Environmental Research Letters

LETTER

How protective is China’s National Ambient Air Quality Standards on short-term PM$_{2.5}$? Findings from blood pressure measurements of 1 million adults

Tianjia Guan$^{1,2}$, Tao Xue$^1$, Jian Guo$^1$, Xin Wang$^1$, Yixuan Zheng$^1$, Baohua Chao$^3$, Yuting Kang$^4$, Zuo Chen$^5$, Linfeng Zhang$^6$, Congyi Zheng$^6$, Linlin Jiang$^6$, Ying Yang$^6$, Qiang Zhang$^6$, Zengwu Wang$^7$, Yuanli Liu$^8$ and Runlin Gao$^9$

1 School of Health Policy and Management, Chinese Academy of Medical Sciences and Peking Union Medical College, Beijing 100730, People’s Republic of China
2 Institute of Reproductive and Child Health/Ministry of Health Key Laboratory of Reproductive Health and Department of Epidemiology and Biostatistics, School of Public Health, Peking University, Beijing 100191, People’s Republic of China
3 Department of Cardiology and Medical Research Center, Peking Union Medical College Hospital, Chinese Academy of Medical Sciences and Peking Union Medical College, Beijing 100005, People’s Republic of China
4 Division of Prevention and Community Health, National Center for Cardiovascular Disease, National Clinical Research Center of Cardiovascular Disease, State Key Laboratory of Cardiovascular Disease, Fuwai Hospital, Chinese Academy of Medical Sciences and Peking Union Medical College, Beijing 102308, People’s Republic of China
5 Center of Air Quality Simulation and System Analysis, Chinese Academy for Environmental Planning, Beijing 100012, People’s Republic of China
6 China Stroke Data Center, National Health Commission of the People’s Republic of China, Beijing 100101, People’s Republic of China
7 Department of Earth System Science, Tsinghua University, Beijing 100084, People’s Republic of China
8 Department of Cardiology, Fuwai Hospital, Chinese Academy of Medical Sciences and Peking Union Medical College, Beijing 100037, People’s Republic of China
9 E-mail: suetaoqk_9032@126.com and wangzengwu@foxmail.com

Keywords: ambient fine particulate matter (PM$_{2.5}$), blood pressure, hypertension, exposure-response curve, China’s National Ambient Air Quality Standards

Supplementary material for this article is available online

Abstract

Although short-term exposure to fine particulate matter (PM$_{2.5}$) air pollution has been shown to induce elevated blood pressure (BP), limited evidence is available regarding the association between ambient PM$_{2.5}$ and BP levels in nationwide China and how the association may change. This study sought to explore acute BP changes with exposure to PM$_{2.5}$ at levels below China’s current National Ambient Air Quality Standards (NAAQS). Based on a spatiotemporal study of over 1 million adults, we linked BP measurements to daily estimates of PM$_{2.5}$ from multiple sources (i.e. in situ observations, satellite measurements of aerosol and numeric simulations of air quality model) after adjusting for several individual-level covariates and further conducted the below-criteria models by restricting the analyses within subsets of individuals with short-term PM$_{2.5}$ exposure below 75 $\mu$g m$^{-3}$ (i.e. NAAQS of 24 h PM$_{2.5}$ in China). We further explored variations in BP-PM$_{2.5}$ associations by pollution level and for different demographic groups. With full adjustments, a 10 $\mu$g m$^{-3}$ increase in PM$_{2.5}$ was statistically significantly associated with a 0.049 mmHg (95% confidence interval, CI: 0.041, 0.057) increase in systolic BP, a 0.022 mmHg (95% CI: 0.017, 0.027) increase in diastolic BP and a 0.77% (95% CI: 0.62%, 0.92%) increased risk of hypertension (HPN). For both BP and HPN, the exposure-response curves were linear, with no threshold effects, at the low-concentration ends and sublinear at the high-concentration ends. Below the current NAAQS, the associations in population level remained statistically significant and were even stronger. A 10 $\mu$g m$^{-3}$ increase in below-NAAQS PM$_{2.5}$ was associated with a 1.95% (95% CI: 1.44%, 2.47%) increased risk of HPN. Specific subpopulations were more susceptible to PM$_{2.5}$ exposure. These findings can help support decisions by policymakers to revise related environmental regulations to protect public health.
1. Introduction

Ambient exposure to fine particulate matter (PM$_{2.5}$) has been shown to contribute to a global burden of 4 million premature deaths, approximately one quarter of which occur in China (Cohen et al 2017). To protect the public from adverse health effects of ambient PM$_{2.5}$, China developed an action plan of air pollution control and prevention in 2013, which has considerably improved the air quality (Zheng et al 2017). According to a product of gridded estimates of PM$_{2.5}$ (the details of which are described in the method section), the population-weighted average of the polluted period (PM$_{2.5}$ $> 75$ µg m$^{-3}$) was reduced from 110 d in 2013 to 51 d in 2017. With the improving air quality, it may be time to rethink China’s National Ambient Air Quality Standards (NAAQS) of PM$_{2.5}$, which was set according to a combination of the daily average of 75 µg m$^{-3}$ and the annual average of 35 µg m$^{-3}$, equal to the interim target 3 in World Health Organization guidelines. A recent study reported that in 2013, ambient PM$_{2.5}$ was associated with 1.2 million deaths, which were attributed to stroke, ischemic heart disease, lung cancer and chronic obstructive pulmonary disease (Zheng et al 2017). Can the current NAAQS protect the public from the health impacts of ambient exposure to PM$_{2.5}$? Although many epidemiological studies have associated PM$_{2.5}$ with multiple diseases, few studies have explored such associations under a certain concentration due to limited sample sizes. Researchers have reported that the associations between low concentrations of PM$_{2.5}$ and mortalities were statistically significant for residents in the United States (Shi et al 2016, Di et al 2017a, 2017b, Makar et al 2017). For the Chinese population, the health effects of slightly polluted air, particularly the risk of exposure to ambient PM$_{2.5}$ below the current NAAQS, remain unclear.

