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Associations between ambient fine particulate air pollution and hypertension: A nationwide cross-sectional study in China

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Abstract

Limited evidence is available regarding the long-term effects of fine particulate ($PM_{2.5}$) air pollution on hypertension in developing countries. This study aimed to explore the associations of long-term exposure to $PM_{2.5}$ with hypertension prevalence and blood pressure (BP) in China. We conducted a cross-sectional study based on a nationally representative survey (13,975 participants). We estimated the long-term average exposure to $PM_{2.5}$ for all subjects during the study period (June 2011 to March 2012) by a satellite-based model with a spatial resolution of 10 × 10 km. We applied multivariable logistic regression models to evaluate the associations between $PM_{2.5}$ and hypertension prevalence and linear regression models for the associations between $PM_{2.5}$ and systolic BP and diastolic BP. We also explored potential effect modification by stratification analyses. There were 5715 cases of hypertension, accounting for 40.9% of the study population in this analysis. The annual mean exposure to $PM_{2.5}$ for all participants was 72.8 μg/m^3 on average. An interquartile range increase (IQR, 41.7 μg/m^3) in $PM_{2.5}$ was associated with higher prevalence of hypertension with an odds ratio of 1.11 [95% confidence interval (CI): 1.05, 1.17]. Systolic BP increased by 0.60 mmHg (95% CI: 0.05, 1.15) per an IQR increase in $PM_{2.5}$. The effects of $PM_{2.5}$ on hypertension prevalence were stronger among middle-aged, obese and urban

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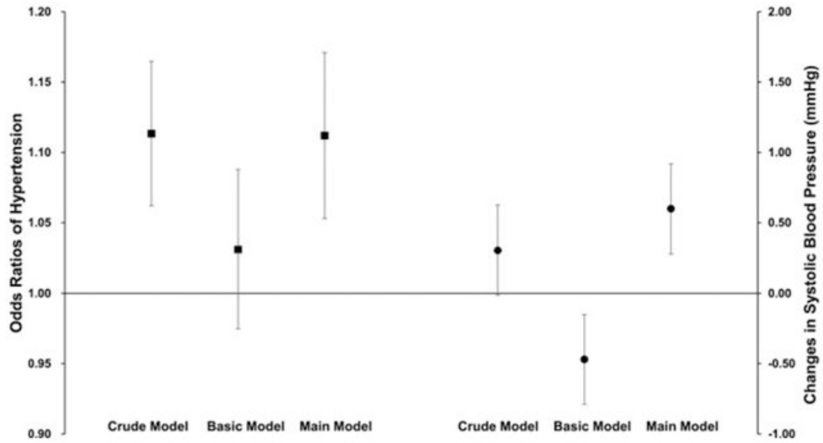
participants. This national study indicated that long-term exposure to $PM_{2.5}$ was associated with increased prevalence of hypertension and slightly higher systolic BP in China.

Graphical Abstract



Keywords

Hypertension; Blood pressure; Fine particulate matter; Ambient air pollution; Cross-sectional study

1. Introduction

High blood pressure (BP) is a well-established risk factor for cardiovascular morbidity and mortality (Brook et al., 2010; Lawes et al., 2008; Pope and Dockery, 2006). It was evidenced that high BP was a leading single risk factor for the global burden of diseases, and there were two-thirds of adults with hypertension living in developing countries (Lim et al., 2012). Recent studies revealed that the average level of systolic blood pressure (SBP) was declining in developed countries but increasing in low-income and middle-income countries (Bromfield and Muntner, 2013). Therefore, identifying the potential risk factors for hypertension is of great significance to global public health.

Epidemiological studies have reported that short-term exposure to fine particulate matter ($PM_{2.5}$) was significantly associated with hypertension and BP variations (Auchincloss et al., 2008; Dai et al., 2016; Dvonch et al., 2009). However, the long-term effects of $PM_{2.5}$ on hypertension were less reported and the results were inconsistent. For example, two cross-sectional studies in Asia found significant associations of long-term PM_{10} exposure with hypertension prevalence and increased BP (Chuang et al., 2011; Dong et al., 2013). However, another cross-sectional study in Germany found insignificant associations between $PM_{2.5}$ exposure and hypertension prevalence (Fuks et al., 2011).

