile organic compounds (VOCs) were measurable in the blood and in the breathing-zone air of people exposed to gasoline fumes and automotive exhaust. We sampled blood of 40 subjects, placed organic vapor badges on 40 subjects, and obtained personal breathing-zone samples from 24 subjects. We limited this analysis to 19 subjects who wore the organic vapor badges for at least 5 h. VOC levels, as determined by the organic vapor badges, were highly correlated with blood levels of these same compounds. Using detection in blood as the gold standard, we found the badges to be more sensitive than conventional charcoal tube samples in detecting low levels of methyl tert-butyl ether (0.60 vs 0.08), toluene (0.95 vs 0.64), and *o*-xylene (0.85 vs 0.64). In this study, organic vapor badges provided data on VOC exposure that correlated with blood assay results. These organic vapor badges might provide a convenient means of determining human exposure to VOCs in epidemiologic studies.

Key words Vapor badge · Volatile organic compound · Epidemiology · Benzene

Introduction

In April 1993, the Centers for Disease Control and Prevention (CDC) was invited to assist New York state health officials in investigating whether exposure to methyl tert-butyl ether (MTBE) in fuels was measurable in people occupationally exposed and people not occupationally exposed (Mannino et al. 1993) to low concentrations of this chemical. Albany was selected as the site for this investigation because MTBE is used in only small (generally less that 5% by weight) concentrations in this area. As part of this study, participants' exposure to volatile organic compounds (VOCs) was determined via organic vapor badges and personal breathing zone charcoal tube samples on the same day that their blood was collected for VOC level measurement. We wanted to determine how well the VOC levels from the organic vapor badges and charcoal tube samples correlated with VOC levels measured in the blood.

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Materials and methods

The protocol for this investigation was reviewed and approved by the CDC Institutional Review Board before we began collecting data. People who provided venous blood samples signed informed consent forms. Study participants received no compensation or incentives and constituted a convenient, but not random, sample of people 18 years or older who worked or attended college at a variety of locations around Albany, New York.

Field activities were conducted during the week of 3 May 1993. Phlebotomists from the New York State Department of Health collected venous blood samples from 40 volunteers, including 19 city commuters and 21 people who worked around automobiles or automobile exhaust. Blood samples from commuters were collected at the end of the morning commute and blood samples from other subjects were collected in an office at the worksite at the end of the workshift. The phlebotomists used special collection tubes (Ashley et al. 1992) and followed procedures to ensure the accuracy with which low levels of VOCs were measured. Blood samples were refrigerated and shipped on ice to the Division of Environmental Health Laboratory Sciences, National Center for Environmental Health, CDC, where a modified technique of gas chromatography/mass spectrometry (Ashley et al. 1992) was used to measure levels of MTBE, tertiary butyl alcohol (TBA, a metabolite of MTBE (NIOSH 1984; Savolainen et al. 1985; Leuschner et al. 1991)], benzene, *o*-xylene, *m,p*-xylene, toluene, 1,1,1-trichloroethane, and tetrachloroethene.

The analytical limits of detection for measured compounds were 0.050 μg/l for MTBE, 0.500 μg/l for TBA, 0.030 μg/l for benzene, 0.020 μg/l for ethylbenzene, 0.040 μg/l for *o*-xylene, 0.033 μg/l for *m,p*-xylene, 0.092 μg/l for toluene, 0.086 μg/l for 1,1,1-trichloroethane, and 0.030 μg/l for tetrachloroethene.

