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Fine particulate matter components and emergency department visits among a privately insured population in Greater Houston

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HIGHLIGHTS

- Br, K, Na^+, and SO_4^{2-} were significantly associated with total ED visits.
- Br and Ni were statistically associated with increased visits of stroke.
- Al, Cr, and K were associated with increased respiratory visits.
- $PM_{2.5}$ mass, As, Br, K, Na^+, NH_4^+, NO_3^-, and SO_4^{2-} were associated with increased SSID visits.
- Effect estimates for most $PM_{2.5}$ components were higher during the warm season.

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ABSTRACT

Although adverse health effects of $PM_{2.5}$ (particulate matter with aerodynamic diameter less than 2.5 μm) mass have been extensively studied, it remains unclear regarding which $PM_{2.5}$ components are most harmful. No studies have reported the associations between $PM_{2.5}$ components and adverse health effects among a privately insured population. In our study, we estimated the short-term associations between exposure to $PM_{2.5}$ components and emergency department (ED) visits for all-cause and cause-specific diseases in Greater Houston, Texas, during 2008–2013 using ED visit data extracted from a private insurance company (Blue Cross Blue Shield Texas [BCBSTX]). A total of 526,453 ED visits were included in our assessment, with an average of 236 (±63) visits per day. We selected 20 $PM_{2.5}$ components from the U.S. Environmental Protection Agency's Chemical Speciation Network site located in Houston, and then applied Poisson regression models to assess the previously mentioned associations. Interquartile range increases in bromine (0.003 μg/m^3), potassium (0.048 μg/m^3), sodium ion (0.306 μg/m^3), and sulfate (1.648 μg/m^3) were statistically significantly associated with the increased risks in total ED of 0.71% (95% confidence interval (CI): 0.06, 1.37%), 0.71% (95% CI: 0.21, 1.22%), 1.28% (95% CI: 0.34, 2.24%), and 1.22% (95% CI: 0.23, 2.23%), respectively. Seasonal analysis suggested strongest associations occurred during the warm season. Our findings suggest that a privately insured population, presumably healthier than the general population, may be still at risk of adverse health effects due to exposure to ambient $PM_{2.5}$ components.

1. Introduction

A recent assessment on health effects of particulate matter (PM) exposure conducted by the United States (U.S.) Environmental Protection Agency (EPA) has concluded that both short- and long-term exposure to ambient fine particulate matter ($PM_{2.5}$; PM with aerodynamic diameter less than 2.5 μm) cause mortality and cardiovascular effects (and likely cause respiratory effects) (EPA, 2012). However, simply relating $PM_{2.5}$ mass to health effects is not sufficient enough to explain the associations because $PM_{2.5}$ is a complex mixture of ions, trace metals, and carbonaceous species (Bell et al., 2007) and their proportions in $PM_{2.5}$ mass vary by source, season, and geographical location (Metzger et al., 2004). Many studies have found differential toxicity across $PM_{2.5}$ components, and these findings were summarized in several review articles (Chen and Lippmann, 2009; Kelly and Fussell, 2012; Rohr and Wyzga,

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2012; Schlesinger, 2007; Stanek et al., 2011). Although they suggest that certain $PM_{2.5}$ components (e.g., nickel, vanadium, elemental carbon, and organic carbon) were more closely associated with health impacts, no consensus has yet been reached regarding which $PM_{2.5}$ components are more harmful than others.

In the U.S., only a few studies have examined the associations between short-term exposure to $PM_{2.5}$ components and emergency department (ED) visits. Several studies were conducted in Atlanta, Georgia using ED data collected during 1993–2004. These studies examined the associations of short-term exposure to $PM_{2.5}$ mass and components with ED visits for cardiovascular diseases (CVD) and respiratory diseases (RESP) (Metzger et al., 2004; Peel et al., 2005; Sarnat et al., 2008; Sinclair et al., 2010; Strickland et al., 2010). Specifically, CVD visits were found to be associated with $PM_{2.5}$ mass, elemental carbon, and organic carbon (Metzger et al., 2004), whereas respiratory visits were associated with elemental carbon, water-soluble metals, and sulfate (Peel et al., 2005; Sarnat et al., 2008). In addition, asthma was also reported to have a significant association with elemental carbon, zinc, and air pollutants from traffic sources (Peel et al., 2005; Sinclair et al., 2010; Strickland et al., 2010). Despite the fact that most studies were conducted in the Atlanta metro area, a recent study examining the short-term associations between $PM_{2.5}$ components and ED visits was conducted in St. Louis, Missouri–Illinois from June 1, 2001 through May 30, 2003 (Sarnat et al., 2015). In this study, statistically significantly associations were found between CVD visits and zinc, as well as between respiratory visits and calcium.

Most previous time-series studies of $PM_{2.5}$ components and ED visits were based on ED visit data collected from hospitals that included patients without distinction. No studies have examined the health effects of $PM_{2.5}$ mass and components among a privately insured population. In our study, we retrieved ED visit data from a private insurance company (Blue Cross Blue Shield Texas [BCBSTX]), which is the state's largest health insurer, covering a relatively healthy, high-income population of more than 10 million persons. Taking advantage of this data set, we hypothesize that the insured population, presumably healthier than the general population due to healthy worker effect, would produce different results than previous studies. In this study, we performed a Poisson regression in generalized additive models (GAM) to estimate the association between all-cause and cause-specific ED visits and $PM_{2.5}$ components in Greater Houston during 2008–2013.