China is a developing country with severe air pollution problems. Several national surveys have revealed that hypertension prevalence was rapidly increasing and the number of hypertension patients was estimated to exceed 300 million by 2025 (He, 2016; Kearney et al., 2005; Li et al., 2016; Li et al., 2012). Thus, it is of great public health importance to explore the long-term health effects of $PM_{2.5}$ on BP in China. Therefore, we aimed to explore the associations between long-term exposure to ambient $PM_{2.5}$ and hypertension prevalence and BP. This is a cross-sectional study based on the China Health and Retirement Longitudinal Study (CHARLS) project.

2. Material and methods

2.1. Study population

We obtained data from the baseline survey of the CHARLS project, which started in June 2011 and finished in March 2012. Details of this project have been documented in previous publications (Zhao et al., 2014). In brief, to ensure the national representativeness of the project, the study populations were selected by a four-stage, stratified and cluster sampling method from 28 provinces (150 counties or districts) of China. A total of 17,708 middle-aged and elderly (age range: 35–100 years) residents from urban and rural areas were enrolled. Locations of the study sites were shown in Fig. 1. Face-to-face interviews were performed using a standard questionnaire to collect basic information on socio-demography (home address, age, sex, educational level), housing conditions (types of energy used for cooking and heating) and health status. Non-response rate of the survey was 19.5%, which was due to refusal (8.8%), inaccessibility of contact (8.2%) and other reasons (2.5%).

2.2. Health data

The health survey consisted of a self-reported questionnaire and a physical examination. Overall, 13,975 participants completed the whole survey. Information were collected on smoking status, alcohol consumption and whether they had physician-diagnosed hypertension. Standardized resting BP measurements were performed by trained nurses using electronic sphygmomanometers (OMRON Corporation, HEM-7200). All electronic sphygmomanometers were factory calibrated before physical examinations. Participants were told not to smoke, eat or drink alcohol within 30 min before the test. Each participant was instructed to rest for 10 min after arrival. Left upper arm BP at sitting position was measured 3 times under the guidance of our staff. We considered the measurements unstable if the differences of the last two readings were over 5 mmHg, and another one to three measurements were taken until the differences were within 5 mmHg. The second and third measurements were averaged to calculate the SBP and DBP. In this analysis, hypertension was defined as: (1) individuals who reported having diagnosed hypertension or (2) had an average measured SBP ≥ 140 mmHg, DBP ≥ 90 mmHg, or both.

2.3. Exposure assessment

The average $PM_{2.5}$ concentrations at participants' addresses over the study period were generated by a satellite-based exposure assessment model. Detailed information on the model specifications has been documented elsewhere (Ma et al., 2016). Monthly $PM_{2.5}$ concentrations in China were estimated at a resolution of 10 km × 10 km, and were then averaged over the study period. Results of cross-validation showed that this model could well capture the monthly and seasonal variation of historical $PM_{2.5}$ (R^2 = 0.79 and relative prediction error = 35.6%).

To allow for the adjustment of ozone when assessing the effects of $PM_{2.5}$ on BP, we obtained data on annual-average ozone concentration at a 10 × 10 km resolution estimated by the 2013 Global Burden of Disease project (Brauer et al., 2016). We also derived daily mean temperature of each study site from China's National Meteorological Information Center, and then averaged the data over the study period.

At last, we geocoded the participants' home addresses and assigned exposure measurements in ArcGIS software (ESRI Corporation). To be specific, the averaged concentration in each grid cell (10 km × 10 km) was merged with the geographic shape files with information on the official region boundaries of China. The estimates of exposure were then equally assigned to the participants that resided in the same grid.

