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Long-term effects of $PM_{2.5}$ and its components on incident hypertension among the middle-aged and elderly: a national cohort study

Xiangtong Liu[1,2*†], Wenhan Xie[1†], Shiyun Lv[1,2], Yuan Li[1], Meiling Hu[1], Shuting Li[1], Yaoyu Hu[1], Shan Xu[1], Yanfang Tan[1], Jing Wei[3] and Xiuhua Guo[1,2,4]

Abstract

Background The long-term health effects of fine particulate matter ($PM_{2.5}$) on hypertension remain incomprehensive. We evaluated the relationship of $PM_{2.5}$ and its components with hypertension incidence in middle-aged and elderly adults.

Methods We utilised data from the China Health and Retirement Longitudinal Study collected between 2011 and 2018. We obtained annual modelled data from the dataset of Tracking Air Pollution in China, including black carbon (BC), sulphate (SO_4^{2-}), organic matter (OM), ammonium (NH_4^+), and nitrate (NO_3^-). Time-varying Cox models and quantile g-computation models were employed to explore the associations. Exposure-response curves were portrayed to investigate potential non-linear effects.

Results We enrolled 7,032 individuals with a mean age of 57.14 (range: 45–95) years. Over 36,997 person-years of follow-up (average time: 5.26 years), 3,119 individuals suffered from hypertension. With per interquartile range increment, the hazard ratios and 95% confidence intervals (*CIs*) of $PM_{2.5}$ (3.82 [95% *CI*: 3.48–4.18]), BC (4.17 [95% *CI*: 3.54–4.92]), SO_4^{2-} (4.24 [95% *CI*: 3.50–5.12]), OM (3.76 [95% *CI*: 3.14–4.50]), NH_4^+ (3.20 [95% *CI*: 2.91–3.52]), and NO_3^- (1.94 [95% *CI*: 1.77–2.13]) were discovered with lag 1 year. And the mixed effect was 18.0% [95% *CI*: 16.8%–19.2%], which was mainly driven by BC (66.0%) and SO_4^{2-} (34.0%). Approximate J-shaped exposure-response relationships were revealed.

Conclusions The positive associations of long-term exposure to $PM_{2.5}$ and its components with hypertension incidence were discovered in adults aged ≥ 45 years. Controlling the emissions of $PM_{2.5}$ components, especially BC and SO_4^{2-}, could alleviate the burden of hypertension.

Keywords Black carbon, Sulphate, Hypertension incidence, Time-varying Cox regression model, Quantile g-computation model

†Xiangtong Liu and Wenhan Xie contributed equally to this work.

*Correspondence:
Xiangtong Liu
xiangtongl@ccmu.edu.cn
[1]School of Public Health, Capital Medical University, No. 10 Xitoutiao, You'anmen Wai, Fengtai District, Beijing 100069, China
[2]Beijing Municipal Key Laboratory of Clinical Epidemiology, Beijing 100069, China
[3]Department of Atmospheric and Oceanic Science, Earth System Science Interdisciplinary Centre, University of Maryland, College Park, MD 20740, USA
[4]National Institute for Data Science in Health and Medicine, Capital Medical University, Beijing 100069, China

Background

Hypertension, a prevailing chronic disease ubiquitously afflicting populations worldwide, renders nearly 9 million lives annually on a global scale [1]. This formidable burden is shouldered by an estimated 1,278 million adults, predominantly dwelling in low- and middle-income countries [2]. In China, a high level of systolic blood pressure (SBP) is a prominent risk determinant contributing to mortality as well as the burden of disability-adjusted life-years [3]. Hypertension stands as a major cause of cardiovascular disease [4, 5]. Moreover, hypertension may even lead to chronic kidney disease in America [6]. Hence, it is necessary to study the risk factors precipitating incident hypertension.

Increasing evidence indicates that numerous environmental factors influence the incidence, progression, and severity of hypertension, including air pollution, green spaces, temperature variation, etc [7, 8]. Of these, air pollution, exceptionally fine particulate matter ($PM_{2.5}$), emerges as a preeminent environmental health issue contributing to incident hypertension [9, 10]. $PM_{2.5}$ exposure is linked to 30,696.9 excess deaths related to hypertension in the United States [11]. Per 10 μg/m³ increase in long-term exposure to $PM_{2.5}$ has a significant relation to the increase of 11.0% in incident hypertension. In China, adverse changes in blood pressure (BP) can also be observed for short-term exposure to $PM_{2.5}$ [12].

