ORIGINAL ARTICLE

The spatial variation in the effects of air pollution on cardiovascular mortality in Beijing, China

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Owing to lack of data from multiple air quality monitoring stations, studies about spatial association between concentrations of ambient pollutants and mortality in China are rare. To investigate the spatial variation of association between concentrations of particulate matter less than 10 μm in aerodynamic diameter (PM_{10}), nitrogen dioxide (NO_2) and carbon monoxide (CO) and cardiovascular mortality in Beijing, China, we collected data including daily deaths, concentrations of PM_{10} , NO_2 and CO, and meteorological factors from 1 January 2009 to 31 December 2010 in all 16 districts of Beijing. Generalized additive model (GAM) and generalized additive mixed model (GAMM) were used to examine the citywide and district-specific effects of PM_{10} , NO_2 and CO on cardiovascular mortality. The citywide effect derived from GAMM was lower than that derived from GAM, and the strongest effects were identified for 2-day moving average lag 0–1. The interquartile increases in concentrations of PM_{10} , NO_2 and CO were associated with 2.46 (95% confidence interval (CI), 1.22–3.72), 4.11 (95%CI, 2.82–5.42) and 2.23 (95%CI, 1.14–3.33) percentage increases in daily cardiovascular mortality by GAMM, respectively. The relative risk of each district compared with reference district was generally statistically significant. The death risk associated with air pollutants varies across different geographic districts in Beijing. The data indicate that the risk is high in suburban areas and rural counties. We found significant and spatially varied adverse effects of air pollution on cardiovascular deaths across the rural and urban areas in Beijing.

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INTRODUCTION

Association of air pollution with human health has been evaluated in numerous time-series studies by fitting Poisson regression model at community or city level.^{1–7} Results of these studies suggest that short-term exposure to ambient air pollution is associated with increased mortality from cardiovascular diseases. Meanwhile, extensive clinical and toxicological studies have also provided evidence for stronger association between air pollution and deaths from cardiovascular diseases.^{8–11} However, most of these studies were conducted in developed countries and there were limited amount of research done in China.

From 2003 to 2012, annual average levels of particulate matter less than 10 μm in aerodynamic diameter (PM_{10}) in the 31 provincial capitals in China were significantly reduced (Figure 1); however, they were still at the higher end of air pollution level in the world. In 2013, the report on Global Environmental Competitiveness ranked the air quality of China 87th out of 133 countries.¹² Beijing, the capital of China, experienced rapid urban expansion and transportation development and hence, led to a serious air pollution problem in the past 10 years,¹³ during which the number of its resident population increased from 14.56 million in 2003 to 21.15 million in 2013.¹⁴ Over the same period, the number of automobiles, a major source of ambient air carbon

monoxide (CO) and nitrogen oxides (NO_x) emissions, increased by 2.5 times, totaling 5.4 million at the end of 2013.¹⁵ Beijing is still facing a substantial challenge of balancing economic growth and environmental protection.

Concerns about effects of air pollution on population health, for example, cardiovascular diseases,^{6,16} respiratory diseases^{16–18} and emergency hospital visits^{19–22} have been increasing in Beijing. However, most of the existing studies characterized exposures using citywide average ambient concentrations of pollutant, which ignored the within-city spatial variation in concentrations of ambient air pollutants because of lacking data from multiple air quality monitoring (AQM) stations. In fact, exposure levels vary greatly across the whole area of Beijing.²³ A study showed that air quality in the southern part was worse than that in the northern part in Beijing.²⁴ And from the southeast plain to the northwest mountain area in Beijing, pollution levels presented a decreasing trend. Chen et al.²⁵ pointed that the spatial variation in the effects of PM_{10} on health outcomes needs to be considered in assessing the health effect of air pollution, particularly for big cities. The study by Zhang et al.²⁶ applied district-specific PM_{10} concentrations to quantify the impact of PM_{10} on population health. However, the study did not include the suburban and rural districts and examined the effects of nitrogen dioxide (NO_2) and

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Figure 1. Annual average ambient levels of PM₁₀ and NO₂ in 31 provincial capitals (including Beijing) of China 2003–2012. The gray-dotted line indicates air quality as Class II based on its annual levels by the National Ambient Air Quality Standards (NAAQS) in China. Data source: China Statistic Yearbook 2004–2013.