2.4. Statistical analysis

We applied multivariable logistic regression models to explore the health effects of $PM_{2.5}$ on the prevalence of hypertension. In the basic model, we controlled for the following variables as potential confounders based on previous studies in this field (Chan et al., 2015; Chen et al., 2015; Dong et al., 2013): sex, age, educational level (low: illiterate; medium: ≤ 6 years; high: > 6 years), BMI, smoking history (current smokers; ex-smokers, quitted smoking ≥3 years; non-smokers), pack-years (years of smoking multiplied by packs per day) for current smokers, frequency of alcohol consumption (none, less than or once a month, more than once a month), types of heating resources (clean: solar power, electricity, natural gas, central heating; unclean: coal and biomass; others) and types of energy for cooking (clean and unclean). In the fully-adjusted model (the main model), we further controlled for annual mean temperature because a number of studies had reported an inverse association between temperature and BP (Su et al., 2014; Wang et al., 2017). We also added a factor variable of season (i.e., summer, winter and spring) into the main model to account for potential seasonal variations in BP (Lewington et al., 2012; Woodhouse et al., 1993). At last, we introduced ozone into the main model because it was reported to affect BP (Chuang et al., 2011; Hoffmann et al., 2012).

We used multivariate linear regression models to examine the associations between $PM_{2.5}$ and BP. The covariates in this model were exactly the same as those in above-mentioned logistic regression models.

We conducted a stratification analysis to test whether the above associations could be modified by age (less than or equals 60 years and over 60 years), sex (males and females), educational level (low, ≤ 6 years; high >6 years), BMI (< 24 kg/m^2 and ≥24 kg/m^2, in accordance with the Chinese criteria on defining normal-weight and over-weight) (Zhou, 2002), smoking status (yes; no: never and former), drinking (yes and no), heating energy (clean and unclean) and cooking energy (clean and unclean). The statistical significance of effect modification was tested by including an interaction term between $PM_{2.5}$ and a potential modifier.

We examined the sensitivity of our results by using the alternative definitions of hypertension. In addition to the main definition, we used self-reported hypertension and diagnostic hypertension with SBP ≥ 140 mmHg and/or DBP ≥ 90 mmHg that was measured in this survey.

All the statistical analyses were conducted in SPSS Statistics 22.0 (IBM Corporation). We used two-sided statistical tests, and P values smaller than 0.05 were considered to be statistically significant. The effect estimates for hypertension prevalence were presented as ORs and their 95% confidence interval (CIs) per an interquartile range (IQR) increase in $PM_{2.5}$ concentrations. The effect estimates for SBP and DBP were presented as the absolute mean changes and their 95% CIs associated with an IQR increase in $PM_{2.5}$ concentrations.

3. Results

The basic characteristics of study participants are summarized in Table 1. Our study population consisted of 13,975 middle-aged or older residents with a mean age of 59.3 years and an approximately equal sex distribution (47.2% males and 52.8% females). Nearly 65% participants had educational attainment <6 years. The averaged BMI was 23.9 kg/m^2. A total of 29.2% participants were current smokers and 24.2% drunk more than once a month. Generally, there were weak or moderate correlations among the covariates included in the main model (data not shown). There were 5715 hypertension patients, accounting for 40.9% of the study population. The averaged SBP and DBP were 130.6 mmHg and 75.9 mmHg, respectively.

Table 2 shows the summary statistics on environmental variables. The annual average exposure to $PM_{2.5}$ varied greatly among study participants. The mean of residential $PM_{2.5}$ exposure was 72.8 μg/m^3, which is much higher than the interim target-3 (35 μg/m^3) of the Air Quality Guidelines issued by the World Health Organization (WHO, 2006). The annual mean O_3 concentration (average: 62.6 μg/m^3) and temperature (average: 14.1 °C) also varied appreciably in this analysis.

As shown in Table 3, the OR of hypertension per an IQR increment in $PM_{2.5}$ (41.7 μg/m^3) was 1.11 (95%CI: 1.06, 1.16) in the crude (unadjusted) model. The effect estimate was positive but statistically insignificant (OR = 1.03, 95%CI: 0.97,1.09) in the basic models and turned to be statistically significant in the fully-adjusted (main) model (OR = 1.11, 95%CI: 1.05, 1.17).

Table 3 also summarizes the associations between $PM_{2.5}$ and BP measurements. The effects of $PM_{2.5}$ on SBP was statistically significant only in the main model, in which an IQR increase in $PM_{2.5}$ was associated with an increment of 0.60 (95%CI: 0.05, 1.15) mmHg. However, we did not observe a significant association between $PM_{2.5}$ and DBP in all models.