2. Methods

2.1. Study location

The study area is Houston-The Woodlands-Sugar Land Metropolitan Statistical Area (MSA), which is also commonly referred to as "Greater Houston" (U.S. Census Bureau, 2013) (see Supplemental Material Fig. S1). This area consists of nine counties, including Austin, Brazoria, Chambers, Fort Bend, Galveston, Harris, Liberty, Montgomery, and Waller counties. As of 2013, Greater Houston had a population of 6.3 million (U.S. Census Bureau, 2014). As the fifth largest metropolitan area in the U.S. (U.S. Census Bureau, 2014) and a highly industrialized city, Greater Houston has many local sources of ambient $PM_{2.5}$. Examples include the petrochemical complex along the Houston Ship Channel, ports in Houston, Texas City, and Galveston, numerous industrial facilities scattered in the entire metropolitan area, and emissions from on-road motor vehicular traffic (Bahreini et al., 2009; Chiou et al., 2010; Nowak et al., 2010; Sexton et al., 2006). In addition to local sources, $PM_{2.5}$ in Greater Houston can be also transported from regional sources such as dust storms originating in areas of West Texas and the New Mexico area, agricultural burning in Mexico and Central America (TCEQ, 2013), and marine vessel emissions in the Gulf of Mexico and secondary particulate matter from upwind regions (Parrish et al., 2009).

2.2. Emergency department visit data

We retrieved daily counts of ED visits for Greater Houston from claims data insured by BCBSTX from January 1, 2008 through December 31, 2013. BCBSTX covers approximately one-third of the privately insured population in the Texas. It includes mostly people under 65 who are receiving insurance through employment (their dependents were also covered). There is a small portion of individuals over 65 years of age, though they were still fully employed and included in the study. We restricted our analysis to BCBSTX enrolled members living in Greater Houston and visiting a hospital or clinic located in Greater Houston. In addition, observations with ICD-9 codes greater than 799 (injury, poisoning, external causes of injury, and supplemental classification) and those with ICD-9 codes missing (2% of total visits) were excluded from the main analysis.

International Classification of Diseases 9th Revision (ICD-9) diagnosis codes were used to classify outcome groups, which include: total ED visits [001–799], CVD visits [390–429], stroke visits [430–438], RESP visits [460–519], chronic obstructive pulmonary disease (COPD) visits [490–492, 494, and 496], pneumonia (PNA) visits [480–486], asthma visits [493], and symptoms, signs, and ill-defined conditions (SSID) visits [780–799]. Three SSID subgroups were further analyzed, including general symptoms [780], symptoms involving cardiovascular system [785], and symptoms involving respiratory system and other chest symptoms [786]. Additionally, because injuries were positively associated with air pollution (Ha et al., 2015), we performed analyses on the outcome group injury and poisoning [800–999] and its subgroups, including effects of foreign body entering through body orifice [930–939], burns [940–949], and other and unspecified effects of external causes (e.g., overexertion, drowning, exposure to electric current, and submersion) [990–995]. This study was approved by the Committee for the Protection of Human Subjects at The University of Texas Health Science Center at Houston.

2.3. Air quality and weather data

We obtained $PM_{2.5}$ mass and speciation data from U.S. EPA Air Quality System (AQS) (https://aqs.epa.gov/api) for 2008–2013. $PM_{2.5}$ mass data were extracted from four $PM_{2.5}$ monitoring sites in Greater Houston using federal reference methods (FRM) (see Supplemental Material Fig. S1). Three of the four monitoring sites continuously monitored $PM_{2.5}$ mass in the study period while the fourth operated during 2013. Daily average concentrations for $PM_{2.5}$ mass across multiple monitors in Greater Houston were calculated for each day in the study period. Speciation data were extracted from the monitor located in "Houston Deer Park", the only chemical speciation network (CSN) site in Greater Houston (see Supplemental Material Fig. S1). CSN typically collects $PM_{2.5}$ samples on a one-in-three or one-in-six day schedule. This schedule restricted our analysis to include only days when data on both hospital admissions and $PM_{2.5}$ component concentrations were available for our primary analyses. We included 20 species in our analysis: aluminum (Al), ammonium (NH_4^+), arsenic (As), bromine (Br), calcium (Ca), chromium(Cr), copper (Cu), elemental carbon (EC), iron (Fe), manganese (Mn), nickel (Ni), nitrate (NO_3^-), organic carbon (OC), potassium (K), silicon (Si), sodium ion (Na^+), sulfate (SO_4^{2-}), titanium (Ti), vanadium (V), and zinc (Zn). These species were chosen because they represented major local sources (Sullivan et al., 2013) and had been studied previously in other epidemiologic studies (Dai et al., 2014; Krall et al., 2013; Ostro et al., 2007; Zanobetti et al., 2009). EPA implemented a new method to analyze EC and OC at Houston Deer Park in 2009 and a validated correction method is not yet available; therefore, we included only EC and OC data that were collected between 2009 and 2013 in our assessment.

