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Determinants of environmental styrene exposure in Gulf coast residents

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Abstract

Background: In a previous study of exposure to oil-related chemicals in Gulf coast residents, we measured blood levels of volatile organic compounds. Levels of styrene were substantially elevated compared to a nationally representative sample. We sought to identify factors contributing to these levels, given the opportunities for styrene exposure in this community.

Methods: We measured blood styrene levels in 667 Gulf coast residents and compared participants' levels of blood styrene to a nationally representative sample. We assessed personal and environmental predictors of blood styrene levels using linear regression and predicted the risk of elevated blood styrene (defined as above the National Health and Nutrition Examination Survey 95th percentile) using modified Poisson regression. We assessed exposure to styrene using questionnaire data on recent exposure opportunities and leveraged existing databases to assign ambient styrene exposure based on geocoded residential location.

Results: These Gulf coast residents were 4–6 times as likely as the nationally representative sample to have elevated blood styrene levels. The change in styrene (log ng/mL) was 0.42 (95% CI: 0.34, 0.51) for smoking, 0.34 (0.09, 0.59) for time spent in vehicles and 1.10 (0.31, 1.89) for boats, and –0.41 (–0.73, –0.10) for fall/winter blood draws. Residential proximity to industrial styrene emissions did not predict blood styrene levels. Ambient styrene predicted elevated blood styrene in subgroups.

Conclusions: Personal predictors of increasing blood styrene levels included smoking, vehicle emissions, and housing characteristics. There was a suggestive association between ambient and blood styrene. Our measures of increased regional exposure opportunity do not fully explain the observed elevated blood styrene levels in this population.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

INTRODUCTION

To address community concerns about exposure to potentially harmful oil spill-related chemicals among Gulf coast residents, we measured blood volatile organic compound (VOC) levels in a subset of Gulf Long-Term Follow-up Study (GuLF STUDY) participants 2–3 years after the *Deepwater Horizon (DWH)* oil spill. We previously reported that blood levels of specific oil-related VOCs such as benzene, toluene, ethylbenzene and xylenes were similar to those found in the National Health and Nutrition Examination Survey (NHANES) (1). Among the VOCs included in the CDC-based test panel, only styrene was substantially elevated. We further investigated styrene levels due to increased exposure opportunity in the region.

Styrene, a hazardous air pollutant, is an established neurotoxicant at occupational levels (2–4). However, it has not been studied at environmental levels experienced by the general population. Styrene is used in plastics, fiberglass, rubber, and resins to manufacture building materials and consumer products, such as fiberglass boats, automotive parts, car tires, Styrofoam, and plastic drinking glasses (2). The U.S. produces over 12 billion pounds of styrene annually, with atmospheric emissions of 28 million pounds per year (2, 5). Environmental release of styrene from the manufacture, use, and disposal of styrene-based products occurs primarily through the air (6).

Emissions from industrial activities and motor vehicle exhaust are the primary sources of styrene in outdoor air. Ambient measurements of styrene typically show airborne concentrations less than 1 part per billion by volume (ppb). Rural or suburban air generally contains lower concentrations of styrene than urban air (7), which is attributed to increased motor vehicle emissions in urban areas (8). Elevated ambient styrene concentrations are observed near styrene emitting industries, suggesting that individuals living near manufacturing or processing facilities may experience increased styrene exposure (2). Ambient styrene's atmospheric lifetime is 1 to 2 days (2) and the half-life of styrene in blood is approximately 13 hours (3).

Indoor air styrene levels result primarily from tobacco smoke, off-gassing of building materials and consumer products, and emissions from photocopiers and laser printers (2). Smoking is the single most important individual predictor of human exposure to styrene (2, 9–15). Exposure to environmental tobacco smoke is also associated with higher styrene exposure, particularly for non-smokers living with a smoker (11, 14). Typically, indoor air contains higher styrene levels than outdoor air (13).