Generally, $PM_{2.5}$ originates from diverse sources, including forest fires, combustion of fossil fuel and wood, industrial processes, agriculture activities, and traffic emissions [13, 14]. $PM_{2.5}$ comprises diverse chemical constituents, including black carbon (BC), sulphate (SO_4^{2-}), organic matter (OM), ammonium (NH_4^+), nitrate (NO_3^-), etc [15]. Previous studies have indicated that $PM_{2.5}$ components are linked with hypertension prevalence in Chinese children and adolescents [16], as well as adults [17]. However, fewer studies have been conducted among middle-aged and elderly people. Li G. et al. [18] have assessed the effect of follow-up exposure to $PM_{2.5}$ components on hypertension among the middle-aged and elderly indicating that the components are associated with normal BP to elevated BP and elevated BP to hypertension, but normal BP to hypertension. However, the effect of mixed exposure to $PM_{2.5}$ components and the contribution of each component have not been adequately studied.

To fully explore the effects of $PM_{2.5}$ and its components on hypertension, we conducted a national longitudinal study among middle-aged and elderly Chinese to evaluate the long-term effects of single or mixed exposures to BC, SO_4^{2-}, OM, NH_4^+, and NO_3^- on hypertension incidence.

Methods

Study population and setting

In our research, all participants were enrolled from the China Health and Retirement Longitudinal Study (CHARLS, http://charls.pku.edu.cn/) [19]. CHARLS is a nationally representative longitudinal survey, aiming at assessing the health and socioeconomic status of individuals randomly selected from Chinese households. To ensure sample representativeness, CHARLS covered 150 district-level units and 450 village-level units in China, reflecting the middle-aged and elderly (aged 45 years and above) Chinese population collectively. The baseline survey was performed in 2011–2012, with subsequent follow-up every two or three years. To date, four waves (2011, 2013, 2015, and 2018) of data collection have been completed. We utilised the data of this database through the baseline survey to wave 4 (2018) to do the nationwide cohort study in China. All interviewees aged 45 or older without hypertension at the baseline survey were enrolled. Individuals who lacked hypertension diagnostic information in any wave ($n = 1{,}037$), exposure data of air pollutants ($n = 114$), or covariates were excluded ($n = 413$) (Fig. S1).

The CHARLS study was approved by the Biomedical Ethics Committee of Peking University (IRB00001052–11015) and each participant supplied written informed permission.

Outcome

Every participant was followed from the baseline survey up to the time of incident hypertension or the end of wave 4. Hypertension was defined as (1) individuals who were diagnosed with hypertension by self-report, (2) individuals who were taking antihypertensive drugs or (3) with SBP $\geq$ 130 mmHg, diastolic blood pressure (DBP) $\geq$ 80 mmHg, or both [20]. Notably, BP was measured thrice per wave by trained interviewers, and the average of the three measurements was utilised to reduce measurement error [21]. No participant took antihypertensive medication without self-reported hypertension.

Air pollution and meteorology data

The annual average concentrations of $PM_{2.5}$ and its components were calculated and determined as the exposure levels, which were assigned based on geocodes (longitude and latitude) of individual home addresses provided at the baseline survey of CHARLS at the city level. The daily data of 10 km gridded air pollution from 2010 to 2017 were sourced from the dataset of Tracking Air Pollution in China (TAP, http://tapdata.org.cn) [22, 23]. TAP used machine learning algorithms and various data sources to build a multi-source data fusion system that integrated ground observation data, satellite remote sensing information, high-resolution emission inventories, and air quality model simulations. $PM_{2.5}$ component information was obtained from Weather Research and Forecasting-Community Multiscale Air Quality (CMAQ) model simulations with $PM_{2.5}$ concentration as the main constraint. To correct simulation deviations of the CMAQ model, the dust emission simulation module was improved. A model that could accurately convert $PM_{2.5}$ data to its component data was developed to refine the relative contribution of simulated $PM_{2.5}$ component concentrations, based on $PM_{2.5}$ component observation data and the extreme gradient boosting algorithm. The dataset had good agreement with the observations (correlation coefficients ranged from 0.67 to 0.80 at the daily scale; the most normalized mean biases were within ± 20%).

We obtained meteorological data from 2010 to 2017 through the National Meteorological Information Centre of China (https://data.cma.cn/en), covering 699 meteoro logical monitoring stations in 31 provinces and regions. Meteorological data from these stations were converted into grid data with a resolution of 0.1° × 0.1° through inverse distance weighted interpolation. We calculated the average yearly concentrations of relative humidity, temperature, etc., and matched the geocoded individual home addresses at the city level.

Covariates

We selected covariates from the previous literature to analyse the influence of $PM_{2.5}$ and its components on hypertension incidence [24]. We adjusted five types of covariates, including (a) demographic characteristics: age (years), sex (male or female), educational qualifications (primary school and lower grades or middle school and upper grades), marital status (married or other status), and residence (rural or urban); (b) lifestyle factors: drinking status (never, former, or current drinker), smoking status (never, former, or current smoker), and body mass index (BMI, kg/m^2); (c) the health status: diabetes prevalence (yes or no); (d) the dietary habit: cooking fuel (clean or unclean); and (e) meteorological factors: relative humidity (g/kg) and temperature (K).