We retrieved hourly weather observations measured at George Bush Intercontinental Houston Airport (IAH) from the National Climate Data

Center (NCDC, 2014). We then calculated daily mean temperature and dew-point temperature based on the hourly data.

2.4. Statistical analysis

We applied generalized additive models to examine the associations between daily counts of ED visits for each disease outcome and daily concentrations of $PM_{2.5}$ mass and the $PM_{2.5}$ components during 2008–2013. We also conducted a stratified analysis examining the seasonal effect for total ED. Each season was defined as: warm (April–September), and cold (October–March). The parameters specifying the distribution of ED visit counts were assigned by quasi-Poisson distributions to account for overdispersion. We used the following Poisson regression model:

$$\mathbf{log}[\mathbf{E}(\mathbf{Y_t})] = \boldsymbol{\alpha} + \boldsymbol{\beta}\mathrm{P}_{(t)} + \mathbf{ns}(\mathbf{T}, 8/\mathbf{Y}) + \boldsymbol{\gamma}\mathbf{DOW} + \mathbf{ns}(\mathbf{Temp}, 3) + \mathbf{ns}(\mathbf{Dew}, 3) + \mathbf{offset}\,[\mathbf{log}(\mathbf{Pop})] \quad (1)$$

where $\mathbf{E}(\mathbf{Y_t})$ denotes the expected ED visit counts at day t; $\boldsymbol{\alpha}$ is the intercept; $\boldsymbol{\beta}$ denotes the log relative rate of ED visits associated with a one unit increase in the selected pollutant. "P" refers to $PM_{2.5}$ mass or any $PM_{2.5}$ component. The mean value of each pollutant on the same day (t) was included in the model; ns is the natural cubic smoothing spline function, which was used for all smooth functions in the model; (T, 8/Y) is the calendar time with 8 degrees of freedom (df) per year (4 per season for seasonal analysis); DOW is a set of indicator variables each representing a day of the week; $\boldsymbol{\gamma}$ is a vector of coefficients; (Temp, 3) is the three-day moving average temperature with 3 df; (Dew, 3) is the three-day moving average dew point with 3 df. The term offset [log (Pop)] was used to adjust for the confounding from population growth. In our case, population (Pop) referred to all members covered by BCBSTX in Greater Houston. The selection of covariates (the calendar time, day of the week, three-day moving average temperature, and three-day moving average dew point) and their df were adapted from a previously published study (Zanobetti et al., 2009). To report the results, we computed percent change in daily ED visits for an interquartile range (IQR) increase in $PM_{2.5}$ mass or the $PM_{2.5}$ component concentrations, with corresponding 95% confidence intervals (CIs). We primarily reported and discussed results based on the same day's exposure (lag 0) due to the fact that no scientific consensus has yet been reached on the appropriate time lag associated with exposure to the $PM_{2.5}$ components. Poisson regression models were fitted using the "mgcv" package (version 3.0.2) in the R statistical software (R Project for Statistical Computing; http://R-project.org). SAS (version 9.3; SAS Institute Inc., Cary, NC) was used to merge the ED visit data, the weather data, and $PM_{2.5}$ data, as well as to generate descriptive statistics.

To examine the robustness of our results, we performed several sensitivity analyses. First, we repeated our analyses using mean exposure on the previous day (lag 1), 2 days before (lag 2), and 3 days before (lag 3) to estimate associations with increased risk of ED visits. Second, we repeated our analyses using varying df to smooth the effect of time (4, 6, 10, and 12 per year) and the weather variables.

3. Results

Table 1 presents descriptive statistics for ED visit data during 2008–2013 in Greater Houston extracted from the BCBSTX insurance database. This data set included a total of 526,453 ED visits for all diagnoses except for external causes, with an average of 236 ($\pm$63) visits per day. Among these, 58.7% were female patients, and 73.07% were patients ages 18–65 (see Supplemental Material Table. S1). The most common cause of visits is SSID (average daily counts: 74 $\pm$ 21), followed by RESP (34 $\pm$ 19) and CVD (10 $\pm$ 4).

Table 2 summarizes the descriptive statistics for $PM_{2.5}$ and its components during 2008–2013. We found high correlations ($r \geq 0.74$) between any pair of four $PM_{2.5}$ mass monitoring sites in Greater Houston, indicating $PM_{2.5}$ concentrations were stable across the monitors in the region (see Supplemental Material Table. S3). The mean value of $PM_{2.5}$ mass 12.01 ($\pm$4.75) almost equaled the annual U.S. National Ambient Air Quality Standards (NAAQS) for $PM_{2.5}$ (12 μg/m^3). The largest contributors to $PM_{2.5}$ mass were SO_4^{2-} (21%), OC (15%), NH_4^+ (6%), NO_3^- (6%), and EC (4%). The levels of $PM_{2.5}$ mass and two major components (NH_4^+, SO_4^{2-}) gradually declined from 2008 through 2013, while the other three major components remained almost unchanged (OC, NO_3^-, EC) (see Supplemental Material Fig. S2). Meanwhile, there was only one day (12/31/2009: 36.7 μg/m^3) when the citywide $PM_{2.5}$ average exceeded the daily NAAQS standard of 35 μg/m^3.

