Original Article

Association between Ambient Air Pollution and Hospital Emergency Admissions for Respiratory and Cardiovascular Diseases in Beijing: a Time Series Study*

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Abstract

Objective To investigate the association between ambient air pollution and hospital emergency admissions in Beijing.

Methods In this study, a semi-parametric generalized additive model (GAM) was used to evaluate the specific influences of air pollutants (PM_{10}, SO_2, and NO_2) on hospital emergency admissions with different lag structures from 2009 to 2011, the sex and age specific influences of air pollution and the modifying effect of seasons on air pollution to analyze the possible interaction.

Results It was found that a 10 μg/m^3 increase in concentration of PM_{10} at lag 03 day, SO_2 and NO_2 at lag 0 day were associated with an increase of 0.88%, 0.76%, and 1.82% respectively in overall emergency admissions. A 10 μg/m^3 increase in concentration of PM_{10}, SO_2 and NO_2 at lag 5 day were associated with an increase of 1.39%, 1.56%, and 1.18% respectively in cardiovascular disease emergency admissions. For lag 02, a 10 μg/m^3 increase in concentration of PM_{10}, SO_2 and NO_2 were associated with 1.72%, 1.34%, and 2.57% increases respectively in respiratory disease emergency admissions.

Conclusion This study further confirmed that short-term exposure to ambient air pollution was associated with increased risk of hospital emergency admissions in Beijing.

Key words: Ambient air pollution; Time-series; Hospital emergency admissions

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INTRODUCTION

During the past 5 decades, human activities more extensively changed natural ecosystems compared with any time in the history. Ambient air pollution mainly caused by the combustion of non-renewable fossil fuels for electricity generation, transport and industry is responsible for the increasing mortality and morbidity of disease, especially respiratory and

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cardiovascular diseases every year[1-3]. In the last decades, many studies applied time-series methods to evaluate the association between air pollution and human health[4-6].

Beijing, the capital of China, has a serious air pollution problem, similar to many large cities[7-9]. Over the past 30 years, Chinese researchers in the field of environmental sanitation conducted a series of studies on association between ambient air pollution and human health. For example, the surveillance data of particulate matter with aerodynamic diameters less than 10 μm (PM_{10}) from Beijing Environmental Protection Bureau (BJEPB) from 2000 to 2004 indicated that PM was major air pollutant in Beijing[10]. Ambient air pollution caused the increase of cardiovascular or respiratory disease morbidity in Beijing during 2003-2008[11]. A 10 μg/m^3 increase in $PM_{2.5}$ levels was associated with a increase of 0.63% in respiratory disease morbidity (95% CI: 0.25%-0.83%) and 1.38% of circulatory disease mortality (95% CI: 0.51%-1.71%) in Beijing during 2005-2009[12]. Most studies focused on the association between air pollutants and the morbidity/mortality of cardiovascular disease or respiratory disease, but few studies used hospital emergency admission data as outcome indicator, which might be more sensitive in the study of ambient air pollution's health related impact.

Due to the considerable efforts to improve air quality, it is well known that the contains of atmospheric pollutants in Beijing declined significantly and met the requirement for Beijing Olympics game in 2008. However, in recent years, ambient air pollution remains to be a serious environmental and public health problem in Beijing[13-14]. The geographical condition worsens the problem in Beijing, where the surrounding mountains prevent air circulation and pollutant dispersion[15-16]. Extensive coal fired heating in winter and the unprecedented increase of motor vehicles (4.98 million motor vehicles have been registered by December 2011) have reduced the effects of many ambient air pollution control measures.

This study was aimed to evaluate the short-term effect of major air pollutants, including SO_2, NO_2, and PM_{10}, on human health by analyzing the data of hospital emergency admissions due to respiratory disease and cardiovascular disease in Beijing during 2009-2011. A time series analysis was conducted to evaluate the overall and sex/age specific associations between air pollution and hospital emergency admissions. The modifying effects of the seasons on air pollutants influences were analyzed to understand the possible interactions. Better understanding the influences of ambient air pollution on hospital emergency admissions will provide evidence for developing public health policies and risk assessments of ambient environment.

MATERIALS AND METHODS

Materials

The data of daily hospital emergency admissions were collected in 3 first grade general hospitals in Beijing from 1 January, 2009 to 31 December, 2011. The cases were selected according to the code in International Classification of Diseases, tenth revision (ICD-10) for all diseases (ICD: A00-R99), respiratory disease (ICD 10:J00-J99), cardiovascular disease (ICD 10:I00-I99). The cases' basic information were used in this study, i.e., age, sex, residential address, date of admission, diagnosis and diagnostic codes. According to the residential addresses of the cases, the patients who lived in Beijing were included in this study.

The meteorological data (daily mean temperature and relative humidity) were obtained from Beijing Meteorological Bureau. The weather data were collected from a fixed-site station of Beijing Meteorological Bureau located in the study area. The monitoring standard was consistent with World Meteorological Organization (WMO) standard, and the data were representative, though small variations due to the urban micro-climate effect in study area could not be ruled out.

The daily ambient air pollution data, including PM_{10}, SO_2, and NO_2, levels were obtained from Beijing Municipal Environmental Protection Monitoring Center. The daily concentrations of pollutants were average of monitoring results of eleven fixed-site stations. According to the national technical guidelines, the location of these monitoring stations should have sufficient distance away from traffic intersections or major industrial polluters and any other emitting source to reflect the air pollution level in study area.