Besides, we utilised a directed acyclic graph (DAG, http://dagitty.net/) [25] to identify the potential confoun ders for the sensitivity analysis (Fig. S2). We selected the minimal sufficient adjustment set to address suspected confounders, consisting of age, sex, marital status, residence, occupation, living standard, educational qualifications, temperature, and relative humidity.

Statistics

We assessed the normality of variables and characterized their distributions. Spearman's rank correlation was used to evaluate the correlation among $PM_{2.5}$ components. According to previous literature [26, 27], we computed annual average concentrations of 1 to 3 years before the year when individuals got hypertension or the end of wave 4, aiming to investigate the long-term impacts of $PM_{2.5}$ and its components.

Time-varying Cox regression models were utilised to evaluate the linear associations of $PM_{2.5}$ and its components with hypertension incidence. The hazard ratios (HRs) with 95% confidence intervals (*CI*s) were calculated to quantify the risks of hypertension incidence associated with an interquartile range (IQR) increment in concentrations of $PM_{2.5}$ and its components. Given the multicollinearity, we conducted separate models to estimate the associations between each pollutant and hypertension. Three models were performed: (1) model 1 was the crude model; (2) model 2 was adjusted for significant variables in univariate analysis, i.e., age, sex, educational qualifications, marital status, residence, BMI, drinking and smoking status, diabetes prevalence, and cooking fuel; and (3) model 3 was the main model further adjusted for relative humidity and temperature. We added the time-varying covariates that failed to meet the proportional hazard assumption.

Quantile g-computation (QG) models were conducted to explore the effect of mixed exposure to $PM_{2.5}$ components on hypertension and the contribution weight of each component, which were adjusted by age, sex, educational qualifications, marital status, residence, drinking status, smoking status, relative humidity and temperature.

We investigated the exposure-response curves of $PM_{2.5}$ and its components with hypertension through restricted cubic splines with reference to the 50th percentiles, which defined threshold values for segmented fits of outcomes in Cox models. The curves were selected to fit with 3, 4, or 5 knots, according to the discrimination index (where larger values indicate better fit). To evaluate the potential modification impacts, we performed subgroup analyses by age (under and above or equal to 60 years), sex, educational qualifications, marital status, drinking, and smoking status with the main model in lag 1 year. Two sample Z-tests were conducted to ascertain whether the groups differed.

To assess our study's robustness, we conducted numerous sensitivity analyses. (1) We adopted another diagnosis standard of hypertension, namely SBP ≥ 140 mmHg or DBP ≥ 90 mmHg, instead [28]. (2) We adjusted for the potential confounders selected by DAG. (3) We additionally conducted normal Cox proportional hazard models. (4) We performed multiple interpolations for completely random missing variables and repeated the mixed effect analysis based on the QG model.

All statistical analyses were run with "survival", "qgcomp", and "rms" packages on R version 4.2.3. $P < 0.05$ was regarded as statistically significant for a 2-tailed test.

Results

Descriptive results

In total, 7,032 participants with a mean age of 57.14 (range: 45–95) years were enrolled in our study. After a follow-up of 36,997 person-years and an average of 5.26 years, 3,119 (44.4%) individuals developed hypertension. Statistical differences could be significantly observed between non-hypertension and incident hypertension individuals in terms of age, sex, educational qualifications, marital status, BMI, drinking status, smoking status, cooking fuel, and diabetes prevalence ($P < 0.05$) (Table 1). Individuals with hypertension seemed to be elderly, unmarried, with high BMI or lower education level contrary to some without hypertension.

Table 2 outlines the annual distributions of $PM_{2.5}$, its components and meteorological factors in lag 1 year, and the distribution information in other lag years can be seen in Table S1. Strong positive correlations between $PM_{2.5}$ components were disclosed ($r_s > 0.8$) (Fig. S3).

The association of $PM_{2.5}$ and its components with hypertension incidence

As shown in Fig. 1, all components were linked with hypertension incidence. Per IQR uptick concentration of $PM_{2.5}$, BC, SO_4^{2-}, OM, NH_4^+, or NO_3^- was related to 3.82 (95% *CI*: 3.48–4.18), 4.17 (95% *CI*: 3.54–4.92), 4.24 (95% *CI*: 3.50–5.12), 3.76 (95% *CI*: 3.14–4.50), 3.20 (95% *CI*: 2.91–3.52), or 1.94 (95% *CI*: 1.77–2.13) fold risk of