Table 1
Descriptive statistics of all-cause and cause-specific emergency department visits in Greater Houston during the period January 1, 2008–December 31, 2013.

Visit type[a]	ICD-9 codes	Mean	SD[b]	Min[c]	Max[d]
Total ED	001–799	236	63	121	512
CVD	390–429	10	4	1	25
Stroke	430–438	3	1	0	9
RESP	460–519	34	19	5	175
COPD	490–492, 494, and 496	3	2	0	18
PNA	480–486	4	2	0	14
Asthma	493	4	2	0	16
SSID	780–799	74	21	29	141

[a] Total ED, all-cause emergency department visits. CVD, cardiovascular disease. RESP, respiratory disease. COPD, chronic obstructive pulmonary disease. PNA, pneumonia. SSID, Symptoms, signs, and ill-defined conditions.
[b] Standard deviation.
[c] Min, minimum daily counts.
[d] Max, maximum daily counts.

Fig. 1 presents the associations between the same-day concentrations of $PM_{2.5}$ mass and 20 $PM_{2.5}$ components and ED visits for all diagnoses, CVD, stroke, and SSID. Br (0.71% [95% CI: 0.06, 1.37%]), K (0.71% [95% CI: 0.21, 1.22%]), Na^+ (1.28% [95% CI: 0.34, 2.24%]), and SO_4^{2-} (1.22% [95% CI: 0.23, 2.23%]) were significantly associated with increased total ED visits. Br (7.36% [95% CI: 0.50, 14.69%]) and Ni (1.75% [95% CI: 0.01, 3.52%]) were significantly associated with increased stroke visits. $PM_{2.5}$ mass, As, Br, K, Na^+, NH_4^+, NO_3^-, and SO_4^{2-} were found to be significantly associated with increased SSID visits. SSID contains a number of subgroups that represent different biological endpoints (see Supplemental Material Table. S4). Further analysis indicates that elements As, Br, NH_4^+, and SO_4^{2-} were significantly associated with one selected subgroup - respiratory system and other chest symptoms (ICD-9: 786). Meanwhile, element Ni was significantly associated with cardiovascular system symptoms (ICD-9: 785) (see Supplemental Material Table. S5). We did not find any statistically significant associations between the $PM_{2.5}$ components and CVD.

Fig. 2 presents the associations between the same-day concentrations of $PM_{2.5}$ mass and 20 components and ED visits for RESP, COPD, PNA, and asthma. The element K (1.43% [95% CI: 0.11, 2.78%]) was significantly associated with increased RESP visits. The elements Al (1.39% [95% CI: 0.02, 2.79%]) and Cr (0.58% [95% CI: 0.02, 1.14%]) were significantly associated with increased COPD visits. No associations were observed for pneumonia or asthma.

Fig. 3 shows the season-specific associations between the same-day concentrations of $PM_{2.5}$ mass and 20 $PM_{2.5}$ components and all ED visits. We observed more statistically significant ($P < 0.05$) associations (K, NH_4^+, NO_3^-, OC, and SO_4^{2-}) in the warm season as compared to the cold season (Na^+). We also found that effect estimates of most components, especially major $PM_{2.5}$ components (EC, NH_4^+, NO_3^-, OC, and SO_4^{2-}), were higher during the warm season than during the cold season.

Our sensitivity analysis showed a declining trend from lag 0 to lag 3 for $PM_{2.5}$ mass and several components (As, Br, K, Na^+, NH_4^+, SO_4^{2-}, and V), while effect estimates for the remaining components either increased with lag times (Cu and EC) or trendless (see Supplemental

Table 2
Descriptive statistics[a] of $PM_{2.5}$ and the $PM_{2.5}$ components in Greater Houston, Texas for the period January 1, 2008–December 31, 2013.