Methods

Spearman's correlation coefficients were used to evaluate the inter-relations between air pollutants and weather conditions. As the number of daily hospital admission data belongs to small probability event and has a Poisson distribution[17]. Poisson generalized additive model (GAM) was used to explore the associations between daily mean air pollutant concentrations and daily hospital emergency admissions. There were two steps in the model establishing and fitting.

Firstly, the basic models were established for hospital admissions, respectively, excluding the air pollution variables. The regression spline function was used to control long-term trends and seasonal patterns, as well as the daily mean temperature and relative humidity[18]. The partial autocorrelation function (PACF) was used to guide the selection of model parameters[19]. Specifically, 4-6 degrees of freedom (*df*) per year were used for time trend. When the absolute magnitude of the PACF plot was less than 0.1 for the first two lag days, the basic model was regarded as adequate; otherwise, auto-regression (AR) terms for lag up to 7 d was introduced to improve the model[20]. For weather conditions, 3 *df* (whole period of study) were used for both temperature and humidity because this has been shown to control well for their effects on health outcomes[21]. Day of the week (DOW) and public holidays (Holiday) were included as dummy variables in the basic model. Residuals of the basic models were examined to check whether there were discernable patterns and autocorrelation by means of residual plots and PACF plots.

After the basic model was established, ambient air pollutants (PM_{10}, NO_2, and SO_2) were added as variables to the basic model and analyzed their effects on hospital admissions. The independent model is as follow:

$$\text{Log}[E(Yt)]=\alpha+s(\text{time},df)+DOW+\text{Holiday}+s(\text{temperature},df)+s(\text{humidity}, df)+\beta Zt \quad (1)$$

Where *t* refers to the day of the observation; E (*Yt*) denotes estimated daily hospital emergency admissions recorded on day *t*; *α* is the intercept; s () denotes a regression spline function for nonlinear variables; time is the days of calendar time on day *t*; *df* is the degree of freedom; *DOW* is the day of the week on day *t*. β represents the log-relative rate of daily hospital emergency admissions associated with a unit increase of air pollutants; *Zt* represents major air pollutants concentrations on day *t*.

Secondly, a binary variable was created for season, with 0 for warm season (from May to October) and 1 for cold season (November to April). Then a product term between pollutants and season was added into the core model to test the possible interaction between air pollution and season. Model 2 is as follows:

$$\text{Log}[E(Yt|x)]=\alpha+\beta_1\text{pollutant}+\beta_2\text{season}+\beta_3\text{pollutant}\times\text{season}+COVs \quad (2)$$

Where *COVs* were all time varying confounders identified in the core model (1). β_1 signifies the main effect of the pollutant in the warm season, and (β_1+β_3) was the pollutant effect in the cold season. β_2 is a vector for coefficients of the season, and β_3 is a vector for coefficients of the interactive term between the pollutant and seasons[22].

Additionally, the sex and age specific associations between ambient air pollution and hospital emergency admissions were evaluated. Both single-pollutant models and multiple-pollutant models were fitted with a different combination of pollutants to assess the stability of the major air pollutants influences on hospital emergency admissions. Delayed effects were investigated with single day lags (from L0 to L6) and cumulative lag days (L01 and L06) for air pollutants. For example, in single-day lag models, a lag of 0 day (L0) refers to the current-day air pollutant concentration and a lag of 1 day refers to the previous-day air pollutant concentration. In multi-day lag models, L02 refers to 3-day moving average of pollutant concentration of the current and previous 2 day values. We chose the lagged day with the largest estimated effect in model (1) to analyze the other steps in the study. The estimated effects were expressed as the increase percentage and their 95% confidence interval (95% CI) of daily hospital admissions for total, respiratory, cardiovascular disease with a 10 $\mu g/m^3$ increase in daily air pollutants. All analyses were conducted with R3.0.0 statistical software in mgcv package (R Development Core team, 2012)[23-24].

RESULTS

The mean of hospital emergency admissions, meteorological measures and air pollutant concentrations are shown in Table 1. From 1 January 2009 to 31 December 2011 (1095 d), a total of 895,833 hospital emergency admissions were recorded including 52,203 emergency admissions due to cardiovascular disease (5.83%) and 246,872 emergency admissions due to respiratory disease (27.56%). On average, there were approximately 818 hospital emergency admissions per day, in which 48 were due to cardiovascular disease and 226 were due to respiratory disease (Table 1). During the study period, the mean daily average temperature and relative humidity were 13.15 °C and 50.43%, reflecting the continental monsoon climate with sub-humid warm temperature in Beijing. Meanwhile, the mean daily average air pollutant concentrations were 110.16 μg/m^3 for PM_{10}, 28.07 μg/m^3 for SO_2, and 51.88 μg/m^3 for NO_2. The annual average concentration of PM_{10} and NO_2 were higher than the Grade II national standards for air quality (100 μg/m^3 for PM_{10} and 40 μg/m^3 for NO_2) (Table 1). The annual average concentration of SO_2 was lower than the Grade II national standards for air quality (60 μg/m^3) (Table 1). SO_2 concentration showed an obvious seasonality, which was about two times higher in cold season than in warm season and peaked during November-April. The average concentrations of PM_{10} and NO_2 showed small season specific variations.

Table 2 shows the Spearman correlation coefficients between air pollutants and weather variables. PM_{10}, SO_2 and NO_2 levels had strong positive correlations with each other. There was a certain degree of collinearity among the pollutants, especially between SO_2 and NO_2 levels (r=0.649, P<0.01), PM_{10} and NO_2 (r=0.647, P<0.01), and between PM_{10} and SO_2 levels (r=0.517, P<0.01). Meanwhile, NO_2 and SO_2 levels were negatively correlated with temperature and relative humidity. However, PM_{10} level was positively correlated with temperature and relative humidity.