Inhalation of contaminated air is the principal route of styrene exposure for the general population (2), and the main source of concern for health effects due to styrene toxicity (16). The highest styrene exposures generally occur in the workplace, where styrene-exposed workers have blood levels that are 25 times higher on average than those in the general population (3, 17, 18). Occupational exposure to airborne styrene has been well-characterized among reinforced plastics manufacturing workers (19–25).

The Gulf States are home to many styrene-emitting industries and over half of all U.S. styrene production (2, 26). In addition to a prolific petrochemical industry, the Gulf region is

home to many industrial and manufacturing facilities that use and emit styrene. This geographic clustering of industries potentially exposes Gulf residents to a disproportionately high intensity of environmental styrene emissions.

METHODS

Study Design and Participants

Approximately 2–3 years after the April 2010 *Deepwater Horizon (DWH)* disaster and oil spill, we took advantage of the ongoing enrollment of participants in the GuLF STUDY to recruit individuals living in the Gulf region for a sub-study of current blood levels of VOCs (27). The GuLF STUDY is a prospective cohort of adults (ages 21 and older) who participated in oil spill response activities and others who received safety training but were not hired following the *DWH* disaster. A detailed description of this study is available elsewhere (28). As part of their participation in the sub-study, termed the Chemical Biomonitoring Study (CBS), 994 individuals provided blood specimen sufficient for quantification of styrene levels. Because styrene is rapidly cleared from the body and blood measurements were obtained 2–3 years after the oil spill, these levels represent exposures occurring around the time of sample collection (i.e., they are not due to oil spill cleanup work).

In concert with ongoing home visits for the GuLF STUDY we enrolled participants for the CBS between September 2012 and May 2013. Eligible participants were 11 193 English- or Spanish-speaking individuals who lived in Florida, Alabama, Mississippi, Louisiana, or eastern Texas and participated in a home visit examination. CBS participants were a convenience sample selected from among GuLF STUDY participants whose home exams were scheduled in the later months of study enrollment and participation involved providing an extra blood sample for measuring styrene and other compounds and completing a questionnaire about usual and past 24-hour exposure opportunities. Study personnel geocoded participants' residential locations using handheld global positioning system devices. We initially oversampled nonsmokers and women, but because of timing of the parent study, we ultimately invited all remaining eligible participants to participate. Of the 994 individuals who provided blood samples of sufficient quantity and quality to measure styrene levels (29–31), 935 also had both a measurement for the tobacco smoking biomarker 2,5-dimethylfuran (2,5-DMF) and provided self-reported smoking information. These 935 participants were included in analyses comparing blood VOC levels between the CBS and the NHANES 2005–2008 (32, 33).

After we excluded participants who did not complete the questionnaire on recent exposure opportunities (n=125) or were missing data on demographic factors (n=142), we restricted the remaining analyses to participants who had complete information on all modeled predictors (n=667).

Participants provided written consent, and the Institutional Review Board of the National Institute of Environmental Health Sciences approved this study.

Exposure Monitoring Questionnaire

We collected demographic, socioeconomic, occupational, lifestyle, and health information during the GuLF STUDY enrollment and home visit interviews. CBS participants additionally answered questions about potential contributors to blood styrene levels. These included residential building characteristics, self-reported proximity to industrial operations and waste sites (i.e., participants were asked to indicate whether they lived within a half mile of each of the following: major highways, a boatyard, docks, an oil refinery, a petroleum storage or transfer facility, a gas station, a factory, a power plant, a hazardous waste or Superfund site, and a landfill), personal chemical exposures, perceived air quality, drinking and bathing water source, smoking and tobacco use, and hobbies and activities, including exposure opportunities in the past 24 hours (e.g. refueling vehicles or lawn equipment). We used an adapted version of the Centers for Disease Control and Prevention (CDC) NHANES 2007–2008 questionnaire (32) and US Environmental Protection Agency Detroit Exposure and Aerosol Research Study (DEARS) survey (34).

National Emissions Inventory

Point sources of styrene emissions were identified using the 2011 National Emissions Inventory Version 2 (NEI), the United States Environmental Protection Agency's (EPA's) latest comprehensive database of annual criteria, precursor, and hazardous air pollutant emissions (35). State, local, and tribal air agencies report emissions sources, which are then augmented with information from the Toxics Release Inventory, the Acid Rain Program, and EPA's regulatory air toxics data.