Pollutant	Sampling period	N	Mean	SD	IQR	Min	P25	Median	P75	Max
$PM_{2.5}$	1/01/2008–12/31/2013	2083	12.010	4.754	5.850	1.933	8.650	11.200	14.500	36.700
Al	1/01/2008–12/30/2013	712	0.102	0.219	0.058	0.003	0.013	0.031	0.070	1.840
As	1/01/2008–12/30/2013	712	0.001	0.002	0.001	0.000	0.000	0.000	0.001	0.033
Br	1/01/2008–12/30/2013	712	0.004	0.004	0.003	0.000	0.002	0.003	0.005	0.076
Ca	1/01/2008–12/30/2013	712	0.061	0.059	0.037	0.002	0.030	0.044	0.067	0.521
Cr	1/01/2008–12/30/2013	712	0.003	0.011	0.002	0.000	0.000	0.001	0.002	0.255
Cu	1/01/2008–12/30/2013	712	0.013	0.021	0.017	0.000	0.001	0.002	0.018	0.182
EC[b]	4/02/2009–12/30/2013	566	0.443	0.303	0.394	0.001	0.212	0.371	0.606	1.780
Fe	1/01/2008–12/30/2013	712	0.093	0.134	0.056	0.001	0.033	0.052	0.089	1.120
K	1/01/2008–12/30/2013	712	0.077	0.071	0.048	0.002	0.040	0.056	0.088	1.004
Mn	1/01/2008–12/30/2013	712	0.002	0.003	0.002	0.000	0.001	0.002	0.003	0.022
Na^+	1/01/2008–12/30/2013	716	0.272	0.276	0.306	0.006	0.070	0.180	0.376	1.547
NH_4^+	1/01/2008–12/30/2013	716	0.735	0.583	0.696	0.008	0.335	0.595	1.030	4.620
Ni	1/01/2008–12/30/2013	712	0.002	0.003	0.001	0.000	0.001	0.001	0.002	0.066
NO_3^-	1/01/2008–12/30/2013	716	0.728	0.591	0.467	0.022	0.378	0.545	0.844	4.185
OC[b]	4/02/2009–12/30/2013	566	1.819	1.174	1.446	0.066	0.945	1.483	2.390	8.870
Si	1/01/2008–12/30/2013	712	0.249	0.474	0.145	0.004	0.048	0.088	0.193	3.920
SO_4^{2-}	1/01/2008–12/30/2013	716	2.521	1.372	1.648	0.002	1.540	2.223	3.188	8.750
Ti	1/01/2008–12/30/2013	712	0.007	0.015	0.003	0.001	0.002	0.003	0.005	0.124
V	1/01/2008–12/30/2013	712	0.004	0.003	0.003	0.001	0.002	0.002	0.005	0.020
Zn	1/01/2008–12/30/2013	712	0.007	0.010	0.008	0.000	0.002	0.005	0.010	0.136

[a] The unit for all pollutants is $\mu g/m^3$. SD, standard deviation. IQR, interquartile range. Min, minimum daily value. P25, the 25th percentile. P75, the 75th percentile. Max, maximum daily value.
[b] We included a shorter sampling period for EC and OC due to sampling method change in the year 2009 (see Methods for details).

Material Fig. S3). Effect estimates were robust to varying df used to smooth effects of time and weather.

In addition to our primary analysis, we estimated associations between $PM_{2.5}$ mass and components and injury. Descriptive statistics of total injury and its selected subgroup was summarized in Table. S4. We found that $PM_{2.5}$ mass and element K were statistically significantly associated with increased total injury visits (see Supplemental Material Table. S5). However, we did not find any significant associations between $PM_{2.5}$ mass and components and the selected injury subgroup representing unintentional injuries.

4. Discussion

To the best of our knowledge, this study is the first to examine health effects of $PM_{2.5}$ mass and components among a privately insured population particularly in a rapid growing city with numerous pollutant sources. Previous studies have used ED visit data from hospitals or national social insurance program such as Medicare or Medicaid. Little is known about the associations between short-term exposures to $PM_{2.5}$ and ED visits among privately insured population. Our results show that Br, K, Na^+, and SO_4^{2-} were statistically significantly ($P < 0.05$) associated with increased total ED visits. For ED visits of specific diagnoses, Br and Ni significantly increased risk of stroke visits, element K significantly increased risk of RESP visits, and Al and Cr significantly increased risk of COPD visits. In addition, $PM_{2.5}$, As, Br, K, Na^+, NH_4^+, NO_3^-, and SO_4^{2-} were all significantly ($P < 0.05$) associated with SSID. Our seasonal analysis indicates that effect estimates for the major $PM_{2.5}$ components (EC, NH_4^+, NO_3^-, OC, and SO_4^{2-}) were higher during the warm season than during the cold season.

Although a number of previous time-series studies have found statistically significant associations of $PM_{2.5}$ mass with increased ED visits (Mathes et al., 2011; Strickland et al., 2010; Zanobetti et al., 2009), we observed a positive but not significant association of $PM_{2.5}$ mass with increased total ED visits. The effect estimate (0.44% [95% CI: - 0.09, 0.96%]) was generally lower than previous findings. The most likely reason for the weak association is that the study population is younger, healthier, and wealthier as compared to the general public. The insignificant association may be also attributable to the reduced sample size since we used BCBSTX members as the studied population. Meanwhile, we did find significant associations between $PM_{2.5}$ components and several