Table 4 presents the results of stratification analyses. For hypertension prevalence, the ORs were significantly larger among those who were ≤60 years old, had a BMI ≥ 24 kg/m^2 or resided in urban areas.

As shown in Table S1, the use of alternative definitions resulted in an appreciably lower prevalence of hypertension (24.3% or 30.8%) than the main definition (40.9%). Accordingly, the estimated OR per an IQR increase of $PM_{2.5}$ was also appreciably changed, but was still statistically significant.

4. Discussion

This cross-sectional study demonstrated that long-term exposure to ambient $PM_{2.5}$ was significantly associated with increased prevalence of hypertension and slightly elevated levels of SBP in China. Our estimate was relatively robust to different definitions of hypertension. In addition, the effects of $PM_{2.5}$ on hypertension were particularly stronger among middle-aged, obese and urban residents. Up to our knowledge, this is the first nationwide study in China to explore the long-term effects of air pollution on hypertension and BP.

Although there are abundant evidence in short-term studies to assess the effects of air pollution on BP, limited knowledge is available on the long-term associations. In our study, we estimated an OR of 1.11 (95%CI: 1.05, 1.17) in hypertension prevalence associated with an IQR (41.7 μg/m^3) increase in long-term average $PM_{2.5}$ concentrations. Our finding was comparable to another cross-sectional study in three northern cities of China, which reported an OR of 1.12 (95%CI: 1.08, 1.16) per an IQR (19 μg/m^3) increase in PM_{10} (Dong et al., 2013). However, a similar study in Germany failed to find an association of one-year $PM_{2.5}$ exposure with hypertension prevalence (Fuks et al., 2011). The inconsistency may be explained by the differences in PM levels and composition as well as the susceptibility of populations.

We found a weak but statistically significant association between $PM_{2.5}$ and SBP in the fully-adjusted model. The previous findings on the association between $PM_{2.5}$ and BP were mixed. For example, Chan et al. reported in the Sister study that a 10 μg/m^3 increase in long-term $PM_{2.5}$ was significantly associated with 1.4 mmHg (95% CI: 0.6, 2.3) higher SBP, but not with DBP (Chan et al., 2015). A cross-sectional study involving 27,752 elderly residents in Taiwan reported an increment of 0.73 mmHg (95%CI: 0.44, 1.03) in DBP per 10 μg/m^3 increase in PM_{10}, but null association with SBP (Chen et al., 2015). However, another similar study in Taiwan found significant effects of $PM_{2.5}$ on both SBP and DBP (Chuang et al., 2011). These inconsistent findings might be due to the heterogeneity in PM mixture, population characteristics (age structure, ethnicity, lifestyle, etc.), exposure assessment methodology, as well as the adjustment for confounders and the in-between collinearity. For example, the use of fixed-site monitoring data as in the aforementioned studies may cause exposure misclassification and eventually bias the results (Auchincloss et al., 2008; Dong et al., 2013).

Identification of potentially susceptible subgroups was crucial to reduce the adverse effects of air pollution. In stratification analyses, $PM_{2.5}$ had stronger effect on urban residents, probably because they were more likely to be exposed to higher levels of $PM_{2.5}$. Also, consistent with a previous study (Zhang et al., 2016), we found larger effects of $PM_{2.5}$ in middle-aged participants (45–60 years). The sympathetic and autonomic nervous system might be less responsive to external stimuli in the elderly (Cohen et al., 2012). Old residents may also spend more time indoors, reducing their exposure to ambient $PM_{2.5}$. In addition, our inability to adjust for antihypertensive medication led to an imprecise estimate among the elderly who had a large proportion of hypertension patients (40% in the present study). Besides, we observed stronger associations between $PM_{2.5}$ and hypertension and BP in obese participants, which were consistent with two other studies (Dong et al., 2015; Zhao et al., 2013). This susceptibility might be caused by the inherent inflammation state and higher inhalation rate in obese people (Brochu et al., 2014; Dubowsky et al., 2006).