Table 1 Baseline characteristics of participants in the study

Characteristic	Total (*n* = 7032)	Incident hypertension		*P* value
		No (*n* = 3913)	Yes (*n* = 3119)	
Age, median (IQR), years	56 (13)	55 (12)	58 (13)	**< 0.001**
Sex, *n*(%)				**< 0.001**
Male	3223 (45.83)	1723 (44.03)	1500 (48.09)	
Female	3809 (54.17)	2190 (55.97)	1619 (51.91)	
Educational qualifications, *n*(%)				**< 0.001**
Primary school and lower	4602 (65.44)	2487 (63.56)	2115 (67.81)	
Middle school and upper	2430 (34.56)	1426 (36.44)	1004 (32.19)	
Marital status, *n*(%)				**< 0.001**
Married	6396 (90.96)	3631 (92.79)	2765 (88.65)	
Single/widowed/divorced	636 (9.04)	282 (7.21)	354 (11.35)	
BMI, *n*(%), kg/m^2				**< 0.001**
< 18.5	438 (6.23)	280 (7.16)	158 (5.07)	
18.5–23.9	3198 (45.48)	1949 (49.81)	1249 (40.04)	
24-27.9	1313 (18.67)	715 (18.27)	598 (19.17)	
≥ 28	321 (4.56)	144 (3.68)	177 (5.68)	
NA	1762 (25.06)	825 (21.08)	937 (30.04)	
Drinking status, *n*(%)				**0.031**
Never	4427 (62.95)	2516 (64.30)	1911 (61.27)	
Former	473 (6.73)	257 (6.57)	216 (6.93)	
Current	2132 (30.32)	1140 (29.13)	992 (31.80)	
Smoking status, *n*(%)				**0.031**
Never	4450 (63.28)	2521 (64.42)	1929 (61.85)	
Former	482 (6.86)	246 (6.29)	236 (7.56)	
Current	2100 (29.86)	1146 (29.29)	954 (30.59)	
Residence, *n*(%)				0.683
Rural	4502 (64.02)	2497 (63.81)	2005 (64.28)	
Urban	2530 (35.98)	1416 (36.19)	1114 (35.72)	
Cooking fuel, *n*(%)				**0.002**
Clean	3126 (44.45)	1805 (46.13)	1321 (42.35)	
Unclean	3862 (54.92)	2088 (53.36)	1774 (56.88)	
NA	44 (0.63)	20 (0.51)	24 (0.77)	
Diabetes prevalence, *n*(%)				**0.002**
Yes	215 (3.06)	97 (2.48)	118 (3.78)	
No	6757 (96.09)	3778 (96.55)	2979 (95.51)	
NA	60 (0.85)	38 (0.97)	22 (0.71)	

Notes: the bolded $P < 0.05$; cooking fuel was the fuel used in cooking as an indicator of indoor pollution. Abbreviations: IQR, interquartile range; NA, not available

Table 2 Distribution of $PM_{2.5}$, its components and meteorological factors in lag 1 year

Pollutant	Mean	SD	Min	P_{25}	Median	P_{75}	Max
BC (μg/m^3)	2.24	0.76	0.86	1.68	2.05	2.64	4.80
SO_4^{2-} (μg/m^3)	8.67	3.40	2.63	6.04	7.99	10.74	18.69
OM (μg/m^3)	11.17	3.99	4.47	8.22	10.36	13.53	24.36
NH_4^+ (μg/m^3)	6.99	3.05	2.37	4.39	6.40	9.08	15.21
NO_3^- (μg/m^3)	10.07	4.89	2.76	5.95	9.27	13.20	22.91
$PM_{2.5}$ (μg/m^3)	45.85	18.90	17.62	30.80	41.49	57.51	104.73
RHU (g/kg) × 10^{-3}	9.17	2.63	3.66	7.40	9.55	10.81	14.96
TMP (K)	285.02	5.47	267.30	283.42	285.77	288.24	294.06

Abbreviations: BC, black carbon; SO_4^{2-}, sulphate; OM, organic matter; NH_4^+, ammonium; NO_3^-, nitrate; $PM_{2.5}$, fine particulate matter; RHU, relative humidity; TMP, temperature; SD, standard deviation; Min, minimum; P_{25}, 25th percentile; P_{75}, 75th percentile; Max, maximum

hypertension incidence in the main model and lag 1 year ($P<0.05$). The association remained robust in model 1 and model 2 (Fig. S4). The effect sizes of most components in lag 1 year were the largest (Fig. 1). Besides, the subgroup analyses indicated that the differences between age, sex, educational qualifications, marital status, drinking, and smoking status were not statistically significant (*P* values ranging from 0.057 to 0.999) (Table S2).

The mixed effect of $PM_{2.5}$ components and hypertension incidence

QG analyses indicated that mixed exposure to $PM_{2.5}$ components was positively associated with hypertension incidence. With each quartile increase of $PM_{2.5}$ components, the risk of hypertension incidence increased 18.0% (95% *CI*: 16.8%–19.2%) ($P<0.001$) (Fig. 2a). Furthermore, BC (0.660) and SO_4^{2-} (0.340) represented positive effects, while OM (-0.642), NH_4^+ (-0.047), and NO_3^- (-0.311) represented the negative in lag 1 year, which indicated that the mixed effect was mainly driven by BC (66.0%) and SO_4^{2-} (34.0%) (Fig. 2b). The results kept robust in other lag years (Fig. S5).