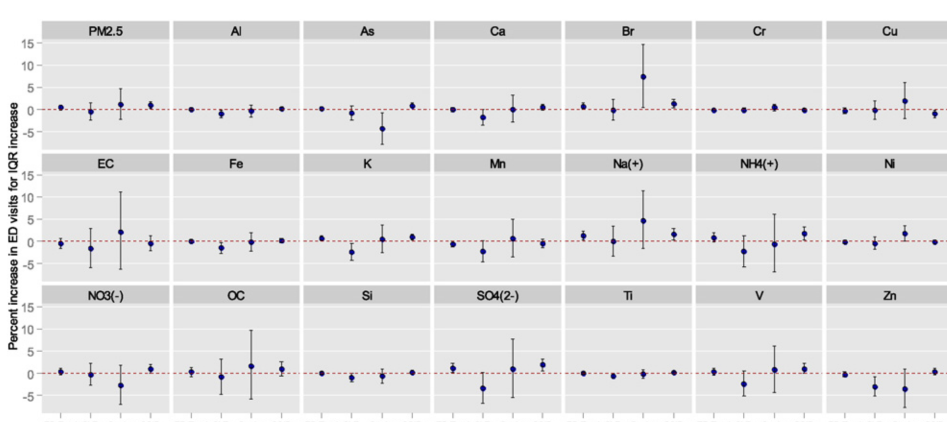

Fig. 1. Percent changes and 95% CIs of ED visits for all-cause patients and those patients diagnosed as CVD, Stroke, and SSID patients for an interquartile increase of $PM_{2.5}$ mass and components on the same day (lag 0) in Greater Houston, Texas, during 2008–2013. ED total, all-cause emergency department visits; CVD, cardiovascular disease; and SSID, Symptoms, signs, and ill-defined conditions.

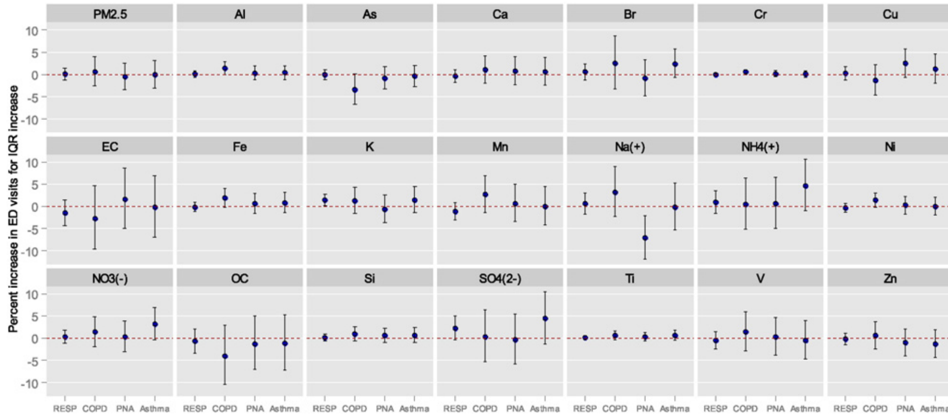

Fig. 2. Percent changes and 95% CIs of ED visits for patients diagnosed as RESP, COPD, PNA, and asthma for an interquartile increase of $PM_{2.5}$ mass and twenty $PM_{2.5}$ components on the same day (lag 0) in Greater Houston, Texas, during 2008–2013. RESP, respiratory disease; COPD, chronic obstructive pulmonary disease; PNA, Pneumonia.

specific disease groups and these results are partly consistent with previously reported associations of $PM_{2.5}$ components and cardiopulmonary ED visits.

The ion Na^+ was significantly associated with total ED visits. This is consistent with the finding of a multi-city study based on data extracted from Medicare billing records for 2000–2003. This study examined whether ratios of components to $PM_{2.5}$ total mass modified the association between short-term $PM_{2.5}$ concentrations and emergency hospitalizations in 26 U.S. communities (Zanobetti et al., 2009). This study found that Na^+ modified the association between $PM_{2.5}$ and emergency hospitalization for respiratory diseases, CVD, and MI. In another multi-city time-series study, Na^+ was found to be associated with estimated increases in mortality (Krall et al., 2013). Na^+ in $PM_{2.5}$ mainly comes from aerosolized sea salt (Schlesinger, 2007; Sullivan et al., 2013). The mechanism of Na^+ induced biological effects remains unknown.

The ion SO_4^{2-} was also statistically significantly associated with total ED visits. Subsequent seasonal analysis showed that ions SO_4^{2-}, NH_4^+, and NO_3^- were all significantly associated with total ED visits during the warm season. Previous literature suggests that SO_4^{2-} was associated with both respiratory and CVD visits (Ito et al., 2011; Peel et al., 2005; Sarnat et al., 2008; Strickland et al., 2010). For example, SO_4^{2-} were observed to have a significant association with both respiratory visits in general (Sarnat et al., 2008) and upper respiratory visits (Peel et al., 2005) in two studies conducted in Atlanta, GA. Consistent with our findings, one study found a significant association between SO_4^{2-} and pediatric asthma ED visits during the warm season (Strickland et al., 2010). In a study conducted in New York City (NYC), the authors investigated associations between emergency hospitalization for CVD and $PM_{2.5}$ components for 2000 through 2006 (Ito et al., 2011). This study found CVD hospitalization was significantly associated with ions SO_4^{2-} and NO_3^- at lag 0. SO_4^{2-} was found to be significantly associated with increased mortality risk as well in a recently published local time-series study (Liu and Zhang, 2015). SO_4^{2-} and NO_3^- in $PM_{2.5}$ were from their precursors: sulfur dioxide (SO_2) and nitrogen oxides (NO_x) in the air through naturally occurring chemical processes. In Greater Houston, sources of SO_2 and NO_x can be regional or local. An example of regional sources is the emissions of marine vessels in the Gulf of Mexico (Parrish et al., 2009). Local sources include coal-fired power plants (Parrish et al., 2009), and mobile and industrial sources (Kemball-Cook et al., 2009). For sulfate- and nitrate-containing particles, one possible machanism involved was that the acidity of these particles may alter pulmonary toxicity of PM-associated components or physical properties (Kelly and Fussell, 2012).