We abstracted all records of reported styrene emissions from the 2011 NEI point source database and mapped participants' home geocodes onto the locations of the NEI point sources to calculate the distance between each participant's residence and proximal point sources. We assigned exposure to point sources of styrene emissions based on number of sources, linear distance to point source locations, and volume of emissions at one-half, one, two, five, and ten mile buffers surrounding participants' homes.

National Air Toxics Assessment

The EPA's 2011 National-scale Air Toxics Assessment (NATA) evaluates 180 air toxics across the United States using emissions inventories, dispersion modeling, photochemical modeling, exposure modeling, and toxicity analyses (36, 37). NATA uses dispersion modeling to generate annual average ambient air toxic concentrations for each U.S. census tract. The model predicts annual average census tract concentrations for each major source type (point, nonpoint, mobile), which are then summed to a total concentration value for all source types combined. Styrene concentrations in NATA 2011 arise from all three major source types.

We employed NATA styrene estimates as indicators of typical, long-term environmental exposure by mapping each participant's geocoded home location to a 2010 U.S. census tract, and applying the annual average total and source-partitioned concentrations for that census tract to the participant.

Blood collection and blood volatile organic compound measurements

Glass blood collection tubes containing potassium oxalate and sodium fluoride anticoagulant were used to collect 10 mL of blood for styrene measurement. Blood samples were collected using tubes and stoppers that had been pre-treated by the CDC laboratory to remove VOC residues to minimize pre-collection contamination (38, 39). Samples were stored in a 4°C refrigerator prior to being shipped overnight on cold packs in biweekly batches to the Centers for Disease Control and Prevention in Atlanta, Georgia for analysis of VOCs. This laboratory conducts all NHANES VOC analyses. Analysis of styrene followed the standard CDC procedures for NHANES samples, using equilibrium headspace solid-phase micro-extraction with benchtop gas chromatography/mass spectrometry (29, 31), allowing direct comparisons between measurements in CBS and NHANES. 3 mL of blood was required per analysis.

We measured 2,5-dimethylfuran (2,5-DMF), a VOC used as a smoking biomarker with comparable sensitivity and specificity to serum cotinine (a well-validated nicotine biomarker) (40). Blood 2,5-DMF concentration of 0.014 ng/mL has been established as a threshold for distinguishing between current daily smokers (≥ 0.014 ng/mL) and nonsmokers (< 0.014 ng/mL) (40, 41), with the latter comprising infrequent smokers whose blood styrene levels have returned to that of nonsmokers. Unless otherwise specified, we use this definition to identify smokers and nonsmokers throughout all analyses.

Statistical Analysis

We compared the distributions of blood styrene levels measured in CBS participants (n=935) to those observed in NHANES participants ages 21 and older who had blood styrene measured during the 2005–2006 and 2007–2008 NHANES cycles (N=3,958). All comparisons between NHANES and CBS were stratified by the 2,5-DMF threshold for smoking status (0.014 ng/mL). For comparisons to NHANES, we imputed blood styrene concentrations below the limit of detection (LOD) as the LOD divided by the square root of two (42), as is done in NHANES. For all other statistical analyses, we used all measured blood styrene values, including the actual values below the LOD (43).

We also calculated the smoking-specific age- and sex-standardized prevalence ratio of CBS participants with blood styrene levels above the NHANES 95th percentile standardized to the CBS sample. We presented this standardization approach without applying NHANES sampling weights, but also conducted parallel analyses using NHANES sampling weights to verify that the weighting approach didn't influence results. Styrene concentrations were approximately log-normally distributed, so we used natural logarithmically-transformed concentrations in continuous analyses.