Exposure-response curves of $PM_{2.5}$ and its components with hypertension

We utilised the restricted cubic splines with 5 knots to illustrate the nonlinear relationship of $PM_{2.5}$ and its components with incident hypertension for various lag years, whose average discrimination index was 0.402 (Table S3). As seen in Fig. 3 and Fig. S6, $PM_{2.5}$ and its components showed approximate J-shaped associations with hypertension in lag 1 year, which increased with moving lag years (all *P* for nonlinear < 0.001). The evidence was found for increasing HR values of $PM_{2.5}$ and its components on the risks of hypertension incidence above the specific concentration levels (Fig. 3). Specifically, BC (3.56 [95% *CI*: 3.20–3.97] vs. 2.31 [95% *CI*: 2.15–2.48], Z = -6.632, $P<0.001$) and SO_4^{2-} (1.38 [95% *CI*: 1.35–1.40] vs. 1.06 [95% *CI*: 1.04–1.08], Z = -19.037, $P<0.001$) at concentrations greater than the thresholds resulted in higher risks with statistically significance of incident hypertension than those below the thresholds.

Sensitivity analyses

Sensitivity analyses validated the robustness of the main analysis. Firstly, 2,977 (33.1%) individuals had hypertension after utilising another diagnostic criterion for hypertension. The effect sizes of $PM_{2.5}$ and its components exposure on hypertension incidence were decreased with the lag-year increase and attained the largest in lag 1 year [HR (95% *CI*) of model 3: BC, 6.27 (95% *CI*: 5.42–7.26); SO_4^{2-}, 4.94 (95% *CI*: 4.22–5.79); OM, 4.54 (95% *CI*: 3.84–5.38); NH_4^+, 3.27 (95% *CI*: 2.72–3.94); NO_3^-, 1.95 (95% *CI*: 1.61–2.35); $PM_{2.5}$, 3.96 (95% *CI*: 3.31–4.73)] (Table S4). Besides, similar results were found in the model adjusted by DAG (Table S5). The effect sizes of $PM_{2.5}$ components at lag 1 year were the largest, and the effect sizes of the other two lag years were approximate. A similar tendency was found in normal Cox proportional hazard models (Table S6). After multiple interpolations, the β of the QG model in lag 1 year was 0.177 ($P<0.001$), with BC (67.7%) and SO_4^{2-} (32.3%) remaining as the dominant components, which was consistent with the main analysis (Fig. S7).

Discussion

Our study clarified positive associations of $PM_{2.5}$ and its components with hypertension incidence, which remained robust in sensitivity analyses. BC and SO_4^{2-} were the main contributors to the mixed effect of the $PM_{2.5}$ components. In addition, we found approximate J-shaped curves of $PM_{2.5}$ and its components with hypertension risk, with the risks of hypertension increasing as concentrations increased.

$PM_{2.5}$ was associated with hypertension, as were its components. A previous study indicated that long-term exposure to specific $PM_{2.5}$ components, such as BC, SO_4^{2-}, NH_4^+, and NO_3^-, was related to the increased risk of hypertension incidence in Chinese adults [29], which is similar to our results. Besides, similar sources may lead to high correlations among $PM_{2.5}$ components. OM