Exposure to ambient pollutants has been reported to trigger increased blood pressure (BP) and even hypertension (HPN) (Cai et al 2016, Yang et al 2018), which yields insight into the biological pathways (e.g. inflammation, systemic oxidation stress and imbalance of the autonomic nervous system) underlying PM$_{2.5}$-associated cardiovascular diseases (CVDs) (Brook et al 2010), which account for about three quarters of the mortality burden attributable to PM$_{2.5}$ (Zheng et al 2017). Therefore, as a clinical indicator of PM$_{2.5}$-associated CVDs, BP change can serve as a general metric to quantify the health impacts of exposure to PM$_{2.5}$, particularly short-term exposure to PM$_{2.5}$. Although an increasing number of studies has associated both acute and chronic BP increments with exposure to ambient PM$_{2.5}$ (Guo et al 2010, Dong et al 2013, Lin et al 2017, Liu et al 2017, Yang et al 2017, Huang et al 2018, Zhang et al 2018), existing evidence is controversial (Yang et al 2018), possibly due to the heterogeneity in aspects of studying population compositions and chemical components of particles. Large national-scale studies with identical study designs are therefore necessary to re-evaluate the association between PM$_{2.5}$ and BP.

Using BP elevation as a biomarker for exposure to PM$_{2.5}$, our goal was to evaluate the association between BP change and short-term exposure to PM$_{2.5}$ in nationwide China, based on a representative population of over 1 million individuals, 2013–2016. Below-criteria models were further developed to examine the association between BP changes and low-concentration PM$_{2.5}$ in China, aiming to explore the protective effects of China’s current air quality standard on short-term PM$_{2.5}$ exposures.

2. Methods

2.1. Study population

The study population, consisting of 1 035 018 valid samples, was derived from a combination of two nationwide surveys in China: the China National Stroke Screening Survey (CNSSS, n = 572 229) and the China Hypertension Survey (CHS, n = 462 789). The CNSSS is an ongoing survey of all residents aged above 45 years from >400 communities during 2013–2015, and the CHS randomly sampled adults (≥18 years old) by sex-age strata from >500 communities during 2012–2015. Detailed information about the two databases was documented in previous publications and supplemental materials, which are available online at https://stacks.iop.org/ERL/15/125014/mmedia (Guan et al 2017, Wang et al 2014; appendices 3 and 4).

BP was measured twice for two arms for participants in the CNSSS, and three times for participants in the CHS, both at the survey time, by the well-trained interviewers. The specific survey date was documented for each subject. Since both of the two surveys were community-based and conducted by face-to-face interviewers, theoretically speaking, the specific hours of BP measurements were randomly distributed in the working time. Additionally, since the diurnal variation of BP is different from that of PM$_{2.5}$ in China (Zhao et al 2009, Kawano 2011), we ignored the specific time of BP measurements, and conducted all analyses in daily scale.

In this study, we first calculated the average of the systolic BP (SBP) and the diastolic BP (DBP) for participants in the two surveys. Then we excluded invalid records with missing BP values or measurement dates, which left >1 million samples from 942 communities. We further excluded 12 communities with a sample size <70. Finally, we involved >1 million valid records from 929 communities (419 CNSSS communities and 520 CHS communities), which covered 229 of 330 cities in China (figure 1). According to their address, there is no duplication of the communities.

Given that the two surveys collected different sets of population characteristics, our study only involved
covariates from the intersection of the two sets, including urban/rural residence, sex, age, education, marriage, body mass index (BMI), smoking status, drinking status, self-reported diagnosis of stroke, self-reported diagnosis of HPN, and antihypertensive medicine intake within the past two weeks. All of those available risk factors for HPN were incorporated into the regressions to control for potential confounding effects. Additionally, according to the BP measurements, we also derived a binary variable of HPN (defined as SBP $\geq 140$ mmHg or DBP $\geq 90$ mmHg) for each record.

2.2. Environmental variables
To evaluate acute exposure of the surveyed subjects to ambient PM$_{2.5}$, we obtained a product of daily estimates with a spatial resolution of $0.1^\circ \times 0.1^\circ$ from 2013 to 2017. The PM$_{2.5}$ concentrations were estimated by combining in situ observations, satellite-retrieved AOD and CMAQ simulates. The estimates were in good agreement with independent observations from in situ monitors during 2013–2017 ($R^2 = 0.72$; figure S1). Details of the algorithm and additional validation results were documented in other publications (Xue et al 2017, Zheng et al 2017). For each surveyed subject, PM$_{2.5}$ exposure was assigned according to the centroid coordinate of his/her residential community because a specific address was censored to protect individual privacy.

We also obtained daily values of mean temperature and relative humidity (RH) as potential confounders in the association between BP and PM$_{2.5}$. Temperature was also collected from a data assimilation product (2000–2016), which combined outputs from the Weather Research Forecast (WRF) model, satellite measurements of ground surface temperature and in situ observations. The ten-fold cross-validation results indicated that the temperature estimates were highly correlated with the in situ observations ($R^2 = 0.96$; figure S2) during the study period. For more details about the estimation, please refer to the supplemental materials. RH was directly obtained from the WRF model. The original outputs from the WRF had a spatial resolution of 36 km $\times$ 36 km and were further downscaled to the $0.1^\circ \times 0.1^\circ$ grid. Detailed settings of the WRF simulates were also documented in previous papers (Xue et al 2017, Zheng et al 2017).