For regression analyses, we further restricted to participants who completed the exposure monitoring questionnaire (n=810) and had complete covariate information for demographic factors, potential predictors, and ambient exposure metrics (n=667). We selected predictors *a priori* based on previous literature (14, 44–49), with residential building characteristics, lifestyle and behaviors, recreational and occupational activities, and relevant recent exposures as candidate predictors. We additionally considered ambient styrene predictors,

including NATA total and source-partitioned (point, nonpoint, and mobile) concentrations as well as NEI point source emissions of styrene. Metrics of emissions included binary indicators (presence or absence of sources), number of sources, and distance- and volume-weighted intensity of sources surrounding participants' homes. We used analysis of variance and t-tests to prioritize candidates based on the strength and statistical significance of their unadjusted relationship with blood styrene levels.

We implemented a predictive modeling approach using least squares regression aimed at maximizing the model adjusted R^2 and retained covariates with p-values < 0.10 . We chose this approach because many sources of styrene exposure were rare in this population. We maintained a statistical significance threshold of $\alpha=0.05$, and report the change in log-styrene concentration (β coefficient) attributed to each predictor, and its associated 95% confidence interval and p-value.

We also used multivariable regression to estimate prevalence ratios and corresponding 95% confidence intervals (PR, 95% CI) for a blood styrene measurement exceeding the smoking-specific NHANES 95th percentile. Due to model convergence problems for the log-binomial model, all analyses were completed using a modified log-binomial approach with a Poisson distribution (50). The same predictive modeling approach described for the analysis of continuous styrene was used to specify the modified Poisson model.

Due to concerns about varying data reporting and quality of NATA estimates between states, we evaluated agreement between NATA modeled ambient styrene concentrations and observed styrene concentrations from EPA Ambient Monitoring Archive (AMA) monitors in the study region. We compared annual average monitored concentrations to corresponding census tract NATA estimates for each state. Lacking sufficient sample size to conduct individual state regression analyses, we conducted sensitivity analyses excluding one state at a time to evaluate the influence of state reporting differences on the association between NATA exposure data and elevated blood styrene levels.

To more efficiently examine ambient predictors of elevated blood styrene (i.e., NATA and NEI exposures), we identified a subgroup with no tobacco smoke-related styrene exposure ($n=300$) by restricting to participants with blood 2,5-DMF < 0.014 ng/mL and removing an additional 97 individuals who reported any active or passive tobacco smoke exposure in the past 24 hours. We further restricted to participants living in states where NATA best reflected observed AMA concentrations ($n=224$), and removed individuals with spring blood draws to account for seasonal differences in ambient styrene, resulting in a sample of 195 participants. We then used the same modified Poisson model to estimate associations between ambient exposures and blood styrene exceeding the NHANES 95th percentile in this subgroup.

All statistical analyses were conducted in SAS 9.4 (Cary, NC, USA) and spatial analyses were completed in Esri ArcGIS Desktop 10.3 (Redlands, CA, USA).

RESULTS

Blood styrene levels for these CBS participants (n=935) were two to three times higher than those reported in NHANES (n=3,958) (Table 1) for both smokers and nonsmokers, but considerably lower than levels typically observed among occupationally exposed populations. Among nonsmokers, detection rates were considerably higher in CBS (61.9%) than NHANES (23.7%). Among smokers, rates were more comparable between study populations (CBS, 99.2%; NHANES, 96.1%). The distribution of blood styrene in CBS is right-skewed, regardless of smoking status. Nonsmokers in CBS were almost six times as likely to have elevated blood styrene (blood measurement above the NHANES 95th percentile), and smokers in CBS were more than four times as likely to have elevated blood styrene, as their NHANES counterparts (Figure 1). The apparent second peak in the blood styrene distributions above the NHANES 95th percentile for both smokers and non-smokers in CBS suggests that an elevated styrene measurement may indicate membership in a subgroup with a higher mean exposure distribution.

Overall, two-thirds of CBS participants included in predictor models (n=667) are younger than 50, three-fourths are male, half are white, and three-fourths are overweight or obese (Table 2). Most participated in oil spill cleanup work (85.8%), and over half are unemployed. Approximately 40% of modeled CBS participants had blood 2,5-dimethylfuran levels characteristic of smoking. Smokers tended to be younger, less educated, more likely to be nonwhite, and have lower body mass index. They were also more likely than nonsmokers to report lower income and unemployment.