Although the exact mechanisms behind the association between $PM_{2.5}$ and elevated BP were unclear, the proposed biological pathways were plausible. The activation of pulmonary reflexes induced by inhalation of $PM_{2.5}$ may lead to autonomic nervous system imbalance (Brook et al., 2009). Hypertrophic remodeling of resistance vessels may cause medial thickness, which will also result in BP elevations (Valavanidis et al., 2008). Besides, $PM_{2.5}$ could induce systematic inflammation, oxidative stress, endothelial dysfunction and DNA methylation (Brook et al., 2010; Pope and Dockery, 2006; Wang et al., 2016), resulting in elevated BP.

Our study had two strengths. First, this is the first nationwide study in China to explore the association between long-term exposure to $PM_{2.5}$ and hypertension prevalence and blood pressure. Second, we utilized a satellite-based spatial statistical model to predict the exposure of $PM_{2.5}$, which was especially valuable in areas without regular air quality monitors.

Some limitations should also be noted. First, this was a cross-sectional study design, and thus a causal relationship between $PM_{2.5}$ and BP could not be obtained. Second, exposure misclassification was inevitable because individual-level monitoring was impractical and the spatial resolution of our exposure model was still not high enough which would probably lead to an underestimate on the associations (Sheppard et al., 2012). Third, the data on the use of antihypertensive agents was not available in this study, which might have confounded our estimations on $PM_{2.5}$ and BP values. Fourth, potential individual-level confounders such as physical activity, dietary structure, occupational history and time-location activity pattern were not evaluated in this study due to the lack of data. Fifth, traffic noise was another confounder that we failed to control. This might not be a big problem because this is a nationwide study covering urban and rural areas, and only a very small fraction of participants was supposed to reside near main roads.

5. Conclusions

Our study demonstrated an association of long-term exposure to $PM_{2.5}$ with higher prevalence of hypertension and slightly increased SBP in China. The effects of $PM_{2.5}$ on hypertension were particularly stronger among middle-aged, obese and urban participants. Our findings added to the existing evidence with regard to the long-term effects of $PM_{2.5}$ on hypertension from a large developing country with severe air pollution problems.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgements

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The following is the supplementary data related to this article.Table S1. Odds ratios (point estimates and 95% CIs) of hypertension using different definitions associated with an interquartile range increase (41.7 μg/m^3) in $PM_{2.5}$ in the fully-adjusted model. Table S1 provided the results of sensitivity analysis to test the robustness of different definitions of hypertension. Supplementary data associated with this article can be found in the online version, at http://dx.doi.org/10.1016/j.scitotenv.2017.01.133.

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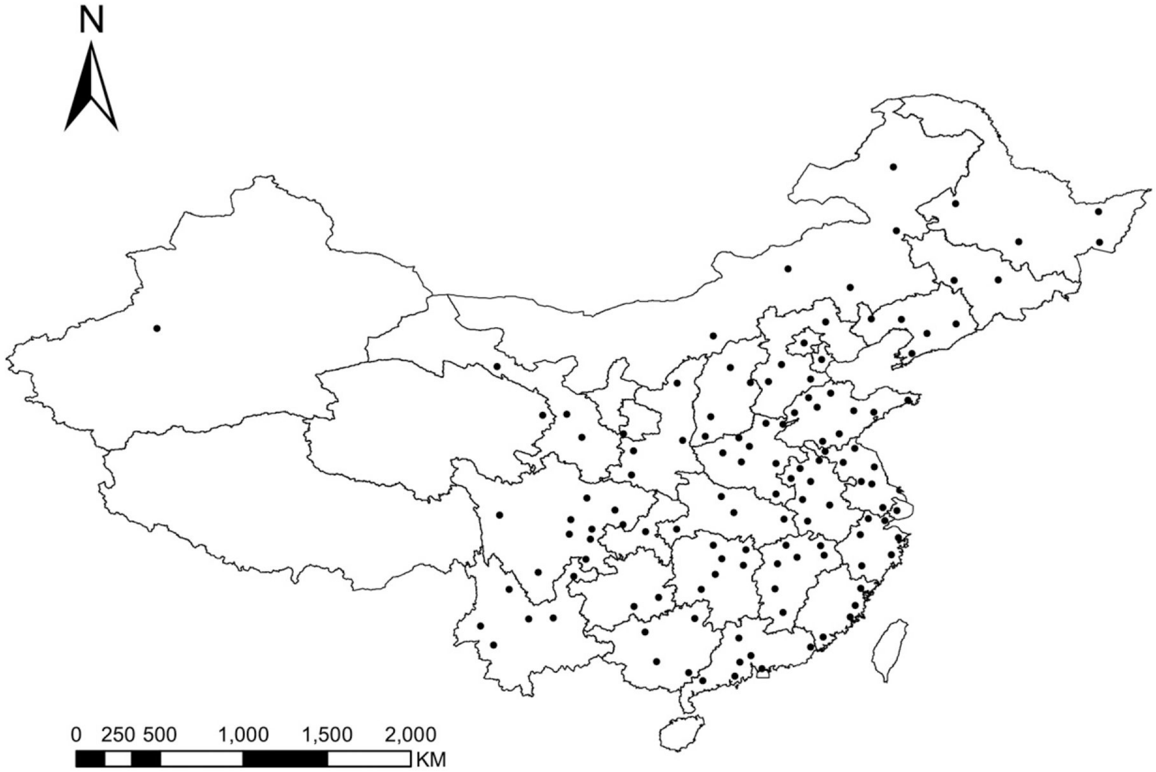