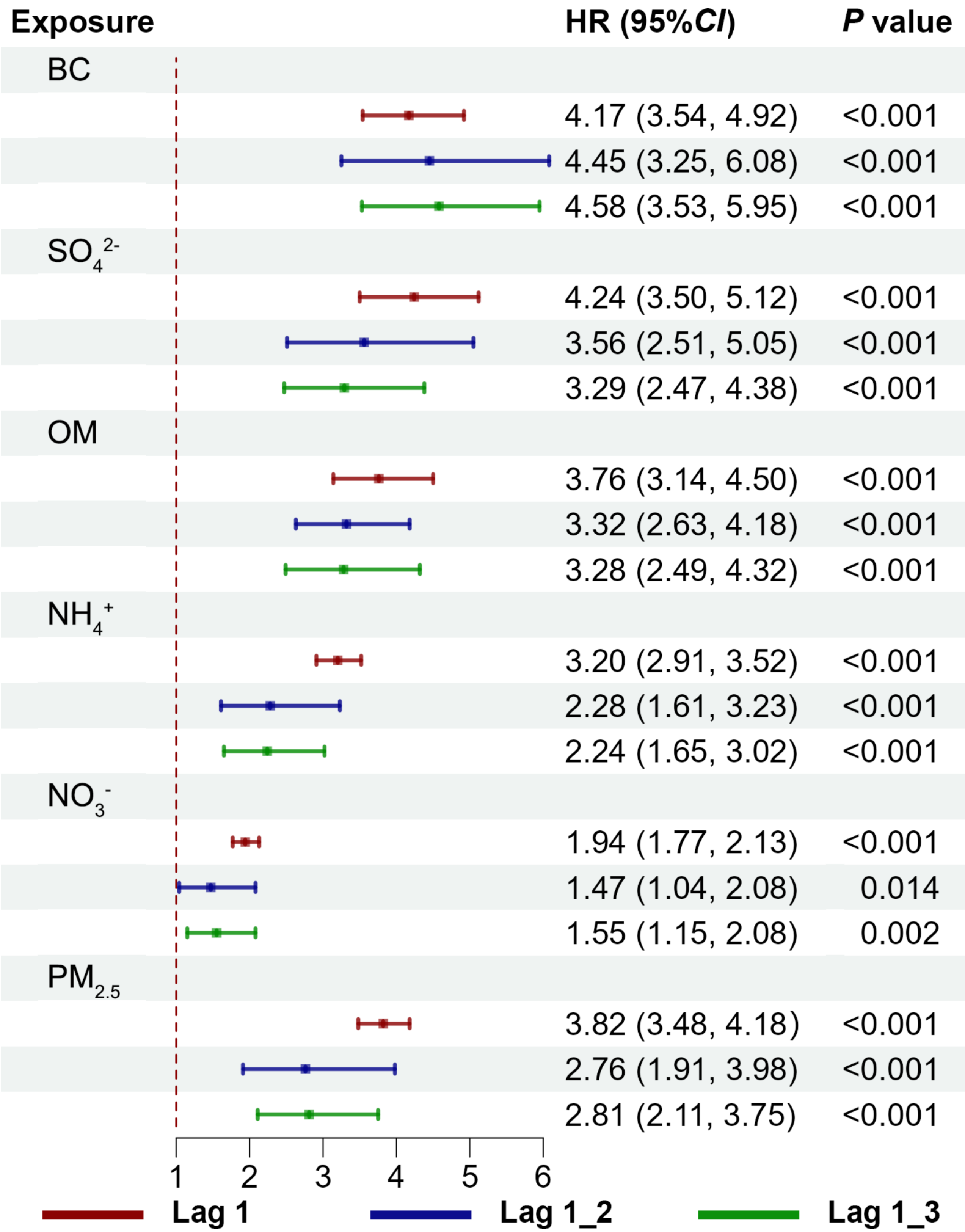

Fig. 1 HR (95% *CI*) for hypertension incidence with each IQR increase in $PM_{2.5}$ and its components in the main model. Abbreviations: HR, hazard ratio; *CI*, confidence interval; IQR, interquartile range; BC, black carbon; SO_4^{2-}, sulphate; OM, organic matter; NH_4^+, ammonium; NO_3^-, nitrate $PM_{2.5}$, fine particulate matter. Notes: The time-varying Cox model was adjusted by age, sex, educational qualifications, marital status, residence, BMI, drinking and smoking status, diabetes prevalence, cooking fuel, relative humidity, and temperature