Table 1. Mean of Hospital Emergency Admissions, Air Pollution Levels and Meteorological Variables in Beijing, 2009-2011

Daily Data	Mean	SD	Min	P_{25}	Median	P_{75}	Max
Hospital emergency admissions							
Total	818.11	150.06	431.00	719.00	817.00	913.00	1569.00
Cardiovascular	47.70	11.20	16.00	40.00	48.00	55.00	84.00
Respiratory	225.50	89.80	70.00	169.00	208.00	255.00	882.00
Metrologic measures							
Temperature (°C)	13.15	11.54	-12.50	1.80	14.90	24.20	34.50
Relative humidity (%)	50.43	19.79	9.00	33.00	51.00	67.40	92.10
Air pollutants concentrations							
PM_{10} (μg/m^3)	110.16	63.28	11.00	58.00	104.00	152.00	544.00
SO_2 (μg/m^3)	28.07	28.39	5.00	9.00	18.00	35.00	234.50
NO_2 (μg/m^3)	51.88	23.60	11.20	35.20	46.40	62.40	241.60
Cold season[a]							
PM_{10} (μg/m^3)	114.05	72.54	11.00	54.00	104.00	158.00	544.00
SO_2 (μg/m^3)	42.82	33.48	11.00	19.00	33.00	56.00	235.00
NO_2 (μg/m^3)	57.37	26.86	5.00	37.00	53.00	75.00	157.00
Warm season[b]							
PM_{10} (μg/m^3)	106.23	52.43	12.00	62.00	106.00	148.00	430.00
SO_2 (μg/m^3)	13.56	8.56	5.00	7.00	11.00	17.00	52.00
NO_2 (μg/m^3)	46.53	18.35	16.00	35.00	43.00	54.00	242.00

Note. SD: standard deviation; Min: minimum; P_{25}: 25th percentile; P_{75}: 75th percentile; Max: maximum; IQR: inter quartile range. [a]Cold season: from November to April; [b]Warm season: from May to October.

Table 2. Spearman Correlation Coefficients Between Air Pollutants and Weather Conditions in Study Period

Factors	Temperature	Relative Humidity	PM_{10}	SO_2	NO_2
Temperature	1.000	-	-	-	-
Relative humidity	0.341*	1.000	-	-	-
PM_{10}	0.085*	0.305*	1.000	-	-
SO_2	-0.551*	-0.264*	0.517*	1.000	-
NO_2	-0.242*	-0.108*	0.647*	0.649*	1.000

Note. *P<0.01; n=1095.

Table 3 shows the estimates for the increase percentage of hospital emergency admissions associated with a 10 μg/m[3] increase of pollutants' concentrations in different lag structures after adjustment for the long-term trend, DOW, holiday and weather conditions. For overall hospital admissions, greater increases were found for PM_{10} at lag 03 day (L03), SO_2 and NO_2 at lag 0 day (L0), respectively. For cardiovascular disease and respiratory disease emergency admissions, the influences of the 3 air pollutants peaked at lag 5 day (L5) and lag 02 day (L02). For example, a 10 μg/m[3] increase in concentration of PM_{10} at lag 03 day, SO_2 and NO_2 at lag 0 day were associated with an increase of 0.88% (95% CI: 0.33%-1.43%), 0.76% (95% CI: 0.41%-1.10%), and 1.82% (95% CI: 1.02%-2.62%) respectively in overall emergency admissions. a 10 μg/m[3] increase in concentration of PM_{10}, SO_2 and NO_2 at lag 5 day were associated with an increase of 1.39% (95% CI: 0.09%-2.69%), 1.56%

Table 3. Increase Percentage of Hospital Emergency Admissions with a 10 μg/m[3] Increase of Air Pollutant Concentrations in Beijing, 2009-2011[a]

