Association of emergency room visits for respiratory diseases with sources of ambient PM$_{2.5}$

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ABSTRACT

Previous studies have reported associations of short-term exposure to different sources of ambient fine particulate matter (PM$_{2.5}$) and increased mortality or hospitalizations for respiratory diseases. Few studies, however, have focused on the short-term effects of source-specific PM$_{2.5}$ on emergency room visits (ERVs) of respiratory diseases. Source apportionment for PM$_{2.5}$ was performed with Positive Matrix Factorization (PMF) and generalized additive model was applied to estimate associations between source-specific PM$_{2.5}$ and respiratory disease ERVs. The association of PM$_{2.5}$ and total respiratory ERVs was found on lag4 (RR = 1.011, 95%CI: 1.002, 1.020) per interquartile range (76 $\mu$g/m$^3$) increase.

We found PM$_{2.5}$ to be significantly associated with asthma, bronchitis and chronic obstructive pulmonary disease (COPD) ERVs, with the strongest effects on lag5 (RR = 1.072, 95%CI: 1.024, 1.119), lag4 (RR = 1.104, 95%CI: 1.032, 1.176) and lag3 (RR = 1.091, 95%CI: 1.047, 1.135), respectively. The estimated effects of PM$_{2.5}$ changed little after adjusting for different air pollutants. Six primary PM$_{2.5}$ sources were identified using PMF analysis, including dust/soil (6.7%), industry emission (4.5%), secondary aerosols (30.3%), metal processing (3.2%), coal combustion (37.5%) and traffic-related source (17.8%). Some of the sources were identified to have effects on ERVs of total respiratory diseases (dust/soil, secondary aerosols, metal processing, coal combustion and traffic-related source), bronchitis ERVs (dust/soil) and COPD ERVs (traffic-related source, industry emission and secondary aerosols). Different sources of PM$_{2.5}$ contribute to increased risk of respiratory ERVs to different extents, which may provide potential implications for the decision making of air quality related policies, rational emission control and public health welfare.

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Introduction

Numerous epidemiological studies have reported positive associations of air pollution with respiratory diseases in recent years (Hwang et al., 2017a, 2017b; Leitte et al., 2011; Wong et al., 2002). Among the different air pollutants, fine particulate matter (PM$_{2.5}$) pollution has been arousing worldwide concern and become the seventh-leading risk...
factor for men, as well as the sixth for women in terms of mortality and morbidity globally (GBD 2016 Risk Factors Collaborator, 2017). Globally, over 80% of the residents in urban areas are exposed to PM$_{2.5}$ pollution at levels exceeding the WHO limit (10 µg/m$^3$ for annual concentrations) (WHO, 2018). Being exposed to PM$_{2.5}$ pollution may result in various symptoms and diseases of respiratory system, such as coughing, asthma, airway inflammation and so on (Gehring et al., 2015; Patel et al., 2009; Shi et al., 2016). Previous studies indicated that the increased ERVs were associated with the short-term exposure to PM$_{2.5}$ (Hwang et al., 2017b; Leitte et al., 2011; Xu et al., 2016).

The constituents of ambient PM$_{2.5}$ vary spatially and temporally and differ with the influence of various pollution sources (Thurston et al., 2005). Many epidemiologic studies have estimated the effects of PM$_{2.5}$ chemical constituents on respiratory diseases (Chen et al., 2017; Hwang et al., 2017b). However, few focused on PM source contributions. Krall et al. (2016) estimated associations between source-specific PM$_{2.5}$ and respiratory disease emergency department visits for four U.S. cities and examined between-city heterogeneity. They found that biomass burning PM$_{2.5}$ was associated with respiratory-related health and different PM$_{2.5}$ sources varied across cities. Nevertheless, PM$_{2.5}$ concentration was relatively low in the country mentioned in that study (under 20 µg/m$^3$), and the health effects of different PM$_{2.5}$ sources remain unclear in areas with severe outdoor PM$_{2.5}$ pollution, such as China. The annual ambient PM$_{2.5}$ concentration is about 73 µg/m$^3$ in 2016 in Beijing. Moreover, the chemical compositions of high-concentration ambient PM$_{2.5}$ in severely polluted area differ from those in least polluted area. In consideration of the fact that the chemical compositions of PM$_{2.5}$ were related with different health outcomes, further research about source-specific PM$_{2.5}$ is needed in China, and will provide potential implications for studies in severely polluted countries in the future. Source apportionment analysis for PM$_{2.5}$ is important to investigate the association between PM$_{2.5}$ sources and health outcomes, which may provide meaningful information for taking preventive measures to reduce the adverse health effects on population. A better understanding of constituent characterization and related pollution sources may lead to an improved environment and general health welfare (Brook et al., 2010).