Trace metal Al and Cr were significantly associated with COPD visits. This result was partly consistent with previous finding that Al exposure was associated with COPD in the aluminum industry (Priest and O'Donnell, 1997). In a study aimed to examine associations between daily exposure to fine particle components and symptoms in children with asthma, the authors found Al was statistically significantly associated with wheeze at lag 2, persistent cough at lag 0 and 2, and shortness of breath at 0 and 2 (Gent et al., 2009). Al was also found to be associated with changes in birth weight (Bell et al., 2010) and mortality (Dai et al., 2014). Al in $PM_{2.5}$ is mainly from crustal material such as soil dusts, but can also derive from combustion (Schlesinger, 2007). The major source

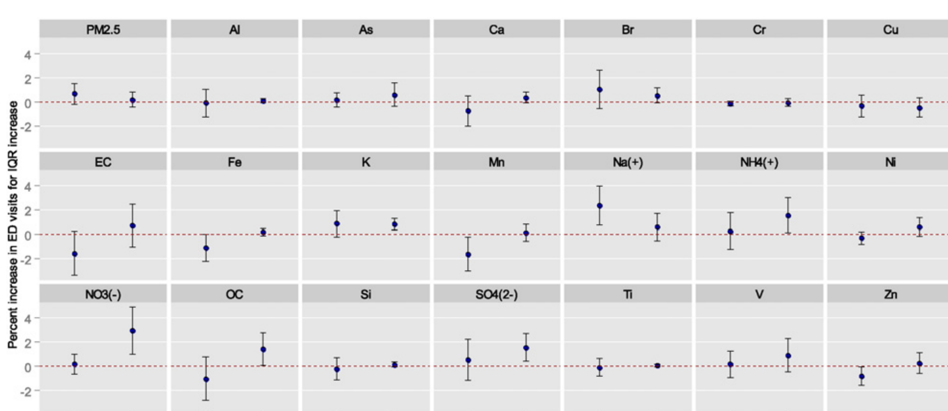

Fig. 3. Percent changes and 95% CIs of total ED visits for an interquartile increase of $PM_{2.5}$ mass and twenty $PM_{2.5}$ components on the same day (lag 0) by season in Greater Houston, Texas, during 2008–2013. Warm season, (April–September); and cold season, (October–March).

of particle-bound Al in Greater Houston is crustal material (Sullivan et al., 2013). A potential mechanism for the toxicity of Al is that the inhaled aluminum can pass through the cribriform plate and reach the olfactory bulb, therefore having direct access to brain tissue (Schlesinger, 2007).

Trace element K was significantly associated with total ED visits and RESP in the all-year analysis and during the warm season. It was also significantly associated with RESP in the all-year analysis. K was reported to have significantly increased ED visits for CVD (Sarnat et al., 2008) and wheeze (Gent et al., 2009). In addition, K was also found to be significantly associated with mortality risk in a number of time-series studies (Mar et al., 2000; Ostro et al., 2007; Zhou et al., 2011). The source of K in Greater Houston is biomass burning (Sullivan et al., 2013).

Trace metal Br and Ni were significantly associated with increased stroke visits. Br was statistically significantly associated with total ED visits as well. Our findings on Br were consistent with a previous study that Br was significantly associated with CVD mortality and hospitalization (Ito et al., 2011). Br is used for fuel additives and can be emitted from vehicles (Sullivan et al., 2013; Zanobetti et al., 2009). Ni is regarded as one of the $PM_{2.5}$ components that are most closely associated with health impacts and has been reported to be associated with mortality and hospitalizations (Rohr and Wyzga, 2012). In Greater Houston, Ni is primarily produced from the large petrochemical complex along the Houston Ship Channel (Sullivan et al., 2013). Ni was found to be responsible for increased pulmonary permeability (Chen and Lippmann, 2009).

Carbonaceous species EC and OC were frequently studied for their associations with cardiopulmonary morbidity. In our analysis, we only observed a significant association between OC and total ED visits at lag 0 during the warm season. This result was comparable to a previous study that OC was significantly associated with asthma visits at lag 4 and upper respiratory visits at lag 0 (Peel et al., 2005). One study compared results between two periods (25 months for the first period and 28 months for the second period) for the association of asthma visits with several $PM_{2.5}$ components and found that EC and OC were significantly associated with childhood asthma in both periods (Sinclair et al., 2010). EC and OC were also found to be associated with CVD visits (Bell et al., 2007; Sarnat et al., 2008). One major source of EC and OC in Greater Houston is on-road vehicles (Sullivan et al., 2013). EC can also be released from biomass burning (Sullivan et al., 2013).

It is noteworthy that our study found no statistically significant associations between any $PM_{2.5}$ component and CVD visits. One possible reason is that this privately insured BCBSTX population is younger and presumably healthier than the aged Medicare population and has a higher socioeconomic status than the Medicaid insured population.