CO. In our study, we aimed to apply the generalized additive mixed model (GAMM) to investigate the spatial characteristics of association between air concentrations of PM₁₀, NO₂ and CO and daily cardiovascular mortality in the whole area of Beijing.

MATERIALS AND METHODS

The study was based on Causes of Death Registry (CDR) of the China Centers for Disease Control and Prevention (China CDC), but did not access any individually identifiable patient data. The study was approved by the Institutional Review Board of Institute of Basic Medical Sciences, Chinese Academy of Medical Sciences.

Study Area and Period

Beijing is located in the North China Plain with an area of approximate 16,807 km² and a population of 21.15 million by the end of 2013.¹⁴ The study area covered 16 administrative districts of Beijing, including six urban districts (Dongcheng, Xicheng, Chaoyang, Fengtai, Shijingshan and Haidian), eight suburban districts (Mentougou, Fangshan, Tongzhou, Shunyi, Changping, Daxing, Huairou and Pinggu) and two rural counties (Yanqing and Miyun) (Figure 2). The study was carried out from 1 January 2009 to 31 December 2010.

Data Collection

The data here include the number of daily cardiovascular deaths, air quality, road density and meteorological conditions.

Cardiovascular mortality data were obtained from CDR of China Centers for Disease Control and Prevention (CDC). All deaths in CDR were coded according to the International Classification of Diseases, version 10 (ICD-10), with codes I00–I99 used as deaths from cardiovascular diseases.

Air quality data, including the concentrations of PM₁₀, NO₂ and CO, were generated by district AQM stations at 12 fixed sites in Beijing (Figure 2). All district AQM stations are operated by the Chinese National Monitoring Network for Air Quality Control. The hourly average concentrations for each pollutant were presented. Data from one AQM station (Dingling station in Changping district) were excluded because it was used as the background station for calibration. For the districts having two AQM stations, arithmetic mean of the concentrations of the two stations was used. For the districts without AQM station, a generalized linear model was used to project their pollutant concentrations. The method was described in detail elsewhere.²⁷

To adjust the effect of weather condition on mortality,^{28,29} data on meteorological conditions, including mean daily temperature, relative humidity, wind speed and barometric pressure during the same period were obtained from the Beijing Municipal Meteorological Bureau.

Data Analysis

We used the district-level daily cardiovascular deaths as the dependent variable and the corresponding district-level daily PM₁₀, NO₂ and CO as the

main independent variables. Generalized additive model (GAM) was used to associate the mortalities and the pollutants,³⁰ and GAMM to account for overdispersion and random effect of district to the additive predictor,³¹ under the assumption that the number of daily deaths from cardiovascular diseases follows a Poisson distribution. Natural splines were used to fit the non-linear time trend of the mortality, adjusting for potential confounders, such as day of week (DOW) and meteorological conditions.³² The full GAMM included smoothing function for variables time, temperature and humidity, categorical variable DOW and random effect of district, which can be expressed as:

$$\log(E(Y_{it})) = \beta_0 + \beta_1(\text{DOW}_t) + \beta_2(\text{pollution}_{it}) + s(\text{time}_t, 2 \times \text{years}) + s(\text{temperature}_t, 5) + s(\text{humidity}_t, 2) + \mu Z_i$$

where $E(Y_{it})$ refers to the expected count in district i on day t , DOW is dummy variable for day of week, and Z_i is a random intercept for districts i . $s(\cdot)$ is the smoothing function realized by natural spline with 2 degrees of freedom (d.f.) per year for time to adjust for seasonal and long-term trends and 5 degrees of freedom for temperature and 2 for relative humidity. The most appropriate degrees of freedom of the time, temperature and relative humidity were determined by minimizing Akaike Information Criterion (AIC).³¹

We also compared the citywide effects derived from GAMM and those from GAM. The GAM and GAMM models include the same non-parametric smoothing function for PM₁₀, NO₂ and CO and other confounding factors. The GAM can be expressed as:

$$\log(E(Y_t)) = \beta_0 + \beta_1(\text{DOW}_t) + \beta_2(\text{pollution}_t) + s(\text{time}_t, 2 \times \text{years}) + s(\text{temperature}_t, 5) + s(\text{humidity}_t, 2)$$

Furthermore, we examined the associations with different lag structures, including single-day lags (from lag 0 to lag 4) and multiday lags (moving average lag 0–1 to lag 0–4).