In this study, we collected the daily counts of ERVs due to respiratory causes from 2014 to 2016 in a major hospital in Beijing and explored the association of ERVs for respiratory diseases with ambient PM$_{2.5}$ concentration and sources in Beijing. Positive matrix factorization (PMF) was applied to perform source apportionment to evaluate the association of ERVs for respiratory diseases with source-specific PM$_{2.5}$.

**1. Materials and methods**

**1.1. Data on hospital emergency room visits**

Data on ERVs were obtained from medical records of Peking University Third Hospital, which were daily counts of ERVs due to respiratory causes from Jan 1, 2014 to Dec 31, 2016. Including information of date of ERVs, age, sex, diagnosis and address. The cases were classified according to the International Classification of Diseases, 10th edition coding (ICD-10) for respiratory diseases (ICD-10: J00-J99), such as chronic obstructive pulmonary disease (COPD) (ICD10-J44.901), asthma (ICD-10: J45.901) and bronchitis (ICD-10: J40.X03).

**1.2. Air pollution and meteorological data**

Daily average air pollution data of Beijing city were obtained from Beijing Environmental Protection Bureau through the website, including daily 24-hr average concentration data for PM$_{2.5}$, sulfur dioxide (SO$_2$), nitrogen dioxide (NO$_2$), carbon monoxide (CO) and daily maximum 8-hr-ozone (O$_3$) during the study period.

We also measured PM$_{2.5}$ concentrations, with measurement systems located on the roof of a building which is within 500 m of Peking University Third Hospital, the place where we collected data of ERVs. We conducted the sampling with cyclone (URG-2000-30EH, URG, USA) and filter pack system (URG-2000-30FG, URG, USA). The average flow rate was 16.7 L/min for 24 hr on the sampling day. PM$_{2.5}$ was collected onto 47-mm Teflon filters (PTFE membrane filters, PALL Corp., USA), which were packed with aluminum foil and stored at −20°C after collection until analysis. The samples were dried and weighed with the balance (AND HM-202, AND, Japan) with a resolution of 0.01 mg.

PM$_{2.5}$ were collected on Teflon filters, which were analyzed in the laboratory and the following chemical constituents were determined with professional techniques including ion chromatography, thermo/optical transmission method and inductively coupled plasma atomic emission/mass spectrometry: ions including ammonium (NH$_4^+$), sulfate (SO$_4^{2-}$), nitrate (NO$_3$), chlorine (Cl$^-$); crustal metals including aluminum (Al), calcium (Ca), chromium (Cr), copper (Cu), iron (Fe), potassium (K), magnesium (Mg), manganese (Mn), sodium (Na), nickel (Ni), lead (Pb), silicon (Si), strontium (Sr), titanium (Ti), vanadium (V), zinc (Zn), bromine (Br); carbonaceous fractions of organic carbon (OC) and elemental carbon (EC).

In addition, we obtained data of daily meteorological from Chinese Meteorological Bureau during the study period, including the temperature and relative humidity.

**1.3. Statistical analysis**

**1.3.1. Health-exposure related analysis**

We linked together 3 years (1096 days) of records including air pollutants, temperature, humidity and counts of ERVs of respiratory diseases. The rate of missing values air pollutants monitoring is low (<1%). We replaced the sporadic missing values by the mean of nearby daily values (2 days before and 2 days after). According to the address of patients on the medical records obtained from the hospital, we sorted out patients who lived within 10 km from the place where PM$_{2.5}$ sampling system was located and analyzed the associations of source-specific PM$_{2.5}$ with ERVs of respiratory diseases.