We identified several predictors of blood styrene levels (Figure 2), though the overall model adjusted R² was 0.19. Continuous log-transformed blood 2,5-dimethylfuran level was a strong predictor of increasing blood styrene level (β , 0.42 log ng/mL; 95% CI: 0.34, 0.51), demonstrating the importance of smoking as a styrene exposure source (Supplemental Table 1). Living in a home painted in the past six months (n=82; β , -0.46 log ng/mL; 95% CI: -0.75, -0.17) was associated with lower styrene levels, while concrete/cinderblock (n=169; β , 0.37; 95% CI: 0.11, 0.64) and wood (n=265; β , 0.35; 95% CI: 0.13, 0.57), home exteriors predicted higher blood styrene levels. Other significant predictors of increasing styrene included boating in the Gulf in the past 24 hours (n=10; β , 1.10; 95% CI: 0.31, 1.89), spending at least three hours in motor vehicles in the past 24 hours (n=122; β , 0.34; 95% CI: 0.09, 0.59), living in a mobile home, RV, or boat (n=99; β , 0.35; 95% CI: 0.07, 0.63), and reporting recreational fishing (n=330; β , 0.20; 95% CI: 0.0002, 0.39). Being employed (n=374; β = 0.19; 95% CI: -0.01, 0.38) was a positive predictor of blood styrene, of borderline significance. Blood draws in fall or winter (n=597; β , -0.41; 95% CI: -0.73, -0.10) were associated with lower blood styrene levels, compared to spring blood draws. Ambient nonpoint styrene concentrations were weakly and non-significantly predictive of increasing blood styrene levels, with the strongest association in the second quartile. State of residence was non-significantly associated with blood styrene levels, with Florida residents (n=165) having the highest blood styrene levels (β , 0.27; 95% CI: -0.07, 0.61). Predictors of elevated blood styrene (when defined as above the NHANES 95th percentile) in the overall sample were similar in magnitude and direction to the observed predictors of continuous blood styrene (Supplemental Figure 1).

We identified a subgroup to more efficiently assess ambient, as opposed to personal, predictors of styrene. The subgroup was defined as those unexposed to tobacco smoke (active or passive), with fall or winter blood draw, and not living in Alabama. Predictors of elevated blood styrene (above the NHANES 95th percentile) among these participants included ambient nonpoint styrene concentration and Florida residence (Figure 3). We excluded Alabama based on results of a sensitivity analysis examining associations between NATA estimated concentrations and AMA observed concentrations by state (Appendix I). Using the limited data available, we determined that Alabama demonstrated appreciably less agreement with observed concentrations than the four remaining states. In this subgroup analysis, we observed a weak increasing exposure-response relationship across quartiles of ambient nonpoint styrene concentration, where participants in the highest exposure group were twice as likely to have elevated blood styrene as those in the lowest group (PR, 2.1; 95% CI: 1.0, 4.4). Florida residents were twice as likely to have elevated blood styrene as their counterparts from Mississippi (PR, 2.0; 95% CI: 1.1, 3.7). Exposure to point source emissions of styrene was not associated with elevated blood styrene levels for any of the exposure metrics or spatial scales we examined (data not shown).

DISCUSSION

We conducted this study to characterize blood styrene levels among Gulf coast residents and identify determinants of styrene exposure. Blood styrene levels among CBS participants were substantially elevated compared to NHANES, particularly in the upper tail of the distribution. These levels, while higher than NHANES, are orders of magnitude lower than occupational exposure levels. Participants living in Florida had the highest blood styrene levels. Personal, as well as environmental factors, predicted blood styrene levels in the overall CBS sample. In a subgroup identified to facilitate examination of environmental factors, ambient styrene from nonpoint sources was associated with elevated blood styrene with a suggestive exposure-response relationship. However, proximity to industrial styrene emissions from point sources was not related to blood styrene.