Sensitivity analyses were conducted to investigate the robustness of the citywide associations by changing degree of freedom per year for time trend, using penalized spline for time trends and adding barometric pressure.

All statistical tests were two-sided. The effects of pollutants were presented as percentage changes and corresponding 95% confidence intervals (CIs) of mean number of daily deaths per interquartile ranges (IQR) increment in daily concentrations of PM₁₀, NO₂ and CO. Incidence rate ratios (IRRs) were calculated to evaluate the relative risk of other districts compared with the reference district. All the analyses were conducted by using “mgcv” package available in the R software (version 3.0.2).

RESULTS

Descriptive Statistics

Descriptions of pollutant concentrations, meteorological conditions and cardiovascular mortality in Beijing from 1 January 2009 to 31 December 2010 are given in Table 1.

During the 2-year study period, annual mean concentrations of the three air pollutants were $121.0 \mu\text{g}/\text{m}^3$, $55.0 \mu\text{g}/\text{m}^3$ and $1.5 \text{ mg}/\text{m}^3$ for PM_{10} , NO_2 and CO, respectively. Annual mean concentrations of PM_{10} and NO_2 were above the Class II limits of the National Ambient Air Quality Standards of China ($100 \mu\text{g}/\text{m}^3$ for PM_{10} and $40 \mu\text{g}/\text{m}^3$ for NO_2 , respectively).³³ Average temperature was 12.98°C ranging from -12.5°C to 34.5°C , and average relative humidity was 50.98% ranging from 13.0% to 92.0% during the same time period, showing a typical sub-humid warm continental monsoon climate of Beijing. In the study period, a total of 74,775 cardiovascular deaths occurred within the whole area of Beijing, with average daily deaths of 102.4.

District-specific median concentrations and their IQRs of PM_{10} , NO_2 and CO are shown in Table 2. Median daily concentrations of PM_{10} , NO_2 and CO range from 82.5 to $129.0 \mu\text{g}/\text{m}^3$, 30.0 to $59.0 \mu\text{g}/\text{m}^3$ and 0.90 to $1.40 \text{ mg}/\text{m}^3$, respectively, with the highest levels in Shijingshan, Xicheng and three central urban districts (Shijingshan, Dongcheng and Xicheng), respectively. The highest number of daily deaths from cardiovascular diseases was found in Chaoyang district.

In six districts of Beijing, the daily average concentrations of the three air pollutants in most of the days exceeded the limits of Class II in the National Ambient Air Quality Standards of China (Table 3).³³ For the whole area of Beijing, the number of days with daily 24-h average concentration of PM_{10} higher than the limit accounted for about one quarter of the

period, which was observed in five urban districts (Shijingshan, Dongcheng, Haidian, Xicheng and Chaoyang) and one suburban district (Shunyi).

Table 1. Daily pollutant concentrations, meteorological conditions and number of daily deaths from cardiovascular disease in Beijing from 2009 to 2010.

	Mean	SD	Percentile				
			Min	25th	Median	75th	Max
Air pollutant concentrations (24-h mean)							
PM ₁₀ (µg/m ³)	121.0	75.3	4.9	69.0	107.0	149.0	651.2
NO ₂ (µg/m ³)	55.0	24.0	9.9	39.3	50.4	64.4	180.7
CO (mg/m ³)	1.5	1.0	0.3	0.9	1.2	1.8	7.8
Meteorological measures (24-h mean)							
Temperature (°C)	13.0	11.7	−12.5	1.7	14.7	24.3	34.5
Humidity (%)	51.0	19.2	13.0	35.0	52.0	67.0	92.0
Atmospheric pressure (kPa)	101.2	1.0	99.0	100.4	101.1	101.9	103.7
Daily deaths from cardiovascular disease	102.4	20.5	54.0	87.0	100.0	117.0	173.0

Abbreviations: CO, carbon monoxide; NO_2 , nitrogen dioxide; PM_{10} , particulate matter less than $10 \mu\text{m}$ in aerodynamic diameter; SD, standard deviation.

Figure 2. Distribution of 16 administrative districts and 12 air quality monitoring stations in Beijing.

Table 2. Summary statistics for air pollutant concentrations and cardiovascular mortality in 16 districts of Beijing from 2009 to 2010.