Organic vapor badges (3M Company, Minneapolis, Minn.) were placed on all subjects who had blood drawn. Occupationally exposed workers wore these badges for their entire workshift, and commuters wore them for the time they were commuting. The badges were sealed at the time the blood was drawn and subsequently analyzed by the New York State Department of Health. The badges were eluted with 1.5 ml of carbon disulfide which contained two internal standards, 1,4-difluorobenzene (4 mg/l) and dibromoethane (50 μg/l). The solvent was added to the badge sampling chamber through one of the inlets in the sealing cap. The inlet was resealed and the solvent allowed to stand in contact with the badge adsorbent for 30 min with occasional shaking. The resulting solution was removed and analyzed by gas chromatography using both electron capture detection (ECD) for the halogenated compounds and flame ionization detection (FID) for MTBE and hydrocarbons. The chromatography column used was a 105 × 0.53 mm fused silica column coated with Rtx 502.2 liquid phase of 3 μm film thickness (Restex Corporation, Belfonte, Pa.). The analysis conditions for the ECD system were column head pressure 1.05 kg/cm^2, injector temperature 220°C, detector temperature 300°C, and a column oven temperature programmed from 50°C to 220°C at a rate of 4°C per minute, holding 10 min at the initial temperature and 30 min at the final temperature. We used a solvent vent valve with the ECD to vent the solvent peak away from the detector while maintaining make-up gas flow to the detector. The valve was electronically switched at 2 min after the run start to vent solvent and the flow returned from the column to the detector at 12.4 min prior to the elution of target compounds. The analysis conditions for the FID system were column head pressure 1.05 kg/cm^2, injector temperature 220°C, detector temperature 280°C and a column oven temperature programmed from 35°C to 220°C at a rate of 8°C per minute, holding 10 min at the initial temperature and 30 min at the final temperature. Venting was not needed with the FID system. The average air concentration of target compounds was calculated using the diffusion rate obtained from 3M Company for the specific badge configuration, the elapsed sampling time, and the amount detected in the elution solvent using internal standard quantitation. The limits of detection (for a 400-min exposure) were 40.0 μg/m^3 for 8 μg/m^3 for toluene, ethylbenzene, *m,p*,-xylene, and *o*-xylene, 2 μg/m^3 for 1,1,1-trichloroethane and 1 μg/m^3 for tetrachloroethene. For longer exposures the limits of detection would be slightly lower.

A certified industrial hygienist monitored levels of MTBE, benzene, toluene, and xylene present in a subset of 24 workers who were occupationally exposed. Breathing zone air was sampled at a nominal flow rate of 0.2 l/min for approximately 8 h during the workday. After sampling, the charcoal tubes were removed and desorbed with 2 ml of carbon disulfide, and the resulting solution was analyzed by gas chromatography-FID (NIOSH 1984, method #1615). The analytical limit of detection was 0.010 mg per sample for MTBE, toluene, and benzene and 0.002 mg/sample for xylene. The limits of detection (for a 400-min exposure) were 125.0 μg/m^3 for MTBE, toluene, and benzene and 25 μg/m^3 for xylene.

We restricted these analyses to 19 subjects who wore the organic vapor badges for at least 300 min (range 320–482 min). If the level of the compound was not detectable, we set the level at one-half the detection limit. We did our analyses after using natural logarithms to transform the data, which had a positively skewed distribution (Shott 1990). We used the statistical program SAS (SAS Institute, Cary, N.C.) to determine Pearson correlation coefficients between organic vapor badge measurements and blood determinations and between personal air sampler measurements and blood determinations in both the overall group and in subgroups stratified by smoking status. We determined the sensitivity of the organic vapor badges and the personal air samplers using detectable blood levels of the compound of interest as the gold standard. Using Fisher's exact test, we also compared the sensitivity of the organic vapor badges with that of the charcoal tubes in detecting MTBE, toluene, and *o*-xylene.

Results

Study participants

Of the 19 subjects included in this study, 12 were nonsmokers and seven were current smokers. The demographic characteristics of the study population and the levels of MTBE and toluene detected in the blood, on the organic vapor badges, and in the charcoal tubes are shown in Table 1.