Fig. 1.
Location of the study sites in the CHARLS project.

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Table 1

Descriptive statistics of the study participants (n = 13.974).

Variables	Value
Sociodemographic characteristics	
Age (years, mean ± SD)	59.3 ± 9.9
Sex (%)	
Male	46.7
Female	53.3
Educational level (%)	
Low	28.6
Medium	40.7
High	30.7
BMI (kg/m^2, mean ± SD)	23.9 ± 3.6
Smoking status (%)	
Current	30.6
Former	8.9
Never	60.4
Pack-years of cigarette for current smokers	23.4 ± 21.0
Alcohol-consumption frequency (%)	
≥1/month	24.4
<1/month	7.8
Never	67.8
Residence (%)	
Urban	37.1
Rural	62.9
Type of heating energy (%)	
Clean (solar energy, electricity, central heating)	26.1
Unclean (coal or biomass)	56.4
Others	17.5
Type of cooking energy (%)	
Clean (solar energy, electricity, natural gas)	43.6
Unclean (coal or biomass)	56.4
Prevalence of hypertension (%)	40.9
Blood pressure	
Systolic (mm Hg, mean ± SD)	129.6 ± 21.5
Diastolic (mm Hg, mean ± SD)	75.5 ± 12.2

Abbreviations: SD, standard deviation; BMI, body mass index.

Table 2

Summary statistics on $PM_{2.5}$, O_3 and temperature during the study period.

Variables	Mean	SD	Min	Median	Max	IQR
$PM_{2.5}$[a] (μg/m^3)	72.8	27.4	25.5	69.6	127.9	41.7
O_3[b] (μg/m^3)	62.6	5.9	43.2	63.6	79.1	4.7
Temperature[c] (°C)	14.1	4.9	0.7	14.7	23.2	4.8

Abbreviation: IQR, interquartile range; SD, standard deviation; $PM_{2.5}$, particulate matter with an aerodynamic diameter less than or equal to 2.5 μm; O_3, ozone.

[a]Data derived from a study by Ma et al. and used in the main analyses.

[b]Data derived from the database of the 2013 Global Burden of Disease project.

[c]Data derived from China's National Meteorological Information Center.

Table 3

Odds ratio (and its 95% confidence interval) of hypertension, increments (mmHg, mean and 95% CI) in systolic BP and diastolic BP associated with an interquartile range increase in $PM_{2.5}$.