Lag Structures	Overall		Cardiovascular		Respiratory	
	IP% (95% CI)	*P* Value	IP% (95% CI)	*P* Value	IP% (95% CI)	*P* Value
PM_{10}						
Single-day lag						
0	0.38 (0.03—-0.73)	0.05	0.51 (-1.13—-2.15)	0.13	0.62 (0.12—1.12)	0.02
1	0.37 (0.02—-0.72)	0.04	-1.66 (-3.22—0.11)	0.26	0.96 (0.29—1.64)	0.01
2	0.47 (0.13—0.81)	0.01	-0.87 (-2.26—0.52)	0.23	1.10 (0.49—1.71)	<0.01
3	0.23 (-0.01—0.47)	0.17	-1.33 (-2.65—0.01)	0.17	0.31 (-0.29—0.92)	0.31
4	-0.41 (-0.71—0.11)	0.07	-0.40 (-1.01—0.21)	0.25	-0.15 (-0.75—0.45)	0.62
5	-0.49 (-0.81—0.18)	0.25	1.39 (0.09—2.69)	0.01	-0.26 (-0.86—0.34)	0.39
6	-0.63 (-0.95—0.31)	0.39	0.39 (0.03—0.75)	0.04	0.25(-0.34—0.84)	0.40
Cumulative-day lag						
01	0.59 (0.13—1.05)	0.01	-0.93 (-2.84—0.98)	0.35	1.21 (0.34—2.08)	0.01
02	0.67 (0.28—1.06)	0.01	-1.59 (-3.95—0.77)	0.21	1.72 (0.82—2.62)	<0.01
03	0.88 (0.33—1.43)	<0.01	-2.17 (-4.57—0.23)	0.17	1.46 (0.59—2.33)	0.01
04	0.54 (-0.04—1.12)	0.07	-2.37 (-4.78—0.05)	0.06	1.47 (0.61—2.33)	0.01
05	0.22 (-0.41—0.85)	0.50	-1.29 (-3.86—1.27)	0.34	1.28 (0.34—2.23)	0.03
06	-0.18 (-0.27—0.09)	0.61	-0.99 (-3.13—1.15)	0.49	1.42 (0.42—2.42)	0.02
SO_2						
Single-day lag						
0	0.76 (0.41—1.10)	<0.01	-0.38 (-1.82—1.07)	0.61	0.35 (0.05—0.65)	0.03
1	0.35 (0.16—0.54)	0.01	-0.35 (-1.67—0.98)	0.60	0.81 (0.23—1.39)	0.01
2	0.27 (-0.01—0.55)	0.07	-0.99 (-2.22—0.25)	0.12	1.30 (0.67—1.93)	<0.01
3	0.34 (0.05—0.63)	0.02	-0.72 (-1.87—0.45)	0.23	-0.22 (-0.76—0.32)	0.35
4	-0.30 (-0.89—0.32)	0.53	-0.26 (-3.68—3.27)	0.66	-0.47 (-1.27—0.34)	0.30
5	-0.37 (-0.96—0.22)	0.50	1.56 (0.40—2.73)	0.01	-0.39 (-1.05—0.27)	0.20
6	-0.22 (-0.51—0.07)	0.13	1.01 (0.16—1.86)	0.04	0.54 (0.03—1.06)	0.03
Cumulative-day lag						
01	0.13 (0.02—0.24)	0.04	-0.49 (-2.08—1.10)	0.55	0.43 (0.18—0.68)	0.02
02	0.31 (0.05—0.57)	0.02	-1.09 (-3.34—1.16)	0.23	1.34 (0.04—2.64)	<0.01
03	0.50 (0.03—0.97)	0.01	-1.40 (-3.27—0.47)	0.15	0.99 (0.15—1.83)	0.02
04	0.08 (-0.42—0.26)	0.75	-1.44 (-3.43—0.55)	0.16	-0.14 (-1.47—1.19)	0.76
05	-0.40 (-0.93—0.14)	0.15	-0.44 (-1.96—1.08)	0.39	-0.60 (-1.57—0.37)	0.23
06	-0.45 (-1.02—0.12)	0.12	0.16 (0.02—0.31)	0.04	-0.27 (-1.68—1.14)	0.61
NO_2						
Single-day lag						
0	1.82 (1.02—2.62)	<0.01	0.39 (-1.07—1.86)	0.61	2.13 (1.07—3.19)	<0.01
1	1.49 (0.95—2.03)	<0.01	-0.01 (-0.27—0.24)	0.98	0.69 (0.13—1.25)	0.02
2	0.86 (0.37—1.35)	<0.01	-1.01 (-2.15—0.13)	0.08	1.01 (0.53—1.50)	<0.01
3	-0.09 (-0.20—0.02)	0.70	-0.69 (-1.73—0.36)	0.20	-0.05 (-0.52—0.41)	0.42
4	-0.42 (-0.97—0.13)	0.31	-0.45 (-1.48—0.59)	0.40	-0.50 (-0.11—0.12)	0.33
5	-0.71 (-1.17—0.25)	0.21	1.18 (0.15—2.21)	0.02	-0.74 (-1.19—0.27)	0.25
6	-0.23 (-0.69—0.22)	0.32	0.65 (0.36—0.94)	0.03	-0.25 (-0.71—0.21)	0.28
Cumulative-day lag						
01	1.34 (0.61—2.07)	<0.01	0.20 (-1.38—1.88)	0.79	2.19 (1.43—2.95)	<0.01
02	1.39 (1.07—1.71)	<0.01	-0.64 (-2.41—1.13)	0.48	2.57 (1.75—3.39)	<0.01
03	1.41 (0.58—2.25)	<0.01	-1.19 (-3.03—0.65)	0.25	2.01 (1.17—2.86)	<0.01
04	0.87 (0.23—1.51)	0.05	-1.29 (-3.21—0.63)	0.20	1.40 (0.53—2.29)	<0.01
05	0.34 (-0.79—0.11)	0.48	-0.39 (-2.44—1.65)	0.71	0.81 (-0.11—1.74)	0.08
06	0.17 (-0.80—0.46)	0.73	0.05 (-2.12—2.23)	0.96	0.62 (-0.36—1.60)	0.22

Note. [a] Models were controlled for the time trend, DOW, holiday, mean temperature, humidity.

(95%CI: 0.40%-2.73%), and 1.18% (95%CI: 0.15% -2.21%) respectively in cardiovascular disease emergency admissions. For lag 02, a 10 μg/m^3 increase in concentration of PM_{10}, SO_2 and NO_2 were associated with 1.72% (95% CI: 0.82%-2.62%), 1.34% (95% CI: 0.04%-2.64%), and 2.57% (95% CI: 1.75% -3.39%) increases respectively in respiratory disease emergency admissions.

Figure 1 shows the exposure-response relationships between air pollutants and overall, respiratory disease and cardiovascular disease emergency admissions in the single-models. The linear like relationships were observed between PM_{10} level and all the emergency admissions and between SO_2 level and the overall and cardiovascular disease emergency admissions. The J-shaped exposure response relationship was observed between SO_2 and respiratory disease emergency admission. For NO_2, the exposure-response relationships similar to those of SO_2 were observed. It was important that even the pollution levels of the 3 pollutants were below the current air quality standard in residential area of China (24-h average: 150 μg/m^3 for PM_{10}, 150 μg/m^3 for SO_2 and 80 μg/m^3 for NO_2), the obvious health effects of PM_{10}, SO_2, and NO_2 were still observed from the curves of Figure 1.