Although several different environmental, behavioral, and social factors have been identified as determinants of styrene exposure, these factors typically explain less than 25% of the variance in measured styrene exposure (8, 14). In our study, smoking, spending time in boats or vehicles in the past 24 hours, recreational fishing, being employed, and living in mobile housing were positively associated with blood styrene levels. Living in a home painted in the past six months and fall/winter blood draws were inversely associated with blood styrene levels.

We observed a highly significant, precise, positive association between the biomarker for smoking (2,5-dimethylfuran) and blood styrene. Previous studies indicate that smokers have blood styrene levels approximately fourfold higher than those of nonsmokers (2, 10, 13–15, 51–54). Although cigarettes are considered the dominant source of styrene exposure among smokers, environmental tobacco smoke contributes only about 8% of nonsmokers' exposure (12).

Spending at least three hours in a vehicle or any time in a boat in the Gulf of Mexico in the past 24 hours were both associated with increasing styrene levels. Likewise, recreational fishing was a predictor of styrene exposure. These predictors likely confer increased styrene exposure from combustion engine emissions, an established source of outdoor styrene exposure (8, 12, 55, 56).

The association between employment and increasing blood styrene suggests that sources outside the home could be driving higher exposures in non-smokers (55). We conducted a preliminary analysis of reported occupation, industry, and main job activities to ascertain styrene-related occupational exposure opportunities. We determined that such opportunities were too rare in our population (<0.1%) to account directly for the association between employment status and blood styrene.

Participants who reported living in mobile housing had higher blood styrene levels. This association may reflect housing materials with more off-gassing than other types of residences, or lower air exchange rates resulting in higher indoor styrene levels (57). Mobile housing is likely to be smaller than apartments, townhouses, and detached homes, with fewer rooms and windows. Previously, smaller house size and lower number of windows have been associated with increased styrene exposure (55).

Blood styrene levels are fairly consistent within season, though monitoring suggests significantly lower ambient styrene levels in the spring compared to all other seasons (58). We observed lower blood styrene levels in fall and winter compared to spring, however the seasonal distribution of blood collection (90% in fall or winter) precluded seasonally-stratified analyses and further exploration into this relationship. We did not observe correlations between ambient and blood styrene levels, so the discrepancy with previously reported monitored data is not entirely surprising.

Previous research suggests that individuals living near styrene manufacturing or processing facilities may experience increased exposure from point source emissions, totaling 47.3 million pounds annually in the U.S. (2). Residential proximity to styrene emitting industrial facilities has been shown to confer up to 15 ppb of annual average styrene exposure (59) with elevated concentrations detected up to 10 kilometers away (60). In our analyses, however, styrene levels varied independently of residential proximity to point source emissions, with no relationship to volume, intensity, distance, or type of emission source at a range of buffers from 0.5 miles to 10 miles. Similarly, NATA estimated concentrations attributable to point sources were not associated with blood styrene levels. Our measures of exposure to point source emissions may be insufficient to capture episodic exposure scenarios, as both data sources rely on annual reporting. These measures fail to reflect seasonality or temporal variability that may influence prediction of a single blood draw. Because national-scale ambient styrene monitoring is limited, with poor spatial and temporal coverage, we were unable to evaluate monitored styrene concentrations in association with contemporaneous blood styrene levels.

We evaluated total NATA concentrations, as well as source-partitioned values for each major source type. Total, point, and mobile concentrations were not associated with styrene levels

in the full study population. However, when we looked in the subgroup identified to better examine environmental sources of elevated blood styrene, NATA nonpoint styrene concentration showed a positive exposure response relationship. This association only emerged among nonsmokers with no reported environmental tobacco smoke exposure, who had fall/winter blood draws, and did not live in Alabama. We selected this group to reduce other major sources of styrene variability and measurement error so that we could better assess the relationship between ambient and blood styrene. Improving the signal to noise ratio in this way did allow us to detect an association that was not apparent in the main analysis.

Nonpoint sources are smaller sources or sources related to residential activity (residential wood combustion, consumer and commercial solvent usage, etc.), which are inventoried at the county level, and subsequently allocated to census tracts. These types of styrene exposure sources may demonstrate more temporal consistency within seasons than point source emissions, and therefore be more relevant predictors of spot blood styrene levels than sources which vary episodically. Reporting for nonpoint sources may also be more reliable than other major source types, so that modeled concentrations are a more accurate representation of nonpoint exposures than other source types.