2.3. Statistical analysis
We associated individual measurements of SBP, DBP and HPN to daily concentrations of PM$_{2.5}$ using the following spatiotemporal regression model (equation (1)).

$$ y_i \sim \eta(s_i) + f_1(t_i) + \beta \cdot \text{PM}_{2.5,i} + f_2(\text{Temperature}_i) + f_3(\text{RH}_i) + Z_i \gamma, \quad (1) $$

where $i$, $s$ and $t$ denote the indices of the subject, community and date, respectively; $y_i$ denotes a health outcome; $\beta$ denotes the effect per unit increment of PM$_{2.5}$; $\eta(s)$ denotes a random effect for each community; $f(\bullet)$ denotes a natural spline term; $Z_i$ denotes a set of weekday indicators and individual covariates; and $\gamma$ denotes the corresponding regression coefficient. The spatial random effect ($\eta$) is utilized to adjust for the unmeasured risk factors that are clustered in regional level. Those factors, for example, include regional patterns in dietary type (e.g. salt-intake), and indoor fuel type (e.g. usage of biomass). When modeling BP (i.e. $y$ denotes SBP or DBP).
DBP), we utilized a normal regression; when modeling HPN (i.e. y denotes a binary indicator for HPN), we utilized logit regression. To model the spline terms, we set 4 degrees of freedom per year for the temporal trend \((f_1)\) and 3 degrees of freedom for temperature \((f_2)\) or RH \((f_3)\) on the current day of BP measurements. The individual-level covariates included urban/rural residence, sex, age group, education attainment, marriage status, BMI, smoking status, drinking status, stroke diagnosis and HPN diagnosis and treatment. To explore the lagged effect of PM\(_{2.5}\) on BP, we set the exposure term \((PM_{2.5})\) as the daily concentrations at the current day of BP measurement or 1–3 d before the measurement. To address missing values in individual-level covariates, we utilized multivariate imputation by chained equations before the regression analysis (van Buuren and Groothuis-Oudshoorn 2011). Considering the imbalanced sampling probabilities for different subpopulations, we applied the approach of inverse probability weights. For each record, the sample probability \((P)\) was calculated as \(P = n_k/N_k\), where \(k\) denotes the index of a specific demographic group, which was defined by a combination of sex, age and urbanity in this study; \(n_k\) denotes the total sample size within a community; and \(N_k\) denotes the corresponding population size within the community and was obtained from the 2010 census. Similar models (i.e. regression with a spatial random effect and a smoothed temporal trend) have been utilized in many spatiotemporal studies on other adverse effects of ambient pollutants (Shi et al 2016). To explore how covariates adjustment impacted the estimated associations, we conducted a series of sequentially-adjusted models, which incorporated different sets of covariates one by one, from unadjusted to full-adjusted model. To examine the threshold effect of the current NAAQS, we re-estimated the association among the records with concentrations of short-term PM\(_{2.5}\) < 75 \(\mu\text{g m}^{-3}\), which parallels previous studies in the United States (Di et al 2017a).

In exploratory analyses, we examined (a) the curvature of PM\(_{2.5}\)-BP associations, (b) effect modifications of individual characteristics, and (c) subgroup-specific associations. First, to model the nonlinear association, we replaced the linear term of PM\(_{2.5}\) with a set of thin-plate-spline terms, as given in equation (1). Second, we performed an interaction analysis to examine the modifying effect of each categorical variable (e.g. sex and age) on the linear association between BP and PM\(_{2.5}\). Third, given the heterogeneity in the effects of PM\(_{2.5}\) in different subpopulations, we derived the subgroup-specific PM\(_{2.5}\)-BP associations as an extension of the effect-modification analysis. We defined an indicator for demographic subgroups using three categorical variables (age, sex and urban/rural residence) and estimated the modifying effect of the indicator on the PM\(_{2.5}\)-BP associations. Considering model complexity, we used random slopes to model the interaction terms between the demographic indicator and PM\(_{2.5}\). All statistical analyses were performed using the R statistical package (version 3.4.1, R Core Team, Vienna, Austria). All results were evaluated per 10 \(\mu\text{g m}^{-3}\) increment in PM\(_{2.5}\) concentration.

3. Results

3.1. Descriptive summary

The spatial coverage of the surveyed communities is shown in figure 1, which indicates that the combined CHS and CNSSS databases covered most populous areas and regions with different pollution levels. Summary statistics of the study population are presented in table 1. Among the 1 035 018 participants, 327 069 (31.6%) were classified as HPN, and 292 404 (28.3%) were patients with pre-diagnosed HPN. Among the 716 656 subjects without awareness of HPN, 116 140 (16.2%) were identified as hypertensive. In the database, urban and rural residents were sampled in equal probability (50.1% vs 49.9%), but more females were involved than males (53.3% vs 46.7%). As the CNSSS surveyed an older population than the CHS, the prevalence of HPN was higher in the former dataset (39.2%) than in the latter (22.1%). Among all subjects, the mean value of SBP or DBP was reported as 130.8 mmHg or 79.1 mmHg, respectively. For the hypertensive subjects, the average daily PM\(_{2.5}\) on the day before BP measurement was 72.4 \(\mu\text{g m}^{-3}\), which was higher than the corresponding value (66.0 \(\mu\text{g m}^{-3}\)) for the non-hypertensive subjects but slightly lower than the NAAQS. The interquartile range of the PM\(_{2.5}\) was 55.4 \(\mu\text{g m}^{-3}\), from 32.9 \(\mu\text{g m}^{-3}\) to 88.3 \(\mu\text{g m}^{-3}\).

3.2. Associations

Figure 2 presents the estimated association between BP and PM\(_{2.5}\) for different lag times. Short-term exposure to PM\(_{2.5}\) during the period of 0–3 d prior to BP measurement significantly increased the SBP, DBP or risk of HPN, and the strongest association was identified for PM\(_{2.5}\) exposure on the day before BP measurements. Because the PM\(_{2.5}\) concentrations were autocorrelated in the temporal dimension, effective exposure might occur within a narrow time window and result in significant associations for the nearby periods. For comparability between BP-associated exposure to PM\(_{2.5}\) and NAAQS, in this study, we focused on the effect of PM\(_{2.5}\) exposure within a single day and, thus, assume a lag of 1 d as the effective time-window for all following analyses.