Time-series methods of Poisson regression were used to investigate the short-term effects of PM$_{2.5}$ on ERVs. A generalized additive model (GAM) was used to calculate
associations between PM$_{2.5}$, meteorological values and ERVs of respiratory diseases in terms of their relative risks (RR) and 95% confidence intervals (CI). After controlling for confounders such as long-term trend, holiday, day of the week (DOW) and environmental factors (including temperature and relative humidity), we set up the model as follows:

$$\log(E(Y_k)) = \alpha + \text{DOW} + \text{Holiday} + \beta X_k + s(\text{time})$$

$$+ s(\text{temperature}) + s(\text{humidity})$$  (1)

where, $k$ denotes the day of the observation; $E(Y_k)$ denotes the expected ERVs of respiratory diseases on day $k$; $\alpha$ refers to intercept; DOW is the day of the week on day $k$; Holiday is a binary variable indicating a public holiday on day $k$ (coded as 0 indicates no holiday, and 1 indicates a holiday); $s(\cdot)$ denotes a spline smoothing function for nonlinear variables; $\beta$ represents the regression coefficient; $X_k$ indicates concentrations of air pollutants on day $k$; Time denotes long-term trends.

In the GAM model, the partial autocorrelation function (PACF) was used to select the best degrees of freedom (df) for time-varying variables for lags up to 30 by the minimization, in which DOW and holiday were also included as sub-variables. We chose the model with the smallest Akaike information criterion (AIC) values as the final model (Akaike, 1987). Different lag structures for the effect of air pollutants were examined, including single day lags from current-day lag (lag0) up to 6 days before (lag6), multi-day lags, and cumulative lags of 2 (moving average of lag 0–1) to 5 days (moving average of lag-0–4) (Hwang et al., 2017a; Ko et al., 2007; Xu et al., 2016).

Generally, the optimal lag was determined according to the maximum effect estimate. Rs of ERVs of respiratory diseases and their 95%CI were calculated on the basis of an interquartile range (IQR) increase in PM$_{2.5}$ concentration, and the significance level was set at $p < 0.05$ (two-tailed).

### 1.3.2. Source-apportionment analysis

U.S. Environmental Protection Agency’s positive matrix factorization (PMF) version 5.0 was used to identify a series of factors, which could be interpreted as sources of PM$_{2.5}$, thus estimated source-specific contributions of PMF (Hopke, 2008). Paatero and Tapper (1994) created the PMF model and it has been widely used as a tool to help perform source apportionment analysis in previous studies (Song et al., 2006; Thurston et al., 2005; Wu et al., 2014; Zhang et al., 2013). Twenty-three species were analyzed: EC, OC, NH$_4$Cl, NO$_2^{-}$, NO$_3^{-}$, SO$_2$, Cl$^-$, Al, Ca, Cr, Cu, Fe, K, Mg, Mn, Na, Ni, Pb, Si, Sr, Ti, V, Zn and Br. Concentrations of PM$_{2.5}$ were also imported into the model to estimate the factor contribution to total PM$_{2.5}$ (Reff et al., 2007). We first tested four factor solutions, and then we increased the number of factors until the results were stable. After conducting base and bootstrap runs for many times, we obtained an optimal solution which identified six PM$_{2.5}$ sources with a 10% model bootstrap runs for many times, we obtained an optimal solution which identified six PM$_{2.5}$ sources with a 10% model uncertainty. Additionally, we chose value

2. Results

### 2.1. Characteristics of the meteorological conditions and air pollutants

Table 1 shows the descriptive statistics for meteorological conditions and air pollutants during the study in Beijing. The daily mean concentrations of air pollutants were 79.2 (68.4), 104.6 (78.1), 14.4 (17.3), 50.6 (24.4), 1.2 (1.0) and 98.2 (65.2) $\mu$g/m$^3$ respectively for PM$_{2.5}$, PM$_{10}$, SO$_2$, NO$_2$, CO, and O$_3$8h. The PM$_{2.5}$ concentration was higher than the National Grade II standard annual level (PM$_{2.5}$: 35 $\mu$g/m$^3$). Mean value of temperature was 13.9 (11.0)$^\circ$C and relative humidity was 52.7 (20%), respectively. Fig. 1 plotted the time sequence diagram of the daily average PM$_{2.5}$, the concentration of which was higher during winter and lower during summer.