Table 1 Demographic characteristics of study population; levels of MTBE in blood (μg/l), vapor badges (μg/m^3), and charcoal tubes (μg/m^3); and levels of toluene in blood (μg/l), vapor badges (μg/m^3), and charcoal tubes (μg/m^3). Charcoal tubes were placed on only 14 subjects. (*ND* not detected)

Age	Sex	Job exposure	Smoking status	MTBE level			Toluene level		
				Blood	Badge	Tube	Blood	Badge	Tube
43	M	Exhaust	No	0.08	ND	ND	1.15	340	229
24	F	Exhaust	No	0.12	ND	ND	0.23	67	ND
35	M	Exhaust	No	0.11	ND	ND	0.28	63	ND
32	F	Exhaust	No	ND	ND		0.21	35	
44	M	Exhaust	No	ND	ND		0.14	19	
43	M	Exhaust	No	ND	ND		0.17	31	
52	M	Exhaust	Yes	0.08	ND	ND	0.96	59	ND
40	M	Exhaust	Yes	0.11	ND	ND	0.97	180	ND
39	M	Exhaust	Yes	ND	ND	ND	0.76	ND	ND
20	M	Gasoline	No	0.20	530	ND	1.07	280	229
33	M	Gasoline	No	0.38	530	ND	1.13	240	229
46	M	Gasoline	No	0.24	250	ND	1.06	160	115
25	M	Gasoline	No	0.46	5400	ND	1.58	210	229
26	M	Gasoline	No	0.48	1900	ND	2.07	290	229
43	M	Gasoline	No	0.58	1500	ND	1.68	300	229
26	M	Gasoline	Yes	1.50	2000		1.31	800	
32	M	Gasoline	Yes	0.34	460	ND	5.43	270	229
33	M	Gasoline	Yes	0.59	1700	505	3.82	1800	2789
35	M	Gasoline	Yes	0.09	ND		0.73	83	

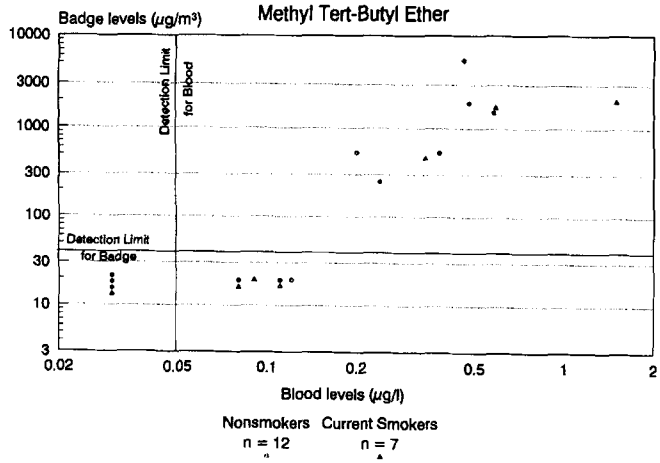

Fig. 1 Levels of MTBE, as determined by organic vapor badges, are plotted against blood levels of MTBE

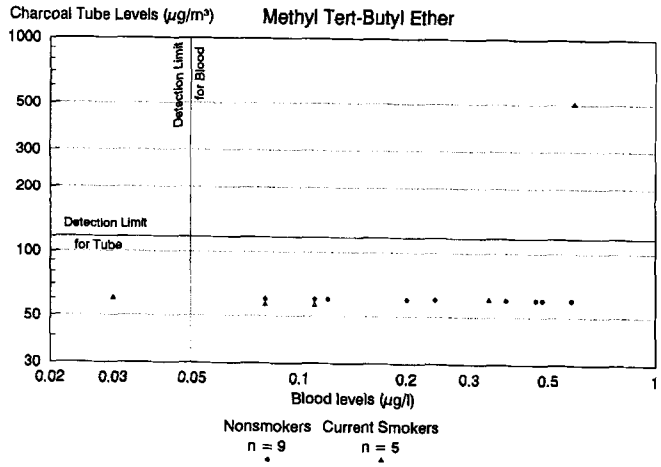

Fig. 2 Levels of MTBE, as determined by charcoal tubes, are plotted against blood levels of MTBE