We also explored the roles that different covariates played in the regression using sequentially adjusted models (figure S3). We found the estimated associations were sensitive to adjustment for
### Table 1. Summary statistics of the study population.

| Variable                      | Group                                | All subjects | Non-hypertensive subjects | Hypertensive subjects |
|-------------------------------|--------------------------------------|--------------|----------------------------|-----------------------|
|                               |                                      | Sample size (% of total) |                           |                        |
| Categorical variables         |                                      |                            |                            |                        |
| Total                         |                                      | 1 035 018 (100%)        | 707 949 (100%)            | 327 069 (100%)        |
| Sex                           | Female                               | 551 171 (53.3%)        | 379 247 (53.6%)          | 171 924 (52.6%)       |
|                               | Male                                 | 483 847 (46.7%)        | 328 702 (46.4%)          | 155 145 (47.4%)       |
| Age (years old)               | 18–34                                | 153 609 (14.8%)        | 146 503 (20.7%)          | 7 106 (2.2%)          |
|                               | 35–44                                | 136 874 (13.2%)        | 114 978 (16.2%)          | 21 896 (6.7%)         |
|                               | 45–54                                | 227 597 (22.0%)        | 160 928 (22.7%)          | 67 069 (20.5%)        |
|                               | 55–64                                | 242 254 (23.4%)        | 142 497 (20.2%)          | 99 402 (30.4%)        |
|                               | 65+                                  | 272 145 (26.3%)        | 141 517 (20.0%)          | 130 628 (39.9%)       |
|                               | Unknown                              | 204 (0.2%)             | 107 (0.2%)               | 96 (0.3%)             |
| Residence                     | Rural                                | 516 248 (49.9%)        | 338 237 (47.8%)          | 178 011 (54.4%)       |
|                               | Urban                                | 518 770 (50.1%)        | 369 712 (52.2%)          | 149 058 (45.6%)       |
|                               | Divorced/widow                       | 51 855 (5.0%)          | 27 663 (3.9%)            | 24 192 (7.4%)         |
|                               | Married                              | 687 428 (66.4%)        | 466 779 (65.9%)          | 220 649 (67.5%)       |
|                               | Single                               | 79 302 (7.7%)          | 74 682 (10.5%)           | 4 620 (1.4%)          |
|                               | Unknown                              | 216 433 (20.9%)        | 138 825 (19.6%)          | 77 608 (23.7%)        |
|                               | College and above                    | 82 044 (7.9%)          | 69 368 (9.8%)            | 12 676 (3.9%)         |
|                               | High school                          | 151 366 (14.6%)        | 120 350 (17.0%)          | 31 016 (9.3%)         |
| Educational attainment        | Middle school and below              | 575 890 (55.6%)        | 373 852 (52.8%)          | 202 038 (61.8%)       |
|                               | Unknown                              | 225 718 (21.8%)        | 144 379 (20.4%)          | 81 339 (24.9%)        |
|                               | Normal (<25)                         | 639 065 (61.7%)        | 484 404 (68.4%)          | 154 661 (47.3%)       |
| Obesity (BMI, kg m\(^{-2}\))  | Overweight                           | 329 149 (31.8%)        | 192 222 (27.2%)          | 136 927 (41.9%)       |
|                               | Obese (30+)                          | 63 140 (6.1%)          | 46 677 (65.9%)           | 15 463 (4.7%)         |
|                               | Unknown                              | 3664 (0.4%)            | 2148 (0.3%)              | 1 516 (0.5%)          |
| Smoker                        | Never                                | 809 995 (78.3%)        | 568 113 (80.2%)          | 241 882 (74.0%)       |
|                               | Yes                                  | 223 652 (21.6%)        | 138 906 (19.6%)          | 84 746 (25.9%)        |
|                               | Unknown                              | 1371 (0.1%)            | 930 (0.1%)               | 441 (0.1%)            |
| Smoker                        | Yes                                  | 699 252 (67.6%)        | 654 027 (65.7%)          | 45 225 (1.4%)         |
|                               | Never                                | 157 961 (15.3%)        | 100 204 (14.2%)          | 57 757 (17.7%)        |
| Smoker                        | Unknown                              | 177 805 (17.2%)        | 142 418 (20.1%)          | 35 387 (10.8%)        |
| Smoker                        | Yes                                  | 968 167 (93.5%)        | 675 854 (95.5%)          | 292 313 (89.4%)       |
| Smoker                        | Unknown                              | 64 255 (6.2%)          | 30 096 (4.3%)            | 34 159 (10.4%)        |
| Pre-diagnosed stroke          | No                                   | 2596 (0.3%)            | 1999 (0.3%)              | 597 (0.2%)            |
| Pre-diagnosed stroke          | Unknown                              | 716 656 (69.2%)        | 600 516 (84.8%)          | 116 140 (35.3%)       |
| Pre-diagnosed hypertension    | No HPN/No MED                        | 73 999 (7.1%)          | 20 356 (2.9%)            | 53 643 (16.4%)        |
| Pre-diagnosed hypertension    | HPN without MED                      | 218 405 (21.1%)        | 74 705 (10.6%)           | 143 700 (43.9%)       |
| Pre-diagnosed hypertension    | HPN with MED                         | 25 958 (2.5%)          | 12 372 (1.7%)            | 13 586 (4.2%)         |
| Pre-diagnosed hypertension    | Unknown                              | 222 600 (21.5%)        | 149 020 (21.0%)          | 73 580 (22.5%)        |
| Pre-diagnosed hypertension    | 2014                                 | 376 252 (36.4%)        | 246 091 (34.8%)          | 130 161 (39.8%)       |
| Pre-diagnosed hypertension    | 2015                                 | 325 486 (31.4%)        | 225 392 (31.8%)          | 100 094 (30.6%)       |
| Pre-diagnosed hypertension    | 2016                                 | 110 680 (10.7%)        | 87 466 (12.4%)           | 23 214 (7.1%)         |
| Pre-diagnosed hypertension    | 2017                                 | 462 789 (44.7%)        | 360 298 (50.9%)          | 102 491 (31.3%)       |
| Pre-diagnosed hypertension    | 2018                                 | 572 229 (55.3%)        | 347 651 (49.1%)          | 224 578 (68.2%)       |
| Pre-diagnosed hypertension    | 2019                                 | 68.0 (51.6%)           | 66.0 (50.5%)             | 72.4 (53.5%)          |
| Pre-diagnosed hypertension    | 2020                                 | 72.4 (53.5%)           | 72.4 (53.5%)             | 13.3 (211.6%)         |
| Continuous variables          |                                      |                            |                            |                        |
| Systolic blood pressure (mmHg)|                                      | 130.8 (18.9)            | 121.1 (10.3)             | 151.6 (16.2)          |
| Diastolic blood pressure      |                                      | 99.3 ~ 130.0            | 125.0 ~ 190.0            |
| Temperature (°C)              |                                      | 11.2 (11.4)             | 11.8 (11.6)              | 9.9 (11.0)            |
| Relative humidity (%)         |                                      | 11.2 (14.8)             | 13.5 ~ 30.0              | 13.4 ~ 29.2           |
| PM\(_{2.5}\) (µg m\(^{-3}\)) |                                      | 72.4 (53.5)             | 72.4 (53.5)              | 13.3 (211.6)          |