Correlation coefficients between daily air pollutants and meteorological factors were shown in Appendix A Table S1. Most of the pollutants were correlated with each other, except O$_3$ and PM$_{10}$. Temperature was negatively associated with PM$_{2.5}$, PM$_{10}$, SO$_2$, NO$_2$, and CO, and positively associated with O$_3$. Relative humidity was negatively associated with SO$_2$, and positively associated with PM$_{2.5}$, PM$_{10}$, NO$_2$ and CO. No significant correlation was observed with O$_3$.

### 2.2. Associations between PM$_{2.5}$ and emergency room visits for respiratory diseases

Table 2 shows the descriptive statistics of daily emergency room visits for respiratory diseases during the study. Associations between PM$_{2.5}$ concentration and different types of respiratory ERVs in single- and two-pollutant model were presented in Table 3. The 95% CIs were given for the current lag (lag0) to lag6 of the PM$_{2.5}$ concentration. As is described in the table, the association of PM$_{2.5}$ and total respiratory ERVs was found on lag4 (RR = 1.011, 95%CI: 1.002, 1.020). The estimated effects of PM$_{2.5}$ on total respiratory ERVs changed little after adjusting for CO and NO$_2$, but tended to attenuate

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<th>Table 1 – Descriptive statistics for meteorological conditions and air pollutants from Jan 1, 2014 to Dec 31, 2016 in Beijing.</th>
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<td><strong>Air pollutants</strong></td>
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SD: standard deviation; IQR: interquartile range.
after adjusting for O3 and SO2. PM2.5 was found to be significantly associated with asthma ERVs, with the strongest estimated effects on lag5 (RR = 1.072, 95%CI: 1.024, 1.119). We also found that PM2.5 was associated with bronchitis ERVs on lag4 (RR = 1.104, 95%CI: 1.032, 1.176). After adjusting for most of the other air pollutants, the associations of PM2.5 with bronchitis ERVs were still significant. However, no significant results were found after adjusting for O3. Association of COPD hospital emergency room visits and PM2.5 reached maximum on lag3 (RR = 1.091, 95%CI: 1.047, 1.135). Similar results were observed on different lag days in the two-pollutant models.

We also stratified the data of total respiratory ERVs by grouping the age into four groups including all ages, children (0–19 years old), adults (19–65 years old) and elderly people (over 65 years old). The results showed that after divided by age, the associations of PM2.5 with total respiratory ERVs become more significant in elderly people and less significant in children (Appendix A Table S2).

2.3. Comparison between heavily polluted and non-heavily polluted period of hospital emergency room visits of respiratory diseases

According to the Air Quality Index (AQI) (Agency, 2010), we could classify the air quality into six levels. Days with AQI above 200 were determined as heavily polluted period. Fig. 2 shows the changes in ERVs of total respiratory diseases on heavily polluted and non-heavily polluted period. We searched records for 2–4 continuous heavily polluted days, of which the prior 1–3 days and post 1–3 days determined as non-heavily polluted period were finally chosen into the analysis. Finally, we obtained 30 sets of records that fitted the "low-high-low" trend. As is shown in Fig. 2, there was an obvious upward trend in the ERVs of total respiratory diseases during heavily polluted period, suggesting that the incidence of respiratory disease may increase during heavily polluted days.

2.4. PM2.5 source apportionment

From the analysis above, we found that the variation of PM2.5 had strong seasonality in Beijing, with especially high concentrations showed up in winter (Fig. 1). In addition, PM2.5 was significantly associated with respiratory diseases ERVs, including total respiratory diseases, asthma, bronchitis and COPD (Table 3). After comparing the changes in ERVs of total respiratory diseases during heavily polluted and non-heavily polluted period (Fig. 2), we found an obvious upward trend during heavy polluted period and a decreasing trend during non-heavily polluted period after the heavily polluted period.