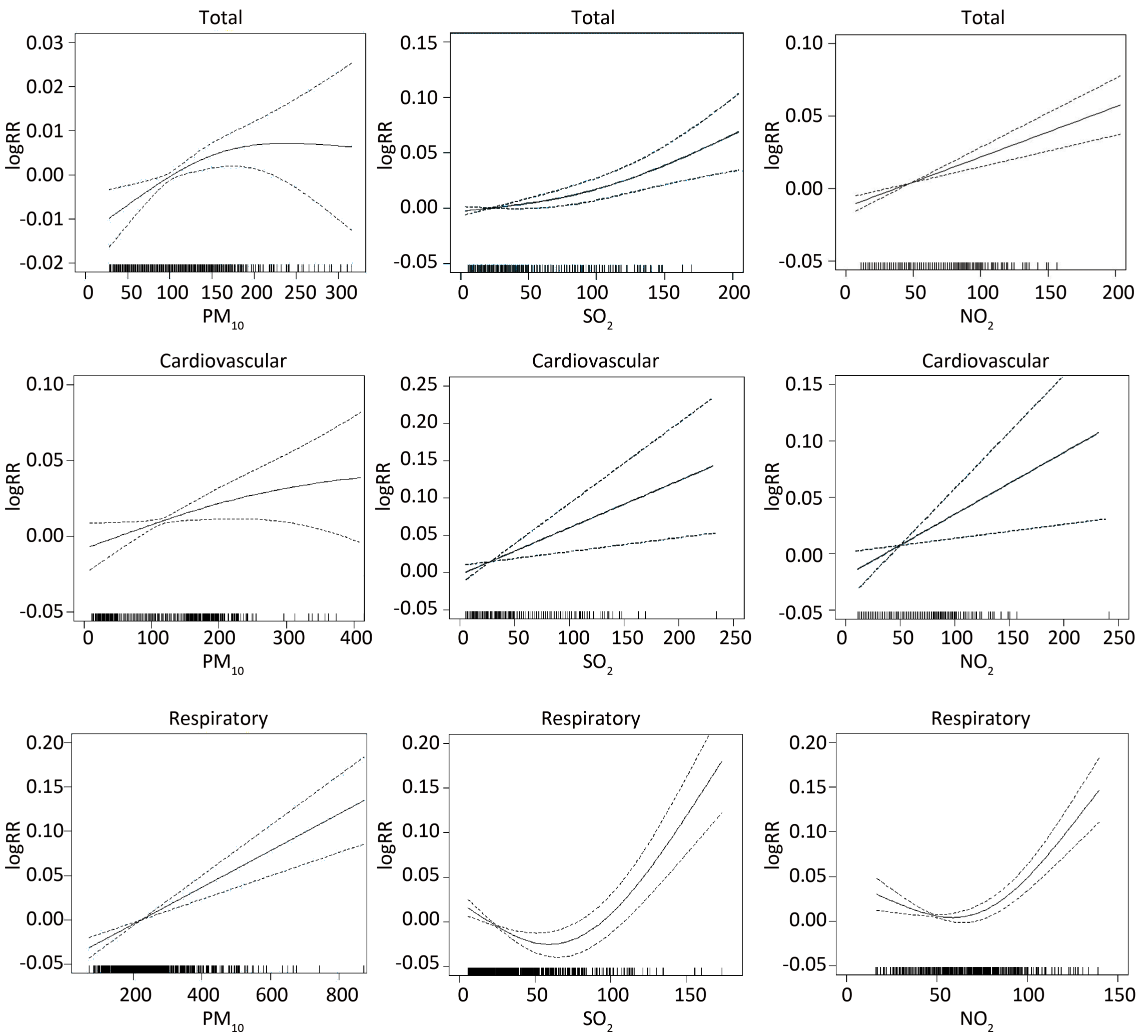

Figure 1. Smoothing plots of air pollutant concentrations against overall, cardiovascular disease and respiratory disease emergency admissions. X-axis is the pollutants concentrations (μg/m^3). The solid lines indicate the estimated mean increase percentage in daily hospital emergency admission, and the dotted lines represent 95% confidence intervals. Cumulative day lag (L03 for PM_{10}) and single day lag (L0 for NO_2 and SO_2) were used for overall hospital admissions. Single day lag 5 (L5 for PM_{10}, NO_2, and SO_2) were used for cardiovascular disease emergency admissions. Cumulative day lag (L03 for PM_{10}, L02 for NO_2 and SO_2) were used for respiratory disease emergency admissions. All the models were controlled for the time trend, DOW, holiday and weather conditions.

Table 4 shows the sex and age specific influences of air pollutants. Significant associations were found between air pollutants and hospital emergency admissions. The influences of air pollutants in females were significantly greater than in males. The influences of air pollutants on overall and respiratory disease emergency admissions in the elderly aged ≥65 years and children aged 0-14 years were greater than those in people aged 15-64 years. For cardiovascular disease, the influence of air pollutants on hospital emergency admission was significantly greater in the elderly aged ≥65 years than in other age groups.

In the season-specific analysis. The associations between air pollutants and hospital emergency admissions seemed to be more obvious in cold season than in warm season (Table 5). The significant associations of SO_2 and NO_2 and overall hospital emergency admissions were observed in both cold season and warm season, but the significant association between PM_{10} and overall hospital emergency admission was only observed in cold season. For cardiovascular disease, significant associations between the 3 air pollutants and hospital emergency admissions were only observed in cold season. For respiratory disease, significant associations between the 3 air pollutants and hospital emergency admissions were observed in both cold season and warm season.