Blood levels of MTBE and other VOCs

MTBE was detected in the blood of 15 of 19 subjects (Table 1). Organic vapor badges detected MTBE in 9 of 15 subjects with detectable blood levels, and the charcoal tube detected MTBE in 1 of 13 subjects with detectable blood levels (Figs. 1, 2). The nine subjects who had MTBE detectable in the organic vapor badge were all either automotive mechanics or gasoline pumpers (Table 1). Toluene and *o*-xylene were detected in the blood of all subjects (Table 2). Organic vapor badges detected toluene in 18 of 19 subjects, and the charcoal tube detected toluene in 9 of 14 subjects (Table 1). Similarly, organic vapor badges detected *o*-xylene in 18 of 19 subjects, and the charcoal tube air sampler detected xylene in 9 of 14 subjects (Figs. 3, 4).

Correlation between organic vapor badge levels and blood levels

In the overall group, vapor badge levels of organic compounds were highly correlated with blood levels (Tables 3, 4). In addition, MTBE levels, as determined by the vapor badges, were highly correlated with levels of other gasoline components measured in the blood: ethylbenzene ($P < 0.001$), *o*-xylene ($P < 0.001$), *m,p*-xylene ($P < 0.001$), and TBA ($P = 0.009$). The correlation coefficients varied by subjects' smoking status.

Correlation between charcoal tube levels and blood levels

We did not do a correlation analysis on MTBE because it was detected in only one charcoal tube. Xylene and toluene levels, as determined by the charcoal tubes, were correlated with blood levels in the overall group and in the subgroups of nonsmokers and smokers (Table 4).

Sensitivity and specificity of badges and personal air samplers

The organic vapor badges were more sensitive than the conventional charcoal tubes in detecting MTBE. Using MTBE detection in blood as the gold standard, we found that vapor badges had a sensitivity of 0.60 for MTBE and that charcoal tubes had a sensitivity of 0.08 for MTBE. Using toluene detection in blood as the gold standard, we found that vapor badges had a sensitivity of 0.95 for toluene and that charcoal tubes had a sensitivity of 0.64 for toluene. Using *o*-xylene detection in blood as the gold standard, we found that vapor badges had a sensitivity of 0.85 for *o*-xylene and that charcoal tubes had a sensitivity of 0.64 for xylene. No other compounds were measured by both methods. When we used detection in blood as the gold standard in measuring MTBE, toluene, and xylene levels, vapor badges and charcoal tubes had specificities of 1.00 (i.e., if the compound was detected in the vapor badge or air sampler, it was always detected in the blood).

Discussion

In this study, the organic vapor badges were more sensitive than the conventional charcoal tubes in detecting low-level exposures to MTBE and other VOCs. In addition, these levels were highly correlated with the levels we detected in our blood assays.

We found the strongest correlation to be between air levels and blood levels of gasoline components such as

Table 2 Median levels and ranges of MTBE, TBA, benzene, ethylbenzene, *o*-xylene, *m,p*-xylene, xylene, toluene, 1,1,1-trichloroethane, and tetrachloroethene measured in blood (μg/l), organic vapor badges (μg/m^3), and charcoal tubes (μg/m^3). (*ND* not detectable)

	Blood levels: median (range)	Vapor badge levels: median (range)	Charcoal tube levels: median (range)
MTBE	0.24 (ND–1.50	1500 (ND–5400)	ND (ND–505)
TBA	2.24 (0.69–13.80)		
Benzene	0.29 (0.12–1.97)		41 (ND–176)
Ethylbenzene	0.23 (0.04–3.03)	54 (ND–780)	
o-Xylene	0.32 (0.07–2.01)	61 (ND–350)	
m,p-Xylene	0.95 (0.16–9.78)	230 (ND–2400)	
Xylene			221 (ND–1901)
Toluene	1.07 (0.14–5.43)	240 (ND–1800)	229 (ND–2789)
1,1,1-Trichloroethane	0.23 (0.03–0.94)	11 (ND–310)	
Tetrachloroethene	0.12 (0.02–0.90)	3 (ND–150)	