The primary strength of our study is the examination of both indoor and outdoor predictors of internal burden of blood styrene in a population with elevated blood styrene levels. While other studies have typically prioritized either indoor or outdoor styrene sources, our study includes detailed self-reported characterization of indoor exposure opportunities and conditions, as well as two different assessments of outdoor styrene levels and sources.

We also used an established biomarker of internal styrene body burden, with a detailed, previously validated questionnaire capturing the relevant timing for the blood measurement (34). This recall period, 24 hours, was sufficiently short to minimize the risk of recall bias and matched the styrene elimination half-life of approximately 13 hours. We ascertained smoking using a validated biomarker and supplemented with self-reported information on environmental tobacco smoke in sensitivity analyses. Blood styrene and 2,5-dimethylfuran levels in both CBS and NHANES were analyzed in the same laboratory, using the same methods, which permit quantification of general population exposure levels (29). Geocoding participants' residential locations allowed for a variety of flexible spatial analyses incorporating distance decay with point source emissions. Finally, our study was carried out in an understudied population that has been frequently exposed to multiple natural and man-made disasters, and lives in a region with enhanced industrial styrene exposure opportunity.

Repeated biomarker measurements may provide a more reliable estimate of usual exposure than the single blood specimen obtained in our study, particularly because of the rapid elimination of styrene from the body. Given the half-life of styrene in blood, blood levels reflect only exposures experienced within the past 12–24 hours.

Occupational data were reported at enrollment and potentially not reflective of the 24-hour exposure window preceding the blood draw. Despite this limitation, it is unlikely that occupational styrene exposure is influencing blood styrene levels in this study population

because styrene-related occupations tend to be highly specific and were reported rarely among CBS participants. Candidate occupations we considered included: working in a fiberglass reinforced plastic or cultured marble factory, fiberglass boat building or repair, manufacturing styrene resin, polymer, rubber, or styrene-butadiene rubber tires, manufacturing fiberglass wind turbines, and relining sewer lines with styrene-based resins pipe.

Reporting to the NEI database is voluntary and designed for regulatory purposes. As such, the quality of the data and availability of information for our intended investigation may not be ideal. These data are limited to annual aggregate values and lack any temporal specificity. Similarly, the NATA estimates are annual averages derived from voluntarily reported inputs, the protocols for which vary between states. Although imperfect, in the absence of sufficient monitoring data, these data sources provide the best available outdoor exposure information for a study of our scope and purpose.

The modestly elevated blood styrene levels among CBS participants created a unique opportunity to assess a range of environmental styrene exposures. Although we were only able to account for approximately 20% of the variability in styrene exposure, this is consistent with what other studies have achieved when attempting to predict blood VOC levels (46, 51). We identified several personal predictors of blood styrene, which were largely consistent with what has been published previously. Despite intense styrene-related industrial activity across the study region, we did not observe any relationship between proximity to point source styrene emissions and blood styrene. Rather, our results suggest that, at least among individuals without appreciable tobacco smoke exposure, exposure from nonpoint sources may be an important predictor of blood styrene levels. Future research in this area would benefit from repeated measures of blood styrene, as well as temporally specified environmental styrene sources, whether through monitoring or improved modeling.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Figure 1.

Prevalence ratio of blood styrene concentrations exceeding the smoking-specific NHANES 95th percentile in the CBS compared to NHANES (n=935).

Solid line indicates CBS study; black shading indicates CBS study 95th percentile.

Dashed line indicates NHANES; grey shading indicates NHANES 95th percentile.

NHANES 95th percentile: nonsmokers, 0.06 ng/mL; smokers, 0.23 ng/mL.

PR, prevalence ratio (95% confidence interval).

Figure 2.

Predictors of blood styrene levels (n=667).

Blood 2,5-DMF (log), log transformed blood 2,5-dimethylfuran concentration.