Table 6 shows the analysis results of single-pollutant models and multiple-pollutant models. For the overall hospital and respiratory disease emergency admissions, the influences of PM_{10} and NO_2 reduced and remained significant after adjusting for other pollutants, while effect of SO_2 reduced and become insignificant after adjusting for other pollutants except PM_{10}. As for cardiovascular disease emergency admissions, there were no any significant associations with multi-pollutants.

Table 4. Sex and Age Specific Increase Percentage of Hospital Emergency Admissions with a 10 μg/m^3 Increase in Air Pollutant Concentrations in Beijing, 2009-2011*

Categories	PM_{10}		NO_2		SO_2	
	IP% (95% CI)	*P* Value	IP% (95% CI)	*P* Value	IP% (95% CI)	*P* Value
Overall						
Sex						
Female	0.90 (0.26—1.54)	0.02	1.04 (0.44—1.64)	<0.01	0.76 (0.26—1.26)	0.02
Male	0.63 (0.05—1.21)	0.03	0.64 (0.13—1.16)	0.01	0.67 (0.19—1.15)	0.02
Age						
0-14	1.12 (0.18—2.06)	0.01	0.47 (0.12—0.82)	0.03	1.48 (0.92—2.04)	0.01
15-64	0.81 (0.13—1.49)	0.02	0.41 (0.09—0.73)	0.04	0.43 (0.17—0.69)	0.02
≥65	1.91 (1.53—2.29)	0.01	0.93 (0.35—1.51)	0.02	0.74 (0.29—1.19)	0.04
Cardiovascular disease						
Sex						
Female	2.71 (0.78—4.64)	0.01	1.64 (0.11—3.17)	0.04	1.47 (0.24—2.70)	0.03
Male	0.41 (-1.35—2.17)	0.65	0.79 (-0.60—2.18)	0.26	1.08 (0.39—1.77)	0.02
Age						
0-14	-4.44 (-9.85—0.97)	0.28	-4.12 (-9.46—1.22)	0.42	-0.18 (-3.64—3.28)	0.61
15-64	1.10 (-0.59—2.79)	0.20	0.76 (-0.56—2.08)	0.26	1.05 (-0.44—2.55)	0.17
≥65	2.23 (1.35—3.11)	0.02	1.59 (0.32—2.86)	0.03	1.84 (0.46—3.22)	0.03
Respiratory disease						
Sex						
Female	2.38 (1.04—3.72)	<0.01	1.90 (0.97—2.84)	<0.01	2.34 (1.29—3.40)	<0.01
Male	1.47 (0.58—2.36)	0.02	1.19 (0.36—2.03)	0.01	1.09 (0.36—1.82)	0.02
Age						
0-14	4.27 (2.45—6.09)	<0.01	3.65 (1.85—5.45)	<0.01	5.93 (3.92—7.94)	<0.01
15-64	1.81 (0.76—2.86)	0.01	1.74 (1.01—2.47)	<0.01	1.24 (0.44—2.04)	<0.01
≥65	3.44 (1.98—4.90)	0.01	3.78 (1.58—5.98)	<0.01	1.51 (0.58—2.44)	0.03

Note. *The greatest effects of cumulative day lag (L03 for PM_{10}) and single day lag (L0 for NO_2 and SO_2) were used for overall hospital admissions. Single day lag 5 (L5 for PM_{10}, NO_2 and SO_2) were used for cardiovascular disease emergency admissions. Cumulative day lag 02 (L02 for PM_{10}, NO_2 and SO_2) were used for respiratory disease emergency admissions. All the models were controlled for the time trend, DOW, holiday and weather conditions.

Table 5. Increase Percentage of Daily Hospital Emergency Admissions with a 10 μg/m^3 Increase of Pollutant Concentrations in Beijing 2009-2011*

Categories	Pollutant	Warm Season		Cool Season		Entire Period	
		IP% (95%CI)	*P* Value	IP% (95%CI)	*P* Value	IP% (95%CI)	*P* Value
Overall	PM_{10}	0.14 (-0.40—0.68)	0.52	1.10 (0.57—1.64)	0.01	0.88 (0.33—1.43)	0.01
	SO_2	0.21 (0.03—0.39)	0.04	1.66 (1.17—2.16)	<0.01	0.76 (0.41—1.10)	0.01
	NO_2	0.38 (0.17—0.59)	<0.01	2.40 (1.82—3.01)	<0.01	1.82 (1.02—2.62)	<0.01
Cardiovascular	PM_{10}	1.10 (-0.89—3.09)	0.28	1.66 (-0.13—3.45)	0.07	1.39 (0.09—2.69)	0.01
	SO_2	-0.60 (-2.12—0.92)	0.44	2.51 (0.85—4.17)	<0.01	1.56 (0.40—2.73)	0.01
	NO_2	0.44 (-0.91—1.79)	0.52	2.09 (0.30—3.88)	0.01	1.18 (0.15—2.21)	0.02
Respiratory	PM_{10}	0.57 (0.26—0.88)	0.04	2.63 (0.59—4.67)	<0.01	1.72 (0.82—2.62)	<0.01
	SO_2	1.15 (0.37—1.93)	0.02	1.85 (0.37—2.33)	<0.01	1.34 (0.04—2.64)	<0.01
	NO_2	1.73 (0.48—2.98)	0.01	3.38 (1.63—5.13)	<0.01	2.57 (1.75—3.39)	<0.01

Note. *The greatest effects of cumulative day lag (L03 for PM_{10}) and single day lag (L0 for NO_2 and SO_2) were used for overall hospital emergency admissions. Single day lag 5 (L5 for PM_{10}, NO_2, and SO_2) were used for cardiovascular disease emergency admissions. Cumulative day lag 02 (L02 for PM_{10}, NO_2, and SO_2) were used for respiratory disease emergency admissions. All the models were controlled for the time trend, DOW, holiday and weather conditions.