\(^{a}\)CHS: China Hypertension Survey.  
\(^{b}\)CNSSS: China National Stroke Screening Survey.  
\(^{c}\)The value at the same date of blood pressure measurements.  
\(^{d}\)The value 1 d before the date of blood pressure measurements.
the random effect of survey community or not. Involving the random term would make the model estimates focusing on within-community variations rather than between-community variations in BP and PM$_{2.5}$. Within-community variations were indicative for the temporal changes in exposures and outcomes, and thus their coherences reflected the effect of acute exposure. In contrast, between-community variations, which were partially determined by the spatial pattern in PM$_{2.5}$, were indicative for the effect of chronic exposure. Without controlling for the spatial term, the estimated associations were mixed by incorporating both acute and chronic effects of PM$_{2.5}$, and thus were stronger than the results from fully-adjusted models, which were focused on acute effect only.

Table 2 presents the estimated associations between BP and PM$_{2.5}$ without or with adjustments. According to the full model (equation (1)), a 10 µg m$^{-3}$ increase in PM$_{2.5}$ was associated with increments of 0.049 mmHg (95% confidence interval, CI: 0.041, 0.057), 0.022 mmHg (95% CI: 0.017, 0.027) and 0.77% (95% CI: 0.62%, 0.92%) in SBP, DBP and HPN risk, respectively. However, before adjusting for covariates, the associations were reported to be stronger than the adjusted estimates. For instance, according to the unadjusted model, a 10 µg m$^{-3}$ increase in PM$_{2.5}$ was associated with a 3.55% (95% CI: 3.47%, 3.64%) increased risk of HPN, which is considerably larger than the value (0.77%) reported by the fully adjusted model. In a nation-scale study, air quality may be correlated with many factors, such as the development level, which further determined the mixture of residents with differential socioeconomic positions (e.g. different levels of education attainment). Therefore, without controlling such potential confounders, the unadjusted models might overestimate the effect of PM$_{2.5}$ on BP. The estimated effects of ambient PM$_{2.5}$ were comparable with those of other risk factors. For instance, 1 cigarette d$^{-1}$ level of smoking was respectively associated with a higher DBP or SBP of 0.05 (95% CI: 0.02, 0.08) or 0.08 (95% CI: 0.03, 0.13) mmHg (Linneberg et al 2015), which were equivalent to the impacts from a PM$_{2.5}$ increment of 22.5 (8.3, 40.3) µg m$^{-3}$ or 16.5 (6.9, 26.9) µg m$^{-3}$, based on the estimates from fully-adjusted models (table 2). In contrast, the concentration of PM$_{2.5}$ has been reported as high as ~500 µg m$^{-3}$ during the haze episodes in China (Wang et al 2015).

**Figure 2.** Fully adjusted associations between blood pressure or hypertension and daily PM$_{2.5}$ at 0–3 lag days.
To examine whether acute exposure to PM$_{2.5}$ less than the NAAQS can still change BP, we conducted a below-criteria analysis. In the below-criteria model 1, we applied the fully-adjusted model to a subpopulation ($n = 699,664$) that was exposed to PM$_{2.5} < 75$ µg m$^{-3}$ on the day before BP measurements. We found that ambient exposure to PM$_{2.5}$ below the NAAQS was still significantly associated with increased BP, and also increased risk of HPN. The estimated associations were slightly stronger than the results based on the full-sample analysis. For instance, according to the below-criteria model 1, a 10 µg m$^{-3}$ increase in PM$_{2.5}$ was associated with a 1.95% (95% CI: 1.44%, 2.47%) increased risk of HPN, which is higher than the full-sample result (0.77%). The stronger effect for the lower-concentration exposure is within expectation given the sublinear exposure-response curve (ERC$_a$ as presented in figure 3 and discussed in next subsection), and is similar to findings on other outcomes of PM$_{2.5}$ exposure, e.g. mortality (Shi et al 2016). Considering the uncertain time-window for effective exposure, we next applied a more rigorous inclusion rule that no daily concentration of PM$_{2.5}$ was beyond the NAAQS during the lag period of 0–3 d and developed the below-criteria model 2 based on 511,753 samples. The two below-criteria models yielded statistically consistent results and suggest that short-term exposure to PM$_{2.5}$ under NAAQS may still increase BP.

### 3.3. Exploratory analyses

The previous analyses assumed that the associations between BP and PM$_{2.5}$ would be linear, which might not be valid. Figure 3 presents the results of the non-linear analysis. We found that the ERC was almost linear at the low-concentration end and slightly sublinear at the high-concentration end for SBP, DBP and HPN, respectively. The sub-linearity might partially explain why associations estimated by the below-criteria models are stronger than the corresponding results from the fully adjusted model (table 2). The ERC also suggests that there is no threshold effect for the hypertensive effect of short-term exposure to PM$_{2.5}$ in China, which is consistent with the findings from the below-criteria analyses.