Districts	PM_{10} ($\mu\text{g}/\text{m}^3$)		NO_2 ($\mu\text{g}/\text{m}^3$)		CO (mg/m^3)		Daily cardiovascular deaths	
	Median	IQR	Median	IQR	Median	IQR	Mean	SD
Shijingshan	129.0	90.5	50.0	28.0	1.4	1.0	2.9	1.6
Haidian	112.0	83.0	54.0	34.0	1.2	1.2	10.5	3.6
Dongcheng	110.3	85.5	53.5	26.0	1.4	1.1	6.4	2.6
Shunyi	108.5	88.0	43.5	26.0	0.9	0.8	6.8	3.0
Chaoyang	106.5	84.0	56.0	29.5	1.3	1.0	13.9	4.3
Xicheng	105.5	82.0	59.0	29.0	1.4	1.0	9.0	3.2
Fengtai ^a	99.7	22.7	42.8	17.5	1.2	0.7	10.1	3.5
Tongzhou ^a	96.4	22.0	38.3	16.1	1.1	0.6	7.1	3.1
Daxing ^a	96.3	22.0	38.2	16.0	1.1	0.6	6.1	2.9
Changping	94.0	81.0	41.0	25.0	1.2	0.9	6.0	2.6
Pinggu ^a	93.9	21.6	35.2	15.4	1.0	0.6	5.3	2.4
Fangshan ^a	93.4	21.6	34.8	15.3	1.0	0.5	7.1	3.5
Yanqing ^a	93.0	21.5	34.2	15.1	1.0	0.6	2.7	1.6
Miyun ^a	92.9	21.5	34.1	15.1	1.0	0.6	4.3	2.3
Mentougou ^a	92.8	21.5	34.0	15.1	1.0	0.6	2.8	1.6
Huairou	82.5	75.0	30.0	26.0	1.0	0.8	3.2	1.8

Abbreviations: CO, carbon monoxide; IQR, interquartile range; NO_2 , nitrogen dioxide, PM_{10} , particulate matter less than $10\text{ }\mu\text{m}$ in aerodynamic diameter; SD, standard deviation. ^aPollution level based on the projected values derived from the exposure estimation model.

Table 3. Number of the days with concentrations of air pollutants in the Class II and Class III of the National Ambient Air Quality Standards of China of the 16 districts in Beijing from 2009 to 2010.

Districts	PM_{10} ($\mu\text{g}/\text{m}^3$)		NO_2 ($\mu\text{g}/\text{m}^3$)		CO (mg/m^3)	
	Class II (≥ 150)	Class III (≥ 250)	Class II (≥ 80)	Class III (≥ 120)	Class II (≥ 4)	Class III (≥ 6)
Shijingshan	257	64	90	19	31	4
Dongcheng	205	51	120	26	42	5
Haidian	190	50	116	20	63	16
Xicheng	185	49	152	35	40	6
Chaoyang	186	44	131	26	32	4
Shunyi	195	43	51	7	9	1
Changping	150	33	56	9	17	1
Huairou	117	19	31	7	5	0
Fengtai	30	0	51	5	6	0
Daxing	23	0	28	1	2	0
Tongzhou	23	0	28	1	2	0
Miyun	14	0	15	0	2	0
Pinggu	14	0	19	0	2	0
Fangshan	14	0	15	0	2	0
Yanqing	14	0	15	0	2	0
Mentougou	13	0	15	0	1	0
Citywide	175	39	99	19	27	4

Abbreviations: CO, carbon monoxide; NO_2 , nitrogen dioxide, PM_{10} , particulate matter less than $10\text{ }\mu\text{m}$ in aerodynamic diameter; SD, standard deviation. Note: The limits of air quality for various sites in the National Ambient Air Quality Standards of China: Class I, for nature reserves, scenic spots and other areas that need special protection; Class II, for residential areas, residents-commercial-transportation mixed areas, cultural areas, general industrial areas and rural areas; Class III, for specific industrial zones.