Table 6. Increase Percentage of Daily Hospital Emergency Admissions with 10 μg/m^3 Increase of Pollutant Concentrations in Beijing*

Models	IP% (95% CI)	*P*	Models	IP% (95% CI)	*P*	Models	IP% (95% CI)	*P*
Overall								
PM_{10}	0.88 (0.33—1.43)	0.01	SO_2	0.76 (0.41—1.10)	0.01	NO_2	1.82 (1.02—2.62)	<0.01
+SO_2	0.82 (0.29—1.35)	0.01	+PM_{10}	0.64 (0.12—1.16)	0.02	+PM_{10}	0.74 (0.20—1.28)	0.01
+NO_2	0.78 (0.16—1.40)	0.01	+NO_2	0.49 (-0.11—1.09)	0.10	+SO_2	0.79 (0.21—1.37)	0.01
+SO_2+NO_2	0.70 (0.03—1.38)	0.04	+PM_{10}+NO_2	0.37 (-0.23—0.97)	0.23	+PM_{10}+SO_2	0.54 (0.09—0.98)	0.02
Cardiovascular disease								
PM_{10}	1.39 (0.09—2.69)	0.01	SO_2	1.56 (0.40—2.73)	0.01	NO_2	1.18 (0.15—2.21)	0.02
+SO_2	0.48 (-1.16—2.12)	0.57	+PM_{10}	1.30 (-0.16—2.76)	0.08	+PM_{10}	0.81 (-0.64—2.26)	0.28
+NO_2	0.67 (-1.16—2.50)	0.48	+NO_2	1.28 (-0.41—2.97)	0.14	+SO_2	0.34 (-1.16—1.84)	0.66
+SO_2+NO_2	0.39 (-1.47—2.25)	0.68	+PM_{10}+NO_2	1.21 (-0.51—2.93)	0.17	+PM_{10}+SO_2	0.17 (-1.54—1.88)	0.85
Respiratory disease								
PM_{10}	1.72 (0.82—2.62)	<0.01	SO_2	1.34 (0.04—2.64)	<0.01	NO_2	2.57 (1.75—3.39)	<0.01
+SO_2	0.92 (0.29—1.55)	0.01	+PM_{10}	0.94 (0.03—1.85)	0.02	+PM_{10}	1.32 (0.40—2.24)	<0.01
+NO_2	0.78 (0.16—1.40)	0.01	+NO_2	-0.53 (-1.56—0.50)	0.32	+SO_2	1.50 (0.85—2.15)	<0.01
+SO_2+NO_2	0.70 (0.03—1.38)	0.04	+PM_{10}+NO_2	-0.47 (-1.51—0.57)	0.42	+PM_{10}+SO_2	1.58 (0.72—2.44)	<0.01

Note. *The greatest effects of cumulative day lag (L03 for PM_{10}) and single day lag (L0 for NO_2 and SO_2) were used for overall hospital emergency admissions. Single day lag 5 (L5 for PM_{10}, NO_2, and SO_2) were used for cardiovascular disease emergency admissions. Cumulative day lag 02 (L02 for PM_{10}, NO_2, and SO_2) were used for respiratory disease emergency admissions. All the models were controlled for the time trend, DOW, holiday, weather conditions.

DISCUSSION

The results of this time-series analysis showed that ambient air pollution (caused by PM_{10}, SO_2 and NO_2) was associated with overall, cardiovascular disease and respiratory disease emergency admissions in Beijing during 2009-2011. The children aged 0-14 years and the elderly aged ≥65 years seemed to be more vulnerable to air pollution than those aged 15-64 years indicated by the analysis on overall and respiratory disease emergency admissions, For cardiovascular disease emergency admission, the influence of air pollutants was more serious in the elderly aged ≥65 years than in other age groups. Females seemed to be more vulnerable to air pollution than males. The association between air pollution and hospital emergency admissions seemed to be more obvious in cold season than in warm season. Also, significant effects of ambient air pollution on cardiovascular and respiratory diseases were observed even the pollution levels of the 3 pollutants were below the air quality standard in China. Therefore, current air quality standards might not be appropriate to protect the public health in Beijing. These findings may have implications for the improvement of environmental and social development policies in Beijing and for the local government to protect human health.

Generally speaking, for overall and respiratory disease emergency admissions, the influence of air pollution was more obvious in children aged 0-14 years and the elderly aged ≥65 years than those aged 15-64 years, which might be explained by the fact that the children and the elderly are susceptible groups due to weaker resistance to diseases. The elderly are prone to be affected by cardiovascular disease and they are high-risk group affected by air pollution. So the identification of target diseases and high risk groups would facilitate the development of appropriate air quality guidelines[25].

According to the analysis on the association between ambient air pollution and hospital emergency admission, it was found that the influence of air pollutant was greater in females than in males, but the reasons are unclear and need further investigation. In Beijing, females have much lower smoking rate than males (0.6% *vs.* 50.6%)[26]. One study suggested that influence of air pollution might be stronger in nonsmokers than in smokers[27]. Oxidative and inflammatory effects of smoking might reduce the influence of pollutant to respiratory tract due to additional exposure to air pollutants in male smokers. In addition, females have slightly greater airway reactivity than males, as well as smaller respiratory tract[28]; therefore, the dose-response reaction might be detected more easily in females than in males. Deposition of particles in the lung is different between males and females, and greater lung deposition of 1 μmol/L particles has been observed in females[29].