We examined the effect modifications of individual-level characteristics on the PM$_{2.5}$-BP associations. The detailed results are presented in supplemental figure S4. Generally, the tested characteristics significantly modified the association between PM$_{2.5}$ and at least one indicator of BP (among SBP, DBP or HPN). We also estimated the associations by specific subgroups, classified by sex, age and residence (figure 4). We found that the PM$_{2.5}$-BP associations varied considerably with demographic characteristics and tended to be stronger among urban residents and females. Variations in the association between different age groups is complex. Compared to other age groups, we found stronger associations for middle-aged adults among urban residents and for females in rural areas, but not for male residents in rural areas. A possible explanation was the specific occupation for the middle-aged rural adults, most of whom were participated in the labor-intensive works in agriculture. Physical activity has been known as a protective factor to mitigate hypertensive risks. Additionally, the inter-individual heterogeneity might also be attributable to non-physiological factors, such as BP measurement time (for instance, middle-aged employed adults tend not to participate into the surveys at working time, and their measurement could be influenced by intraday pattern of BP).

Interpretation of the modifying effects is complicated because individual-level characteristics are highly correlated with each other. Without further exploration, it was unknown whether the modifying effect was attributable to the variable itself or its correlated factors. Particularly, different combination of those modifiers between sub-regions has been reported to result in geographic variations in the BP-PM$_{2.5}$ associations (Guan et al 2020). Therefore, identifying susceptible subpopulations to the hypertensive effect of PM$_{2.5}$ is beyond the scope of this study, although we did acquire some interesting findings (e.g. as shown in figure S4, we found a stronger

### Table 2. Estimated associations between blood pressure (BP) and acute exposure to PM$_{2.5}$ on the day before BP measurement.

| Model                           | Systolic blood pressure (mmHg)      | Diastolic blood pressure (mmHg)   | Excess risk of hypertension (%) |
|--------------------------------|-------------------------------------|-----------------------------------|--------------------------------|
| Unadjusted model$^a$           | 0.376 (0.369, 0.382)                | 0.204 (0.200, 0.208)              | 3.55 (3.47, 3.64)              |
| Fully-adjusted model$^b$       | 0.049 (0.041, 0.057)                | 0.022 (0.017, 0.027)              | 0.77 (0.62, 0.92)              |
| Below-criteria model 1$^c$     | 0.061 (0.034, 0.088)                | 0.068 (0.051, 0.085)              | 1.95 (1.44, 2.47)              |
| Below-criteria model 2$^d$     | 0.082 (0.047, 0.117)                | 0.084 (0.061, 0.106)              | 1.52 (0.85, 2.19)              |

$^a$Generalized linear models with PM$_{2.5}$ as the only independent variable.

$^b$Generalized linear mixed effect models (equation (1)), adjusted by sex, age, urban/rural, marriage, education, obesity, smoker, drinker, prediagnosed stroke, prediagnosed hypertension and treatment, day of week, a spline term of long-term trend and a random community index term.

$^c$The full model, applied to the records with PM$_{2.5} < 75$ µg m$^{-3}$ at 1 lag day.

$^d$The full model, applied to the records with PM$_{2.5} < 75$ µg m$^{-3}$ during 0–3 lag days.
association between PM$_{2.5}$ and SBP among stroke patients (0.107 mmHg, 95% CI: 0.085, 0.130 mmHg) compared with the rest of the sample individuals (0.045 mmHg, 95% CI: 0.036, 0.053 mmHg)).

4. Discussion

Despite some nationwide PM$_{2.5}$-BP studies were reported for long-term exposure (Liu et al 2017), nation-scale evidence for short-term exposure is still scarce. This study adds evidence in support of the overall significant association between PM$_{2.5}$ exposure and acute BP increases, and establishes their exposure-response curves. Although subpopulation-specific associations were different, in population level, they were significantly positive and even at PM$_{2.5}$ concentration levels below the current China NAAQS. To the best of our knowledge, this study is the largest population study on the association between PM$_{2.5}$ and BP and presents the health effects of exposure to below-NAAQS PM$_{2.5}$ in China for the first time.

A recent meta-analysis (Yang et al 2018) derived pooled estimates for the effect of short-term PM$_{2.5}$ on SBP, DBP and HPN based on 13 609, 8627, and 20 006 samples from 30, 30 and 5 studies, respectively. They reported large between-study heterogeneity, particularly for the effects on SBP ($I^2 = 70.9\%$) and DBP ($I^2 = 64.9\%$). Our strength of the representative study population, which has much larger sample size than the meta-analysis, considerably diminished the heterogeneity in population compositions, the study designs, exposure assessment methods, etc. Our estimates were within the range of the reported results from existing evidence, however, they were relatively low. The possible explanations are, (a) most previous studies were conducted among vulnerable sub-populations, in which the PM-induced health effects are much higher (Cai et al 2016, Giorgini et al 2016, Guan et al 2018); while our study involved a large general population, which resulted in more generalizable findings. (b) Limited by the cross-sectional design and potential misclassification in the exposure assessment, it is possible that our study underestimates

![Figure 3. Nonlinear associations between blood pressure (BP) and acute exposure to PM$_{2.5}$ on the day before BP measurement. The gray histogram presents the probability distribution of acute exposure to PM$_{2.5}$ among the surveyed people.](image-url)
the PM$_{2.5}$-BP associations. (c) The unadjusted models generated stronger associations than the fully-adjusted models (figure S3), but they might mix the acute effect of PM$_{2.5}$ with its chronic effect due to the lack of controlling for spatial trends. However, given the poor air quality and the raising prevalence of HPN in China, even a small impact on BP and HPN risk elevation would have enormous public health implication.