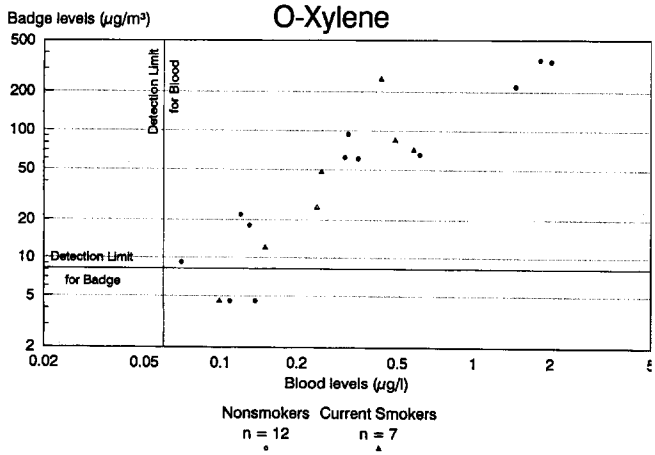

Fig. 3 Levels of *o*-xylene, as determined by organic vapor badges, are plotted against blood levels of *o*-xylene

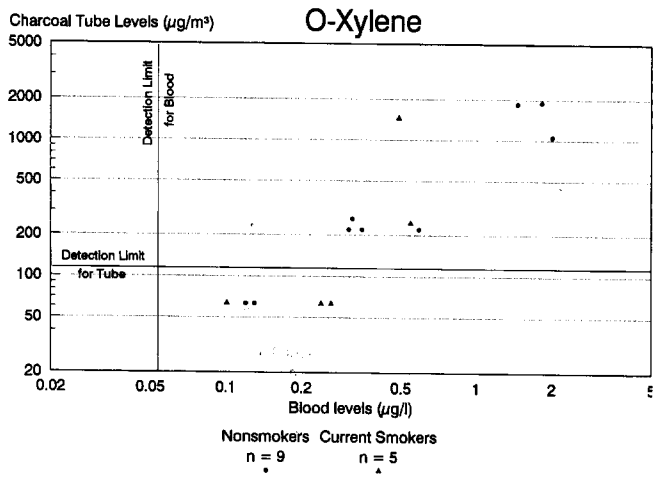

Fig. 4 Levels of xylene, as determined by charcoal tubes, are plotted against blood levels of *o*-xylene

m,p-xylene, *o*-xylene, and MTBE. This likely reflects the occupational exposures of our study group.

Although the subjects in this study had occupational exposures to VOCs, the levels of these exposures were generally lower than those detected in other studies of exposed workers. The median blood levels of benzene among participants in our study was 0.29 μg/l. In other studies of people with low exposure levels, study participants had median levels of 0.24 μg/l (Brugnone et al. 1989), 0.27 μg/l (Brugnone et al. 1989), and 0.26 μg/l (Angerer et al. 1992); more highly exposed chemical workers had a mean level of 1.2 mg/l (Kawai et al. 1992a). Participants in our study had a median blood toluene level of 1.07 μg/l, which is lower than median levels of 90 μg/l (Kawai et al. 1992a) and 20 μg/l (Kawai et al. 1992b) reported in other studies of people with high levels of occupational exposure to toluene. Similarly, the median levels of *m,p*-xylene (0.95 μg/l) and *o*-xylene (0.32 μg/l) that we found were much lower than the levels of *m,p*-xylene (60 μg/l) and *o*-xylene (35 μg/l) reported in another occupationally exposed population (Kawai et al. 1992b). Blood levels of VOCs are known to be good predictors of VOC exposure (Angerer 1985; Brugnone et al. 1986), even though metabolism and excretion decrease levels over time (Brugnone et al. 1986). Another limitation of blood levels is that they may not reflect short-term, high-level exposures, although this is also a limitation of most exposure analyses, with the exception of real-time monitoring (Daisey 1989).