NATA nonpoint, National Air Toxics Assessment 2011 annual average census tract ambient styrene concentration attributable to nonpoint sources. Q1, First quartile; Q2, Second quartile; Q3; Third quartile; Q4, Fourth quartile.

State, participant's state of residence.

Figure 3.

Predictors of blood styrene measurement > NHANES 95th percentile among participants unexposed to tobacco smoke* with fall/winter blood draws, not living in Alabama (n=195).
 *Unexposed to tobacco smoke: jointly defined as having blood 2,5-dimethylfuran < 0.014 ng/mL *and* reporting no active or passive smoke exposure in the 24 hours preceding blood collection.

NATA nonpoint, National Air Toxics Assessment 2011 annual average census tract ambient styrene concentration attributable to nonpoint sources.

Q1, First quartile; Q2, Second quartile; Q3; Third quartile; Q4, Fourth quartile.

Point sources, National Emissions Inventory 2011 point source emitters of styrene within 1 mile of participant's geocoded home location.

Florida, Louisiana, Mississippi, participant's state of residence.

Table 1.

Blood styrene levels in the CBS (n=935) and NHANES (2005–2008) (n=3,958).

	Nonsmokers ¹		Smokers ²	
	CBS	NHANES	CBS	NHANES
N	551	3,137	384	821
Percent detect	61.9	23.7	99.2	96.1
Mean	0.26	0.03	0.34	0.11
Geometric mean	0.07	0.03	0.15	0.07
25th percentile	< LOD	< LOD	0.07	0.06
Median	0.04	< LOD	0.12	0.09
75th percentile	0.08	< LOD	0.28	0.13
95th percentile	1.67	0.06	1.62	0.23
Maximum	4.81	4.10	4.58	0.78

Blood styrene concentration measured in ng/mL. Limit of detection (LOD) = 0.03 ng/mL.

Values below the LOD are imputed as $\text{LOD} / 2 = 0.02 \text{ ng/mL}$.

¹ Nonsmokers defined as having blood 2,5-dimethylfuran > 0.014 ng/mL.

² Smokers defined as having blood 2,5-dimethylfuran concentration ≥ 0.014 ng/mL.

Table 2.

Characteristics of participants with blood styrene measurements in the CBS (n=667).

	Overall (n=667)		Smokers ^I (n=270)		Nonsmokers ^I (n=397)	
	N	%	N	%	N	%
Age (years)						
< 30	123	18.4	59	21.9	64	16.1
30–50	325	48.7	138	51.1	187	47.1
> 50	219	32.8	73	27.0	146	36.8
Body Mass Index (kg/m ²)						
< 25	159	23.8	89	33.0	70	17.6
25–30	200	30.0	75	27.8	125	31.5
> 30	308	46.2	106	39.3	202	50.9
Education						
< High school graduate	128	19.2	66	24.4	62	15.6
High school graduate	249	37.3	109	40.4	140	35.3
> High school graduate	290	43.5	95	35.2	195	49.1
Race						
Black	277	41.5	133	49.3	144	36.3
White	336	50.4	118	43.7	218	54.9
Other	54	8.1	19	7.0	35	8.9
Sex						
Female	164	24.6	57	21.1	107	27.0
Male	503	75.4	213	78.9	290	73.0
Timing of blood draw						
Fall/Winter	597	89.5	244	90.4	353	88.9
Spring	70	10.5	26	9.6	44	11.1
Work status						
Employed	374	43.9	116	43.0	258	65.0
Unemployed	293	56.1	154	57.0	139	35.0
Oil spill clean-up work						
1 day	572	85.8	242	89.6	330	83.1
None	95	14.2	28	10.4	67	16.9
Annual income						
< \$20,000	275	41.2	140	51.9	135	34.0
\$ 20,000 – \$50,000	230	34.5	93	34.4	137	34.5
> \$50,000	162	24.3	37	13.7	125	31.5

^ISmokers defined as having blood 2,5-dimethylfuran concentration 0.014 ng/mL; nonsmokers, blood 2,5-dimethylfuran > 0.014 ng/mL.