Model	Covariates	OR	Systolic BP	Diastolic BP
Crude	Unadjusted	1.11 (1.06,1.16)	0.31 (−0.24,0.85)	0.18 (−0.13,0.49)
Basic	Area, age, sex, education, BMI, smoking status, pack-years, alcohol consumption, heating energy and cooking energy	1.03 (0.97,1.09)	−0.47 (−1.00,0.06)	−0.43 (−0.75,−0.12)
Main	Basic model + temperature + O_3 + season	1.11 (1.05,1.17)	0.60 (0.05,1.15)	0.02 (−0.30,0.34)

Abbreviations: OR, odds ratio; $PM_{2.5}$, particulate matter with an aerodynamic diameter less than or equal to 2.5 μm; CI: confidence interval; IQR, interquartile range; BP, blood pressure.

The specifications for the crude, basic and main model were the same for OR, systolic BP and diastolic BP.

Table 4

Odds ratios of hypertension and estimated absolute increase in systolic BP and diastolic BP (mmHg) (with 95% confidence intervals) associated with an interquartile range (41.7 μg/m^3) increase in $PM_{2.5}$ stratified by potential modifiers.

Variables	Categories	N (%)	ORs	P for interaction	Systolic BP (mmHg)	Diastolic BP (mmHg)
Age	≤60	6898 (49.4)	1.15 (1.07,1.22)	0.008	1.31 (0.66,1.96)	0.41 (0.01,0.82)
	>60	7074 (50.6)	1.07 (0.97,1.16)		−0.33 (−1.33,0.66)	−0.58 (−1.08,0.08)
Sex	Males	6528 (46.7)	1.17 (1.08,1.26)	0.164	0.96 (0.17,1.75)	0.35 (−0.13,0.82)
	Females	7436 (53.3)	1.06 (0.98,1.14)		0.47 (−0.30,1.25)	−0.26 (−0.69,0.16)
Educational level	Low	9672 (69.2)	1.10 (1.03,1.17)	0.160	0.77 (0.07,1.47)	0.05 (−0.34,0.44)
	High	4295 (30.8)	1.11 (0.99,1.21)		0.40 (−0.51,1.30)	−0.09 (−0.66,0.49)
BMI	<24 kg/m^2	7282 (53.4)	1.08 (0.99,1.16)	0.011	0.33 (−0.42,1.07)	−0.33 (−0.75,0.09)
	≥24 kg/m^2	6347 (46.6)	1.16 (1.07,1.24)		1.17 (0.33,2.01)	0.48 (0.02,0.97)
Smoking status	Yes	4272 (30.6)	1.16 (1.05,1.27)	0.423	0.48 (−0.19,1.14)	0.07 (−0.53,0.67)
	No	9686 (69.4)	1.09 (1.02,1.16)		1.19 (0.19,2.19)	−0.01 (−0.38,0.37)
Drinking status	Yes	4493 (32.2)	1.21 (1.10,1.31)	0.482	0.80 (−0.15,1.75)	0.27 (−0.31,0.85)
	No	9472 (67.8)	1.07 (0.99,1.14)		0.65 (−0.03,1.33)	−0.10 (−0.48,0.28)
Heating energy	Clean	6065 (43.6)	1.04(0.94,1.13)	0.474	−1.06 (−2.09,0.04)	−0.59 (−1.11,−0.08)
	Unclean	7835 (56.4)	1.17 (1.09,1.25)		2.01 (1.26,2.76)	0.58 (0.15,1.01)
Cooking energy	Clean	6072 (46.6)	1.12 (1.03,1.21)	0.797	0.06 (−0.5,0.63)	0.07 (−0.37,0.51)
	Unclean	7857 (56.4)	1.10 (1.02,1.18)		1.11 (0.34,1.89)	−0.14 (−0.62,0.34)
Location	Rural	8794 (62.9)	1.05 (0.98,1.13)	0.001	0.76 (0.06,1.46)	0.01 (−0.39,0.42)
	Urban	5180 (37.1)	1.18 (1.08,1.28)		0.44 (−0.5,1.39)	0.03 (−0.51,0.56)

Abbreviations: BP, blood pressure; OR, odds ratio; CI, confidence interval; BMI: body mass index; $PM_{2.5}$, particulate matter with an aerodynamic diameter less than or equal to 2.5 μm; IQR, interquartile range.

Categories for variables were dichotomized: educational level (low ≤6 years; high >6 years); heating and cooking energy (clean: electricity, solar power or natural gas; unclean: coal or firewood).