Table 3 Pearson correlation coefficients and *P*-values derived from a comparison of the natural logarithm of blood levels of MTBE, ethylbenzene, tetrachlorethene, toluene, *m,p*-xylene, *o*-xylene, and 1,1,1 trichloroethane (*111-TCE*) with the natural logarithm of levels as measured by organic vapor badges; for some VOCs not all subjects had assays completed

	MTBE	Ethylbenzene	Toluene	*m,p*-Xylene	*o*-Xylene	111-TCE	Tetrachloroethene
All subjects ($n = 19$)							
Coefficient	0.81	0.79	0.52	0.80	0.78	0.43	0.72
P-value	< 0.001	< 0.001	0.021	< 0.001	< 0.001	0.068	0.005
Number	19	19	19	18	19	19	13
Nonsmokers ($n = 12$)							
Coefficient	0.92	0.82	0.88	0.94	0.90	0.47	0.58
P-value	< 0.001	0.001	< 0.001	< 0.001	< 0.001	0.123	0.170
Number	12	12	12	11	12	12	7
Smokers ($n = 7$)							
Coefficient	0.86	0.66	0.48	0.71	0.80	0.86	0.86
P-value	0.013	0.105	0.271	0.073	0.030	0.013	0.030
Number	7	7	7	7	7	7	6

Table 4 Pearson correlation coefficients and *P*-values derived from a comparison of the natural logarithm of blood levels of benzene, toluene, and *o*-xylene with the natural logarithm of levels as measured by charcoal tube; for some VOCs not all subjects had assays completed

	Benzene	Toluene	*o*-Xylene
All subjects ($n = 14$)			
Coefficient	0.33	0.60	0.82
P-value	0.244	0.024	0.001
Number	14	14	13
Nonsmokers ($n = 9$)			
Coefficient	0.47	0.84	0.85
P-value	0.206	0.004	0.007
Number	9	9	8
Smokers ($n = 5$)			
Coefficient	0.43	0.87	0.88
P-value	0.471	0.055	0.048
Number	5	5	5

The median air level of benzene in this study was 41 $\mu g/m^3$, and in other studies it has been reported to be 7 $\mu g/m^3$ and 36 $\mu g/m^3$ in low-exposure environments (Brugnone et al. 1989). The median air level of toluene in this study was 240 $\mu g/m^3$, which is lower than the median levels of 3500 $\mu g/m^3$ (Kawai et al. 1992a) and 7300 $\mu g/m^3$ (Kawai et al. 1992b) reported in high-exposure occupational environments.

Passive badges have been used for many years by industrial hygienists to detect organic vapor exposures (Kawai et al. 1991; Pristas 1991). Despite the ease with which these badges can be used, conventional charcoal tubes and pumps are still used to determine exposures to organic compounds (Palassis et al. 1993). Although other researchers have correlated organic vapor badge levels with blood levels, the exposure levels in their studies (Kawai et al. 1991) have been much higher than those reported in this study. The results of our study may enable researchers to use these badges in studies of people with low exposures to organic compounds. We found that vapor badges were more sensitive in detecting VOCs than were the charcoal tubes. This finding, however, is related to the lower limit of detection in the vapor badges compared to the charcoal tubes (40 $\mu g/m^3$ vs. 125 $\mu g/m^3$). Under different analytic conditions or with different equipment the charcoal tubes may have functioned as well as or better than the vapor badges. This, however, is independent of our other observation that badge levels of VOCs were highly correlated to blood levels.

Organic vapor badges have other advantages. They are easy to use, and subjects would need minimal instruction in order to apply them at the start of their workshift. They do not interfere with body movement and do not add any appreciable weight to the person. In addition, they do not need to be monitored throughout the course of the workshift. In our study, we had several subjects who refused to wear the charcoal tube personal air sampler but were willing to wear the organic vapor badge.

The main limitations of this study are its small size and the relatively small range of the exposure levels. Passive vapor badges may be less accurate than other devices at higher exposure levels. Despite these limitations, we believe that passive vapor badge technology holds great promise in both industrial hygiene and epidemiologic applications.

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