Our finding of stronger association between air pollution and daily hospital emergency admissions in cold season is consistent with a previous study in Beijing[30] and several other air pollution studies in Hong Kong[31-32] and Athens[33], but inconsistent with other studies reporting greater air pollution influence in warm season[34-35]. In Beijing, the concentrations of PM_{10}, SO_2, and NO_2 are higher and more variable in cold season than in warm season. Because these three pollutants were strong positive correlations with each other, greater influence observed during cold season may also be due to other pollutants that were also at higher levels during that season. Exposure patterns may explain our season-specific observation. During the warm season, Beijing residents use air conditioning (AC) more frequently due to higher temperature and relative humidity, resulting in less outdoor exposures. A previous study in the US showed that higher AC usage was associated with lower health impact for PM[36]. In addition, frequent rain in warm season may reduce personal outdoor exposure time. In contrast, the cold season in Beijing is dry and coal is widely used as the primary fuel for household heating during several winter months.

Cardiovascular and respiratory diseases were selected in our study, because they are prone to be induced by air pollution and the major causes of hospital emergency admissions. Recently there have been many studies on the potential mechanisms of air pollution in inducing cardiopulmonary diseases. For example, air pollution has been considered to be associated with increased plasma viscosity, changes in the characteristics of the blood, abnormality of autonomic function of the heart, including increased heart rate, decreased heart variability, and increased cardiac arrhythmias[37-38]. These findings provide possible pathways in which air pollution affects cardiovascular system. Air pollutants can oxidize mitochondria such as apoptosis or necrosis of macrophages and respiratory epithelial cells, resulting in decrease of host defense to respiratory infection or increasing respiratory tract reactivity[39]. Also, the patients with respiratory disease, such as chronic obstructive pulmonary disease, often have a systemic defect in their antioxidant defenses, and air pollution could cause significant additional oxidative stress as response to lung inflammations[40]. The reduction in hospital emergency admissions after the implementation of intervention program supported the hypothesis of causal link between air pollution and disease.

The influences of the air pollutants on respiratory disease and cardiovascular disease emergency admissions at lag 02 and lag 5 seemed to be the most important in the study, which is consistent with most previous studies. This phenomenon might be explained by that pollutants attack the respiratory system firstly, then the heart and blood vessels of the circulatory system. Although the best lag of each pollutant was chosen by statistical criteria, the chemical and toxicological properties of the pollutants might offer plausible explanations for this phenomenon. The pollutants (PM_{10}, SO_2, and NO_2) can be breathed into the respiratory tract and directly inhaled into the pulmonary alveoli from where blood circulation can take them to the cerebral-vascular system. SO_2 is very soluble in the upper respiratory tract and exerts an immediate irritant effect on the respiratory mucosa. This might explain that the 2-day cumulative lag influence for respiratory disease emergency admissions. NO_2 is highly reactive oxidants which can cause inflammation of the pulmonary epithelium. And it forms nitrous and nitric acid in the respiratory epithelium and alters host defense in animal studies[37], at high concentrations it can cause delayed pulmonary oedema. The pathophysiology of the chemical heterogeneous particulates is unclear. Acid aerosols might be the cause to affect health[39]. In Beijing, the main components of PM_{10} are carbon and sulphates[41]. The acidity of particulates is not assessed here. Nonetheless, the reason for the different lag periods between respiratory disease and cardiovascular disease remains unclear, further investigation is needed.

In the multiple pollutant models, the IP values of the pollutants (PM_{10}, NO_2, and SO_2) for overall and respiratory disease emergency admissions were lower than those in the single pollutant models. Particularly no statistical significant association was found between air pollutants and cardiovascular disease emergency admissions, even though the ambient air pollution is considered to be serious in Beijing, similar to the results of other studies[42]. The smaller influences of air pollutants (SO_2, NO_2, and PM_{10}) on total, respiratory and cardiovascular diseases in the multiple pollutants models may be caused by their statistical co-linear effect[43].

As an environmental epidemiology study, there were some possible limitations in this study. We did not get the air pollution data from nearest stations, average concentrations of SO_2, NO_2 and PM_{10} were obtained from eleven fixed-site stations so that selection bias might exist in this study[44]. Some previous studies have found that particulate matter less than 2.5 μm in aerodynamic diameter ($PM_{2.5}$), submicron and ultrafine particles ozone (O_3) and pollen were important effect factors for disease, especially for respiratory and cardiovascular diseases[45-46], but in this study, the data of $PM_{2.5}$, O_3 and pollen were unavailable, thus limiting the evaluation of the influences of $PM_{2.5}$, submicron and ultrafine particles, O_3 and pollen on hospital emergency admissions. And in order to ensure the enough sample size, we did not control the influenza season which may cause confounding. There also might be statistical spurious associations in this study, because the diagnosis can never be 100% correct.

CONCLUSION

In summary, in this time-series analysis, it was found that ambient air pollution was associated with overall, cardiovascular disease and respiratory disease hospital emergency admissions in Beijing during 2009-2011. Furthermore, the results suggested that season and people's demographic characteristics (e.g. sex, and age) may modify the acute health effects of air pollution. These findings provide new insight about the effects of modifiers on the association between daily hospital emergency admissions and air pollution in developing countries and may have implications for local environmental and social development policies.

CONFLICT OF INTEREST

The authors declare that they have no competing financial interests.

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