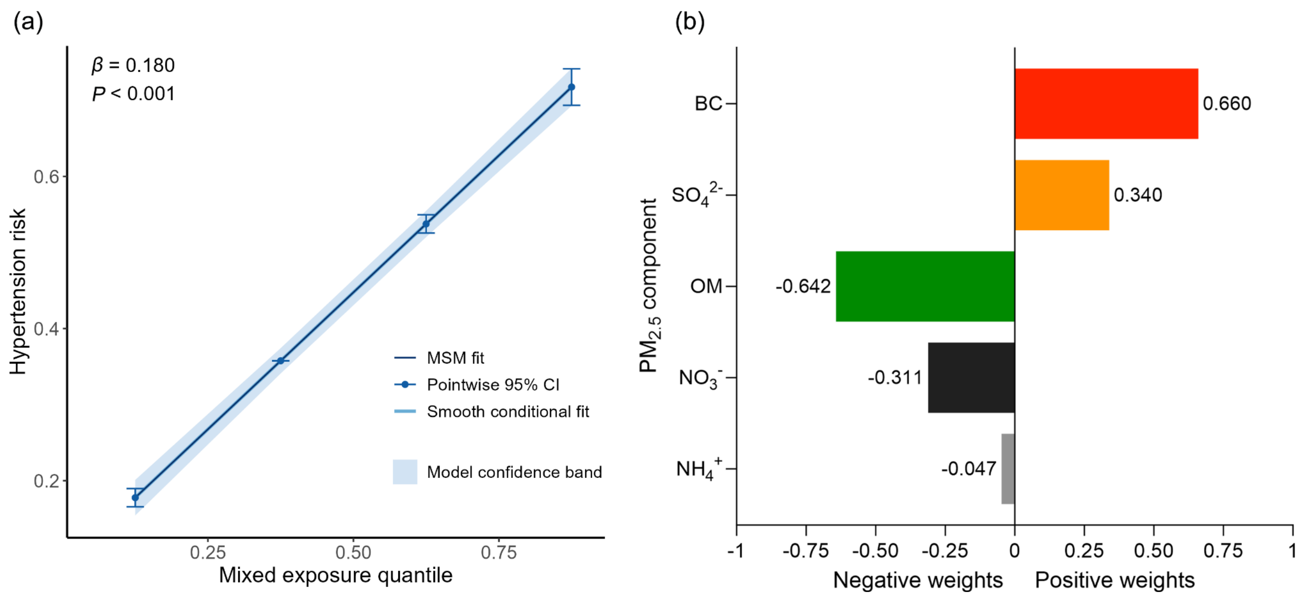

Fig. 2 The mixed effects of $PM_{2.5}$ components on hypertension incidence and their index weights in lag 1 year. Abbreviations: BC, black carbon; SO_4^{2-}, sulphate; OM, organic matter; NH_4^+, ammonium; NO_3^-, nitrate. Note: The quantile g-computation model was adjusted by age, sex, educational qualifications, marital status, residence, drinking and smoking status, relative humidity, and temperature. **(a)** the mixed effect of $PM_{2.5}$ components; **(b)** the weights of $PM_{2.5}$ components

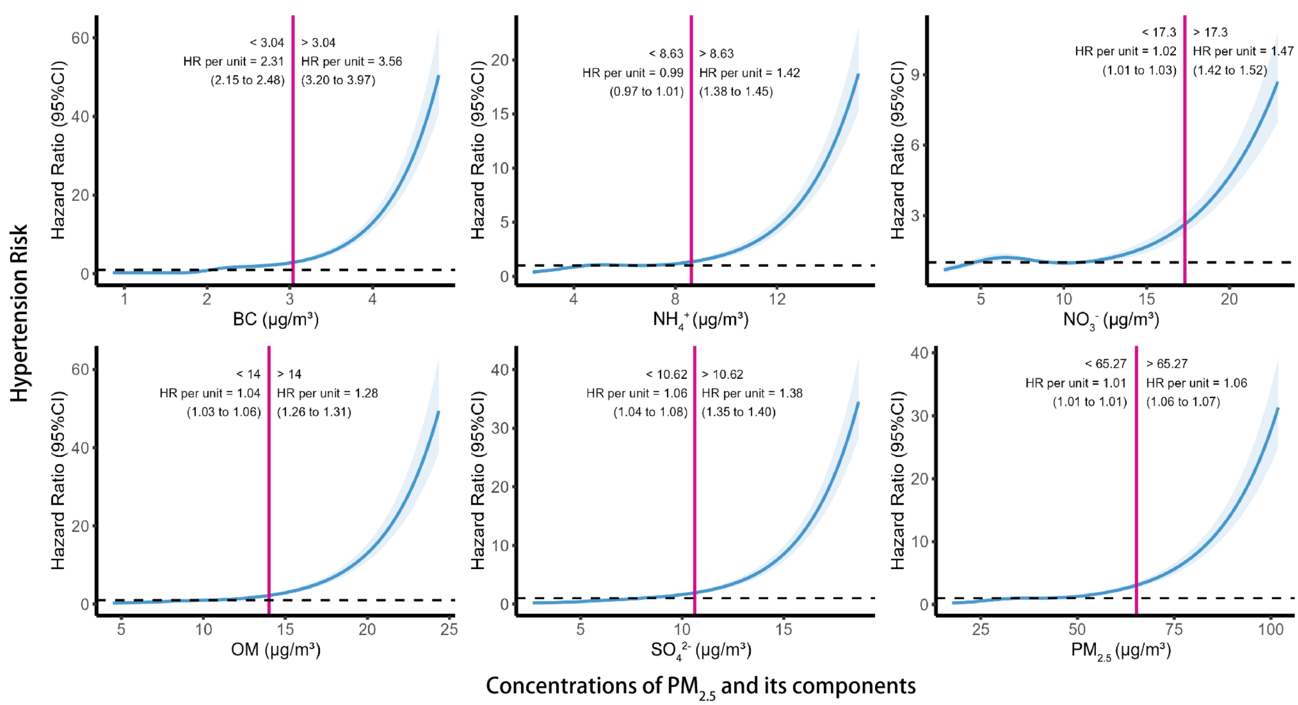

Fig. 3 Exposure-response curves of hypertension incidence and $PM_{2.5}$ and its components in the main model with lag 1 year

is derived from various sources, such as transport emissions and fuel combustion [30], and the main sources of SO_4^{2-} are fossil fuel combustion and wildfires [31]. NH_4^+ and NO_3^- are usually attributed to traffic emissions [32]. Thus, it is necessary to evaluate the effect of individual and mixed exposure to $PM_{2.5}$ components on incident hypertension in our study.

Our study found that BC and SO_4^{2-} showed strong associations with incident hypertension among five components, similar to previous studies [33, 34]. However, another study has shown that NO_3^- contributed the most to hypertension incidence, DBP, and SBP among five components [17]. The difference might be related to the choice of the study population (adults vs. the middle-aged and elderly) and statistical methods. Paying attention to hypertension in the middle-aged and elderly population is essential.