To evaluate the health impacts of non-optimum air quality, PM$_{2.5}$-attributed mortalities and morbidities were often quantified; for health management or disease prevention, particularly at the individual level, however, such outcomes might be less predictive than some clinical or subclinical indicators of PM$_{2.5}$-associated risks. Here we applied elevated BP or HPN as an indicator of the adverse health impacts of short-term PM$_{2.5}$ exposure. Based on the subgroup-specific PM$_{2.5}$-BP associations and HPN prevalence, we calculated the attributable numbers or fractions according to (a) annually averaged concentrations of PM$_{2.5}$ in 2013–2017 and (b) different effect thresholds (See appendix 2 in supplemental materials). Due to China's clean air act, the air quality was considerably increased from 67.4 μg m$^{-3}$ in 2013 to 45.5 μg m$^{-3}$ in 2017 (Zheng et al 2017, Xue et al 2019). With reduced levels of PM$_{2.5}$ exposure, the related HPN burden continuously decreased during the period (figure 5). The threshold concentration, below which short-term exposure to ambient PM$_{2.5}$ would not affect BP, significantly changed the assessment results. In 2013, acute exposure to ambient PM$_{2.5}$ might contribute 0.74% (95% CI: 0.56%, 0.92%) of the total burden of HPN if the effect threshold was set as 75 μg m$^{-3}$, while the attributable fraction would considerably increase to 4.2% (95% CI: 3.2%, 5.2%) after changing the threshold to zero. Although the effect threshold is critical for understanding the risk of PM$_{2.5}$-associated HPN, it has been rarely examined in previous studies. It should be noticed that the PM$_{2.5}$-BP associations were based on analyses during 2013–2015, and might be appropriate to assess the burden in the next few years (e.g. 2016–2017), when the demographics were not considerably changed. Interpretation of our findings under different target populations should be cautious.

Although the PM$_{2.5}$-BP associations have been examined in some lightly polluted regions, the existing evidence remain inconsistent, even in Europe and North America (Yang et al 2018). The effect of short-term PM$_{2.5}$ on SBP or DBP was 0.14 mmHg (−1.03, 1.30) or −0.46 mmHg (−0.76, −0.16) in Europe and 0.97 mmHg (0.24, 1.70) or 0.69 mmHg (0.07, 1.31) in North America, respectively. Due to the poor air quality, the health effects of low-concentration PM$_{2.5}$ has rarely been examined among the Chinese population. We found that short-term exposure to less polluted air (PM$_{2.5}$ < 75 μg m$^{-3}$) among the Chinese adults was still significantly associated with elevated BP (table 2). Although this study did not directly test
whether the threshold concentration equals zero, it suggests that the cut-off value stays below China’s current criterion for short-term PM$_{2.5}$ concentration. According to China’s regulation of ambient air quality, very few hypersensitive people will be affected by ambient exposure to PM$_{2.5}$ below 75 µg m$^{-3}$, and these individuals are recommended to reduce outdoor activities. Our findings that there are statistically significant associations between elevated BP and below-criteria PM$_{2.5}$ in average level of all adults are opposite to such policy suggestions. Although these findings are not conclusive because of the limitations listed below, they can be used as guidance to policymakers to rethink demands to tighten related regulations.

This study is subject to the following limitations. First, to guarantee a sufficient sample size, particularly for the below-criteria models, the analyzed subjects were obtained from two national surveys. The data quality might be affected by inconsistency between the two surveys. For instance, the CHS reported BP as the average of three measurements, while for the CNSSS subjects, we calculated BP as the average of two arm-specific measurements. To examine the potential heterogeneity of the two databases, we created a binary variable to indicate the data source and explored the differences in the source-specific estimates of BP-PM$_{2.5}$ associations using a Wald test. Although we found no statistically significant difference for either SBP (P-value = 0.53) or DBP (P-value = 0.09), the potential influence of inconsistent data quality cannot be completely avoided.

Second, because the two databases were joined, we only adjusted a limited number of variables with consistent meanings as potential confounders in the statistical analyses. Therefore, some important confounders, such as genetic factors and dietary types (e.g. salt intake), were ignored, which may introduce biases into our findings. According to a national survey among 20 provinces in China during 2009–2011,
sodium intake was reported to be the highest in Guangxi, followed by Henan and Fujian (Hipgrave et al 2016). Henan has a high level of PM$_{2.5}$, but the other two have a low level. Although the simple comparison suggests no clear correlation between sodium intake and PM$_{2.5}$, we cannot rule out the possibility of a positive correlation, which might result in an overestimated association between PM$_{2.5}$ and BP elevation. Third, the estimated BP-PM$_{2.5}$ associations might also be confused by unmeasured environmental exposure that covaried with PM$_{2.5}$. For instance, due to the lack of monitoring data, we did not adjust for gaseous pollutants such as nitrogen dioxide or ozone, which have been reported to also be related to BP (Yang et al 2018). Therefore, in this study, PM$_{2.5}$ acted as the general indicator for air quality in China, and the estimated BP-PM$_{2.5}$ association could be attributable to PM$_{2.5}$ itself, or other correlated air pollutants. Given the complex collinearities, distinguishing the toxic species among multiple pollutants is challenging and will be explored in the next stage. Fourth, although this study was conducted at the individual level, it remains an ecological study due to the lack of follow-ups for each subject. Limited by potential ecological biases, the findings of this study, particularly the results of the below-criteria models, should not be overinterpreted. More studies with advanced designs (e.g. cohorts or longitudinal studies) should be performed to confirm or refute our findings. Fifth, due to the lack of specific addresses, we assigned all subjects from a community with the same time series of PM$_{2.5}$ exposure. This procedure ignores the microvariability of air quality in the spatial dimension and could cause exposure misclassification. Additionally, the exposure misclassification might originate from estimation errors associated with the PM$_{2.5}$ concentrations. Our findings enrich the epidemiological evidence on the population-level association between PM$_{2.5}$ and elevated BP among Chinese adults and suggest that policymakers should tighten current regulations of air quality to prevent HPN.