Citywide Effects of Air Pollutions

Figure 3 shows that the point estimates and relevant 95% CIs for the percentage increase in number of citywide daily deaths per IQR increase in concentrations of PM_{10} , NO_2 and CO. Results of GAM fitting indicate the effects of PM_{10} , NO_2 and CO on current day (lag 0), the previous day (lag 1), the moving average 2 days

(lag 0–1), the moving average 3 days (lag 0–2) and the moving average 4 days (lag 0–3) are statistically significant. The statistically significant association of cardiovascular mortality with NO_2 is also found on the moving average 5 days (lag 0–4). Generally, strong single-day effect occurs on lag 1; the strong accumulated effect occurs when 2-day average is used. The cumulative exposure on lag 0–1 has the largest effect. An IQR increase in pollutant concentration was associated with 2.87 (95% CI, 1.66–4.09), 5.02 (95% CI, 3.54–6.52) and 4.11 (95% CI, 2.84–5.40) percentage increase in daily cardiovascular deaths for PM_{10} , NO_2 and CO, respectively.

We found the largest effects at lag 0–1 by using both GAMM and GAM. However, the estimated effects of air pollutions derived from GAM are higher than those derived from GAMM (Figure 3). An IQR increase in concentrations of PM_{10} , NO_2 and CO is associated with 2.46 (95%CI, 1.22–3.72), 4.11 (95%CI, 2.82–5.42) and 2.23 (95%CI, 1.14–3.33) percentage increase in daily cardiovascular deaths, respectively.

District-Specific Effects of Air Pollutions

Because the largest effect of pollutants is generally found on lag 0–1, only the relationship between concentrations of PM_{10} , NO_2 and CO and cardiovascular deaths on lag 0–1 is shown in Figure 4.

The relative risks of every other district compared with Changping are ranked and the same ranking patterns are found for the three pollutants (Figure 4). All districts but Haidian have statistically significant higher risk. Haidian shows a lower significant risk (IRR=0.88, 95%CI, 0.85–0.92).

Each district was used as a reference district in turn, and we compared death risk of district with the reference district respectively. The relative risks are presented in Supplementary eFigure 1. For the three pollutants, the lowest risk of death from cardiovascular disease is in one urban district Haidian, and the highest risk is in one suburban district Pinggu. The death risks in the suburban and rural areas appeared to be stronger than those in the urban areas under the same level of pollutants.

Cardiovascular mortality risks associated with PM_{10} exposure, shown in Supplementary eFigure 1, have statistically significant difference between different districts except Daxing and Shijingshan (IRR=1.04, 95%CI: 0.99–1.11), Yangqing and Dongcheng

Figure 3. Percentage increase in daily cardiovascular deaths associated with an IQR increase in air pollutant concentrations from GAMM (dotted lines) and GAM (solid lines) in Beijing from 2009 to 2010.

(IRR = 1.05, 95%CI, 0.99–1.11), Yanqing and Xingcheng (IRR = 1.01, 95%CI, 0.95–1.07), Fangshan and Yanqing (IRR = 1.03, 95%CI, 0.97–1.10), Shunyi and Fangshan (IRR = 1.02, 95%CI, 0.98–1.07), Huairou and Shunyi (IRR = 1.03, 95%CI, 0.97–1.09) and Miyun and Mentougou (IRR = 1.03, 95%CI, 0.97–1.10). The cardiovascular mortality risks associated with NO₂ (Supplementary eFigure 2) and CO (Supplementary eFigure 3) exposure are similar to that of PM₁₀. In general, the effects of PM₁₀, NO₂ and CO on cardiovascular mortality were different among districts.

Sensitivity Analysis

The change in degree of freedom per year for time trend dose not substantially affect the estimated effects of air pollutants within the range of two to eight degrees of freedom. Different smoothing approaches do not change the effect estimates significantly (results not shown). The analyses suggest that our findings are robust with respect to these issues. Adding barometric pressure to the models result in almost identical estimates.

DISCUSSION

In this multi-site time-series study of excess cardiovascular mortality risk attributable to air pollution, we investigated the spatial variation in associations between short-term exposure to ambient PM₁₀, NO₂ and CO and daily deaths from cardiovascular diseases. It is worth noting that there is significant spatial variation in the estimated effects of PM₁₀, NO₂ and CO on cardiovascular mortality across the 16 districts in Beijing.