Thus, we focused on PM2.5 and its constituents, in order to investigate the source-specific associations of PM2.5 and ERVs of respiratory diseases. As is shown in Fig. 3, we identified six primary PM2.5 sources using the PMF analysis: dust/soil (6.7%), industry emission (4.5%), secondary aerosols (30.3%), metal processing (3.2%), coal combustion (37.5%) and traffic-related source (17.8%). PMF bootstrap runs suggested that the model yielded the most optimal result with a 5% uncertainty and a 0.60 minimum correlation R-value.

The first factor (Factor 1) was identified as dust/soil with high loadings of Al, Ca, Mg, Fe, Si, Ti (Song et al., 2006), which were crustal elements. This source contributed to 6.7% of total PM2.5 mass. Urban construction activities may also contribute to the source because there was high loading of Si that was abundant in cement and sand (Tan et al., 2017).

The second factor (Factor 2) was identified as industry emission with high loadings of V and moderate loading of Cu and Ni. Previous studies indicated that V was widely used as markers of oil combustion (Lee and Hieu, 2011; Mazzei et al., 2008). Concentrations of Cu and Ni were also found to be high in PM2.5 emission source of nonferrous metal smelters (Sun et al., 2004). Therefore, the second source was interpreted as...
industry emission related with industrial activities such as industrial oil burning and nonferrous metal smelting.

The third factor (Factor 3) was identified as secondary aerosols, which were characterized by high loadings of SO$_2^-$, NH$_4^+$ and NO$_3^-$. Coal combustion and vehicle exhausts can also contribute to secondary source due to their emission of precursor chemicals. It is important to know that traffic emission is a major contributor of secondary aerosol source beside its direct emissions as highlighted by Cu, Cr and Ni. Sulfate and nitrate may also originate from transportation related precursor pollutants, such as SO$_2$ and NOx.

The fourth factor (Factor 4) was interpreted as metal processing because high loadings of Sr and Mg were observed. Mg was reported to be emitted from metallurgical processes. This source contributed to 3.2% of total PM$_{2.5}$ mass.

The fifth factor (Factor 5) was identified as coal combustion with high loadings of OC, EC, Cl$^-$, Na, Pb and Zn. Many studies, including chemical analysis (Duan et al., 2006) of PM$_{2.5}$ and source profiles measurements (Zheng et al., 2005), have reported that Cl$^-$ was considered as a tracer element for coal combustion in Beijing. When the usage of leaded gasoline was banned in Beijing in 1997, coal combustion was recognized as the most important source of Pb in China (Mukai et al., 2001). Concentration of Pb was also found with a significant increase near a coal fire thermal power plant than in the background site (Jayasekher, 2009).

The sixth factor (Factor 6) was identified as traffic-related source. Higher loadings of Cu, Cr and Ni and moderate loadings of Na and Zn were observed in the factor. Cu is one of the major additives of lubricating oils and other auto parts.
Fig. 2 – Changes of hospital emergency room visits of total respiratory diseases around heavily polluted period (days with AQI above 200), presented with means and standard deviations. The 1 to 3 days prior (prior 1, prior 2, prior 3) and after (after 1, after 2, after 3) the heavily polluted period (1–4) were included.

Fig. 3 – Source profiles (presented in mass concentrations of μg/m³ and percentages of chemical species) analyzed with PMF for PM$_{2.5}$ in Beijing during the study period from Nov 2014 to Apr 2015. Y-axis on the left side (columns), concentrations of species; Y-axis on the right side (squares), percentages of species (Factor 1, dust/soil; Factor 2, industry emission; Factor 3, secondary aerosols; Factor 4, metal processing; Factor 5, coal combustion; Factor 6, traffic-related source).
of vehicles (Kuang et al., 2004; Lough et al., 2005; Mooibroek et al., 2011). A previous study suggested that Cr and Ni could generate from residual fuel combustion of vehicles and there were more abundant contents of Cr and Ni in the catalyst auto exhaust than in the non-catalyst auto exhaust (Samara, 2005).