QG analyses have shown that the risk of hypertension incidence increases with increasing mixed exposure to $PM_{2.5}$ components, with BC and SO_4^{2-} playing a dominant role. BC and SO_4^{2-} could induce hypertension by elevating the brachial-ankle pulse wave velocity, a marker of arterial stiffness, and influencing cardiac autonomic function. BC can decline the ankle-brachial index, which indicates damage to the arteries [35, 36]. BC can increase the level of 20-hydroxyeicosatetraenoic acid, affect cardiac autonomic function, increase thrombotic activity and systemic inflammation, and then increase hypertension incidence risk [37, 38]. SO_4^{2-} may be associated with vascular and cardiac autonomic functions, which could increase BP [39]. In addition to the above mechanisms, it has recently been reported that $PM_{2.5}$ components, such as SO_4^{2-}, could affect blood pressure by influencing the hypothalamic-pituitary-adrenal axis [40]. In addition, studies have shown that SO_4^{2-} is associated with electrocardiographic abnormalities and signalling of inflammatory pathways, affecting cardiovascular health [41, 42]. More research is needed about the mechanisms for the effects of BC and SO_4^{2-} on cardiovascular diseases such as hypertension.

In addition, we have found that $PM_{2.5}$ and its components have an approximate J-shaped association with incident hypertension, presenting a stronger effect at higher concentrations above specific values. Previous studies have also indicated the trend towards increased risks of hypertension with increasing concentrations of $PM_{2.5}$ and its components [18, 43]. The sharp increase in the risk of hypertension incidence at high concentrations of $PM_{2.5}$ and its components suggests that reducing the concentration of $PM_{2.5}$ and its components is essential to prevent hypertension.

This study has some strengths. To begin with, our study used time-varying Cox regression models, permitting variables to fluctuate over time. Second, we evaluated the different contributions of $PM_{2.5}$ components in the mixed effect on hypertension incidence. Third, we utilised a design of the longitudinal study consisting of a representative national sample of individuals aged ≥ 45 years, who were at high risk for hypertension incidence [44]. Fourth, we verified the robustness of our main result utilising a series of sensitivity analyses.

Limitations

Our study also has a few limitations that should be acknowledged. First, pollutant exposures were matched to individuals based on the municipal addresses provided during the baseline survey, and no account was taken of the influence of residential mobility, which might result in spatial misclassification. Second, despite numerous covariates being selected to adjust for confounders using different ways, the unmeasured persisted, which could lead to bias. Third, there were potential biases in individual exposure to air pollutants due to the physicochemical transformations of the atmosphere and the unequal distribution of emission sources. Fourth, because the study population was middle-aged and elderly adults, who were at higher risk and much already sick at baseline, the sample size of our study was somewhat smaller than at the baseline survey. Fifth, assuming a linear relationship might overestimate the underlying non-linear association, while we utilized restricted cubic spline to explore potential non-linear associations. Sixth, our study only included waves 1–4 of the CHARLS database.

Conclusions

The research indicated that long-term exposure to $PM_{2.5}$ and its components was significantly associated with incident hypertension in middle-aged and elderly Chinese, which was mainly driven by BC and SO_4^{2-}. Controlling the emission of $PM_{2.5}$ components, especially BC and SO_4^{2-}, could reduce the burden of hypertension.

Abbreviations

$PM_{2.5}$	Fine particulate matter
BC	Black carbon
SO_4^{2-}	Sulphate
OM	Organic matter
NH_4^+	Ammonium
NO_3^-	Nitrate
HR	Hazard ratio
CI	Confidence interval
DAG	Directed acyclic graph
CHARLS	The China Health and Retirement Longitudinal Study
TAP	The Tracking Air Pollution in China
IQR	Interquartile range

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s12889-025-21494-0.

Supplementary Material 1

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Author contributions

X.T.L. contributed to conceptualization, funding acquisition, supervision, writing- reviewing & editing. W.H.X. contributed to methodology, data curation, formal analysis, and writing - original draft & reviewing & editing. S.Y.L. contributed to methodology and writing - reviewing. Y. L., M.L.H., and S.T.L. contributed to data curation and software. Y.Y.H., S.X., and Y.F.T. contributed to the methodology. J.W. conducted the data curation and resources. X.H.G. contributed to conceptualization and supervision. All authors read and approved the final manuscript.

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Data availability
The dataset in this study could be obtained from the China Health and Retirement Longitudinal Study (CHARLS, http://www.charls.pku.edu.cn/).

Declarations

Ethics approval and consent to participate
Ethics approval for the CHARLS project was obtained from the Ethics Review Committee of Peking University (IRB00001052-11015) and all of the participants supplied written informed consent.

Consent for publication
Not applicable.

Competing interests
The authors declare no competing interests.

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