We observed the highest levels of PM₁₀ and CO in Shijingshan district, and the highest levels of NO₂ and CO in Xicheng district, where the level of NO₂ was nearly twice as much as that in Huairou district. Shijingshan district is a heavily industrialized zone with iron and steel production industry, metal smelting industry and thermal power plants. Smaller particles and organic pollutants produced during coal combustion and transportation might be the main contributor of the much higher concentrations of PM₁₀ and CO in this district than in other districts.³⁴ Xicheng district is located at the center of Beijing, with high road density and more

Figure 4. The district-specific relative risks (Changping as a reference district) of cardiovascular mortality of air pollutants based on GAMM in Beijing from 2009 to 2010.

serious vehicle traffic jams, which leads to higher emission level of oxynitride and carbon from automobile exhaust.

Many studies provided evidence linking air pollutants with adverse health effects based on the assumption that exposure is uniform within each region or city. Such an assumption might result in errors in estimation of exposure, especially for pollutants with important local sources.³⁵ However, previous studies have suggested that using data from a single AQM station or average concentrations from a few stations might not accurately represent citywide exposure and might lead to bias,²³ as the air pollution levels often vary across the study area.³⁶ Confounding factors that vary between districts might also distort their relation with air pollution. In our study, we modeled PM₁₀, NO₂ and CO at a district level to evaluate their citywide effects on cardiovascular mortality using GAMM. Treating district as a random effect enabled us to account for lack of independence between observations for each district, which might generate more accurate estimates compared with using citywide averaged concentrations. We found significant effects of PM₁₀, NO₂ and CO on cardiovascular mortality, which are similar to those found in the previous studies in the United States,³⁷ Europe^{38,39} and China.^{3,6,16}

Meanwhile, we also fitted a GAM that used average concentration of air pollutants in 16 districts of Beijing. Results show that the

estimated effects of PM₁₀, NO₂ and CO derived from GAM are higher than those derived from GAMM (Figure 3), which is contradicted to findings by Zhang *et al.* and Xu *et al.*^{26,40} However, Zhang's and Xu's studies were conducted in 2008–2009. Annual mean concentration of PM₁₀ in 2008–2009 was slightly higher than that in 2009–2010 (127.7 vs 121.0 $\mu\text{g}/\text{m}^3$). Different time periods and pollution levels might also be potential reasons of the inconsistency. Furthermore, the spatial characteristics of association of gaseous pollutants, such as NO₂ and CO, were not investigated in Zhang's and Xu's studies.

Our findings indicate that there is a spatial variation in estimated effects of PM₁₀, NO₂ and CO on cardiovascular mortality across the 16 districts of Beijing. Consistent with previous reports,⁴¹ we found that suburban and rural residents expose to a greater risk of cardiovascular death correlated with air pollution than urban residents in Beijing. Because of the different emission sources, physicochemical characteristics, weather conditions, geographical factors, industry and transportation infrastructures, and traffic densities, the composition of air pollutants might differ between urban and rural districts.^{34,42} Insufficiency of protection awareness and measures and emergent medical assistance might contribute to this difference.⁴¹ In addition, the population structure might be another factor that may contribute to this

spatial variation. For example, the higher proportion of elderly people and children in some rural areas because of young population migration to urban areas leads higher morbidity and mortality of respiratory and cardiovascular diseases in these areas.⁴³ Access to quality health care could be another potential contributor to spatial variation. High quality hospitals mainly concentrate in urban areas. According to the Beijing Health Development Statistical Bulletin 2009, the number of health institutions in urban areas accounted for 58.8%, and those in rural areas only accounted for 4.5%.⁴⁴

To make our results comparable to those of other Asian cities, we converted our percent increase in daily cardiovascular mortality associated with an IQR increase in pollutant concentrations into $10 \mu\text{g}/\text{m}^3$ increase for PM_{10} and NO_2 . Using 2-day moving average of the air pollutant concentrations, an increase of $10 \mu\text{g}/\text{m}^3$ of PM_{10} was associated with 0.35 (95%CI, 0.21–0.50) percentage increases in cardiovascular mortality, and the corresponding number was 1.97 (95%CI, 1.39–2.55) for $10 \mu\text{g}/\text{m}^3$ increase in NO_2 . A study of PM_{10} and ischemic heart disease mortality in Beijing from 2008 to 2009 indicates that a $10 \mu\text{g}/\text{m}^3$ increase in PM_{10} is associated with an increase of 0.33 (95%CI, 0.13–0.52) percentage.⁴⁰ Our estimate is similar to the result. PAPA study estimates that an increase of $10 \mu\text{g}/\text{m}^3$ in 2-day moving average concentrations of PM_{10} and NO_2 corresponded to 0.27 (95%CI, 0.10–0.44) percentage and 1.01 (95%CI, 0.55–1.47) percentage in Shanghai, 0.57 (95%CI, 0.31–0.84) percentage and 2.21 (95%CI, 1.18–3.06) percentage in Wuhan, 1.9 (95%CI, 0.8–3.0) percentage and 1.8 (95%CI, 0.5–3.1) percentage in Bangkok.⁴⁵ There is little difference between our estimates in Beijing and PAPA results in the other megacities in East Asia. And our results could serve as a complement to the PAPA study.