2.5. Association of source-specific PM$_{2.5}$ with hospital emergency room visits of respiratory diseases

Fig. 4 shows the estimated RRs with 95% CI of different respiratory diseases per IQR increase of source-specific PM$_{2.5}$ concentrations analyzed by PMF. We found 1–2 days (lag2) average PM$_{2.5}$ originated from coal combustion (PMF S5) (RR = 1.094, 95%CI: 1.030, 1.162), secondary aerosols (PMF S3) (RR = 1.067, 95%CI: 1.015, 1.121), dust/soil (PMF S1) (RR = 1.063, 95% CI: 1.009, 1.119) and metal processing (PMF S4) (RR = 1.031, 95% CI: 1.003, 1.060) were associated with increases in ERVs of total respiratory diseases (Fig. 4a). Similar association was found on current day (lag1) average PM$_{2.5}$ from traffic-related source (PMF S6) (RR = 1.058, 95%CI: 1.001, 1.120). Most PM$_{2.5}$ sources are associated with total ERVs, except for industry emission (PMF S2). There were positive insignificant associations between asthma ERVs and source-specific PM$_{2.5}$ (Fig. 4b). Fig. 4c showed the associations between bronchitis ERVs and source-specific PM$_{2.5}$, the strongest association was observed for PM$_{2.5}$ from dust/soil (PMF S1) with 1–3 days (lag3) average (RR = 1.834, 95%CI: 1.067, 3.151). There were significant increases in COPD ERVs in association with current day (lag1) average PM$_{2.5}$ from industry emission (PMF S2) (RR = 1.254, 95%CI: 1.068, 1.472), 1–4 days (lag4) average PM$_{2.5}$ from secondary aerosols (PMF S3) (RR = 1.312, 95%CI: 1.002, 1.719) and traffic-related source (PMF S6) (RR = 1.988, 95%CI: 1.117, 3.539) (Fig. 4d). After grouping the age of the patients of total respiratory ERVs, more significant associations were observed between total respiratory ERVs and dust/soil (PMF S1) in children and adults, secondary aerosols (PMF S3) and metal processing (PMF S4) in elderly people, coal combustion (PMF S5) in children and adults, traffic-related source (PMF S6) in adults (Appendix A Fig. S1).

3. Discussion

The present study investigated the associations of ERVs of respiratory diseases with short-term ambient and source-specific PM$_{2.5}$ changes in Beijing. We observed positive associations between most PM$_{2.5}$ sources and ERVs for respiratory diseases.

Ambient PM$_{2.5}$ may have adverse effects on respiratory system, including respiratory symptoms among healthy people

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Fig. 4 – Relative risks with 95% confidence intervals (95% CI) of different respiratory diseases (a for total respiratory diseases; b for asthma; c for bronchitis; d for COPD) per interquartile increase (IQR) in PMF-resolved source-specific PM$_{2.5}$ concentrations (PMF S1: dust/soil, PMF S2: industry emission, PMF S3: secondary aerosols, PMF S4: metal processing, PMF S5: coal combustion, PMF S6: traffic-related source).
and exacerbation of diseases among patients of respiratory causes (Rice et al., 2015; Wu et al., 2013). In our study, PM$_{2.5}$ was estimated to be positively and significantly correlated with total respiratory ERVs on lag4. Moreover, PM$_{2.5}$ was also significantly correlated with asthma ERVs on lag4, lag5 and lag6, bronchitis ERVs on lag4 and COPD on lag3, lag4 and lag6. These results were generally consistent with previous studies. Ostro et al. (2009) performed a study to analyze the effects of PM$_{2.5}$ and specific species on respiratory related hospital admissions of children. They found correlations between specific compositions of PM$_{2.5}$ and all of the examined respiratory related hospitalizations. An IQR (14.6 µg/m³) increase for a 3-day lag of PM$_{2.5}$ was associated with an excess risk of 4.1% (95% CI: 1.8%, 6.4%) for total respiratory admissions of children. Hwang et al. (2017a) investigated the effects of PM$_{2.5}$ on acute exacerbation of COPD in the hospital admission level in Taiwan and found associations between increased COPD admissions and PM$_{2.5}$ during cold season with an RR of 1.020 (95% CI: 1.007, 1.040). Older people (more than 65 years old) had higher risk of COPD hospital admissions under PM$_{2.5}$ exposure. Xu et al. (2016) investigated associations between PM$_{2.5}$ pollution and total and cause-specific respiratory ERVs in Beijing, and found that increase of PM$_{2.5}$ concentration was associated with respiratory ERVs and the most significant association was found between acute exacerbation COPD on lag0–3 (3.15%, 95% CI: 1.39%, 4.91%).