In addition to cardiopulmonary visits, we also looked at another disease category: SSID. Specifically, a symptom is subjective and described by the patient; a sign is objective and discovered through medical examination by the physician; and an ill-defined condition is one for which a more precise diagnosis cannot be made (Falen and Liberman, 2005). Generally, SSID coding will be applied if the underlying condition that caused the symptom or sign is not known (Falen and Liberman, 2005). Previous studies have evaluated SSID in populations such as minorities, elderly, and war veterans (Becker et al., 1990; Roy et al., 1998; Walsh et al., 2008), and several time-series studies have estimated the short-term associations between air pollution and SSID visits (Szyszkowicz and Rowe, 2016). Our results show that some $PM_{2.5}$ components ($PM_{2.5}$, As, Br, K, Na^+, NH_4^+, NO_3^-, and SO_4^{2-}) were statistically significantly associated with SSID visits for the all-year analysis at lag 0. A more refined analysis on SSID subgroups found that As, Br, NH_4^+, and SO_4^{2-} were significantly associated with respiratory system and other chest symptoms (ICD-9: 786) (see Supplemental Material Table. S5). These findings suggest that the short-term exposure to ambient $PM_{2.5}$ mass and components might play a role in the increased SSID visits, particularly on respiratory symptoms.

Our findings indicate that $PM_{2.5}$ mass and element K were statistically significantly associated with total injury (ICD-9: 800–899). However, no statistically significant associations were found on the selected injury subgroup (ICD-9: 930–949; 990–995) that represents mostly unintentional injuries such as foreign body entering through body orifice, burns, overexertion, drowning, exposure to electric current, and submersion. This was inconsistent with a recently published case-crossover study that reported significant positive associations between several air pollutants and unintentional injury deaths in Korea (Ha et al., 2015). Some factors such as different statistical methods used, different study population, and geographical differences in air pollution may explain this inconsistency.

In this study, we observed a seasonal trend that effect estimates for major $PM_{2.5}$ components (EC, NH_4^+, NO_3^-, OC, and SO_4^{2-}) were higher during the warm season than during the cold season. The warm season also has more associations (K, NH_4^+, NO_3^-, OC, and SO_4^{2-}) as compared to the cold season (Na^+). This was consistent with the results of previous studies. For example, one time-series study examined the associations of SO_4^{2-}, EC, OC, and water-soluble metals with pediatric asthma ED visits and observed the strongest associations in the warm season (Strickland et al., 2010). Another study examined the association between short-term exposure to $PM_{2.5}$ mass and components and CVD mortality for the population ≥ 40 years old in NYC for the years 2000–2006. The authors observed the strongest association for secondary aerosols including Br, EC, OC, Se, and SO_4^{2-} during the warm season (Ito et al., 2011). The stronger associations of major components with total ED visits observed for the warm season are likely due to the change of the prevailing wind directions. The pollutant rose (see Supplemental Material Fig. S4) shows that during the warm season much more $PM_{2.5}$ blew from the southeast (the Gulf of Mexico) as compared to the cold season. As a result, $PM_{2.5}$ from regional sources such as agricultural burning in Mexico and Central America (TCEQ, 2013), and marine vessel emissions in the Gulf of Mexico (Parrish et al., 2009) are more readily transported to Greater Houston.

Our study has several limitations. First, the speciation data we used were collected from a single location, therefore exposure misclassification is inevitable. Compared to $PM_{2.5}$ mass that is relatively homogeneous over the scale of a community, certain $PM_{2.5}$ components (e.g., Ni) are more heterogeneous at a smaller spatial scale (Franklin et al., 2008). Therefore, the use of a single location for collecting speciation data may downwardly bias effect estimates (Ostro et al., 2007). Alternatively, the exposures can be measured by the use of personal samplers. However, it is not feasible to measure exposure at individual level for population-based epidemiologic studies. Second, due to CSN's one-in-six and one-in-three sampling schedules, we had reduced power for the detection of associations between the $PM_{2.5}$ components and ED visits. This schedule also prevented us from fitting distributed lag models to estimate cumulative short-term effects spread over multiple continuous days. Third, due to the high correlation among the $PM_{2.5}$ components, we used a single-pollutant approach and assessed each $PM_{2.5}$ component independently without adjusting for the other $PM_{2.5}$ components. Therefore, the association observed between certain components and ED visits may reflect the associations of other correlated single components or a combination of components.

5. Conclusion

This study appears to be the first to evaluate short-term associations between $PM_{2.5}$ mass and components and ED visits among a privately insured population. We found statistically significant positive associations of all-cause and cause-specific ED visits with exposure to several $PM_{2.5}$ components. We also found evidence that exposure to ambient $PM_{2.5}$ mass and components may play a role in increased visits for SSID. In addition, we observed stronger associations during the warm seasons. Our findings suggest that a privately insured population, presumably healthier than the general population, may be still at risk of adverse health effects due to exposure to ambient $PM_{2.5}$.

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Appendix A. Supplementary materials

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.scitotenv.2016.05.022.

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