To our knowledge, our study is the largest study that examined the spatial variation in effects of ambient PM_{10} , NO_2 and CO concentrations on cardiovascular mortality across the whole area in Beijing. The air quality data measured from 12 fixed AQM stations represented the comprehensive air pollution level across the whole area of Beijing. Fitted GAMM used additive non-parametric functions to describe covariate effects that accounted for between-district heterogeneity and within-district correlation by adding random effects to the additive predictors.⁴⁶ However, there are limitations in our study. First, ambient AQM results can differ from personal exposure to air pollutants.⁴⁷ Numerous factors, such as air conditioning, ventilation between indoor and outdoor air, may affect monitoring results from fixed stations as surrogates of personal exposure to air pollutants.⁴⁸ In addition, as a requirement, AQM stations are located away from the major roads and industrial emission sources; therefore, underestimation and misclassification of exposure might exist. Second, district-specific data of meteorological conditions were unavailable. The use of citywide meteorological data may not reveal their confounding on effects of district level of air pollutants. Third, age structure of study population in each district is different and not adjusted. Population aged more than 60 years old (the older population) in Changping and Daxing districts accounted for the least (less than 10%) and those in Dongcheng and Xicheng district the most (more than 16%). In addition, the proportion of populations aged over 60- are higher in Pinggu, Miyun and Yanqing districts (about 15%) than those in Chaoyang, Fengtai and Shijingshan districts (about 13%). The differences in ratio of the older population might confound the estimates of effects as well. We conducted stratified analyses by age (45–64 years and ≥ 65 years) to examine potential effect modification. We observed that the effects of PM_{10} , NO_2 and CO on cardiovascular mortality are different among districts both in residents aged 45 or older and in aged 65 years or older.

In addition, socioeconomic status is also a factor that may contribute to the spatial variation. We tried to include gross domestic product per capita and number of health institutions per

1000 people of 16 districts in 2009 and 2010 to adjust for potential confounding from socioeconomic factors, however, because these indicators were measured annually in a district level, only 32 values of these indicators corresponding to 730×16 observations resulted in problem of singularity in backsolve in GAM and GAMM. We are collecting individual socioeconomic information from an ongoing cohort and will investigate this issue in future studies.

In general, the results from this study are meaningful for the present situation in Beijing. The yearly average $\text{PM}_{2.5}$ concentration observed by US Embassy in Beijing was about $91\text{--}104 \mu\text{g}/\text{m}^3$ from 2009 to 2014 without obvious trend.⁴⁹ And the yearly average PM_{10} concentration of the whole Beijing during this period was about $108\text{--}121 \mu\text{g}/\text{m}^3$ according to Beijing Environmental Statement 2009–2014.⁵⁰ Therefore the study period, 2009 and 2010, showed similar pollution level with the most recent years, and the findings may have implication for current public health policy decision making. Almost all the existing studies conducted in Beijing that analyzed the effects of air pollution took pollution of the city as a whole. However, our study reveals the spatial variation of such effects across the whole area of the city, which provides important evidence to help identify and explain the inequality in health status between different districts of Beijing in the context of high air pollution level. The findings drive our future efforts toward the further analysis to discover potential interaction between air pollution and socioeconomic factors.

CONCLUSIONS

In summary, we found significant adverse effects of ambient PM_{10} , NO_2 and CO on deaths from cardiovascular diseases. There were spatial variations in ambient concentrations of PM_{10} , NO_2 and CO and relative higher mortality risk of cardiovascular diseases in rural areas in Beijing. Further researches that identify personal exposure and sources of pollutions are needed to confirm our findings and to promote effective strategy of air quality management and public health protection.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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