**Data availability statement**

The data that support the findings of this study are available upon reasonable request from the authors.

**Acknowledgments**

This study was supported by the CAMS Innovation Fund for Medical Sciences (Grant No. 2017-12M-1-004), the National Natural Science Foundation of China (Grant Nos. 71532014, 21507166), the China National Science and Technology Pillar Program (Grant No. 2011BAI11B01), and the National Health and Family Planning Commission, China (Grant No. 201402002).

For the CNSSS database, we are grateful to China Stroke Data Center, National Health Commission of China for all the support.

For the CHS database, the authors are grateful to OMRON Corporation, Kyoto, Japan, for supporting the Blood Pressure Monitor (HBP-1300) and body fat and weight measurement device (V-body HBF-371); Henan Huanan Medical Science &
Conflict of interest

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

ORCID iDs

Tianja Guan https://orcid.org/0000-0002-7820-2898
Zengwu Wang https://orcid.org/0000-0003-1613-5076

References

Brook R D et al 2010 Particulate matter air pollution and cardiovascular disease: an update to the scientific statement from the American Heart Association Circulation 121 2331–78
Cai Y Y et al 2016 Associations of short-term and long-term exposure to ambient air pollutants with hypertension a systematic review and meta-analysis Hypertension 68 62–70
Cohen A J et al 2017 Estimates and 25-year trends of the global burden of disease attributable to ambient air pollution: an analysis of data from the Global Burden of Diseases Study 2015 Lancet 389 1907–18
Di Q et al 2017a Association of short-term exposure to air pollution with mortality in older adults JAMA 318 2446–56
Di Q et al 2017b Air pollution and mortality in the medicare population N. Engl. J. Med. 376 2513–22
Dong G H et al 2013 Association between long-term air pollution and increased blood pressure and hypertension in China Hypertension 61 578–84
Ebel T S, Wilson W E and Brauer M 2005 Exposure to ambient and nonambient components of particulate matter: a comparison of health effects Epidemiology 16 396–405
Giorgini P, Giosia P, Grassi D, Rubenfire M, Brook R and Ferri C 2016 Air pollution exposure and blood pressure: an updated review of the literature Curr. Pharm. Des. 22 28–51
Guan T et al 2017 Rapid transitions in the epidemiology of stroke and its risk factors in China from 2002 to 2013 Neurology 89 53–61
Guan T et al 2018 Differential susceptibility in ambient particle-related first-ever stroke onset risk: findings from a national case-crossover study Am. J. Epidemiol. 187 1001–9
Guan T et al 2020 Geographic variations in the blood pressure responses to short-term fine particulate matter exposure in China Sci. Total Environ. 722 137842
Guo Y M, Tong S, Zhang Y S, Barnett A G, Jia Y and Pan X C 2010 The relationship between particulate air pollution and emergency hospital visits for hypertension in Beijing, China Sci. Total Environ. 408 4446–50
Hipgrave D B, Chang S, Li X and Wu Y 2016 Salt and sodium intake in China JAMA 315 703–5
Huang W et al 2018 Short-term blood pressure responses to ambient fine particulate matter exposures at the extremes of global air pollution concentrations Am. J. Hypertens. 31 590–9
Kawano Y 2011 Diurnal blood pressure variation and related behavioral factors Hypertension Res. 34 281–5
Lin H L et al 2017 Long-term effects of ambient PM2.5 on hypertension and blood pressure and attributable risk among older Chinese adults Hypertension 69 806–12
Linneberg A et al 2015 Effect of smoking on blood pressure and resting heart rate: a Mendelian randomization meta-analysis in the CARTA consortium Circ. Cardiovasc. Genet. 8 832–41
Liu C et al 2017 Associations between ambient fine particulate air pollution and hypertension: a nationwide cross-sectional study in China Sci. Total Environ. 584 869–74
Makr M, Antonelli J, Di Q, Cutler D, Schwartz J and Dominici F 2017 Estimating the causal effect of low levels of fine particulate matter on hospitalization Epidemiology 28 627–34
Shi L et al 2016 Low-concentration PM2.5 and mortality: estimating acute and chronic effects in a population-based study Environ. Health Perspect. 124 46–52
van Buuren S and Groothuis-Oudshoorn K 2011 Mice: multivariate imputation by chained equations in R J. Stat. Softw. 45 1–67
Wang Y H, Liu Z R, Zhang J K, Hu B, Ji D S, Yu Y C and Wang Y S 2015 Aerosol physicochemical properties and implications for visibility during an intense haze episode during winter in Beijing Atmos. Chem. Phys. 15 3205–3215
Wang Z et al 2014 Survey on prevalence of hypertension in China: background, aim, method and design Int. J. Cardiol. 174 721–3
Xue T et al 2017 Fusing observational, satellite remote sensing and air quality model simulated data to estimate spatiotemporal variations of PM2.5 exposure in China Remote Sens. 9 221
Xue T et al 2019 Rapid improvement of PM2.5 pollution and associated health benefits in China during 2013–2017 Sci. China Earth Sci. 62 1847–56
Yang B Y et al 2017 Is prehypertension more strongly associated with long-term ambient air pollution exposure than hypertension? Findings from the 33 communities Chinese health study Environ. Pollut. 229 696–704
Yang B Y et al 2018 Global association between ambient air pollution and blood pressure: a systematic review and meta-analysis Environ. Pollut. 235 576–88
Zhang Z et al 2018 Long-term exposure to fine particulate matter, blood pressure, and incident hypertension in Taiwanese adults Environ. Health Perspect. 126 017008
Zhao X, Zhang X, Xu X, Xu J, Meng W and Pu W 2009 Seasonal and diurnal variations of ambient PM2.5 concentration in urban and rural environments in Beijing Atmos. Environ. 43 2893–900
Zheng Y X et al 2017 Air quality improvements and health benefits from China's clean air action since 2013 Environ. Res. Lett. 12 114020