According to the PM$_{2.5}$ source profiles, PM$_{2.5}$ source contributions were estimated during heavily polluted period in Beijing, respiratory-related health effects of source-specific PM$_{2.5}$ were able to be analyzed. In this study, PM$_{2.5}$ in Beijing’s urban area during heavily polluted period had large contribution from coal combustion (37.5%) and secondary aerosols (30.3%). Other sources including traffic-related source (17.8%), dust/soil (6.7%), industry emission (4.5%) and metal processing (3.2%) were also identified. Our results were consistent with Wåhlin et al. (2006)’s, which showed that traffic-originated particles were identified by high concentrations of Cu and Zn. The traffic related source was identified with metals without ionic or carbon species contributions, which was often determined as “metals” without any further investigations. However, some studies identified the traffic-related source with a large fraction of various metals such as Cu, Fe, Zn, Cr, Ni and Sr (Amato et al., 2009; Kfoury et al., 2016; Moreno et al., 2013; Schauer et al., 2006). Though traffic-related source contributed 17.1% to total PM$_{2.5}$ in the present study, we should know that except for the direct emission, traffic emission is also a critical source of NOx and has great contribution to secondary organic and nitrate constituents of PM$_{2.5}$ (Sun et al., 2004).

A few existed studies have elucidated the associations between sources of PM$_{2.5}$ and health of population including respiratory related hospitalizations and mortality (Ito et al., 2006; Ostro et al., 2011). However, few studies estimated such associations during heavily polluted period in China. In our study, some of the PM$_{2.5}$ sources were identified to have significant associations with ERVs of total respiratory diseases (coal combustion, secondary aerosols, traffic-related sources, dust/soil and metal processing), bronchitis ERVs (dust/soil) and COPD ERVs (traffic-related source, industrial emission and secondary aerosols). However, Sarnat et al. (2008) did not report positive associations of vehicle source, wood smoke or soil with respiratory diseases. Nevertheless, they analyzed the associations in a shorter time frame than our study. While other existed studies have found positive associations between PM$_{2.5}$ from traffic source and road dust and respiratory hospitalizations (Bell et al., 2014; Krall et al., 2016). Furthermore, several studies have reported lag effects between source-specific PM$_{2.5}$ exposure and respiratory-related health outcomes, possibly because of immunosuppression and systemic inflammation (Penttinen et al., 2006; Pun et al., 2015). The mechanism of PM-related respiratory health effect has been investigated in previous studies. PM with small aerodynamic diameters such as PM$_{2.5}$ can reach the alveoli and penetrate into blood circulation, and chemicals attached to PM may induce oxidative stress and increase the level of free radicals and C-Reactive Protein (CRP), leading to acute attack of diseases (Routledge et al., 2006).

According to the results on the associations between source-specific PM$_{2.5}$ and respiratory related health outcomes, targeted emission control may be able to prevent excess disease burden. Our study still has some limitations. There were studies considered effect modifications by socioeconomic status and personal characteristics (Gouveia and Fletcher, 2000; Kan et al., 2008). However, we did not analyze these factors due to lack of related data, and further investigations need to be conducted to estimate such effect modifiers which may affect patients’ choice for hospitalization. In addition, the data of ERVs were obtained from a single center within a limited area, and the results of present study may not represent the total situation of Beijing city. Therefore, multi-center studies need to be conducted for further investigation.

## 4. Conclusions

PM$_{2.5}$ is a critical air pollutant associated with most types of respiratory diseases and specific sources of PM$_{2.5}$ may play critical roles on relative risks of different types of respiratory hospital emergency room visits. Our findings may have potential implications for air quality related policies making, rational emission control and public health welfare.

### Competing financial interests

The authors have declared that they have no actual or potential competing financial interests.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jes.2019.05.015.

REFERENCES


